Energy Renovation towards Net-Zero Energy Buildings using Photovoltaic Systems and Batteries in Residential Buildings

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Master thesis in Energy-efficient and Environmental Buildings

Faculty of Engineering | Lund University

Lund University

Lund University, with eight faculties and a number of research centres and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 112 000 inhabitants. A number of departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and has today a total staff of 6 000 employees and 47 000 students attending 280 degree programmes and 2 300 subject courses offered by 63 departments.

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The degree project is the final part of the master programme leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

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Abstract

As the future energy goals of the building industry involve reducing the energy intensity in buildings as well as increasing the share of renewable energy sources, a suitable approach would be energy renovating existing buildings and further utilizing renewable energy production technology to reach Net-Zero Energy Building (NZEB) standard. This study is therefore investigating the economic feasibility of energy renovating buildings built during the Swedish Million program towards NZEB. The primary goals include finding suitable energy renovation- and PV system design strategies as well as assessing the economic impact in the scenario of removing the tax reduction for sold electricity.

In line with the Swedish NZEB standard, the buildings were initially renovated to passive house standard. From an economic perspective, numerous scenarios were then evaluated in terms of optimal battery and PV array size, optimal battery dispatch strategies, effects of removing the tax reduction for sold electricity, as well as variations in economical parameters such as interest rate and electricity price change. By utilizing well established energy- and PV simulation software, the evaluated buildings and PV systems were modelled to accurately resemble realistic conditions. With the results obtained from the simulations, the economic feasibility was assessed using life cycle cost calculations.

It was found that ambitious energy renovations, such as passive house renovations required by the Swedish NZEB standard, were not profitable in most cases. The evaluated PV systems with battery storage did however show profitability even in the least desired economical scenarios, indicating a low risk investment. By going beyond the requirements for NZEB and maximizing the PV output on the suitable surfaces, an even higher profitability was achieved. It was therefore concluded that, from an economic perspective, maximizing the possible PV output on suitable roof surfaces is preferable as an initial step. According to the PV energy output, the ambitions of renovation should then be adjusted to reach NZEB. This may however mean that the renovation measures might not fulfill the Swedish NZEB standard, indicating it is not primarily promoting economic profitability. It was moreover found that a discontinuation of the tax reduction for sold electricity will significantly increase the value of utilizing battery storage in a PV system while, in the case of the tax reduction being continued, implementation of batteries might not always be the optimal strategy as it does not entail a significant increased profit.

Preface

This study is the finishing chapter of our two years of studies at the master program Environmental- and Energy Efficient Building Design at Lund University, Campus Helsingborg.

We would like to direct a big gesture of appreciation to our supervisor Ricardo Bernardo for his support, interest and dedication in helping us realizing this study. Furthermore, the support given by friends and family has been gratefully acknowledged throughout this project.

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Karlstad Kommun - Figure 2. Typical single-family buildings built during the million program. Photo by Karlstad Kommun (karlstad.se)

Peter Jörgensen - Figure 4. Exterior view of Sems Have in Roskilde. Photo by Peter Jørgensen (byggeplads.dk)

3E - Figure 5. Rendered exterior view of De Duurzame Wijk in Belgium. Render by 3E (3e.eu)

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Abbreviations

A	Ampere (Unit)
AB	Aktiebolag/Stock Company
ACH	Air Change per Hour
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
A_{temp}	Heated floor area
BBR	Boverkets Byggregler/Boverket Building regulations
BREEAM	Building Research Establishment Environmental Assessment Methodology
CAEPBD	Concerted Action Energy Performance of Buildings
CO_2	Carbon Dioxide
DCV	Demand Controlled Ventilation
DHW	Domestic Hot Water
DVUT	Dimensionerande vinterutetemperatur/ Design winter outdoor temperature
FEBY	Forum för energieffektivt byggande/Forum for energy efficient construction
F_{geo}	Geographical Factor
GHG	Greenhouse Gas
HVAC	Heating Ventilation Air-Conditioning
I	Current
IDA ICE	IDA Indoor Climate and Energy
iPHA	international Passive House Institute
kWh	Kilowatt hour
kWp	Kilowatt peak
LCA	Life Cycle Assessment
LCC	Life Cycle Costs
LCP	Life Cycle Profitability
NREL	National Renewable Energy Laboratory
NZEB	Net-Zero Energy Building
PEF	Primary Energy Factor
PHI	Passive House Institute
PV	Photovoltaic
RISE	Research Institutes of Sweden
ROT	Renovering, Ombyggnad och Tillbyggnad/Renovation, Refurbishment and Extension
SAM	System Advisor Model
SEK	Swedish Krona
SOC	State of Charge
SVEBY	Standardisera och verifiera energiprestanda för byggnader/ Standardize and verify energyperformance for Buildings

SVL	Solvärmelast/ Solar heat load
U	Voltage
UA	Thermal Conduction
V	Voltage (Unit)
VFT	Värmeförlusttal/ Heat Loss Number

1 Introduction

Due to the recent escalation of melting glaciers, rising sea levels, climbing global temperatures and other phenomena, people all over the world have become more aware than ever about the state of our planet and its future (Revkin 2019). Research shows that human activity plays a big part in heating up the globe caused by the emissions of greenhouse gases (GHGs) to the atmosphere, which are at higher levels than they have been for the last 800 000 years (Nunez 2019).

According to the World Green Building Council (World Green Building Council 2017), about 39% of global GHGs come from the building and construction industry whereas 28% is associated with heating, cooling and lighting of the buildings and the remaining 11% due to embodied energy linked to materials and construction throughout the life span of the building. The report further reveals that, in order to meet the climate objectives, set out in the Paris agreement, the energy intensity per square meter in the global building sector needs to decrease by 30% until 2030, in reference to 2015.

A suitable strategy targeting these goals might involve energy retrofitting of existing buildings as well as making use of on-site renewable energy production. This study will therefore investigate the renovation possibilities of typical, representative buildings in the Swedish residential building stock, more specifically buildings built during the million program, aiming to reach the Net-Zero Energy Building (NZEB) standard by making use of on-site solar energy production in different economical scenarios.

1.1 Background information

In Sweden, the building and construction industry accounts for 19 %, or 12,2 tons, of the total GHG emissions domestically. Due to the importing of materials, an additional 5,9 tons of GHGs are moreover emitted outside of the country (Boverket 2020c). Since 1993, the emissions of the building and construction industry in Sweden have decreased by almost 50 %. Most of this decrease is due to efficiency strategies in heating of the buildings, such as added insulation or replacement of windows, whereas the emissions from construction and renovating has not seen a notable decrease (Boverket 2020c).

Furthermore, a third of the total energy production in Sweden is used by the building industry. About 75 % of this energy use is due to heating of buildings (Boverket 2020c). Although corresponding to a third of the total energy use, more than 60 % of this energy originates from renewable sources (Boverket 2020c). Considering the Swedish energy goals of 2020, reaching for a renewable energy share of 50 % in all sectors, the building industry is showing promising progress. There is however more to be done, as by 2030, the energy goals state a 100 % renewable electricity production as well as 50 % reduction in energy use intensity (Swedish Energy Agency 2020). By 2045, the goal is to reach net-zero emissions of GHGs.

As 80 % of the building stock that will exist in 2050 in Sweden has already been built (Lång 2019), it is in the existing building stock the greatest potential for accomplishing the energy and climate goals lies.

1.1.1 The Swedish Million program

Between 1965 and 1974, what is known as the “Million program” took place in Sweden. Also known as the “record years”, this refers to the period during which roughly one million dwellings were built to reduce the prevailing housing shortage. The most common building typology during these years were three-story multi-family buildings (Figure 1) accounting for more than half of the construction. However, single-family houses (Figure 2) were also common, making up about one third of the buildings. (Boverket 2020b)

Due to the rapid urbanization in the 1950s, a large housing demand quickly grew in the cities in Sweden. Together with the already existing low housing standards, the government decided to invest a substantial amount of money with the goal of constructing 100 000 dwellings annually during a period of 10 years, hence the name “Million program”. (Hall and Vidén 2005)

Today, these buildings accommodate around 25 % of the Swedish population and, the fact that they were built 50 years ago indicates a great need for renovation, both in respect to the climate as well as the living standards of the inhabitants (Naturskyddsföreningen 2016). According to the research institute RISE, more than half, or 400 000, of the multi-family buildings during the Million program have not been subject to any form of renovation since being built. Out of these, around 140 000 buildings are in critical need of renovation (Ferm 2019). This also goes for the single-family buildings whereas major problems caused by moisture have been encountered or are expected to be encountered in around 40% of the buildings (Hushuvud n.d.).

Figure 1. Typical three story multi-family building built during the million program. (Photo by authors)

Figure 2. Typical single-family buildings built during the million program. Photo by Karlstad Kommun (karlstad.se)

Construction properties and energy use

The common three-story multi-family buildings are generally characterized with a flat or low-pitched roof and a yellow or brown exterior brick facade. The load bearing construction consists of concrete walls in the interior of the building while the exterior walls are mere infill walls, most commonly of a concrete sandwich construction (Warfvinge, n.d.). Being poorly insulated and prone to air leakages, the thermal envelope is subject to a substantial amount of heat losses, not the least through thermal bridges caused by the balcony junctions (Warfvinge, n.d.).

Generally, the thermal envelope is insulated with 10 and 15 cm of insulation in the walls and roof, respectively. The U-value of the windows was usually around 3 W/(m2·K), to be compared to today's standard of around 1.2 W/(m^2·K). Mechanical exhaust air systems were predominant and ventilation heat recovery was uncommon. Moreover, the exhaust fans had low efficiencies, causing for a high building electricity demand.

The single-family buildings were normally constructed with similar insulation thicknesses and window properties. Thermal bridges were however less of an issue as balconies, one of the main causes for thermal bridges in the multi-family buildings, were not common in this building typology.

However, problems brought by moisture are a common occurrence in the single-family buildings. Some typical problems include inadequate ventilation flow and wooden construction materials in contact with wet concrete. Moreover, it is common to encounter critical materials, such as moisture barriers, that are past their life span, further indicating a need for renovation. (Hushuvud n.d.)

Statistics from the Swedish Energy Agency (Energimyndigheten) show that the average energy intensity for space heating and domestic hot water in multi-family buildings built during the record years is around 140 kWh/m^2. For buildings built between 2011 and 2015, the average energy intensity is 90 kWh/m^2 ('Energistatistik för flerbostadshus 2016 – Energy statistics for multi-dwelling buildings in 2016', n.d.). For single-family buildings, this value is slightly lower whereas an average of 110 kWh/m^2 is used in buildings built during the record years and 70 kWh/m^2 in buildings built between 2011 and 2015.

1.1.2 Swedish energy regulations

The Building Regulations from the National Board of Housing, Building and Planning (*BBR, Boverkets Byggregler*) contains regulations and general guidelines in line with the Swedish Planning and Building Act (*Plan- och bygglagen*). Such regulations and advice include fire safety, environmental- and health issues and energy use. (Boverket 2020a)

The regulations regarding energy use are found in the ninth chapter of BBR and the general guideline states that "Buildings should be designed so that the energy use is limited through low heat losses, low cooling demand, effective use of heating and cooling and effective use of electricity" ('Boverkets byggregler (2011:6) – föreskrifter och allmänna råd', n.d.). More specifically, new buildings and buildings that are subject to substantial renovation must fulfill certain requirements regarding delivered primary energy, installed power for heating, average U-value of the thermal envelope as well as air leakage using the blower door test.

In BBR, the delivered energy to a building is the sum of the energy delivered for heating, cooling, domestic hot water and building electricity. Furthermore, each energy carrier is to be multiplied by its respective primary energy factor (PEF) as a means to include the energy needed at the source relative to what is delivered to the building (Table 1). Due to the difference of climate conditions in different areas of Sweden, the heating energy is moreover divided by a geographical factor (F^{geo}) ranging from 0.8 in the south to 1.8 in the north ('Boverkets byggregler (2011:6) – föreskrifter och allmänna råd', n.d.). The maximum allowed delivered energy, installed power for heating, average U-values and air leakage is presented in Table 2 ('Boverkets byggregler (2011:6) – föreskrifter och allmänna råd', n.d.).

Table 1. Primary energy factors according to BBR ('Boverkets byggregler (2011:6) – föreskrifter och allmänna råd', n.d.)

Energy carrier	Primary energy factor
Electricity	1.6
District heat	1.0
District cold	1.0
Bio fuel	1.0
Oil	1.0
Gas	1.0

Table 2. Energy requirements according to BBR ('Boverkets byggregler (2011:6) – föreskrifter och allmänna råd', n.d.)

Building type	Annual primary energy use / kWh/m2	Installed power for heating / kW	Average U-value / W/m2K	Air leakage at 50 pa pressure difference / l/sm2
Single-family houses	90	4,5 + 1,7 * (Fgeo-1)	0.4	Low enough to fulfill primary energy and installed heating power requirements
Multi-family houses	85			

1.2 Motivation

Being accountable for 19 % of the GHG emissions and a third of the energy use in Sweden, the building industry carries great potential for reaching the climate and energy goals. By focusing on the existing building stock, where the possibilities are perhaps most plentiful, the building industry will likely entail significant progression in the effort towards the energy goals and net-zero GHG emissions.

As the buildings specifically investigated in this study are expected to remain for many years to come, reaching for building performances well above the current standards might be the preferable ambitions to pursue as it will entail a longer technical life span and thus diminish the need for further renovations in the near future.

Additionally, implementing on-site renewable energy production on a large scale might lead to more rapid development of such markets, which is much needed given the prevailing out phasing of fossil fuel energy production.

1.3 Aim and objectives

In relevance to the problem motivation, this study aims to investigate the possibilities for energy retrofitting existing multi-family residential buildings, built during the record years, as well as implementing on-site solar electricity production towards reaching the NZEB standard.

The objectives include finding feasible strategies for energy retrofitting, PV system design and energy storage and dispatching approaches through batteries. To enforce feasibility, said strategies are based on life-cycle cost calculations to ensure economical sustainability.

1.4 Limitations

This study primarily focuses on the design of PV systems and batteries towards NZEB from an economical viewpoint. The renovation was performed using simple passive house strategies, in line with the Swedish passive house standard, where the heat loss indicator (värmeförlusttalet, VFT) and primary energy use were the only requirements to be met. Thus, thermal comfort, sound quality and moisture safety were not part of this study. Furthermore, only two building typologies were covered in this study, namely a single family building and a multi family building, both from the million program.

All energy and PV simulations were performed using climate data of Helsingborg in southern Sweden. Moreover, all buildings evaluated were assumed to be south oriented with half of the roof surfaces facing south and the other half facing north. In addition, as only roof surfaces were considered in the PV simulations, it was assumed that no shading was present. This means that the results of this study only may be comparable to buildings with similar geographical and on-site conditions.

Regarding the passive house renovation, investment costs from previous passive house renovations for similar buildings were used in this study whereas the costs were not calculated for the specific energy improvement measures taken in this study. The energy improvement measures were moreover solely based on reaching the Swedish passive house standard whereas no optimization strategies were carried out

In terms of life cycle studies only the life cycle profitability was performed. Environmental studies such as LCA was not covered in this study.

1.5 Research questions

This study is intended to investigate the following research questions:

What strategies should be used to energy renovate and design a PV system to reach NZEB for several building typologies?

What are the most adequate design strategies for batteries in combination with PV toward meeting NZEB for several building typologies?

How would removing the tax reduction affect the economic feasibility of a PV system with and without a rechargeable battery toward meeting NZEB for several building typologies?

What should be the maximum battery cost (SEK/kWh) for the PV system with and without tax reduction for economic viability?

2 Literature review

The literature review includes general information that is a prerequisite to be familiar with in order to understand the work process and the decisions that were made in this study. A brief introduction of the building standards considered in this project are initially presented, whereas principles and examples of such buildings are described further. Finally, a review of the current state of the Photovoltaic (PV) and battery market in Sweden is presented, including cost trends and extent of utilization.

2.1 Passive houses

A passive house is generally known as a highly energy-efficient building that is able to reduce its heating demand by up to 90% compared to conventional buildings (‘What Is a Passive House? [ ]’ n.d.). Through implementing high quality thermal envelopes with thick insulation and high air tightness, the passive house keeps a more stable indoor climate with minimal heat losses through transmission and infiltration. Being able to keep more of the heat energy inside the thermal envelope subsequently allows for more effective utilization of internal heat gains, such as those from the occupants, electrical equipment, and solar irradiation to further reduce the heating demand (‘Passivhaus Institut’ n.d.).

The passive house concept was first coined by Wolfgang Feist and Bo Adamsson during a research project at Lund University, Sweden in 1988. The project concluded that by considering five key principles, a building in a central European climate could be heated “passively” by solar and internal heat gains. These five principles were: excellent insulation, prevention of thermal bridges, airtightness, insulated glazing and controlled ventilation (‘The World’s First Passive House, Darmstadt-Kranichstein, Germany [ ]’ n.d.).

In 1991, the first passive house was built, in Darmstadt Kranichtein, Germany. The building was constructed with, at that time, significantly low U-values of the thermal envelope as well as a demand-controlled ventilation system with 80% heat recovery efficiency. The measurements of the building’s energy balance since it started operating has shown an average annual heating demand of less than 10 kWh (‘The World’s First Passive House, Darmstadt-Kranichstein, Germany [ ]’ n.d.).

Since 1996, the official passive house standard is governed by German Pasivhaus Institut (Passive house institute). To achieve a passive house standard, the Passivhaus Institut states four main criteria as directly transcribed below (‘Passivhaus Institut’ n.d.):

1. The Space Heating Energy Demand is not to exceed 15 kWh per square meter of net living space (treated floor area) per year or 10 W per square meter peak demand.
In climates where active cooling is needed, the Space Cooling Energy Demand requirement roughly matches the heat demand requirements above, with an additional allowance for dehumidification.

2. The Renewable Primary Energy Demand (PER, according to PHI method), the total energy to be used for all domestic applications (heating, hot water and domestic electricity) must not exceed 60 kWh per square meter of treated floor area per year.

3. In terms of airtightness, a maximum of 0.6 air changes per hour at 50 Pascal pressure difference (ACH50), as verified with an onsite pressure test (in both pressurized and depressurized states).

4. Thermal comfort must be met for all living areas during winter as well as in summer, with not more than 10 % of the hours in a given year over 25 °C.

Several countries have however developed their own requirements adapted to their climate conditions.

2.1.1 Passive house in Sweden

The first passive houses in Sweden were completed in 2001. The project was carried out by EEFM Arkitektkontor, Energy and Building Design at Lund University, Chalmers University of Technology as well as the Swedish National Testing and Research Institute and resulted in 20 terrace houses achieving passive house standard, located in Lindås, outside Gothenburg (Wall 2005). Since its completion, the passive houses in Lindås have acted as inspiration for subsequent passive house developers in Sweden and have been subject to several educational visits (Janson 2010). The Lindås passive houses followed the original passive house standards now directed by Passivhaus Institut. Since then, an adapted standard has been developed in Sweden to correspond to the Swedish climate conditions and building codes.

The current official definition for the passive house standard in Sweden is directed by FEBY (*Forum för energieffektivt byggande*/Forum for energy efficient construction). The FEBY standard consists of three different grading levels, bronze, silver and gold, where gold corresponds to the Swedish passive house standard. ('Kravspecifikation För Energieffektiva Byggnader' 2018)

Reaching the gold level includes fulfilling certain requirements regarding heat losses at design winter outdoor temperature (DVUT), annual delivered energy, air tightness, indoor thermal comfort, sound quality and moisture safety. ('Kravspecifikation För Energieffektiva Byggnader' 2018) The criteria for indoor thermal comfort, sound quality and moisture safety are not described further here, in line with the limitations of this study.

The heat losses are expressed as a heat loss coefficient at design winter outdoor temperature, DVUT (VFT_{DVUT}) and is measured in W/m^2. This term considers the sum of all heat losses through transmission, infiltration and ventilation, normalized to the floor area. The FEBY gold level requires a maximum VFT_{DVUT} of 14 W/m^2. Additions to the maximum allowed VFT_{DVUT} may however be made if the building has a floor area of less than 600 m^2 according to equation 1. ('Kravspecifikation För Energieffektiva Byggnader' 2018)

$$VFT_{DVUT,MAX} = 14 + \left(\frac{600 - A_{temp}}{110}\right) \tag{1}$$

Regarding maximum annual delivered energy, the criteria in FEBY only apply to electrically heated buildings. For non-electrically heated buildings, the maximum annual delivered energy to fulfill any of the FEBY grading levels is in line with the requirements stated in BBR. An electrical heated building must however have an annual delivered primary energy of no more than 26 kWh/m^2, including delivered primary energy for heating, cooling, domestic hot water and building electricity. ('Kravspecifikation För Energieffektiva Byggnader' 2018)

The indoor thermal comfort criteria are fulfilled either by presenting calculations of the indoor temperature between the months of April through September or alternatively by calculating the Solar heat load coefficient (SVL). Furthermore, an air tightness of maximum 0.3 l/(s·m^2) at 50 pa pressure difference is required.

A summary of the criteria for FEBY Gold, in addition to the criteria in BBR, is presented in Table 3. Note that an addition to the heat loss coefficient can be made for buildings with a floor area of less than 600 m^2 according to equation 1.

Table 3. Requirements for FEBY Gold

Heating system	Annual delivered primary energy / kWh/m2	Heat loss coefficient / W/m2	Air leakage at 50 pa / l/(s/m2)
Electrical	26	14	0.3
Non-electrical	According to BBR		

2.1.2 Passive house design principles

Thermal envelope

In line with the definitions of a passive house, limiting the heat losses through the thermal envelope, a key principle to consider while designing a passive house, is making sure the thermal envelope will maintain the heat energy inside the building. This can be achieved by using highly insulating materials, thus keeping the U-values low. In Swedish passive houses, the mean U-value of the opaque elements is around 0.1 W/(m^2·K).

Moreover, assuring minimal losses through thermal bridges will furthermore limit the heat losses. By planning the insulation in such a way that, from a section drawing, one can outline the minimum insulation thickness around the whole thermal envelope without a break, a satisfactory design regarding thermal bridges is achieved. ('What Defines Thermal Bridge Free Design? [ ]' n.d.)

Air tightness

The requirements for air tightness in a passive house are strictly set for several reasons. Air leakage through the building envelope increases the risk of draught which may lead to insufficient thermal comfort. Furthermore, warm and humid indoor air leaking into the construction of the building may lead to moisture issues as the air condensates inside the construction. Cold outdoor air infiltrating to the inside of the building may moreover result in an increased heating demand as it is not passed through the heat recovery in the ventilation system. (Janson 2010)

A conclusion made in the Lindås project was that air tightness is one of the more essential factor to consider in order to reach the required values for peak load and space heating demand. (Wall 2005)

Windows and solar gains

Other than having energy efficient windows in regard to low U-value, recommended to be 0.8 $W/(m^2 \cdot K)$ or below, it is also important to consider the placement of the windows and the overall window to wall ratio. As one of the key principles of a passive house is utilizing solar heat gains, windows should, in buildings located in the northern hemisphere, preferably be oriented towards south. During heating season, up to 20 % of the heating demand can be covered by passive solar gains, according to Ekobyggportalen. ('Ekobyggportalen » Passiv solvärme' n.d.)

During cooling season, however, it is less desired to gain extra heating from the sun. To reduce overheating during this period, it is therefore advantageous to implement window overhangs or shading devices which will let the winter sun in and keep the summer sun out. (Janson 2010)

Ventilation

A great share of the thermal comfort, indoor air quality and heat losses can be managed by utilizing the right ventilation system. By being able to mechanically control the ventilation air flow, these factors can be optimized. It is therefore preferable to use a mechanical ventilation system with heat recovery. (Hastings and Wall 2012)

Such a system provides a constantly sufficient air flow as well as heat recovery from the exhaust air, resulting in a significantly improved indoor climate as well as saved heating energy. (Janson 2010) According to the international passive house institution (iPHA), a ventilation system without heat recovery may waste about 24 kWh/m^2 annually. They further recommend the heat exchange efficiency to be at least 75 %.

2.2 Net-Zero Energy Buildings (NZEB)

Perhaps one of the most ambitious building energy definition to achieve is the Net-Zero Energy Building standard (NZEB). In short, a NZEB produces as much energy as it usess at an annual basis by implementation of renewable energy production technology. (Kanters and Wall 2014)

Through highly efficient thermal envelopes, HVAC systems and other strategies, a NZEB operates with low energy needs, allowing the remaining energy to be covered by on-site renewable energy production. (Torcellini, Pless, and Deru, n.d.) Typical renewable energy production technologies include PV, solar hot water, wind, hydroelectric, and biofuels where rooftop PV and solar water heating are the most applicable supply-side technologies for widespread application of NZEBs. It is preferred, and in some national standards mandatory, to have on-site energy production, as opposed to off-site. This is mainly to encourage a reduction of building energy demand, prior to implementing the production facility. (Torcellini, Pless, and Deru, n.d.)

There is however no official definition to what constitutes a NZEB. The definition might depend on the goals of the project and the building owner. For a private owner, cost might be the limiting factor whereas a Net Zero Energy Cost might be the preferable choice. In other cases, the environmental impact could be main concern, in which Net Zero Energy Emission would be favored. (Torcellini, Pless, and Deru, n.d.)

NZEB in Sweden

In Sweden, the NZEB definition is governed by FEBY, referred to as *FEBY Gold Plus house*. The requirements of reaching the Swedish NZEB involves fulfilling the Swedish Passive House standard (FEBY Gold) as well as implementing on-site renewable energy production in order to gain a net-zero or surplus yearly energy balance. (‘Kravspecifikation För Energieffektiva Byggnader’ 2018)

The same methodology for delivered energy according to BBR is applied to the on-site produced energy (including both self-consumption and sold electricity), meaning that if PV generated electricity is produced at the site, it is multiplied by the primary energy factor for electricity before it is included in the net-zero energy balance.(‘Kravspecifikation För Energieffektiva Byggnader’ 2018) This balance is calculated according to the instructions given in BBR for weighted delivered energy.

Examples of existing NZEB in Europe

A report describing several existing NZEB buildings in Europe was compiled by The Concerted Action Energy Performance of Buildings (CA EPBD) in 2014. Out of 32 evaluated buildings, 22 were residential. 25 of the buildings were new constructions and 7 were renovations. The buildings evaluated are a mix of Net-ZEB and Nearly-ZEB buildings. (Erhorn and Erhorn-Kluttig 2014)

The most common heating system was shown to be a heat pump, corresponding to 41 % of the evaluated buildings where ground source and air-to-air were the most prevalent types. Moreover, a mechanical ventilation system with heat recovery was implemented in 85 % of the buildings while the remaining buildings relied on a system without heat recovery or simply used natural ventilation.(Erhorn and Erhorn-Kluttig 2014) PV systems were found to be the most frequent type of on-site renewable energy production, being installed in 70 % of the buildings. Solar thermal systems were moreover implemented in about half of the evaluated buildings. (Erhorn and Erhorn-Kluttig 2014)

The additional costs brought by the projects aiming for NZEB standard, compared to the national building code was assessed for each project. The results showed that, on average, an additional 11 % or roughly 2 100 SEK/m^2 was required to reach NZEB (Erhorn and Erhorn-Kluttig 2014). Three of the buildings evaluated in the previously mentioned report are described below. It should be noted that all buildings do not follow the same national standards and definitions and might therefore have different outcomes depending on which standard that was followed. A summary of the buildings, including location, energy balance and on-site production technology is presented in Table 4.

Table 4. Summary of three different NZEB buildings in Europe

Building name	**Väla Gård**	**Sems Have**	**De Duurzame Wijk**
Location	Helsingborg, Sweden	Roskilde, Denmark	Waregem, Belgium
Building type	Office building	Multi-family house	Multi-family house
Heated floor area / m^2	1750	3388	1050
Heating system	Ground source heat pump	District heating	12 kW Gas boiler
On-site energy production technology	71 kWp PV system	17.3 kWp PV system	3.8 kWp PV system
Construction part	**U-value / W/(m²K)**	**U-value / W/(m²K)**	**U-value / W/(m²K)**
Exterior wall	0.11	0.2	0.12-0.13
Exterior roof	0.08-0.1	0.09	0.13
Ground	0.08	1.1	0.1
Windows	1	1.0	0.78 (1.01 for roof
Energy (primary)	**Annual energy / kWh/m²**	**Annual energy / kWh/m²**	**Annual energy / kWh/m²**
Delievered energy	66.3	23.1	49
On-site produced energy	56.3	6.93	55
Energy balance	10	16.17	-6

Väla Gård

Outside the city of Helsingborg in southern Sweden, the office of Skanska, more known as Väla Gård (Figure 3) has been operating since it was finished in 2012. Being built according to the LEED standard, the project acquired 98 out of 110 possible points, making it the second-best LEED certified building in the world in 2012. (Aronsson 2012)

Figure 3. Exterior view of Väla Gård in Helsingborg, Sweden. Photo by authors

Väla Gård consists of two main two-story buildings with a pitched roof, connected through a smaller building in between. The load bearing structure consists of prefabricated concrete around the whole thermal envelope. To reach low U-values and reduce transmission losses, thick insulation layers are added in the wall, roof and ground construction. (Kempe 2014)

The heating, including domestic hot water is covered by a ground source heat pump system from which free cooling can also be extracted when needed. As a measure to reduce building electricity, a mechanical supply and exhaust air system with demand-controlled ventilation (DCV) and a heat recovery efficiency of 80 % is installed. The air flows are controlled by presence, CO2-levels and temperature meaning it is only running at full capacity when needed. The specific fan powers are furthermore kept at low levels of around 0.7-0.8 kW/ (m^3/s).

The south west facing roofs are covered in 288 PV panels resulting in a 71 kWp system able to annually produce around 67 000 kWh (Kempe 2014). The resulting energy balance is 10 kWh/m^2 on an annual basis, meaning a net total 10 kWh/m^2 is required from the grid. Further studies have however shown that, by utilizing energy storage in batteries, the annual energy balance can be reduced to around 5 kWh/m^2. (Kempe 2014)

Sems Have

In Roskilde, Denmark, a former dormitory- and day care center, distributed in two buildings blocks, were renovated and transformed into 30 low-energy apartments (Figure 4). The buildings had gone past its technical life span and could no longer be used for its original purpose, which was the main reason for the renovation. The main renovation measures taken were improvements to the thermal envelope, implementation of a mechanical ventilation system with heat recovery as well as installing a PV system on the roof. (‘Sems Have, Roskilde’, n.d.)


Figure 4. Exterior view of Sems Have in Roskilde. Photo by Peter Jørgensen (byggeplads.dk)

The buildings were constructed with an internal loadbearing concrete construction with panel walls, to which 100 mm of insulation was added during the renovation. In the roof construction, 200 mm of insulation was added, resulting in a total thickness of 400 mm. The windows were furthermore replaced from double glazed windows with a U-value of 2.8 $W/(m^2 \cdot K)$ to triple glazed low-energy windows with a U-value of 1.0 $W/(m^2 \cdot K)$. ('Sems Have, Roskilde', n.d.)

Due to great losses in the old district heating system, new circuits and tanks were installed with a significantly lower heat loss coefficient. The former ventilation system was replaced from a combination of mechanical and natural ventilation to a pure mechanical ventilation system with a heat recovery efficiency of 84 %. ('Sems Have, Roskilde', n.d.)

A PV system was installed on the roof of each building totaling up to a 17.3 kWp system generating roughly 14 000 kWh annually. With all energy improvements to the buildings, calculations resulted in an annual energy demand of 16.17 kWh/m^2 (Erhorn and Erhorn-Kluttig 2014)

De Duurzame Wijk

In the Flemish region of Belgium, a multi-family house consisting of 7 individual dwellings is under construction (Figure 5). The project strives for ecological and energy-efficient living, using sustainable materials and efficient building technologies. It is furthermore expected to reach the BREEAM Excellent standard.('De Duurzame Wijk: Waarom? | Wienerberger' n.d.)

Figure 5. Rendered exterior view of De Duurzame Wijk in Belgium. Render by 3E (3e.eu)

The supporting structure of the building consists of reinforced concrete and masonry walls. In the wall, roof and ground construction, 24, 36 and 19 cm of insulation is added respectively to minimize the transmission losses. According to previous simulation, the energy performance will fulfill the Belgian standard expected in the year 2021. ('De Duurzame Wijk: 7 Woningen | Wienerberger' n.d.)

A 12 kW gas boiler with exhaust gas heat recovery covers most of the heating demand in the buildings, including domestic hot water. The heat is distributed through an underfloor heating system in the living rooms and kitchens. The bathrooms are equipped with electric towel rails. To reduce the heating demand even further, and to be able to control the indoor climate, a mechanical supply and exhaust air system with an 85 % heat recovery efficiency is installed. (Meuleman 2013)

On the south-facing roof, a 3.8 kWp PV system is installed, estimated to annually produce approximately 22 kWh/m^2. As a result, De Duurzame Wijk can claim itself as a NZEB with a final primary energy use of –6 kWh/m^2. ('De Duurzame Wijk: 7 Woningen | Wienerberger' n.d.)

2.3 Swedish PV market and battery storage

According to the Swedish Energy Agency only PV systems with a capacity over 40 W are considered in the national market. Furthermore, a PV system include modules, inverters, batteries and all other necessary installation and monitoring devices to operate the system. (Lindhal 2017)

Before 2006 the Swedish PV market consisted mostly of small but quite stable off-grid PV systems. Since no feed-in tariff or subsidies existed at that point the system was designed towards self-consumption. However, with the implementation of subsidies for public buildings in 2005 and further subsidies in 2009 the PV trend changed to grid connected systems (Lindhal 2017). By 2018 the installed grid connected PV capacity was 28 times larger than the off-grid PV capacity. Figure 6 and Figure 7 illustrate the installed grid connected and off grid PV power in Sweden. It is obvious that PV systems mounted on commercial facilities and single-family building are leading the market followed by multifamily buildings and PV parks as the lowest share.

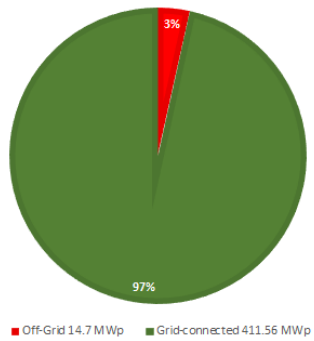

Figure 6. Total installed PV power in Sweden by 2018 (Lindhal et al. 2019)

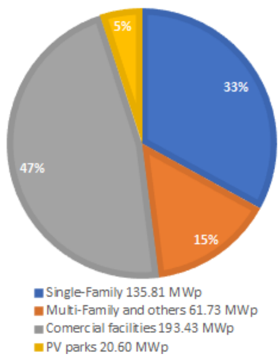

Figure 7. Grid connect share of PV power by 2018 (Lindhal et al. 2019)

Figure 8 illustrates that the gross amount of electrical energy is generated by nuclear and hydro power plants while energy from PV is lagging far behind with a production of about 0.2 TWh/a.

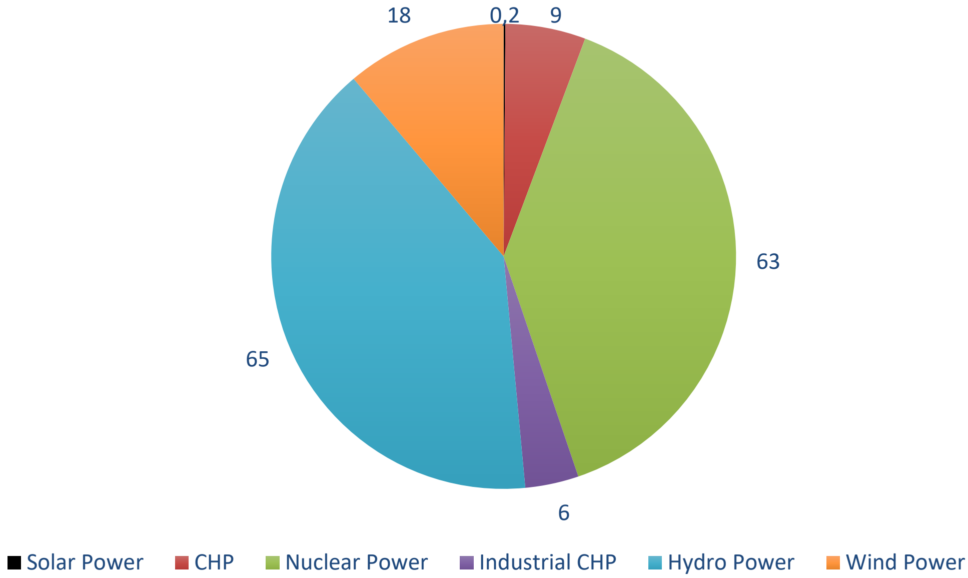

Figure 8. Share of annual electrical energy generation in TWh in Sweden 2017 ('Energy in Sweden 2019' 2020)

One reason for this is probably the cheaper electrical energy generated by nuclear power and hydropower due to much lower investment cost . According to Max Ahman nuclear and hydro power plants have investment costs of about 40 Öre/kWh and 10-15 Öre/kWh (Ahman n.d.) for operation and fuel costs. However, the initial costs for a solar system are 160 Öre/kWh (Ahman n.d.).

Furthermore, the CO2 emissions for generating electrical energy from nuclear and hydro power plants are much smaller than for energy generated by photovoltaic. The yearly LCA report of Vatenfall showed that nuclear power plants emit about 3.5 gCO_2/kWh followed by hydro power plants with 8.5 gCO_2/kWh and wind power with about 15 gCO_2/kWh ('Life Cycle Assessment for Vattenfall's Electricity Generation' 2019). Biomass emissions vary between 8.5 to 18 gCO_2/kWh while as solar power is the backmarker with approximately 26 gCO_2/kWh ('Life Cycle Assessment for Vattenfall's Electricity Generation' 2019) .

In the past decade the electricity price in Sweden was mainly depending on the hydrological balance as well as the availability of nuclear power (Lundberg, n.d.) since these two energy sources have the biggest share in the energy mix as mentioned above . However, since more wind power is being installed the dependence of the electricity is shifting more and more towards windy days ('Why Electricity Prices Are Set for Record Lows throughout 2020 in Sweden' 2020). This so-called spot price is traded on the Nordpool electricity market which is accessible online and can change hourly (Lundberg, n.d.). In general, electricity prices in winter are higher than in summer. As an electricity consumer, the spot price is just one fraction of the actual electricity price which must be paid. This electricity price includes different taxes, certificates and transfer charges of the grid operator (Lindhal et al. 2019). As an owner of a PV system the sold energy has a lower value than bought energy from the grid. The price for buying and selling electricity to the grid is shown in Figure 9.

However, the Swedish government supports the generation of electricity from PV in the form of tax reduction, which is 0.6 SEK/kWh ('Löpande Intäkter Efter Installation' 2019). Nevertheless, the Swedish government set certain limits for the amount of tax reduction which can be received. The maximum amount which can be received is 18 000 SEK/a or for no more than 30 000 kWh/a (skatteverket.se n.d.). Furthermore, tax reduction can only be received for not more than the amount of energy which is bought from the grid (skatteverket.se n.d.). For example, if 10 000 kWh/a is bought from the grid it is only possible to get tax reduction for up to 10 000 kWh/a even though the upper limit is 30 000 kWh/a. Every kilowatt hour exceeding 10 000 kWh would then be sold for the spot price on the market.

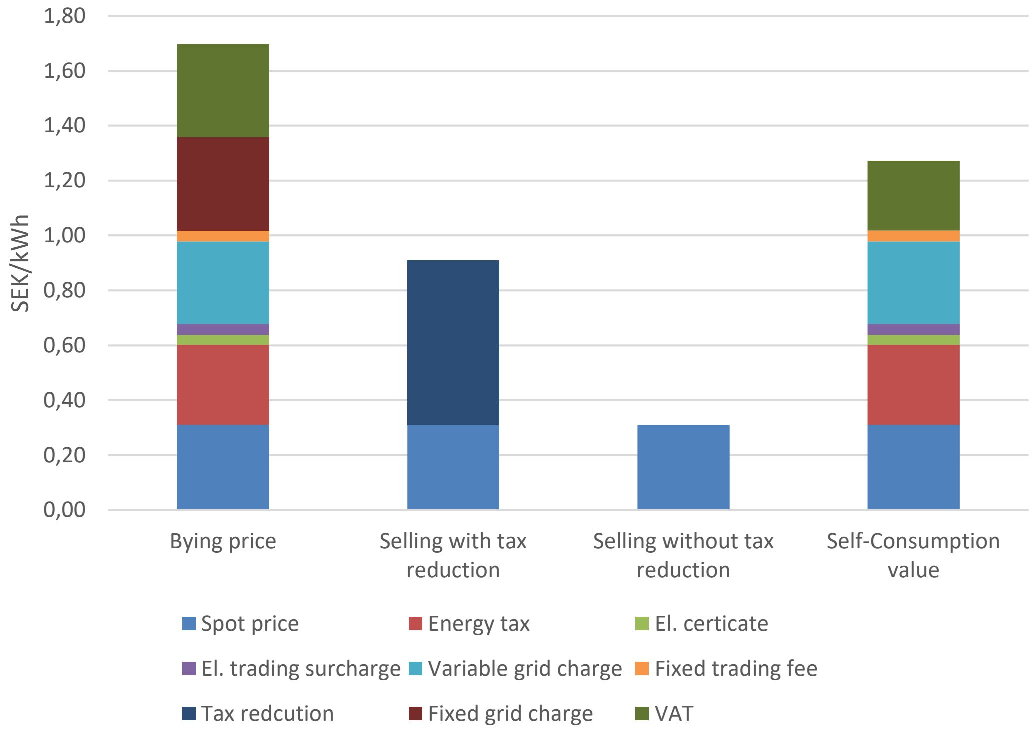

Figure 9. Swedish electricity price cost components (Lindhal et al. 2019)

Besides the tax reduction on sold energy the Swedish government also offers different types of subsidies on solar system installations. The different types are shown in Table 5 below.

Table 5. Swedish investment subsidies on photovoltaic powerplants in Sweden ('Stöd Som Du Kan Få Vid Investering' n.d.)

Who can receive the support?	**Revenue and scope**
Individuals and companies	**Investment** • Contribution of 20% of the investment cost. • Cannot be combined with ROT-deduction. • One-off investment amount. • Applications from companies must have been received before the project started.
Individuals	**ROT-deduction** • Tax reduction of about 9% of the investment cost. • Cannot be combined with investment support. • One-off investment amount.
Individuals	**Investment aid for the storage of self-generated electrical energy**

	• Contribution of 60% of the investment cost, but a maximum of SEK 50,000. • Must be connected to the grid and connected to a plant for self-production of renewable electricity.
Companies in agriculture, gardening, or reindeer husbandry	**Support for companies in agriculture, gardening or reindeer husbandry** • Grants of 40% of eligible expenditure • Unable to combine with investment support

Figure 10 illustrates the share of cost of a typical 4-6 kWp residential roof-mounted PV system. The total cost sums up to about 19.5 SEK/Wp, including VAT (Lindhal 2017). In comparison to that, a commercially installed system has total cost of about 12.7 SEK/Wp. Generally, most items for a commercial used PV system are cheaper. Furthermore, no VAT must be paid by a company in opposite to a private consumer.

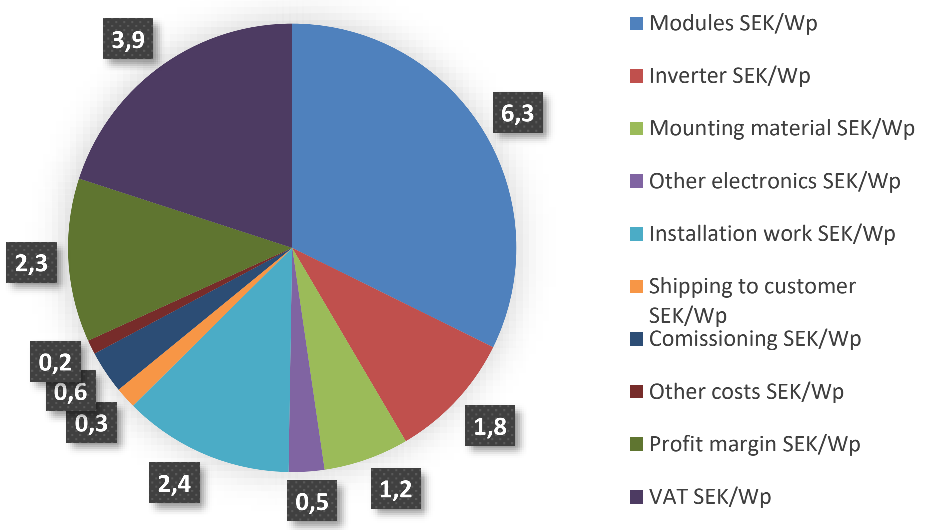

Figure 10. Cost components of a 4-6 kWp singe family PV system (Lindhal 2017)

According to *MarketsandMarkets* the battery storage energy market is about to grow from 2 billion USD in 2018 to about 8.5 billion USD in 2023 ('Battery Energy Storage System Market by Element, Battery Type,Connection Type| COVID-19 Impact Analysis | MarketsandMarkets™' n.d.). It is expected that the market will be dominated by the lithium-ion batteries due to their high energy density, low standby losses, low maintenance need and other technical advantages ('Battery Energy Storage System Market by Element, Battery Type,Connection Type| COVID-19 Impact Analysis | MarketsandMarkets™' n.d.). Figure 11 shows that the price of lithium-ion is falling constantly since 2010 until 2017. Bloomberg forecasts that this trend is going to continue and that by 2030 the price could drop down to $62/kWh.

Reasons for this price fall are the technological improvements in pack design and enhance of energy density at cathode and cell level. Furthermore, a more efficient manufacturing equipment as well as the growth in electrical vehicle sales lead to lower factory and production costs.

Figure 11. Lithium-Ion price trend (historical and forecast) ('A Behind the Scenes Take on Lithium-Ion Battery Prices' 2019)

3 Methodology

To conduct this study, mostly quantitative methods will be applied. Initially, a literature review will be performed to gather necessary information and subsequently support the following data processing. The next phase of the study will consist of simulations and parametric studies. The analysis includes: energy modelling of representative building(s); energy renovation toward passive house standard; modelling of PV array(s) toward NZEB; modelling of adequate battery storage; economic viability of using batteries for other uses such as dispatch strategy according to electricity rates; estimation of minimum battery costs for profitability; LCC calculations for scenarios of exporting and storing energy; sensitivity analysis on electricity prices and other variables. Figure 12 illustrates the general work process.

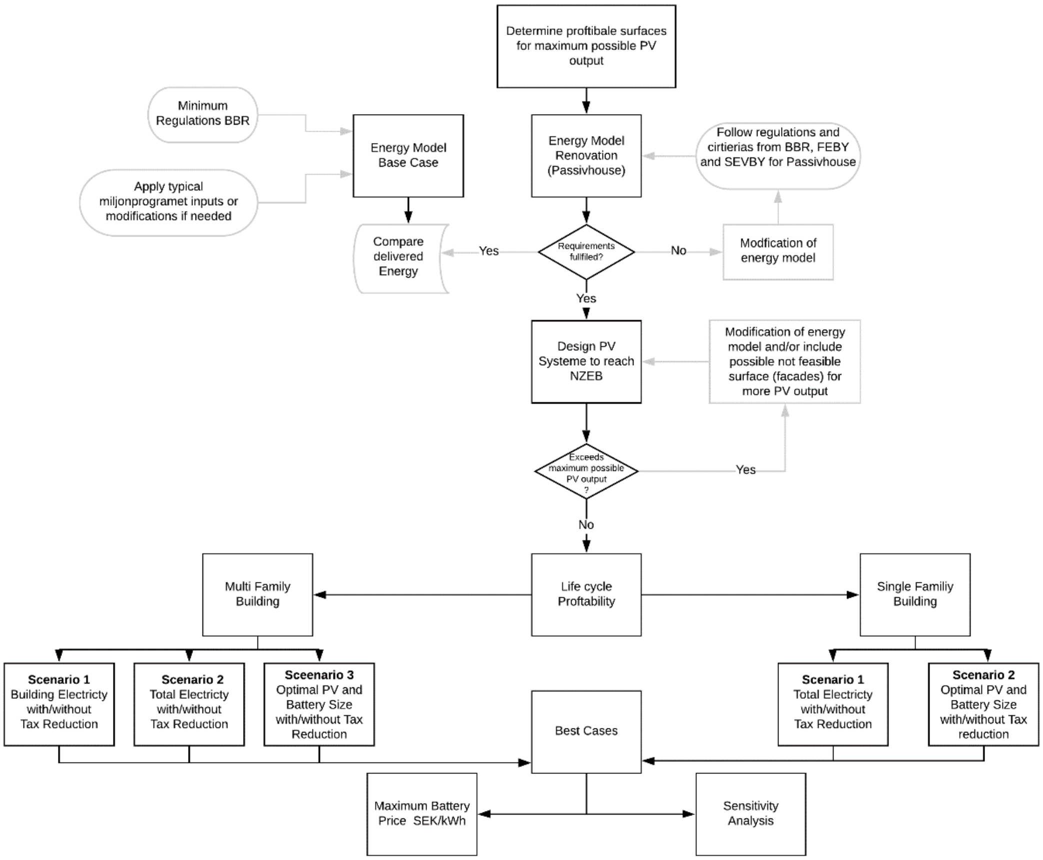

Figure 12. Work Process

3.1 Energy modelling and inputs

Using IDA ICE 4.8, two buildings were modelled to represent two different building typologies, specifically single-family residential (SFR) and multi-family residential (MFR), representing roughly 80 % of the buildings built during the million program.

IDA ICE 4.8 is the latest version of the simulation software IDA ICE, released by Swedish EQUA Simulation AB. The software is used by a wide range of international companies to model and simulate energy and indoor comfort parameters in buildings (EQUA, 2020) ('IDA ICE - Simulation Software | EQUA' n.d.). In this study, IDA ICE was used to obtain hourly, monthly, and annual values of energy use for the two modelled building typologies mentioned above, in an environment representing reality as accurately as possible.

The simulation inputs and building properties used in the simulation software were acquired through the analysis of existing building drawings, energy performance certificates and other previous studies of similar buildings.

Furthermore, to minimize the number of assumptions, data collected by the organization SVEBY were used as a further measure of generalizing the models. SVEBY is an organization run by the construction- and real estate sector, working towards standardizing and verifying energy performance in buildings. They provide data for parameters such as domestic hot water use, household electricity use and occupant density which can be used in various energy calculations and simulations. (‘Om Sveby | Sveby’ n.d.)

The climate file used for all simulations is one provided by ASHRAE, representing the climate conditions of Helsingborg in southern Sweden.

Base case modelling

The desire to address representative buildings, thus making this study applicable to a greater share of the building stock, led to the decision of modelling the residential buildings according to the standards during the Million program.

The modelled buildings were not intended to represent a specific building, but rather a share of the existing building stock. Therefore, most parameters, such as thermal bridge losses, infiltration and distribution losses were found in previous studies and approximated as an average value for similar buildings.

The multi-family building was modelled to represent a three-story apartment building which was the most common building typology during the Million program. For reference, building drawings from the Million program area of Dalhem, Helsingborg were analyzed and used as guidelines for the geometry of the building model. As for the construction and building properties, data established in previous studies such as (Warfvinge, n.d.) and (Martensson and Wörlen 2015) were used. Further building characteristics were moreover found in (Björk, Kallstenius, and Reppen 2013).

Regarding the single-family building, an energy model created in a previous study by Tomas Ekström (Ekström 2017) was adopted. The model was previously used in a similar study examining the profitability of renovating Million program buildings to passive houses.

The inputs used in the energy models before renovation are shown in Table 6 below.

Table 6. Inputs for the Single family building and Multi family building used in the simulations of base case models

Input	Multi family building	Single family building	Method
Heated floor area Atemp / m²	1095	142	Estimated from building model
Envelope area / m²	1480	301	Estimated from building model
Heating setpoint / °C	21 (16 in staircases)	21	SVEBY
Air leakage rate / l/(s/m²) envelope area at 50 pa pressure difference	1.4	1.4	Assumed based on previous studies
Thermal bridges / % of UA	20	20	BBR
Ventilation system	Mechanical exhaust air	Mechanical exhaust air	Assumed based on previous studies
Exhaust ventilation air flow / l/(s/m²), heated floor area	0.35	0.35	Based on minimum BBR requirement
Heating system	District heating	Fuel heating (pellets)	Assumed based on previous studies
Domestic hot water (DHW) use / kWh/m², annually	25	20	SVEBY
Household electricity use / kWh/m², annually	30 (70% of which can be considered as heat gains)	30 (70% of which can be consideres as heat gains)	SVEBY
Construction part	**U-value / W/(m²K)**	**U-value / W/(m²K)**	
External roof	0.23	0.22	Approximated based on previous studies
External wall	0.26	0.23	Approximated based on previous studies
Ground slab	0.57	0.32	Approximated based on previous studies
Windows	2.4	2.4	Approximated based on previous studies
Doors	2.4	2.4	Approximated based on previous studies

Renovation strategies towards FEBY Guld

As the requirement was to reach the Swedish Passive House standard (FEBY Gold) prior to implementing a PV system, the criteria set by FEBY (2018) ('Kravspecifikation För Energieffektiva Byggnader' 2018) were used as guidelines during the renovation process. By initially conducting a preliminary analysis on the PV production using the building envelope (prioritizing the south facing roof), a maximum annual PV production was obtained, which was considered the limiting factor in the renovation process. If the annual PV production exceeded the delivered primary energy after passive house renovation, the system size was decreased until a net-zero balance was achieved. Thereafter, the process progressed to the next step. If not, stricter renovation measures were taken until the PV production on the south facing roof reached the annual delivered primary energy.

As described previously, the FEBY Gold standard requires a heat loss indicator VFT_{DVUT} of maximum 14 W/m^2, calculated according to equation 2.

$$VFT_{DVUT} = H_T \cdot \frac{21 - DVUT}{A_{temp}} \; [W/m^2] \tag{2}$$

The heat losses indicator is represented by the Heat loss coefficient, $\boldsymbol{H_T}$ [W/K], which is the sum of heat losses through transmission, ventilation, and infiltration (equation 3). This coefficient is then multiplied by the temperature difference of indoor and the design winter outdoor temperature, $\boldsymbol{DVUT}$ [°C], and normalized to the floor area, A_{temp} [m^2].

$$H_T = U_m \cdot A_{om} + \rho \cdot c \cdot q_{läck} + \rho \cdot c \cdot q_{vent} \cdot (1 - v) \; [W/K] \tag{3}$$

The transmission losses in the heat loss coefficient are calculated through the average U-value, $\boldsymbol{U_m}$ [$W/m^2 \cdot K$] and the thermal envelope area $\boldsymbol{A_{om}}$ [m^2]. Losses through infiltration are dependent on the density of air $\boldsymbol{\rho}$ [kg/m^3], the specific heat capacity of air, $\boldsymbol{c}$ [J/kg·K] and the air leakage rate $\boldsymbol{q_{läck}}$ [l/s]. Losses through the ventilation system are calculated through the density and specific heat capacity of air, the ventilation flow rate $\boldsymbol{q_{vent}}$ [l/s] and the efficiency of the heat recovery, $\boldsymbol{v}$ [dimless].

The renovation strategies for reaching a sufficient VFT_{DVUT} are based on the five key principles for passive houses, namely *excellent insulation, prevention of thermal bridges, airtightness, insulated glazing and controlled ventilation.* These principles can be directly compared to the equation of the heat loss coefficient H_T, where *excellent insulation, prevention of thermal bridges,* and *insulated glazing* represents the factor U_m, *airtightness* represents the factor $q_{läck}$, and *controlled ventilation* represents the factor q_{vent} as well as the term v.

The building properties for the energy simulations and inputs used in the heat loss indicator calculations for the multi-family house (MFH) and the single-family house (SFH) are found in Table 7. The values are shown as MFH / SFH.

Table 7. Inputs for the Single family building and Multi family building used in the simulations of the passive house models

Input	**Multi family building**	**Single family building**	**Method**
Heated floor area Atemp / m^2	1095	142	Estimated from building model
Envelope area / m^2	1480	301	Estimated form building model
Heating setpoint / °C	21 (16 in staircases)	21	SVEBY
Air change rate per hour (ACH) / h-1	0.6	0.6	FEBY requirement
Thermal bridges / % of UA	20	20	BBR
Ventilation system	Mechanical exhaust and supply air with HR = 80 %%	Mechanical exhaust and supply air with HR = 85 %	Assumed based on literature
Exhaust/supply ventilation air flow / l/(s/m^2), heated floor area	0.38/0.35	0.38/0.35	BBR requirements and assumed 10% more exhaust flow
Heating system	District heating	Outside air-water heat pump	Assumed based on literature
Domestic hot water (DHW) use / kWh/m^2, annually	22.5	18	SVEBY and BEN (10% reduction with efficient installations
Household electricity use / kWh/m^2, annually	30 (70 % of which can be considered as heat gains)	30 (70 % of which can be considered as heat gains)	SVEBY
Construction part	**U-value / W/(m^2K)**	**U-value / W/(m^2K)**	
External roof	0.10	0.09	Approximated to reach FEBY requirements
External wall	0.13	0.11	Approximated to reach FEBY requirements
Ground slab	0.14	0.12	Approximated to reach FEBY requirements
Windows	0.80	0.75	Approximated to reach FEBY requirements
Doors	0.80	0.80	Approximated to reach FEBY requirements

Using the results obtained from the energy simulations, the values were recalculated to comply with the BBR methodology of calculating annual delivered energy, where primary energy factors and location also need to be regarded. The annual delivered energy is thus calculated according to equation 4.

$$EP_{pet} = \frac{\sum_{i=1}^{6}\left(\frac{E_{uppv,i}}{F_{geo}} + E_{kyl,i} + E_{tvv,i} + E_{f,i}\right) \cdot PE_i}{A_{temp}} \; [kWh/m^2] \qquad (4)$$

The annual delivered energy, expressed as primary energy use, considers the sum of delivered energy for heating, $E_{uppv,i}$ [kWh], divided by the geograpichal factor F_{geo} [dimless], cooling, $E_{kyl,i}$ [kWh], domestic hot water $E_{tvv,i}$ [kWh], and building electricity $E_{f,i}$ [kWh]. Each energy carrier is multiplied by its respective primary energy number, PE_i [dimless], and then divided by the heated floor area, A_{temp} [m^2].

3.2 Design of PV systems and batteries

The design of the PV system, including batteries, was done using the software System Advisor Model (SAM). SAM is a techno-economic software, developed by the National Renewable Energy Laboratory (NREL), used to model various types of renewable energy systems, including PV, solar thermal, and wind power. (‘Home - System Advisor Model (SAM)’ n.d.)

PV systems in SAM can be modelled as grid-connected or stand-alone systems. By specifying the desired PV modules, inverters, as well as site conditions such as tilt and orientation, the software will estimate the performance of the designed system. (‘SAM Photovoltaic Models - System Advisor Model (SAM)’ n.d.) The batteries are designed by specifying battery type, battery storage capacity and its dispatch strategy. In this study, a Lithium-Ion battery was used.

As a first step, the available roof surface areas were measured from the building models. With the goal of reaching NZEB, an initial SAM simulation was conducted while covering the most efficient roof surface orientation (south) with PV modules and confirming that such an array would generate enough electricity to reach NZEB. If needed, the PV system size was decreased until it would generate an yearly amount of electricity as close as possible to what was required to reach NZEB.

By implementing an energy storage battery to the system, another factor is induced while searching for the most profitable configuration, namely the dispatch strategy of the battery. There are several different ways in which a battery can operate, depending on the conditions of the studied case. In this study, three different strategies have been examined regarding their resulting profitability. These strategies will be further referred to as, *PV Self-consumption, Time-of-use Optimization,* and *Demand Charge Reduction*. Figure 13 illustrates the general usage of these strategies.

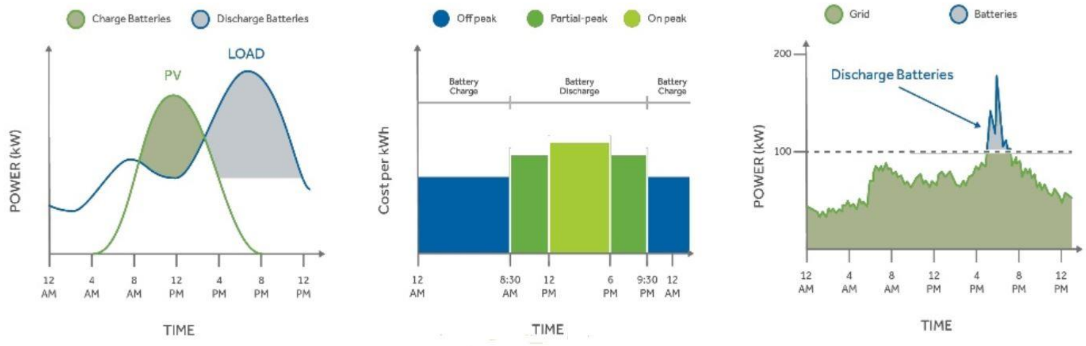

Figure 13. Illustration of three different battery dispatch strategies evaluated in this study

More specifically, *PV Self-Consumption* allows the battery to be discharged at any time when the PV production is lower than the electricity load. As the battery is, in this strategy, not connected to the grid, it is only charged when the PV production exceeds the electricity load. Normally, and depending on the battery size, the battery will be charged during the day while the sun is shining and then dispatch its energy during evenings, nights and mornings. If the battery is too small, it will not have the capacity to cover the whole load during this time, meaning some electricity will have to be bought from the grid. An oversized battery will, on the other hand, rarely be fully charged, meaning its size will not be fully utilized and the profitability of the investment decreases.

The *Time of Use Optimization* takes the hourly variations of electricity prices into consideration. By charging the battery while electricity prices are low and dispatching the energy while the prices are high, the idea is to minimize the need of purchasing expensive electricity. Generally, the electricity is cheaper during winter on a yearly basis and during nighttime on a daily basis, shown in Figure 50 in Appendix A.

Demand Charge Reduction can lower the electricity peaks during a day as the energy in the battery can reduce power demand from the grid. In a residential building, these peaks generally occur during mornings when the occupants are waking up and preparing to go to work and during afternoons when they come back home. By lowering the electricity peaks, a smaller fuse may be used in the building, resulting in a lower annual fee of the fuse. The annual fees of different fuse sizes, according to Vattenfall (‘Elnätspriser - Vattenfall Eldistribution’ n.d.) are shown in Table 8 below.

Table 8. Annual fee of different fuse sizes according to Vattenfall

Fuse size / A	Fee / SEK/year
16	4 330
20	6 050
25	7 570
35	10 370
50	14 900
63	20 100

To determine the most profitable dispatch strategy, SAM simulations and LCC analysis were conducted while utilizing the three different strategies with various battery sizes. The strategy shown to be the most profitable was then used in all further PV simulations for the buildings.

The hourly electricity prices used were obtained from NordPool and represent the hourly electricity prices in southern Sweden of the year 2019. To assess the economic feasability from utilizing *Time of Use Optimization*, a matrix was created where each cell represented the average price of hour 1 to 24 in each month, as shown in Figure 50 in appendix. The battery was then modelled to charge from the grid during hours when the electricity price was below the 25 % percentile average. During hours when a price increase is noted, the battery discharged its stored energy to the load.

The *Demand Charge Reduction* strategy was evaluated by initially calculating the fuse size required for the current loads in both buildings. Thereafter, based on the electricity peak demands, the battery was modelled to save its energy until a peak occurs whereas the energy would dispatch and cover part of the peak electricity demand. This required the battery to be grid connected. The required fuse size before and after peak shaving can be calculated according to equation 5.

$$I = \frac{P}{U}\ [A] \tag{5}$$

In equation 5, the current, ***I*** [A], is calculated by dividing the power, ***P*** [W], during peak demand by the voltage, ***U*** [V]. In Sweden, it is most common to have a 230 V outlet (‘Elnätet | Följ Elens Väg till Dig - E.ON’ n.d.).

Furthermore, the efficiency of the PV modules was set to 20 % and the inverters was sized to reach a DC to AC ratio of 1 – 1.2 in each system.

To further establish the most profitable battery size, a parametric study was conducted in which the battery sizes were varied between 0 – 100 kWh for the multi-family building and 0 – 50 kWh for the single-family building. Table 9 below shows the technical properties of the PV modules and batteries.

Table 9. Technical properties for the PV modules and batteries used in the simulations

PV Modules	Technical parameter used in the simulations
Size of module / m^2	1.62
Efficiency / %	20
Tilt / °	6 (MFH) / 35 (SFH)
Azimuth / °	180 (towards south)
Battery	
Type	Li-Ion
Min. SOC / %	20
Max. SOC / %	95

3.3 Life cycle cost analysis

To determine the economic feasibility of the PV and battery systems, a life cycle cost analysis was performed. As previously mentioned, this study is investigating the life cycle profitability (LCP) by comparing the life cycle cost with and without having a PV system. More specifically, a positive LCP indicates that savings are achieved by implementing a PV system whereas a negative LCP would mean the investment is not economically feasible. The LCP calculations are done separately for the PV systems and the passive energy renovation. In other words, the LCP of the PV systems is only including the investment costs of the PV systems, and not the renovation. The LCP of the renovation is henceforth only including the investment costs of the renovation, and not the PV system.

All LCP calculations are based on an analysis period of 30 years, as this is the expected life span of PV modules (‘Experten Slår Hål På Myter Om Solceller - Vattenfall’ n.d.). Moreover, the calculations considered economical parameters including electricity price change, interest rate, inflation and PV equipment price change. The values used in this study are presented in Table 10.

Table 10. Values for economical parameters used in this study

Electricity price change / %/year	+0.5
PV equipment price change / %/year	-10 (Darby 2016)
Interest rate / %	0
Inflation / %	+1

Moreover, the prices used for PV equipment and batteries are shown in Table 11 [36]. Additionally, a subsidy of 20 % of the investment costs are granted while installing a PV system.

Table 11. Cost breakdown of PV equipment and batteries

Modules / SEK/Wp	6.3
Inverter / SEK/Wp	1.8
Mounting material / SEK/Wp	1.2
Other electronics / SEK/Wp	0.5
Installation work / SEK/Wp	2.4
Shipping to customer / SEK/Wp	0.3
Comissioning / SEK/Wp	0.6
Other costs / SEK/Wp	0.2
Profit margin / SEK/Wp	2.3
VAT / SEK/Wp	3.9
SUM / SEK/Wp	**19.5**
SUM including investment subsidy (20 %) / SEK/Wp	**15.6**
Battery SEK/kWh	1 500

The life cycle cost calculations are based on several different discrete compounding formulas depending on which type of payments are occurring (Chan S. 2004). As both annual price changes and interest rates are considered in these calculations, the annual costs will either increase or decrease depending on the price change factor. The formula used for these types of calculations is shown below in equation 6. More specifically, this equation is used to separately calculate the present value of overall electricity costs before and after implementing a PV system, over a period of 30 years.

$$P = A_1\left(\frac{1-(1+g)^N(1+i)^{-N}}{i-g}\right)\ [SEK] \tag{6}$$

In equation 6, ***P*** [SEK], represents the present worth value after a certain amount of years, represented by ***N*** [years]. Moreover, the annual price change and interest rate is represented by ***i*** [%] and ***g*** [%], respectively. The factor in the brackets is multiplied by a value representing the present worth of the annual payment at year 1, indicated by the term $\boldsymbol{A_1}$ [SEK].

By investing in a PV system, all the savings will occur in the annual electricity bill as well as the revenue gained from selling electricity to the grid. Thus, the LCP is the result of the total net present value caused by the electricity use before and after implementing a PV system, including the investment costs of the PV system and batteries. Accordingly, the LCP is calculated with equation 7.

$$LCP = \left(-FC - P_{p,el1} + P_{s,el1}\right) - \left(-P_{p,el2}\right)\ [SEK] \tag{7}$$

The LCP calculation in equation 7 considers the investment costs of the PV system, ***FC*** [SEK], purchased and sold electricity after installing the PV system, represented by $\boldsymbol{P_{p,el1}}$ [SEK] and $\boldsymbol{P_{s,el1}}$ [SEK], respectively. This term is deducted by the present worth of purchased electricity before installing the PV system, represented by $\boldsymbol{P_{p,el2}}$ [SEK]. A resulting positive value would thus mean that the investment is preferable in an economic perspective.

Furthermore, maintenance of the PV system is generally required throughout its lifespan. The lifespan of the inverters are assumed to be 10 years (‘Solceller Växelriktare’ n.d.), meaning they need to be changed twice during the 30 year life span of the PV modules. The battery is furthermore assumed to have a life span of 15 years (Sunwind.se n.d.), meaning it would need to be changed once during the life span of the PV modules. For these types of calculations, a future value of the costs needs to be calculated initially, shown in equation 8, to then be calculated to a present value using the interest rate, shown in equation 9.

$$F = FC(1+g)^N\ [SEK] \tag{8}$$

The future value ***F*** [SEK] is calculated using the investment cost ***FC*** [SEK], the equipment’s annual price change ***g*** [%] and the amount of years until the cost occurs, ***N*** [years].

$$P = F(1+i)^{-N}\ [SEK] \tag{9}$$

The present value ***P*** [SEK] is calculated using the future value ***F*** [SEK], the interest rate **i** [%] and the amount of years from which the cost occurs, ***N*** [years].

The life cycle cost analysis was performed in several scenarios for the single and multi-family building. Each scenario is characterized by which electricity load was considered, the size of the PV system as well as to whom the investment might result in a profit. The multi-family building is evaluated in three scenarios while the single-family is evaluated in two.

Scenario 1 and 2 for the multi-family building uses the same PV system size, namely the minimum size required to reach NZEB. The difference between these scenarios is the electricity load whereas scenario 1 excludes the household electricity, i.e only the building electricity is considered while both building electricity and household electricity was considered in scenario 2. Scenario 1 was thus meant to represent a building owner whose only electricity expense is that of the building electricity while the tenants in the building are paying for their own electricity. Therefore, the PV system only covers the building electricity to grant maximum profit for the building owner. Scenario 2 is then intended to represent a housing cooperative whereas the PV system is also covering the household electricity, resulting in a maximum profit for the cooperative as a whole. Lastly, scenario 3 is evaluated to assess whether a larger PV system would yield a larger profit. Accordingly, the PV system size found to generate the highest profit, whether it reaches NZEB or not, was thus evaluated in scenario 3.

As for the single-family bouse, a scenario only considering the building electricity was not evaluated as the electricity expenses of a single family house owner always includes both building electricity and household electricity. Scenario 1 for the single family bouse is therefore considering the total electricity load of the building. Similar to the multi-family building, an additional scenario was evaluated where a PV size generating maximum profitability was evaluated, referred to as scenario 2 for the single-family building.

A summary of the scenarios is shown in Table 12 below.

Table 12. Description of the different scenarios assumed in the LCP assessment, based on which electricity load was used and to whom the PV systems will a profit or loss

Scenarios	**Single-Family**	**Viewpoint**	**Multi-Familiy**	**Viewpoint**
Scenario 1	LCP performed for total electricity with and without tax recuction	House owner	LCP performed for buiding electricity with and wihout tax redcution	Building Owner
Scenario 2	LCP performed for optimal PV size and battery disregarding NZEB	House owner	LCP performed for total electricity with and without tax reduction	Building Owner and Tenants
Scenario 3			LCP performed for optimal PV size and battery disregarding NZEB	Building Owner and Tenants

As a way of considering the risk of the investment, sensitivity analyses were carried out for the most profitable cases found in each scenario to reproduce the results during various economical scenarios. This was done by varying the economical parameters in numerous combinations. The parameters varied were interest rate, electricity price change and PV equipment price change. Table 13 shows the combinations of economical parameters used in the sensitivity analysis.

Table 13 – Combinations of economical parameters used in the sensitivity analysis

Interest rate / %	El. price change / %	PV eq. price change / %
2	-2	0
-2	2	-10
0	0.53	-10
1	0.53	-10
-1	0.53	-10
0	-2	0
0	2	-10
1	2	0
-1	-2	0
2	1	-10
-2	-1	0

With the results obtained from the sensitivity analysis, an assessment of maximum battery price to maintain profitability was estimated for the most profitable cases. While assuming each combination of economical parameters separately, the battery price was increased or decreased until it matched the LCP of the case in which no battery was used.

Lastly, in accordance to the limitations, a detailed cost calculation of the energy renovation measures taken in this study has not been carried out. Rather, costs found in previous studies were used as the investment cost of the energy renovation. The savings achieved from reducing the electricity and heating demand were then calculated in a similar manner as for the electricity savings attained from implementing the PV system, using equation 10.

$$LCP = \left(-FC - P_{p,e2}\right) - P_{p,e1} \tag{10}$$

In equation 10, the LCP is calculated with the investment cost of the renovation, $\boldsymbol{FC}$, the present value of purchased energy after renovation, $\boldsymbol{P_{p,e2}}$ and the present value of purchased energy before renovation, $\boldsymbol{P_{p,e1}}$.

The investment costs of renovating the multi-family building are taken from a similar project conducted by the real estate concern Alingsåshem (Odegren and Jorlöv, n.d.). The aim of the project was to renovate a multi-family residential area dating back from the record years to achieve passive house standard. The investment costs were estimated to 15 000 – 20 000

SEK/m^2 whereas 30% of this was allocated to the energy improvement measures. To estimate the investment costs in this study, the price range concluded by Alingsåshem was multiplied by factors ranging from 0.2 – 0.4 to attain wider range of possible investment costs to be used in the LCP calculation. Table 14 shows the range of costs used to estimate the renovation cost of the multi-family building.

Table 14. Range of values used as investment cost for the multi family building

	Fraction of total investment cost allocated to the energy improvement measures				
	20%	25%	30%	35%	40%
Total investment cost / SEK/m^2	**Total investment cost / SEK/m2**				
15 000	3 000	3 750	4 500	5 250	6 000
16 000	3 200	4 000	4 800	5 600	6 400
17 000	3 400	4 250	5 100	5 950	6 800
18 000	3 600	4 500	5 400	6 300	7 200
19 000	3 800	4 750	5 700	6 650	7 600
20 000	4 000	5 000	6 000	7 000	8 000

As for the single-family building, a similar methodology was implemented whereas a previous study, conducted by Tomas Ekström, was analyzed (Ekström 2017). The study aimed at finding cost efficient strategies for renovating single-family houses from the record years to passive house standard. By implementing various heat generation systems, numerous investment costs were concluded, ranging from 2796 to 3085 SEK/m^2, which were used as the investment cost of the single-family house renovation in this study, shown in Table 15. By multiplying the costs found in Ekström's study by factor ranging from 0.9 to 1.1, a wider range of costs were attained to increase the odds of it being applicable to the measures taken in this study.

Table 15. Range of values used as investment cost for the multi family building

Fraction of total investment cost				
100%	105%	110%	95%	90%
Investment cost of energy renovation / SEK / m2				
2 796	2 936	3 075	2 656	2 516
3 613	3 793	3 974	3 432	3 251
3 085	3 239	3 393	2 930	2 776

The resulting LCP for the energy renovation alone is calculated according to equation 10.

Generally, a passive house renovation can imply an increase in market value or a justification for increasing the rents. These factors are not included in the LCP of the renovation as such value increases are highly project specific and largely dependent on location (Ekström 2017), making it subjective to include such values found in previous studies. For reference, the renovation of the multi-family buildings performed by Alingsåshem brought an increased annual revenue from rents of 186 – 386 SEK/m^2. ('Brogården – Passivhusrenovering', n.d.) For a single-family house, the value increase would first be noted when the house is sold.

4 Results and analysis

This section presents all the results obtained by implementing the previously described methodology. The results of the energy performance before and after renovation as well as electricity production are initially presented. Thereafter, the profitability of the PV systems and the renovation during various economical scenarios is shown. The results are presented separately for the single-family and the multi-family building, whereas the single-family building is discussed first in each section.

4.1 Energy performance and PV production towards NZEB

4.1.1 Single-family building

Above mentioned energy efficiency measures for the single-family house resulted in a heat loss coefficient, VFT_{DVUT}, of 18 W/m^2. As the building has a floor area smaller than 600 m^2, additions to the maximum VFT_{DVUT} can be made according to equation 1. With a floor area of 142 m^2 the maximum VFT_{DVUT} is therefore 18.16 W/m^2, meaning that the resulting value of 18 W/m^2 fulfills the requirement of a passive house.

The energy efficiency measures taken in the single-family house showed a reduction in annual delivered primary energy of 126 kWh/m^2 where 166 kWh/m^2 was delivered in the base case while only 40 kWh/m^2 was delivered in the renovated case, shown in Figure 14. Most of the reduction occurs in the zone heating allocation due to the significant improvement of the thermal envelope, the implementation of a heat pump as well as the ventilation heat recovery required to reach passive house standard. A slight increase is however noted in building electricity as more pumps and fans are operating due to the more technical HVAC system.

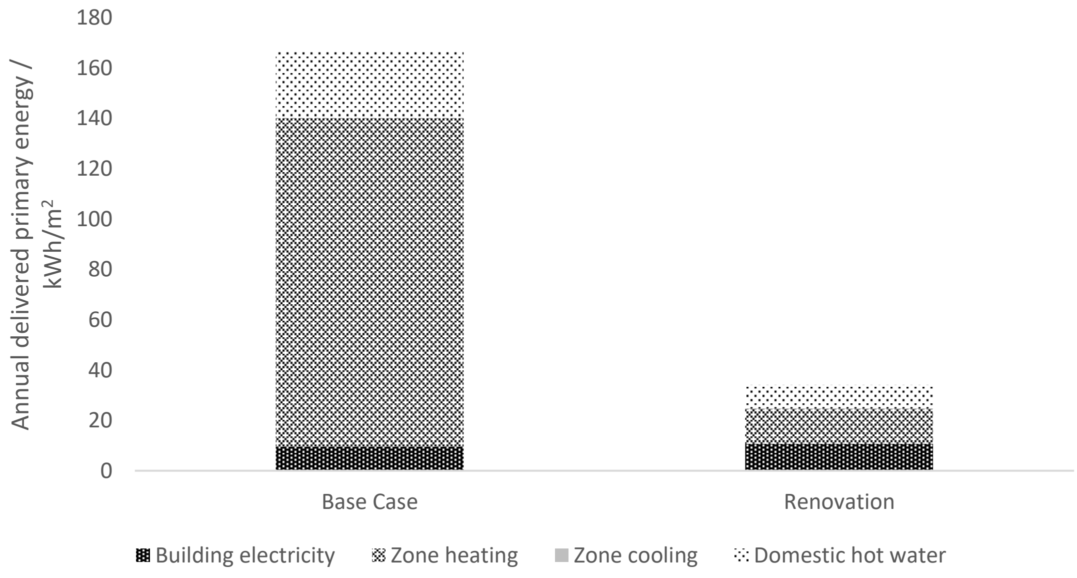

Figure 14. Annual delivered primary energy to the single-family building before and after renovation. The total energy is allocated to its respective uses, Building electricity, Zone heating, Zone cooling, and Domestic hot water.

As mentioned previously, FEBY requires electrically heated buildings to have an annual delivered primary energy of no more than 26 kWh/m^2 to reach the FEBY Gold standard. Even though a sufficient VFT_{DVUT} was attained, the building will not be classified as a passive house solely based on the energy efficiency measures taken in the renovation, hence the VFT_{DVUT} is not the limiting factor in this case. However, according to Boverket, direct own-used energy (self-consumption) produced by an on-site renewable energy source may be taken into account in the primary energy use calculation. ('Värme och tappvarmvatten' n.d.)

Given an annual delivered energy of 40 kWh/m^2 and an area of 142 m^2, the total delivered energy to the building is 5 730 kWh. With a primary energy use of 1.6 for electricity, the required annual production of the PV system is 3 580 kWh to reach a NZEB standard.

Installing a south facing roof top PV system with a peak power of 3.3 kW at a 35 degree tilt, covering 16.2 m^2 out of 45.5 m^2 available on the south facing roof, on the single-family building resulted in an annual electricity production of 3 600 kWh. Table 16 below shows the annual delivered energy while having this system installed. As can be noted, the primary energy use falls below the requirement of 26 kWh/m^2 when self-consumption is also accounted for.

Table 16. Delivered primary energy while having a PV system size of 3.3 kWP installed in the single-family building.

PV system size / kWp	Delivered primary energy / kWh	Primary energy / kWh/m2
3.3	2 178	24.5

The monthly electricity production together with the monthly electricity load is shown in Figure 15. Due to the use of a heat pump running on electricity, the electricity load tends to behave according to the outdoor air temperature.

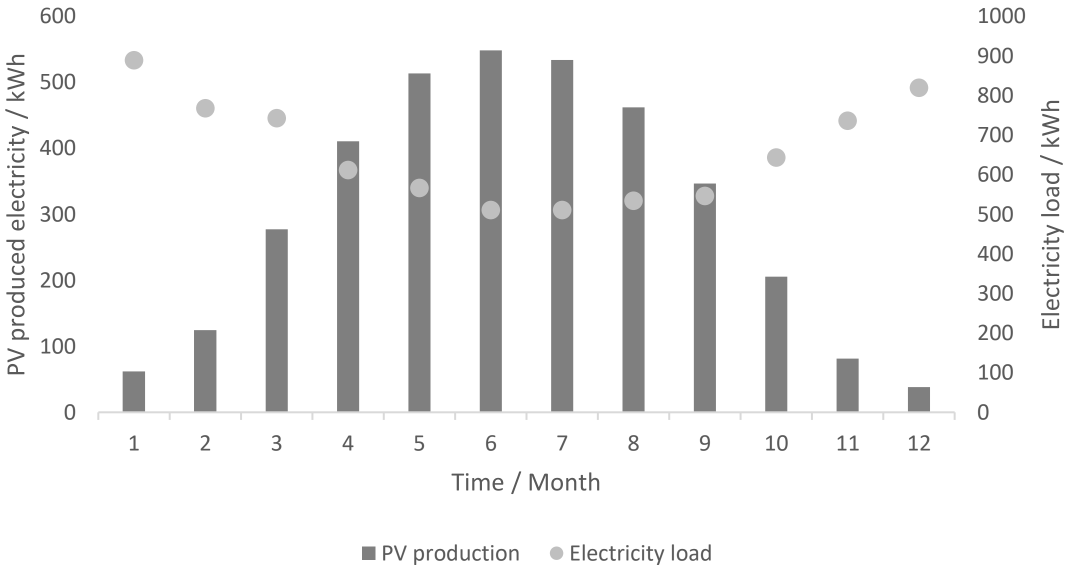

Figure 15. Monthly PV production with a 3.3 kWP system and the electricity load for the single-family building after renovation.

4.1.2 Multi-family building

The energy efficiency measure taken in the multi-family building resulted in a heat loss coefficient, VFT_{DVUT} of 13.9 W/m^2. With a floor area of 1095 m^2, i.e above 600 m^2, no additions to the VFT_{DVUT} can be made. However, the resulting value of 13.9 W/m^2 falls below the requirement of 14 W/m^2, meaning the requirements are fulfilled.

By implementing said energy efficiency measures, a reduction in annual delivered energy of 103 kWh/m^2 was achieved, resulting in an annual delivered energy total of 46 kWh/m^2, as opposed to 149 kWh/m^2 in the base case. As indicated in Figure 16, the greatest improvement occurs, again, for the zone heating where a 78% reduction was attained, reflected to the measures taken in the thermal envelope and ventilation system to reach the passive house standard. Due to the addition of mechanical supply air for the renovation, a slight increase allocated to zone cooling is however noted as cooling energy is occasionally required to keep the supply air at a certain temperature.

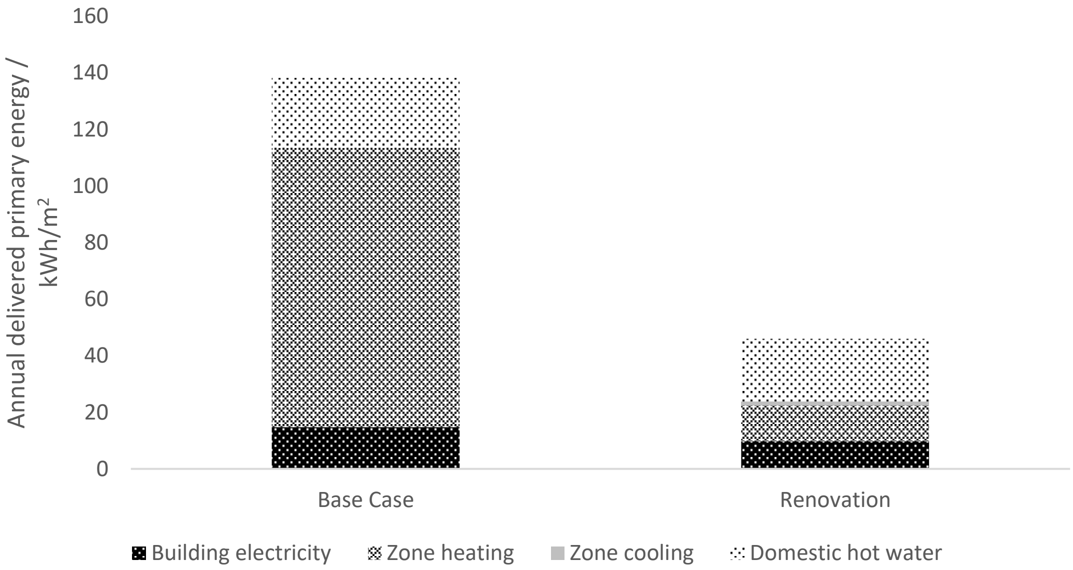

Figure 16. Annual delivered primary energy to the multi-family building before and after renovation. The total energy is allocated to its respective uses, Building electricity, Zone heating, Zone cooling, and Domestic hot water

As there is no additional requirement, other than BBR, regarding delivered energy for non-electrically heated buildings in FEBY, the multi-family building reached the FEBY Gold standard solely through the energy efficiency measures. Thus, the PV system was a mere addition in order to reach the NZEB standard, as opposed to the single-family building where a PV system was required to concurrently reach FEBY Gold.

Given an annual delivered energy of 46 kWh/m^2 and an area of 1095 m^2, the total delivered energy to the building is 50370 kWh. Considering the primary energy number of 1.6 for electricity, the required annual production of the PV system is 31480 kWh to reach a NZEB standard. Installing a south facing roof top PV system with a peak power of 34.2 kWp at a 6 degree tilt, covering 181.4 m^2 out of 184.5 m^2 available on the south facing roof on the multi-family building resulted in an annual electricity production of 31600 kWh. Figure 17 below shows the monthly PV production over a year, including the electricity load with and without household electricity. The electricity loads are fairly stable throughout the year as the heating is supplied from a district heating system, meaning the electricity load does not depend on the outdoor temperature.

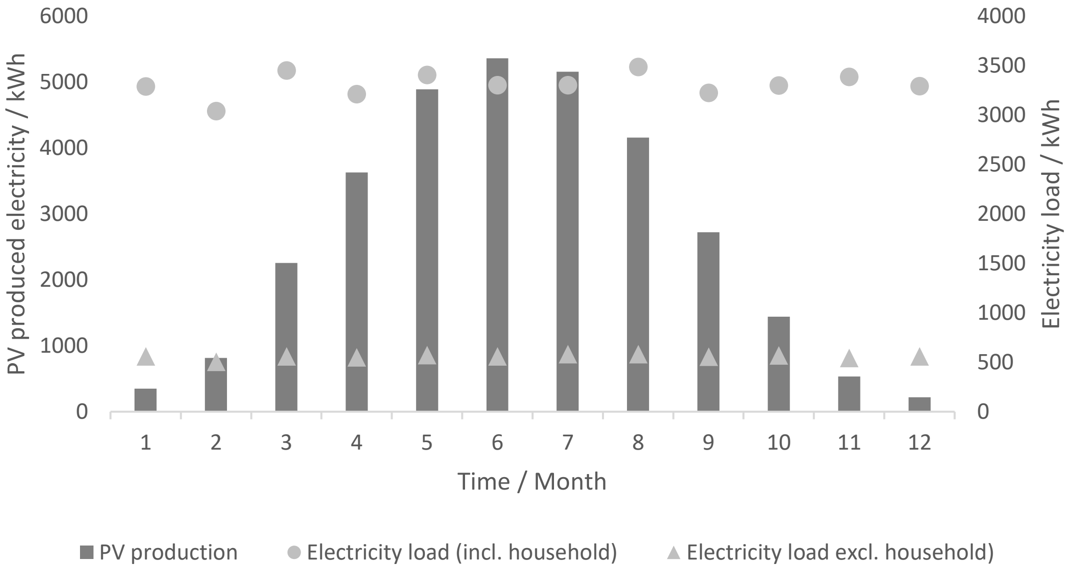

Figure 17. Monthly PV production with a 34.2 kWp system and the electricity load, with and without household electricity for the multi-family building after renovation.

4.2 Life cycle cost

This section presents the life cycle cost results, expressed as life cycle profitability (LCP) for both buildings and their respective scenarios as described previously.

Initially, the LCP while using different battery dispatch strategies is presented whereas the most profitable option is then implemented for all forthcoming PV simulations (namely *PV Self-Consumption* as shown below). Successively, the single-family building is presented first, followed by the multi-family building.

4.2.1 Battery dispatch strategy

Using the given electricity load of the multi-family building (including tenant electricity) and the single-family building, the three different battery dispatch strategies showed results according to Figure 18. The same analysis while excluding the tax reduction for sold electricity is presented in Figure 19. As noted, the dispatch strategy referred to as PV self-consumption shows the highest profitability in all cases, while peak shaving has the lowest profitability.

Perhaps the most important, is that the electricity peak demands in buildings of this size are not high enough to benefit from the main purpose of using peak shaving, namely being able to down-size the fuse capacity and thus paying a reduced fee to the electricity provider. The obtained electricity loads from the energy simulations showed a peak electricity demand of 2.4 kW for the single-family building (Figure 51 and Figure 52 in Appendix B) and 12 kW for the multi-family building (Figure 53 in Appendix B). Given that the multi-family building contains 12 apartments, it can be estimated that the peak electricity demand in each apartment is 1 kW. Using equation 5, the fuse sizes before and after peak shaving can be calculated.

As the *Demand Charge Reduction* battery only operates during electricity peak demands, mostly occurring during early mornings and evenings, it increases the demand for purchased electricity during mid-days where the PV system is unable to cover the whole load, more specifically during winter days. This occurs when the highest electricity prices are noted. Additionally, the early morning electricity peak demands are not high enough to fully discharge the larger sized batteries. Thus, when the sun rises, the battery is already at a relatively high state of charge, meaning less energy from the PV system can be stored in the battery resulting in more energy having to be sold to the grid.

$I = \frac{2400\,W}{230\,V} = 10.4\,A$ (single-family building)

$I = \frac{1000\,W}{230\,V} = 4.3\,A$ (multi-family building)

As the smallest available fuse size is 16 A, utilizing the Demand Charge Reduction strategy will not result in a reduced annual fee for the fuse.

The strategy referred to as *Time of Use Optimization* shows a higher profitability than peak shaving, but lower than PV self-consumption. While analyzing the results, it was found that greater energy losses in the battery occur while using this strategy since the energy is stored for a longer time. Moreover, during certain days, the battery is charged too much during the night and encounters a similar issue as for the peak shaving strategy, namely less energy from the PV system can be stored in the battery resulting in more energy having to be sold to the grid. This strategy may however well be the favorable option in the scenario of greater differences between high and low electricity prices. The electricity price profile used in this study did however show insufficient price differences to make this strategy profitable. In other words, the price differences are not large enough to cover the added energy losses in the battery and the increased need for exporting electricity to the grid.

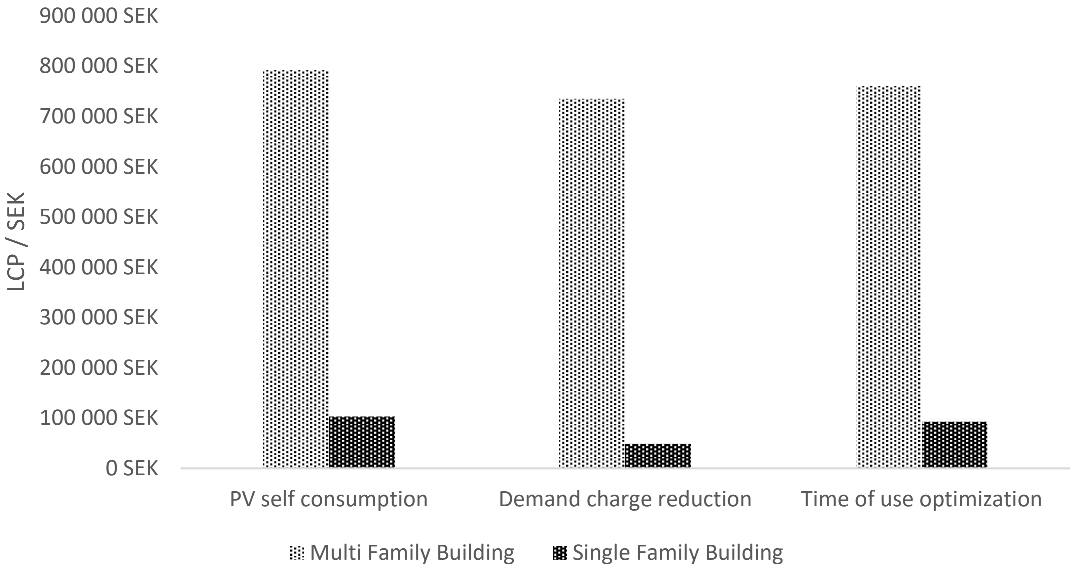

Figure 18. LCP, excluding renovations costs, while utilizing different battery dispatch strategies for the Multi-family building with a 70 kWh battery (light grey) and the Single-family building with a 10 kWh battery (dark grey). The results are calculated with the tax reduction included.

While excluding the tax reduction, the profitability for peak shaving shows an even larger gap to PV self-consumption. This is due to the increased need of exporting energy, in this case, at a considerably reduced price. A similar occurrence can be noted in the time of use optimization strategy, however not as much.

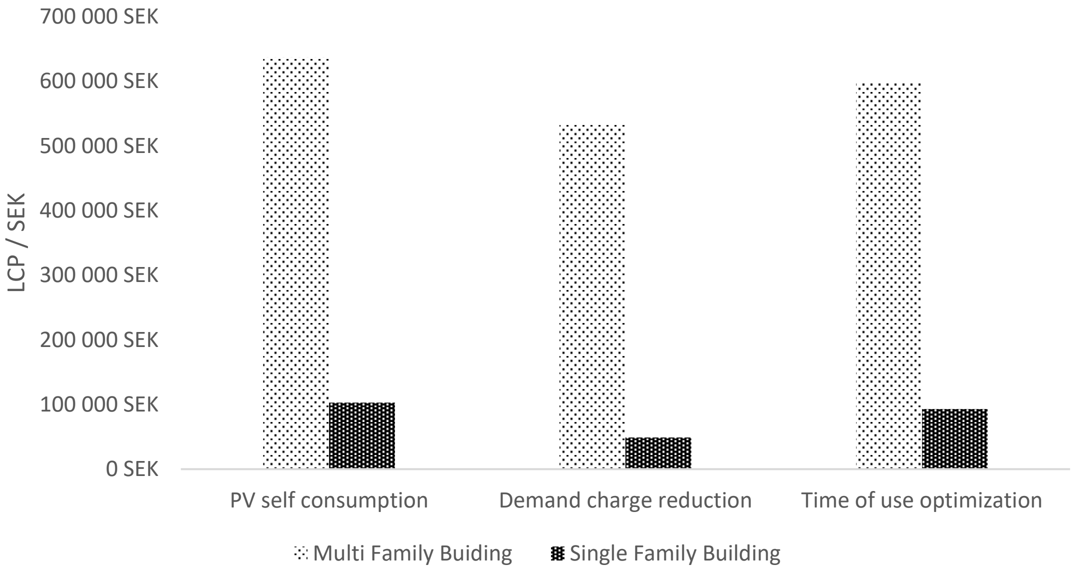

Figure 19. LCP, excluding renovation costs, while utilizing different battery dispatch strategies for the Multi family building with a 70 kWh battery (light grey) and the Single family building with a 10 kWh battery (dark grey). The results are calculated without the tax reduction excluded.

4.2.2 Single-Family Building

The results presented here are divided into two sections, both corresponding to a different scenario as described previously. Each section includes parametric studies of life cycle profitability regarding battery size, annual imported, exported, and self-consumed electricity for the most profitable option and finally a sensitivity analysis where different economical parameters were varied to visualize the economic impact of such variations.

Lastly, the profitability of each scenario, including the sensitivity analyses, are compared to the profitability of the energy renovation towards passive house.

Scenario 1

With a 3.3 kWp PV system installed, Figure 20 shows the life cycle profit while utilizing different battery sizes. While including the tax reduction for sold electricity, the best option is using a 10 kWh battery. In the scenario of excluding the tax reduction, a 10 kWh battery is still the favorable option, however a 15 kWh battery would take its place if a slight decrease in battery prices occurs. The increased value of using batteries is more prominent in the case of excluding the tax reduction as reflected in the steep gradient of the bars. This occurs because of the decreased value of sold electricity, making batteries more profitable as it allows for storing more valuable electricity and diminishing the need of selling the overproduction to the grid.

In the case of including the tax reduction for sold electricity, the negative effect of selling electricity rather than storing it is less impactful which is why adding a battery to the system does not provide as high of an increase profit.

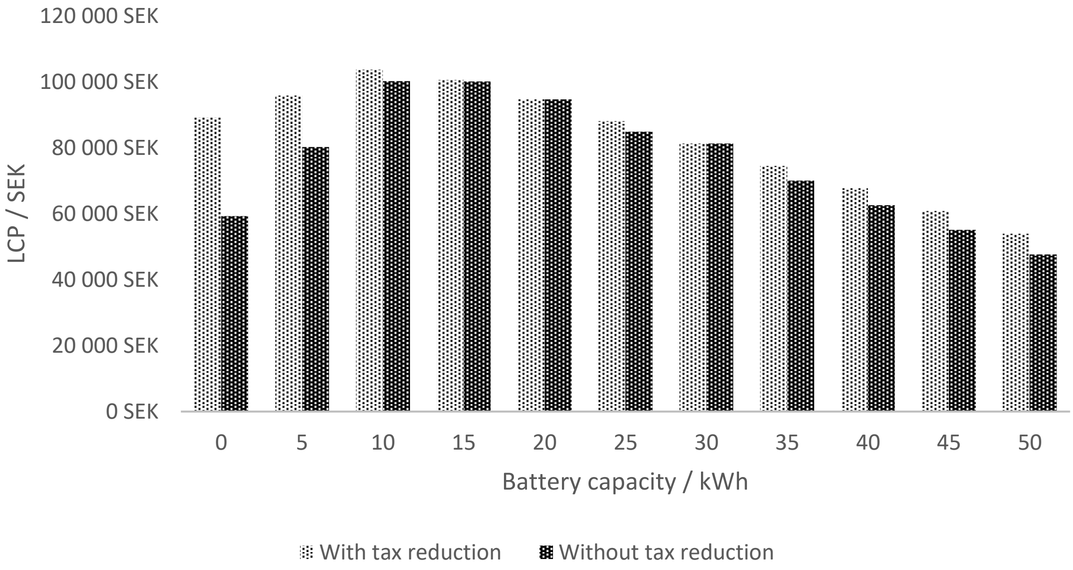

Figure 20. LCP of a 3.3 kWP PV system with the electricity load of the single family building while utilizing different battery sizes, ranging from 0 kWh (no battery) to 50 kWh.

During a sunny summer day, the 10 kWh battery will generally become fully charged at around 2 pm (Figure 21). The battery is kept at a full state of charge until late afternoon (17.00 pm) while the sun is shining and the electricity load is relatively low. A fair amount of electricity is also being sold to the grid until the afternoon electricity peak occurs around 17.30 pm. The PV system and the battery are at this point working simultaneously until 21 pm when all the electricity load is covered by the battery. Given that the battery was fully charged during the day, it is able to cover all of night load including most the morning electricity peak, where only a slight addition of electricity from the grid is needed before it gets charged back up again.

According to the figure, the 10 kWh battery is large enough to cover most of the load that occurs while the electricity generated from the PV is not sufficient. Only a small portion of electricity is purchased from the grid during the morning peak. This does however indicate that the battery is also not oversized to the load.

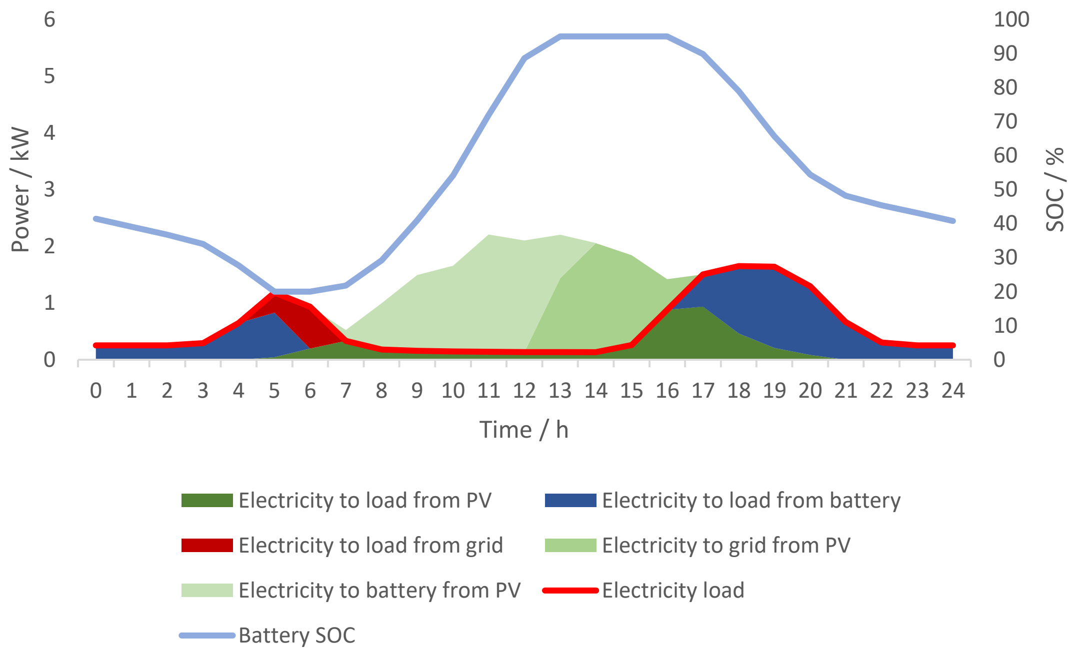

Figure 21. A sunny summer day (Jul 7) showing the 10 kWh battery state of charge, allocations of PV electricity production and battery dispatch while using an 3.3 kWp PV system. The x-axis represents the hours of a full day and night (24 h).

Figure 21 above is, as mentioned, illustrating the case during a sunny summer day. In winter, however, the battery will never get fully charged and thereby not be utilized to its full potential. It is therefore more interesting to look at the summer case. The winter case (Feb 3) is shown in Figure 55 in Appendix C.

Figure 22 shows the amount of imported, exported and own used electricity while utilizing the most profitable battery from Figure 20. As both scenarios showed the highest profit with a 10 kWh battery, both bars show the same values.

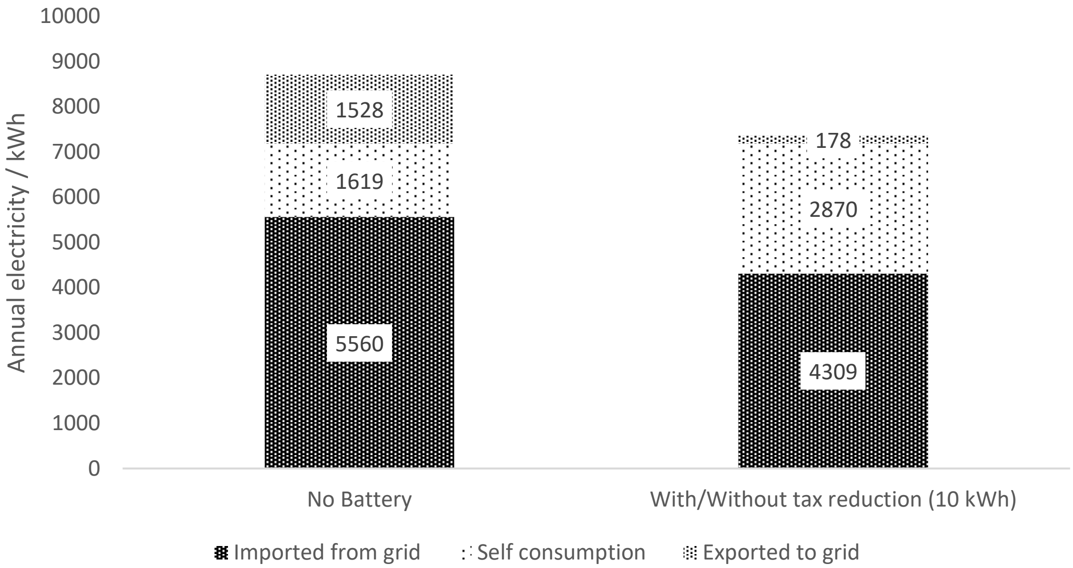

Figure 22. Annual imported, exported and self-consumed electricity while utilizing the most profitable battery, with and without tax reduction as well as without the use of a battery

While varying different economical parameters, the resulting range LCP after 30 years is expressed in box plots in Figure 23 below. The box in the plot represent 50 % of the values with the horizontal line corresponding to the median value. The lines above and below the box each represent the top and bottom quartile (25 %), respectively. The highest profitability occurs while the electricity price change is increasing by 2%, the PV system price is decreasing by 10% and the interest rate is set at 2%. The lowest LCP occurs while the electricity price is decreasing by 2 %, the PV system prices are kept stable at 0% and the interest rate is at -2%. Even in the worst economic scenario, the LCP does not however reach negative values.

Figure 23. LCP of the PV system while utilizing the most profitable battery size during various economical scenarios, with and without tax reduction.

Assuming the same variety of economical scenarios, the maximum battery price in SEK/kWh is shown in Figure 24 below. The current battery price of 1500 SEK/kWh is represented by a red line in the graph. In the case of including the tax reduction, some of the worse economical scenarios require a battery price lower than 1500 SEK/kWh to be profitable, which was assumed as today's market price. The trendline of battery prices is however decreasing rapidly meaning that this case might become profitable in some years, even in the worst economical scenarios.

While excluding the tax reduction however, the battery prices may even increase to maintain profitability in the worst economic scenario. These results indicate therefore that, if tax-reduction is removed, batteries will most probably be profitable in any scenario.

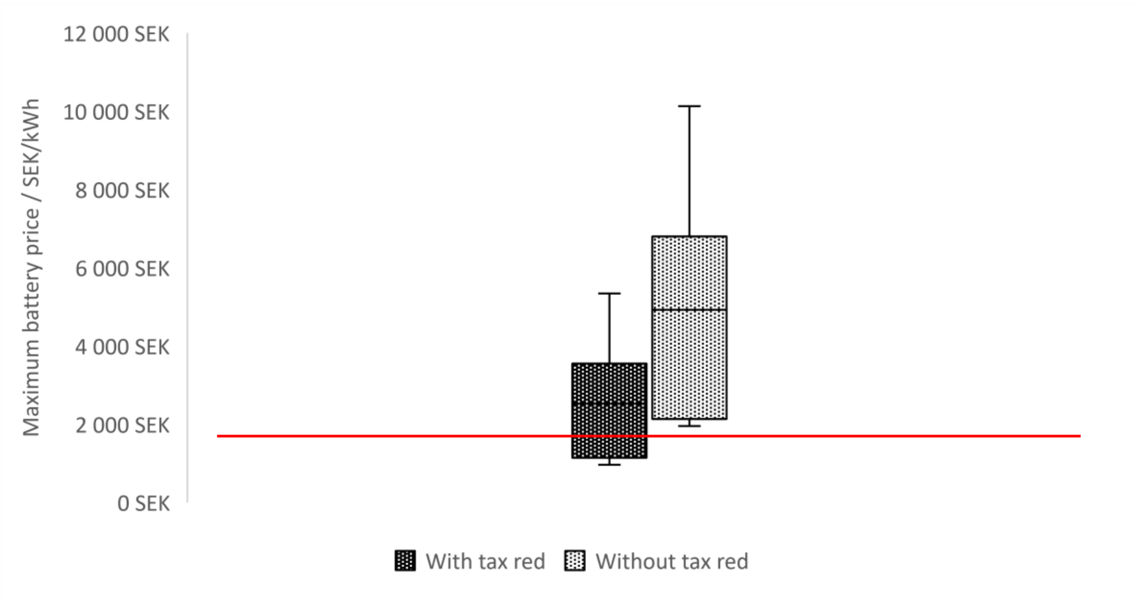

Figure 24. Maximum battery price in SEK/kWh for the most profitable battery during various economical scenarios for maintaining profitability, with and without tax reduction. The red horizontal line represents the current battery price of 1500 SEK/kWh

Scenario 2

In the case of pursuing maximal profit for the PV installation and not setting a limit to merely reach NZEB, the optimal PV system size appears to be an 8.25 kWp system, which is an increase in size of more than double, fully utilizing the area of the south facing roof (45.5 m^2) and producing 8900 kWh annually. Figure 25 below shows the profitability while using this system size together with various sizes of batteries.

With tax reduction, the optimal battery size is 10 kWh, while a 15 kWh battery is more profitable if the tax reduction is excluded. Again, the increased value of utilizing batteries is shown in the gradient of the bars. Even a 50 kWh battery, although significantly oversized for the load, shows a higher profit than not using a battery if the tax reduction is discontinued. On the other hand, using a battery larger than 20 kWh will result in a lower profit than not using a battery if the tax reduction is included.

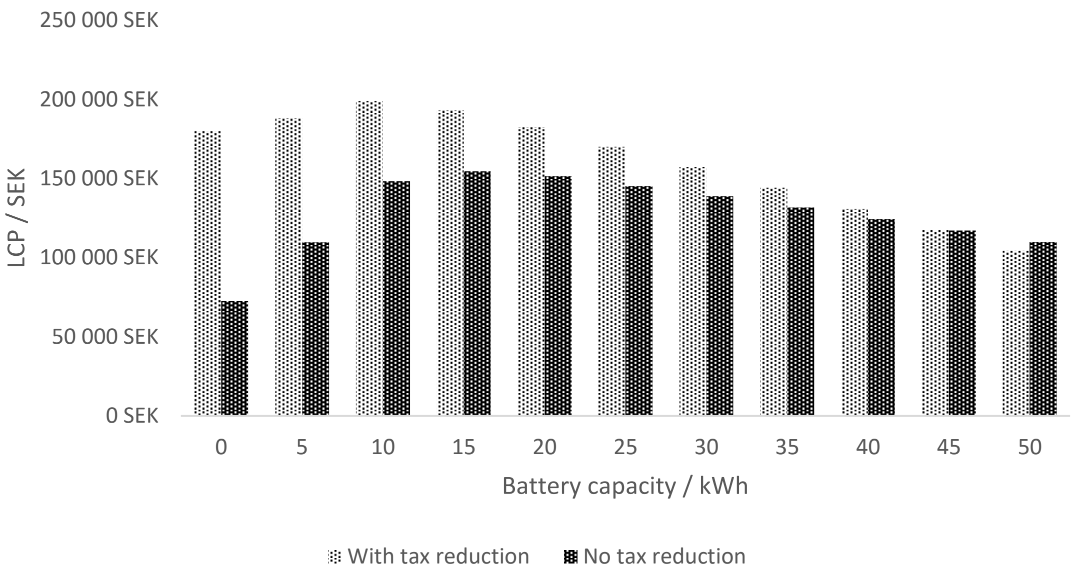

Figure 25. LCP of an 8.25 kWP PV system with the electricity load of the single family building while utilizing different battery sizes, ranging from 0 kWh (no battery) to 50 kWh.

During a sunny summer day, the 10 kWh battery, shown to be the most profitable for the case including tax reduction will generally become fully charged at around 10 am (Figure 26). The battery is kept at a full state of charge until late afternoon (17.00 pm) while the sun is shining and the electricity load is relatively low. A substantial amount of electricity is also sold to the grid until the afternoon electricity peak occurs around 17.30 pm. The PV system and the battery are at this point working simultaneously until 21 pm when all the electricity load is covered by the battery. Given that the battery was fully charged during the day, it is able to cover all of night load including the morning electricity peak before it gets charged back up again. The battery reaches a state of discharge of 30 % (with 20 % being the minimum for this type of battery) meaning it could dispatch one more kWh before it needs charging.

Shown in the figure, the battery is large enough to cover the whole night load, including the afternoon and morning peak. As the battery is not reaching its minimum state of charge, it indicates that it is slightly oversized for a sunny day such as the one considered in the figure. In the case of a less sunny day, however, the battery might still be able to cover the same load.

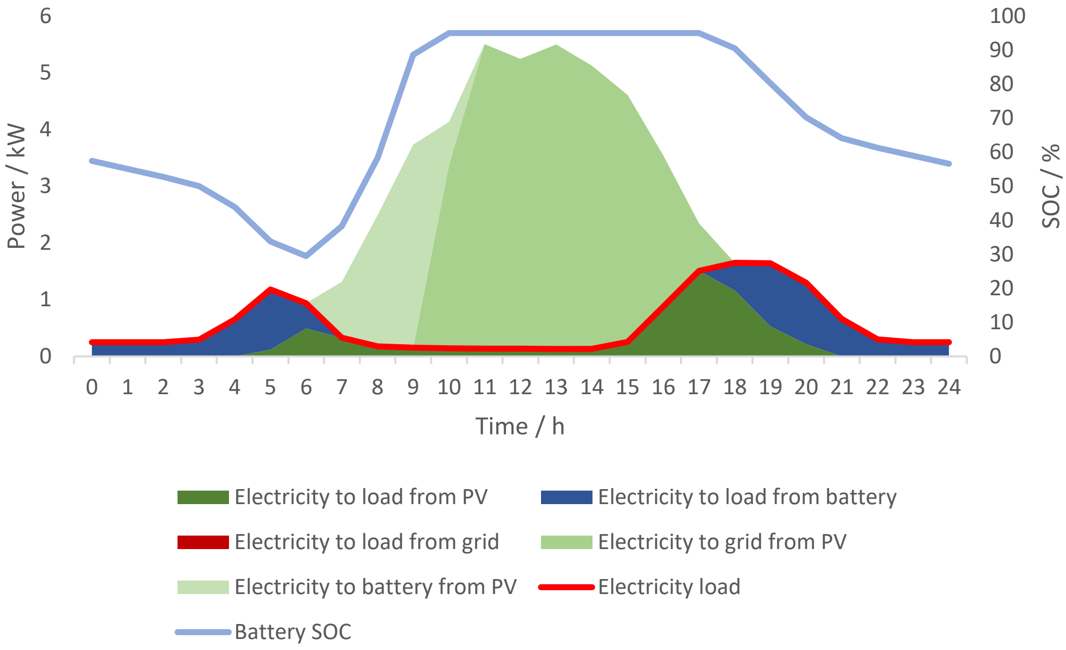

Figure 26. A sunny summer day (Jul 7) showing the 10 kWh battery state of charge, allocations of PV electricity production and battery dispatch while using an 8.25 kWp PV system. The x-axis represents the hours of a full day and night (24 h).

In the case of excluding the tax reduction where a 15 kWh battery showed the highest profitability, no significant differences are noted (Figure 27). The state of discharge is however decreasing at a slightly slower rate as there is more energy to be dispatched. After covering the night load and the morning electricity peak, the battery reaches a state of discharge of around 50 % before it gets charged again. This indicates that there is another 3 kWh of energy to be dispatched, which would cover the electricity load for another few hours in case of a less sunny morning.

Being left at a state of charge of 50 % indicates that the battery size is large enough to diminish the need of purchasing electricity even in a substantially less sunny day.

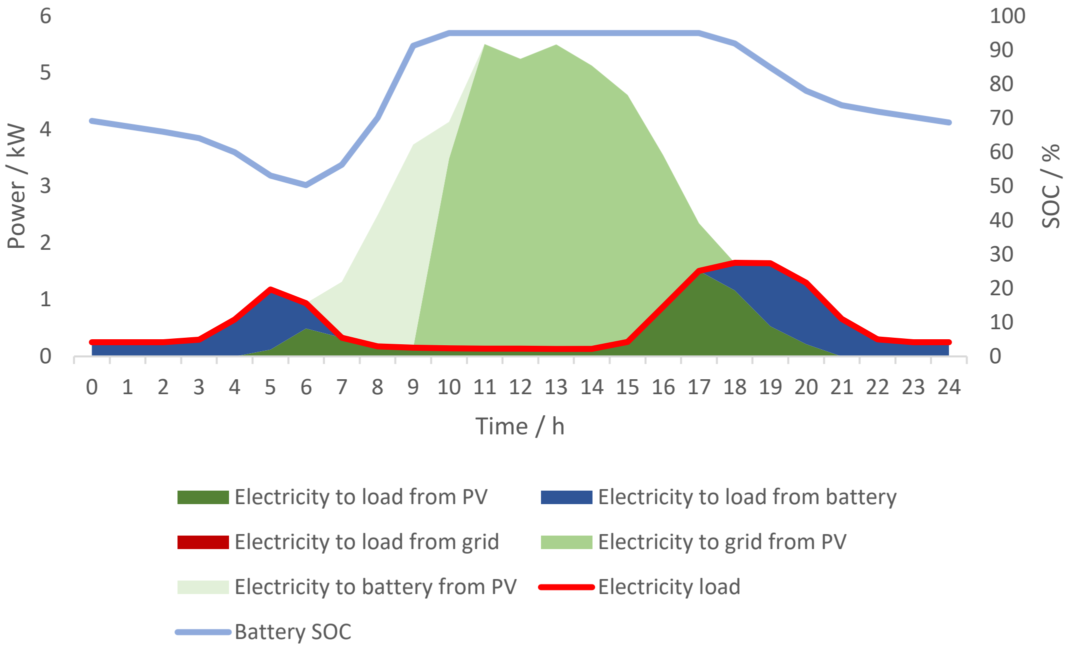

Figure 27. A sunny summer day (Jul 7) showing the 15 kWh battery state of charge, allocations of PV electricity production and battery dispatch while using an 8.25 kWp PV system. The x-axis represents the hours of a full day and night (24 h).

The winter case is shown in Figure 56 in Appendix C.

In Figure 28 below, the annual imported, exported, and own used electricity is shown while using the most profitable battery size according to Figure 25. As a larger battery is used in the case of excluding the tax reduction, a decrease in imported and exported electricity is noted, while an increase in own used electricity occurs.

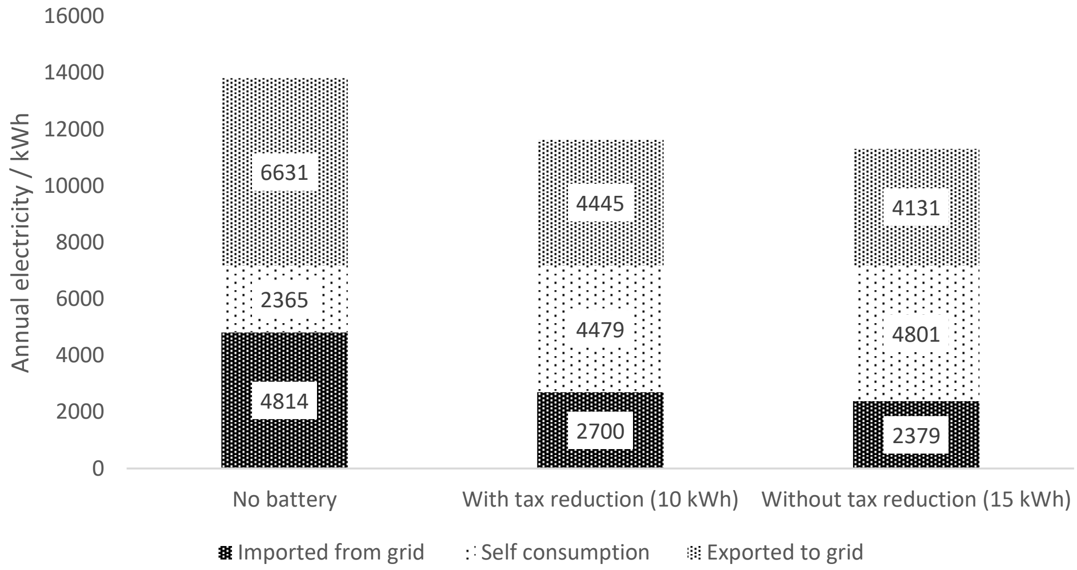

Figure 28. Annual imported, exported and self-consumed electricity while utilizing the most profitable battery, with and without tax reduction as well as without the use of a battery

As shown in Figure 29, varying different economical parameters, the same effect as for the previous case occurs. The worst economic scenario does however, in this case, show a negative profitability if the tax reduction is excluded, indicating a larger investment is more vulnerable to variations in economic parameters.

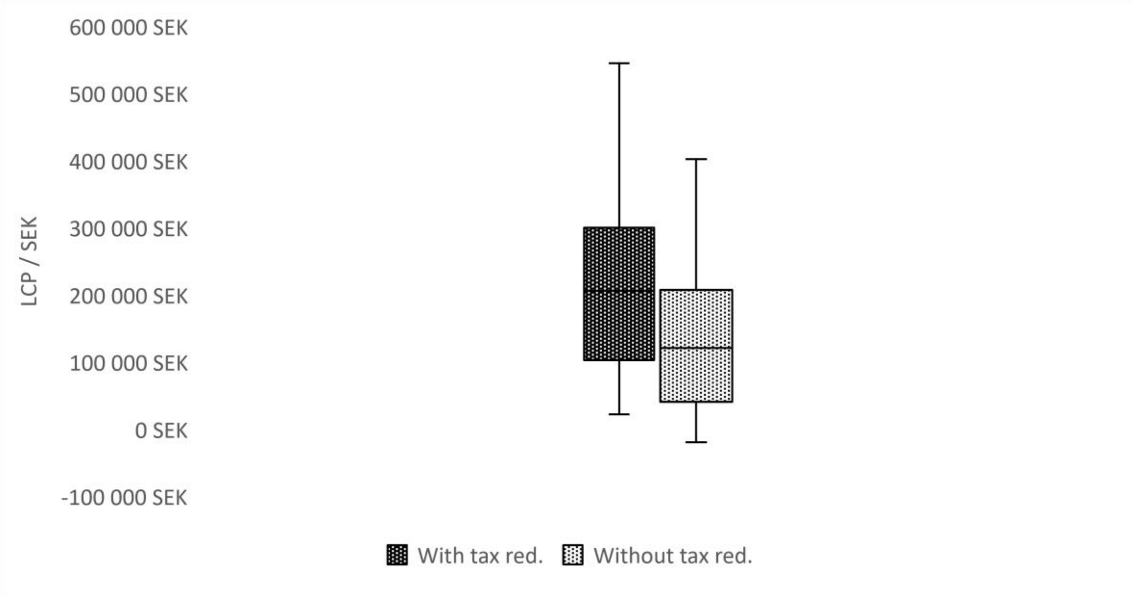

Figure 29. LCP of the PV system while utilizing the most profitable battery during various economical scenarios, with and without tax reduction.

The maximum allowed battery price to maintain profitability is again significantly higher for the case without tax reduction, as a result of more value put in storing and using the produced electricity rather than selling it, shown in Figure 30.

With the tax reduction, the worst economical scenarios do yet again show a required maximum battery price of lower than 1500 SEK/kWh, represented by a red line in the graph.

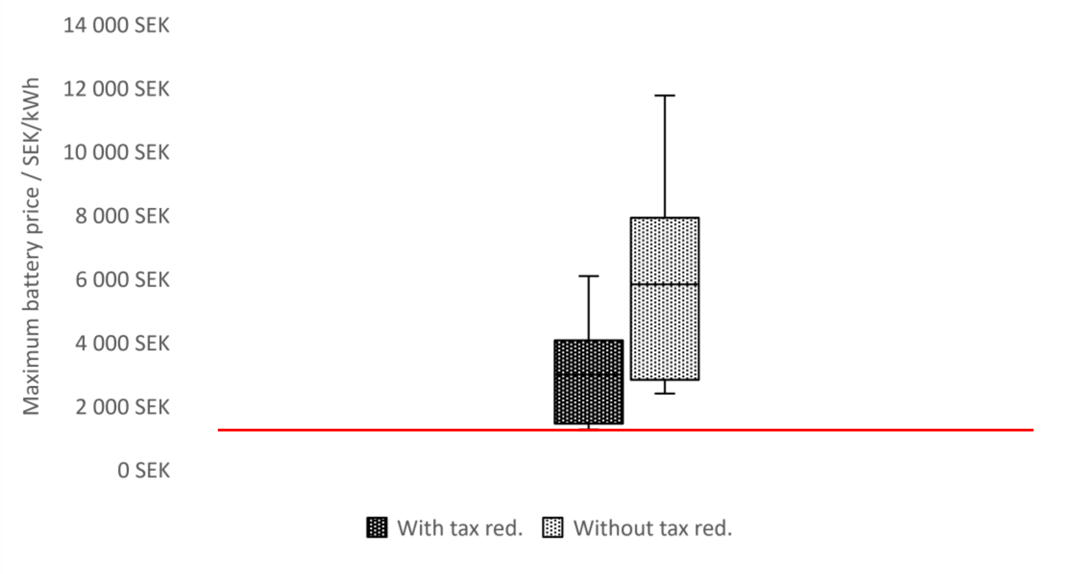

Figure 30. Maximum battery price in SEK/kWh for the most profitable battery during various economical scenarios for maintaining profitability, with and without tax reduction. The red line represents the current battery price of 1500 SEK/kWh

In Figure 31, the LCP during various economical scenarios for both abovesaid cases are shown, however normalized to the floor area. Additionally, the right-most box plot shows the profitability of the energy renovation alone towards passive house, using investment costs found in previous studies. As can be noted, the profitability of the passive house renovation shows consistently negative values, while the profitability of the PV systems show positive values in the majority of the cases.

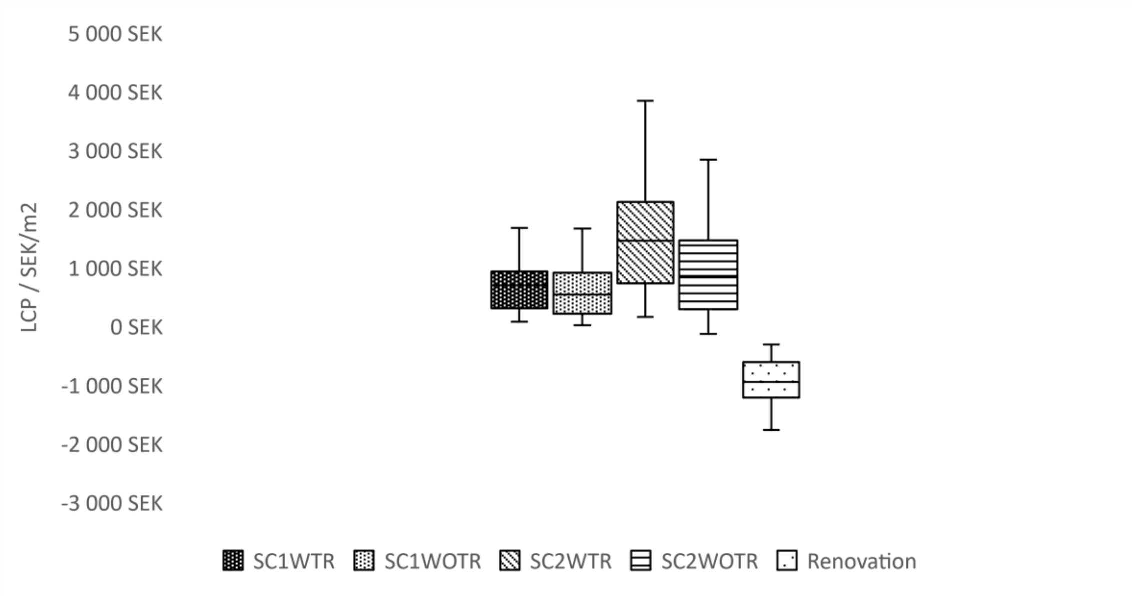

Figure 31. Comparison of the LCP between the two cases, with and without tax reduction. The right-most box plot represents the profitability of the energy renovation alone.

4.2.3 Multi Family Building

The results presented here are divided into three sections, each corresponding to a different scenario, as described previously. Each section includes parametric studies of life cycle profitability regarding battery size, annual imported, exported, and own used electricity for the most profitable option and finally a sensitivity analysis where different economical parameters were varied to visualize the economic impact of such variations.

Lastly, the profitability of each scenario, including the sensitivity analyses, are compared to the profitability of the energy renovation.

Scenario 1

With a 34.2 kWp PV system installed, the LCP while utilizing various battery sizes is shown in Figure 32. For both cases, with and without tax reduction, a 20 kWh battery showed the highest profitability.

As the electricity load in this scenario is relatively low compared to the PV system size, a significant amount of overproduction is noted (see Figure 17). In the case of excluding the tax reduction, a battery is definitely required to reach profitability and avoid selling the high over production for a low price. This effect is clearly reflected in the difference of not using a battery (0 on the x-axis), showing a negative value of about -66 000 SEK. Even with tax reduction, and since overproduction is so high, batteries are still profitable as the amount of sold electricity at lower price is decreased.

Again, as the load is relatively low, using too large batteries would also result in negative profitability as their capacities will not be utilized fully, resulting in unnecessary investment costs.

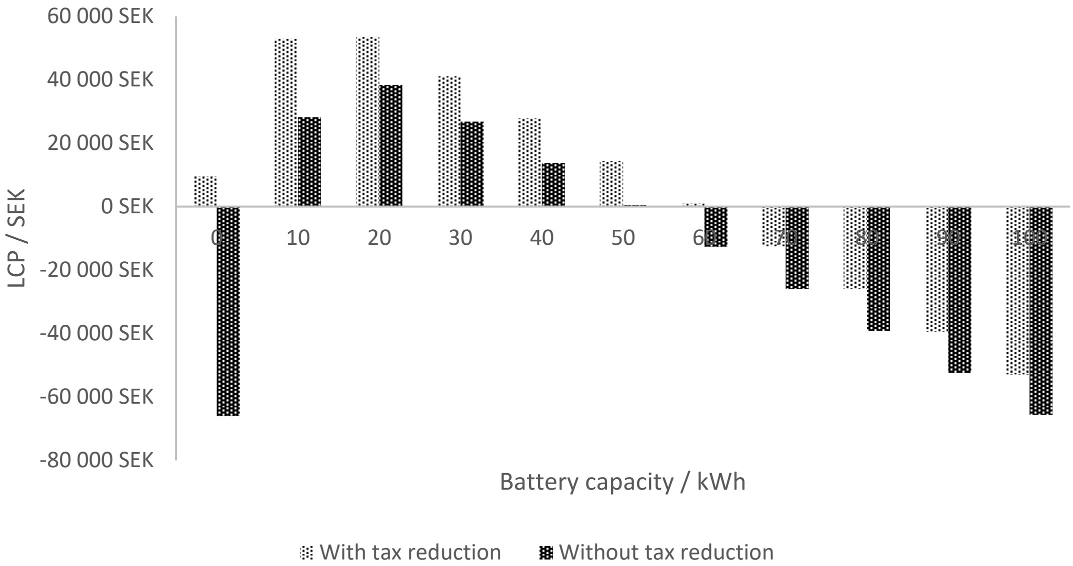

Figure 32. LCP of a 34.2 kWP PV system with the electricity load of the multi family building (excl. household electricity) while utilizing different battery sizes, ranging from 0 kWh (no battery) to 100 kWh.

As the system is oversized to the relatively small load, a sunny summer day will charge the battery to its full state of charge in early morning, at around 7 am, shown in Figure 58 Appendix C. This state of charge will be kept constant during the whole day as the sun is shining and covering the load. When the sun goes down, the battery dispatches its energy to cover the night load, ending at a state of charge of 65 % whereas the process is repeated. Looking at the summer case is therefore not particularly interesting.

In winter, however, on a particularly sunny day, the PV system will manage to charge the battery to its maximum capacity, which occurs at around 13 pm (Figure 33). The low electricity load will even allow for some sold electricity to the grid during the day. As the sun sets earlier in winter, the battery will start dispatching its energy at around 16 pm. Given that the battery was fully charged, it will be able to cover the full night load, reaching a state of charge of 35 %.

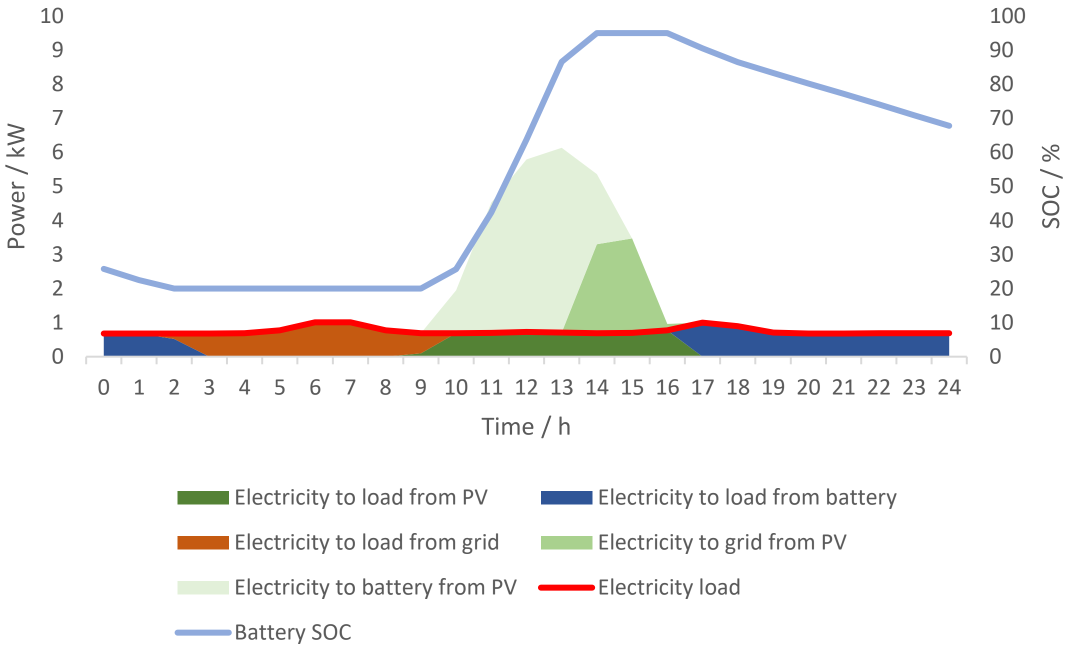

Figure 33. A sunny winter day (Feb 3) showing the 20 kWh battery state of charge, allocations of PV electricity production and battery dispatch while using an 34.2 kWp PV system. The x-axis represents the hours of a full day and night (24 h).

Even while utilizing the 20 kWh batteries, the amount of sold electricity still makes up most of the PV production as shown in Figure 34. This could be regarded as yet another indication that the electricity load considered in this scenario is too low in relation to the PV system size.

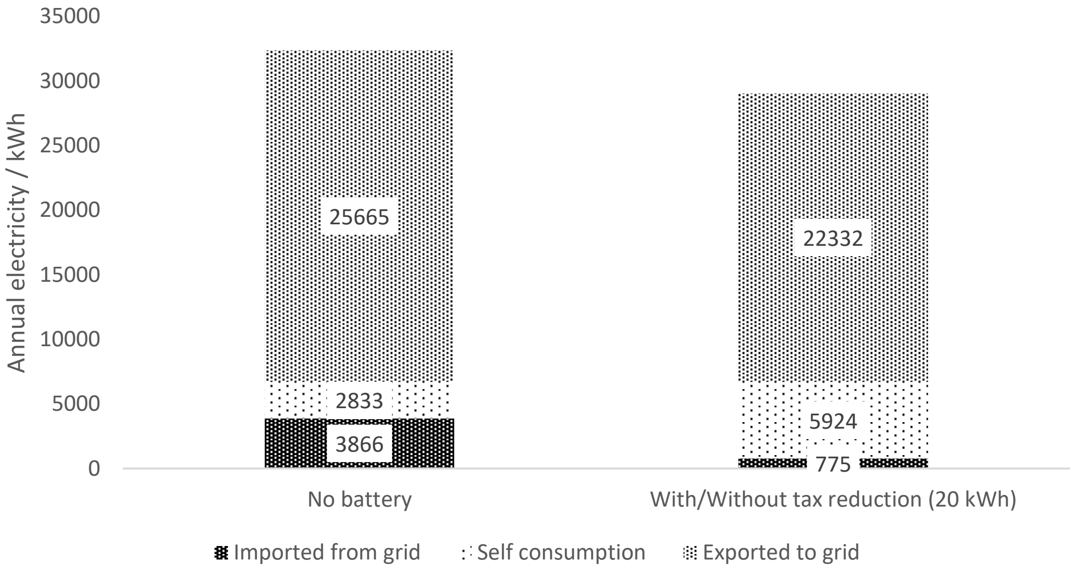

Figure 34. Annual imported, exported and self-consumed electricity while utilizing the most profitable battery, with and without tax reduction as well as without the use of a battery

Varying economical parameters is in this case more sensitive as about half of the variations result in negative profitability for both cases (Figure 35). The highest profitability occurs while the electricity price increases by 2%, the PV system prices decreases by 10% and the interest rate is at 2%. The lowest values occur while the electricity price decreases by 2%, the PV system prices are kept stable at 0% and the interest rate is at -2%

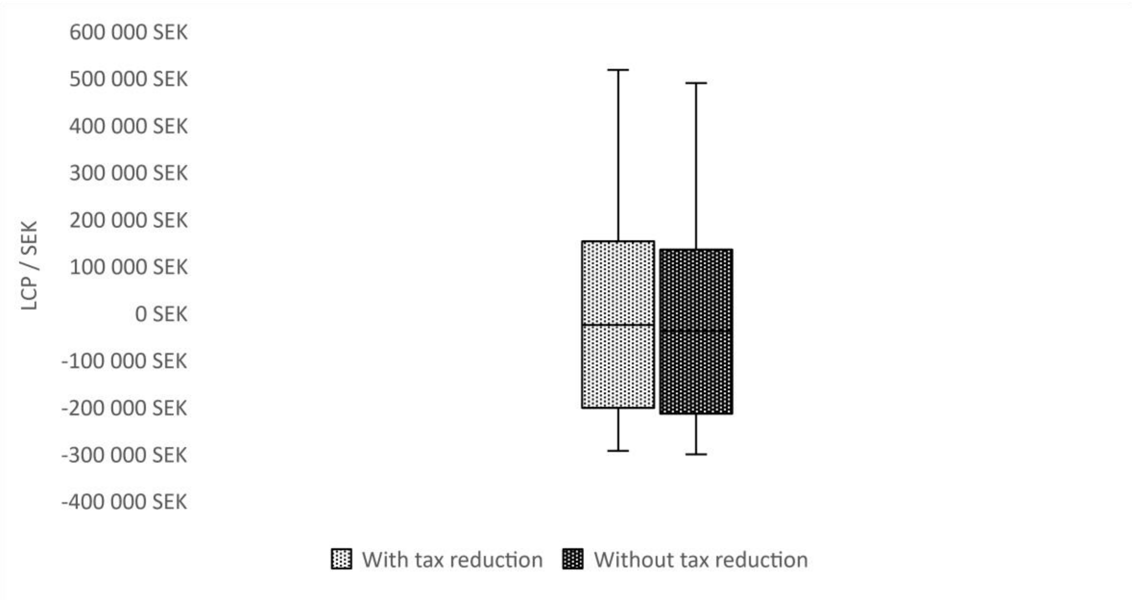

Figure 35. LCP of the PV system while utilizing the most profitable battery during various economical scenarios, with and without tax reduction.

The increased value of using a battery is again reflected in the maximum battery price allowed to maintain profitability, shown to be significantly higher in the case of excluding the tax reduction, as indicated in Figure 36**.** For all economical scenarios, the maximum battery price is above 1500 SEK/kWh if the tax reduction is discontinued, while some of the less favorable economical scenarios would require a price reduction of batteries to maintain profitability if the tax reduction is included.

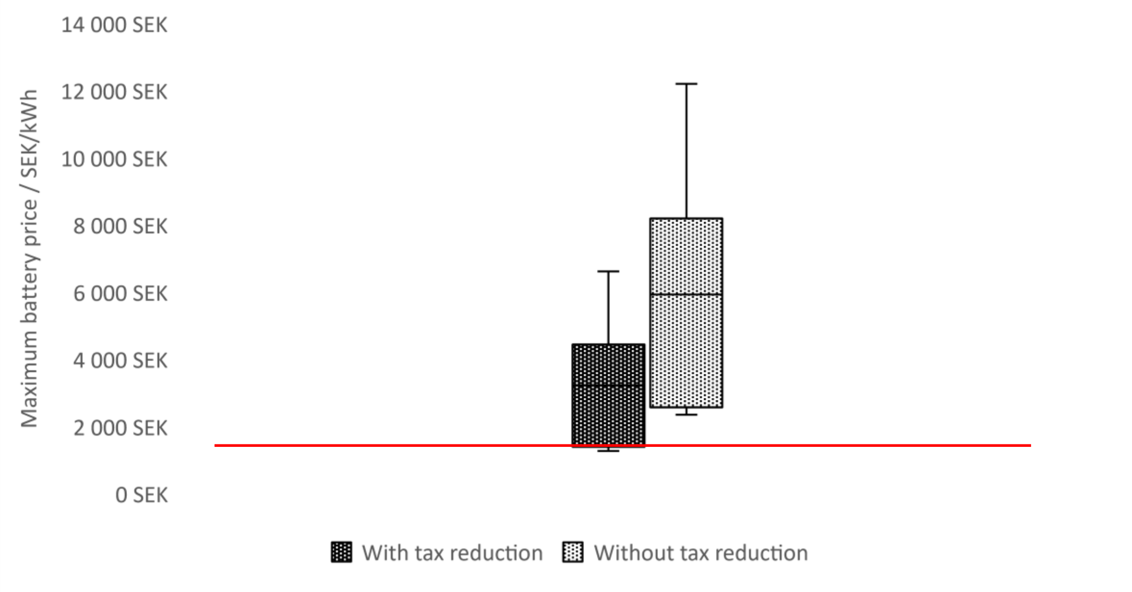

Figure 36. Maximum battery price in SEK/kWh for the most profitable battery during various economical scenarios for maintaining profitability, with and without tax reduction. The red horizontal line represents the current battery price of 1500 SEK/kWh

Scenario 2

With the same PV system size but a higher electricity load (including household electricity), the most profitable batteries are shifted toward the larger sizes (see Figure 17). In the scenario of including the tax reduction, a 70 kWh battery was shown to be the most profitable, while in the other case, i.e excluding the tax reduction, a 80 kWh battery was preferable from an economic standpoint, shown in Figure 37.

The gradient is again steeper if the tax reduction is discontinued, indicating a higher added value while utilizing batteries whereas the increased profit in the scenario of including the tax reduction is not as significant and therefore arguable if worth investing in batteries in such case.

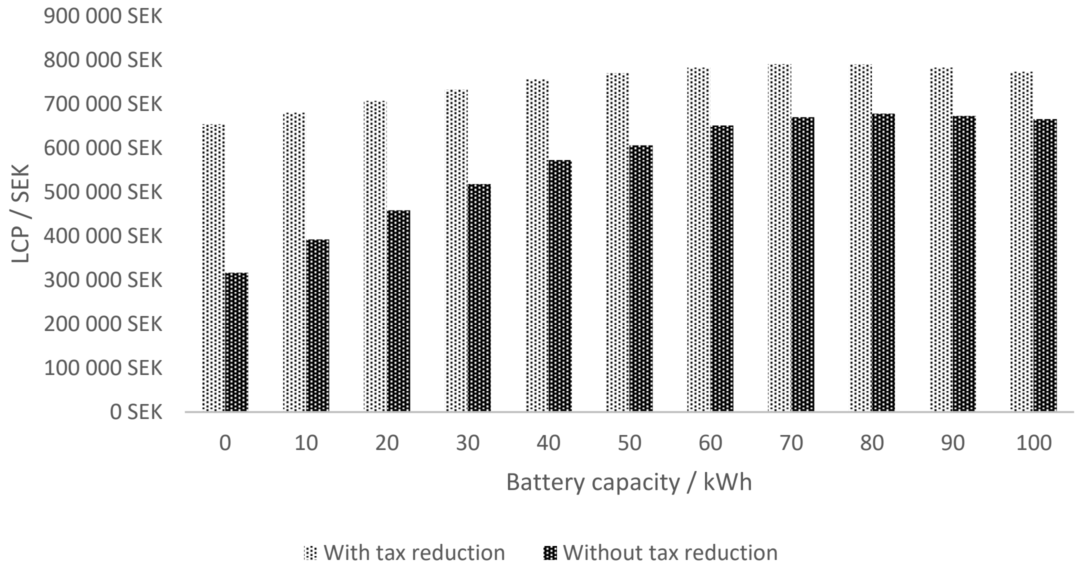

Figure 37. LCP of a 34.2 kWP PV system with the electricity load of the multi family building (incl. household electricity) while utilizing different battery sizes, ranging from 0 kWh (no battery) to 100 kWh.

As the load in this scenario is a lot higher a greater portion of the PV produced electricity is used for the electricity load. It is therefore more interesting to see the battery operating during a summer day, as in winter, it never gets fully charged and is thereby not fully utilized. While using the 70 kWh battery, shown to be the preferable choice while including the tax reduction, the battery will become fully charged at around 11 pm (Figure 38). As the afternoon electricity peak occurs at 17.30 pm, the battery starts dispatching its energy to cover the electricity load together with the PV system. As the sun sets at 21 pm, the battery operates single handedly to cover the load.

During nighttime, the battery covers the whole night load including the morning electricity peak, ending at a state of charge of about 35 % whereas the sun rises and starts charging the battery again.

Again, the battery size is large enough to more or less cover the night load, including the afternoon and morning peaks. With about 15 % left of its capacity, it is indicated that the battery would manage to cover the whole load even during a slightly less sunny day.

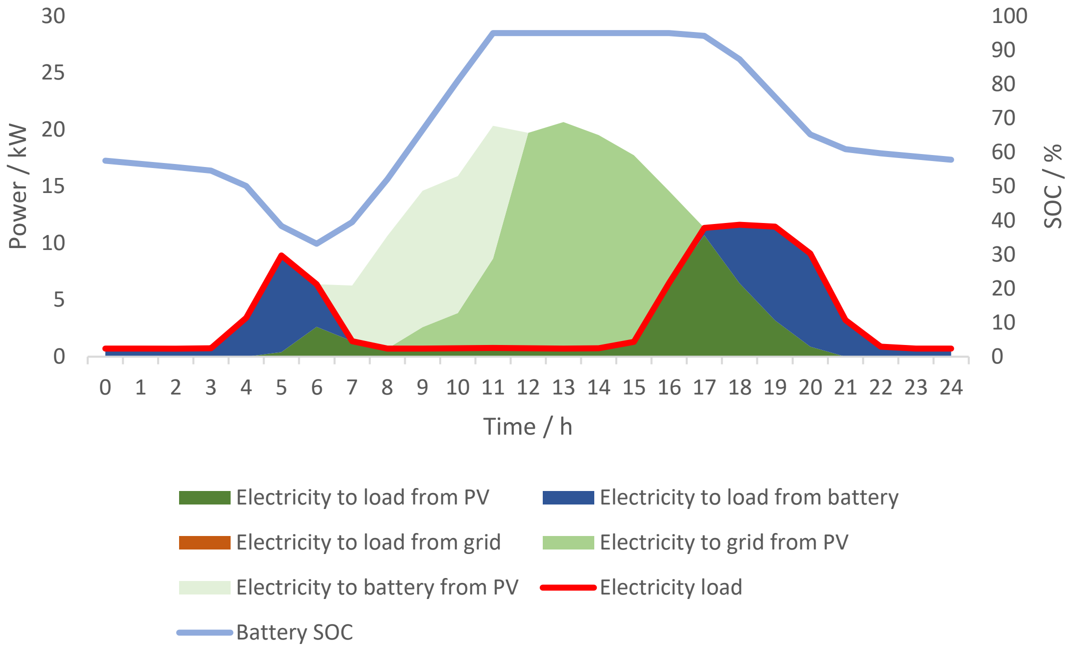

Figure 38. A sunny summer day (Jul 7) showing the 70 kWh battery state of charge, allocations of PV electricity production and battery dispatch while using an 34.2 kWp PV system. The x-axis represents the hours of a full day and night (24 h).

While excluding the tax reduction, the 80 kWh showed the highest profitability. In Figure 39, it can be observed that the battery becomes fully charged at around 11 pm and is kept stable until it discharges as the afternoon electricity peak occurs. The battery then proceeds to discharge its energy to cover the night load including the morning peak. At around 6 am, the battery gets charged back up.

The 80 kWh is left at a slightly higher state of charge compared to the 70 kWh battery. This would indicate that the battery could cover the whole load during a substantially less sunny day.

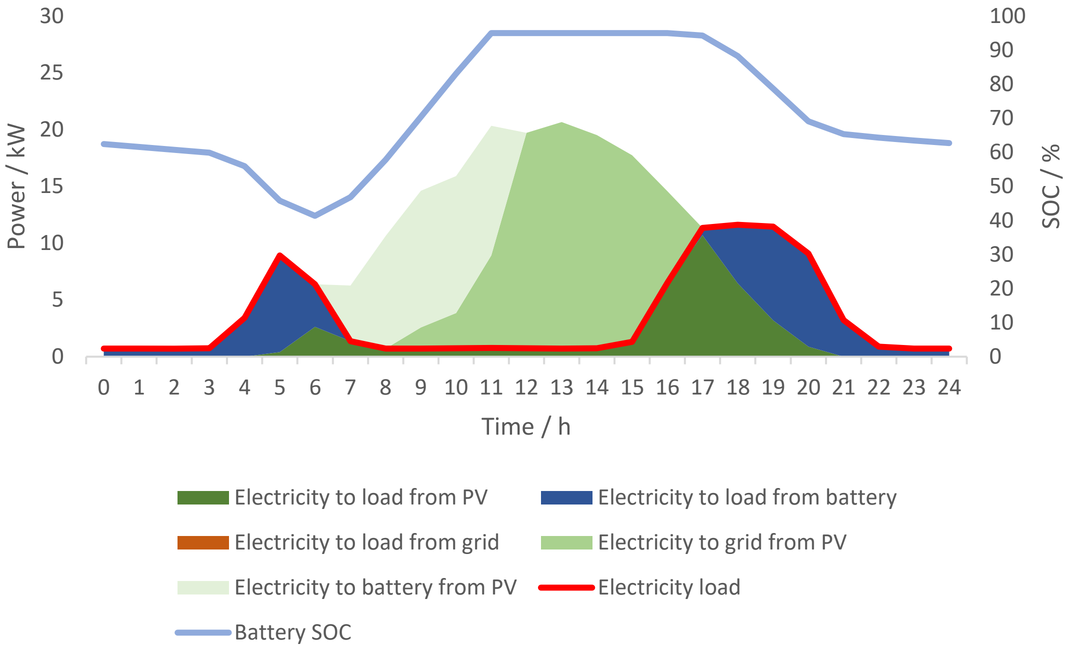

Figure 39. A sunny summer day (Jul 7) showing the 80 kWh battery state of charge, allocations of PV electricity production and battery dispatch while using an 34.2 kWp PV system. The x-axis represents the hours of a full day and night (24 h).

The winter case is shown in Figure 59 and Figure 60 in Appendix C

The annual imported, exported and own used electricity are shown for both cases, in Figure 40, while using the most profitable battery. With the larger, 80 kWh battery, both imported and exported electricity is reduced while the own used electricity is increased.

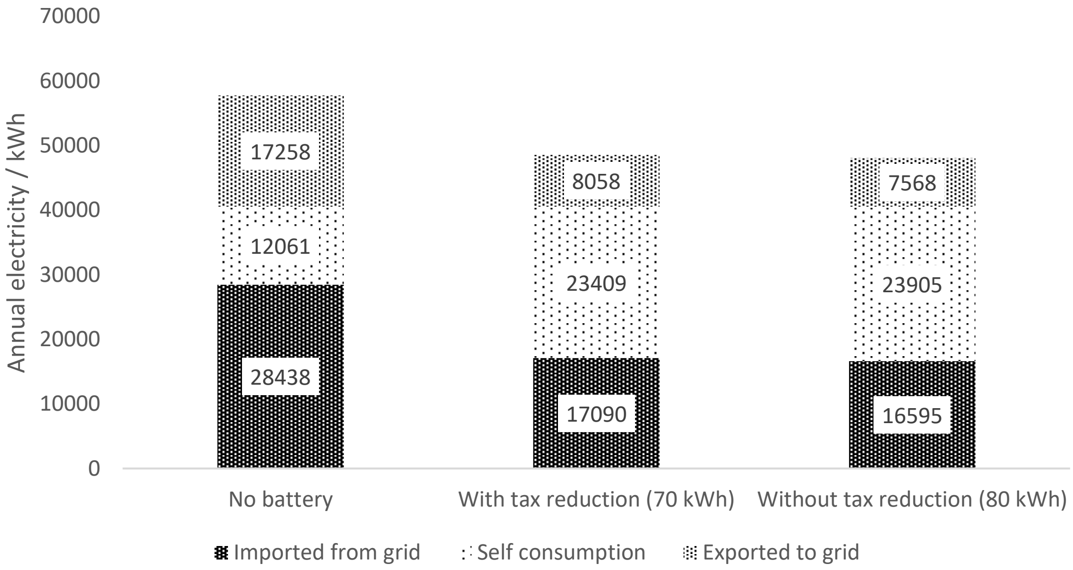

Figure 40. Annual imported, exported and self consumed electricity while utilizing the most profitable battery, with and without tax reduction as well as without the use of a battery

By varying different economical parameters, the LCP for both cases are as shown in Figure 41 below. A negative LCP will only occur if the tax reduction is discontinued while the economical parameters are set as a worst case, i.e a 2% decrease in electricity price, an unchanged price development in PV system components and an interest rate of 2%.

With the tax reduction, a negative LCP will never occur during a period of 30 years according to the variations of economical parameters in this study.

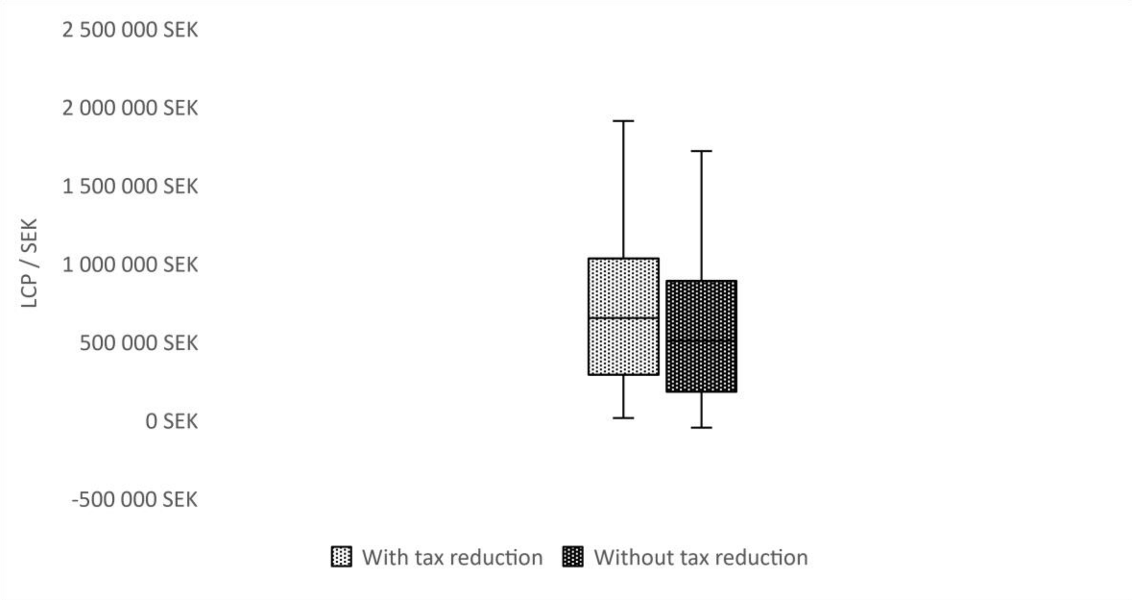

Figure 41. LCP of the PV system while utilizing the most profitable battery during various economical scenarios, with and without tax reduction.

Assuming a discontinuation of the tax reduction and a scenario of the least favorable economic parameters, a slight battery price increase would still result in battery utilization being the most profitable option, as indicated in the right box plot in Figure 42.

In the same economic scenario, a battery price decrease must however occur if the tax reduction is included, to maintain its profitability.

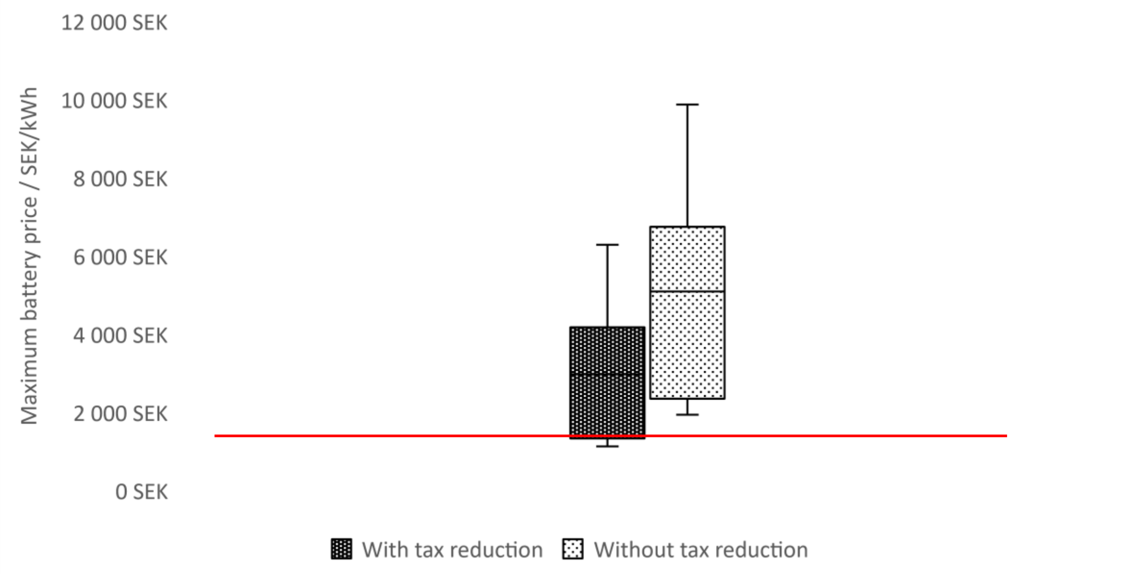

Figure 42. Maximum battery price in SEK/kWh for the most profitable battery during various economical scenarios for maintaining profitability, with and without tax reduction. The red horizontal line represents the current battery price of 1500 SEK/kWh

Scenario 3

By not limiting the system size to simply reach NZEB, higher profits can again be achieved, as shown in Figure 43 below. As opposed to the single family building, the most profitable PV system size depends on whether the tax reduction is included or not. For the case with the tax reduction being included, a 70 kWp system showed the highest profit, utilizing the full area of both the south and north facing roof surfaces. This system produces 59 600 kWh annually, of which 28 000 kWh, or 47 %, is produced by the north facing panels. If the tax reduction is not included however, a 50 kWp system resulted in the highest profitability, whereas the whole south facing roof is utilized and only part of the north facing roof. Similar to scenario 2, the most profitable battery sizes are 70 kWh and 80 kWh while including and excluding the tax reduction, respectively.

It can furthermore be noted that the gradient in this case seems to be slightly steeper while the tax reduction is included, as opposed to all aforementioned cases. This is most likely due to the size of the system resulting in the amount of exported electricity to exceed 30 000 kWh. This would mean a great amount of electricity is sold for a lower price, unless a battery is implemented, which justifies the added value of utilizing batteries.

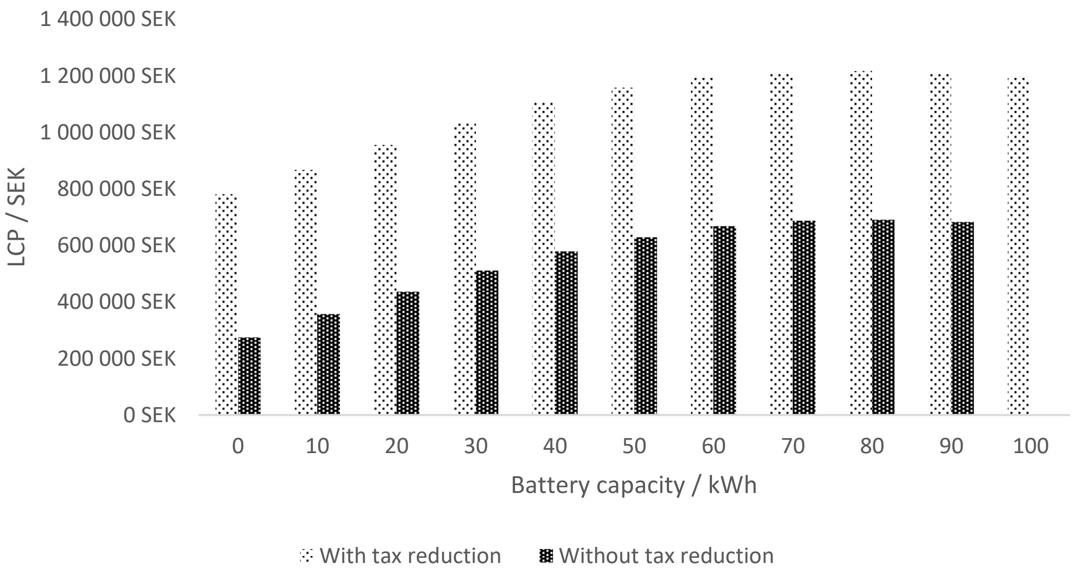

Figure 43. LCP of a 70 kWp (light grey) and 50 kWp (dark grey) PV system with the electricity load of the multi family (incl. household electricity) building while utilizing different battery sizes, ranging from 0 kWh (no battery) to 100 kWh.

With an 70 kWp system and a 70 kWh battery, the battery operates as shown in Figure 44 during a sunny summer day. Due to the increased size of the PV system, relative to the previous case, the battery reaches is maximum state of charge at 9 am. This state of charge is kept stable during the day, whereas a significant amount of electricity sold to the grid can be noted. The battery does not start to discharge its energy until late in to the afternoon peak.

As the sun sets at 21 pm, the battery operates single handedly to cover the full night load including the morning peak. As the sun rises, the battery quickly gets charged back up again and reaches its maximum state of charge at 9 am whereas the process is repeated.

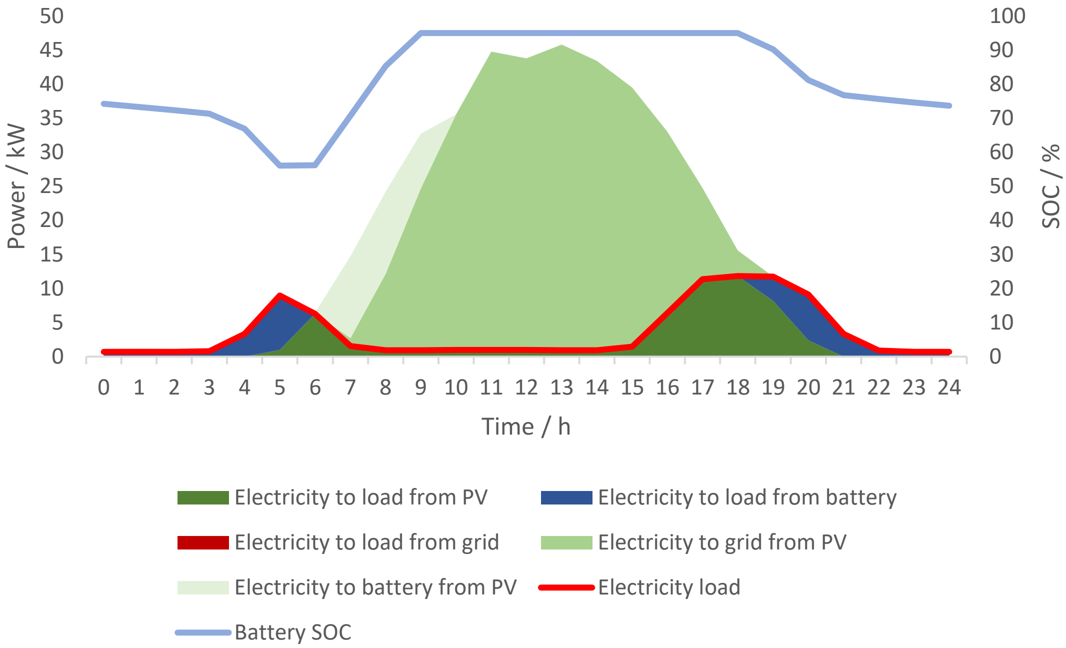

Figure 44. A sunny summer day (Jul 7) showing the 70 kWh battery state of charge, allocations of PV electricity production and battery dispatch while using a 70 kWp PV system. The x-axis represents the hours of a full day and night (24 h).

While excluding the tax reduction, a 50 kWp PV system with an 80 kWh battery was shown to be the most profitable. As can be seen in Figure 45, the battery reaches is maximum state of charge around 10 pm. Due to the decreased system size, the amount of sold electricity is significantly reduced during the day, as opposed to the case where the tax reduction is included. As the afternoon electricity peak occurs, the battery starts operating about half way through it, as the PV system is able to cover the first half single handedly.

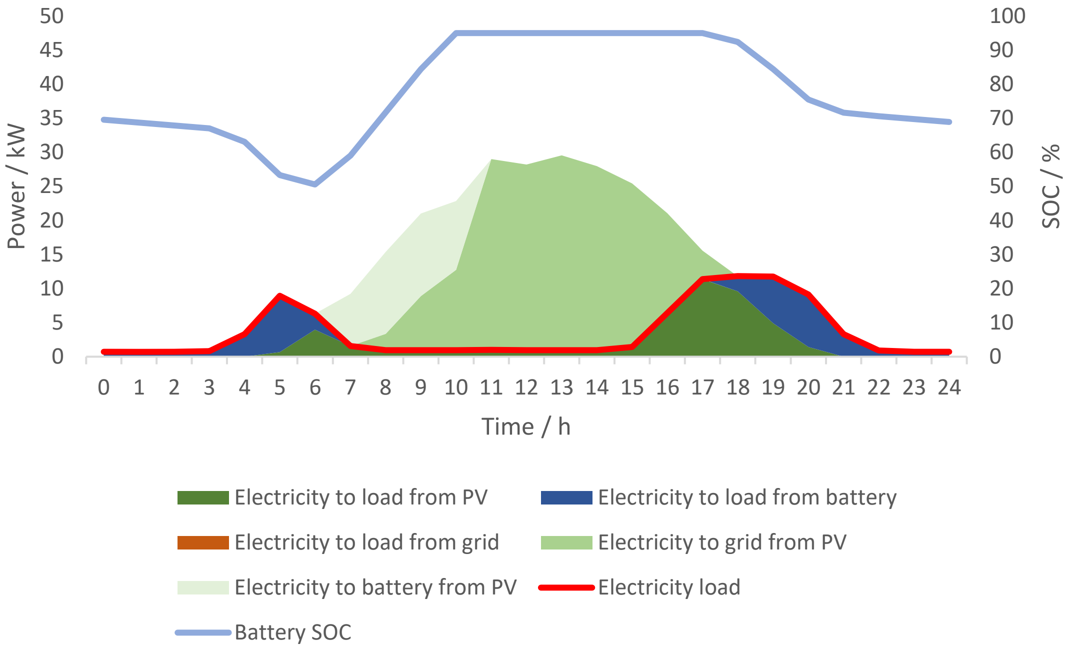

Figure 45. A sunny summer day (Jul 7) showing the 80 kWh battery state of charge, allocations of PV electricity production and battery dispatch while using an 50 kWp PV system. The x-axis represents the hours of a full day and night (24 h).

The winter cases are shown in Figure 61 and Figure 62 Appendix C, indicating that the battery does not get fully charged even during a significantly sunny winter day, thus not utilizing the full potential of the battery.

As the imported, exported and own used electricity shown in Figure 46 below are a result of different PV system sizes, they are less comparable to one another. It can however be noted that the amount of imported and own used electricity does not differ substantially between the cases while the amount of exported electricity is almost doubled for the 70 kWp system. Furthermore, it appears that the 70 kWh battery in the larger system has somewhat limited the exported electricity to an amount fairly close to 30 000 kWh, meaning only 3960 kWh are sold without tax reduction.

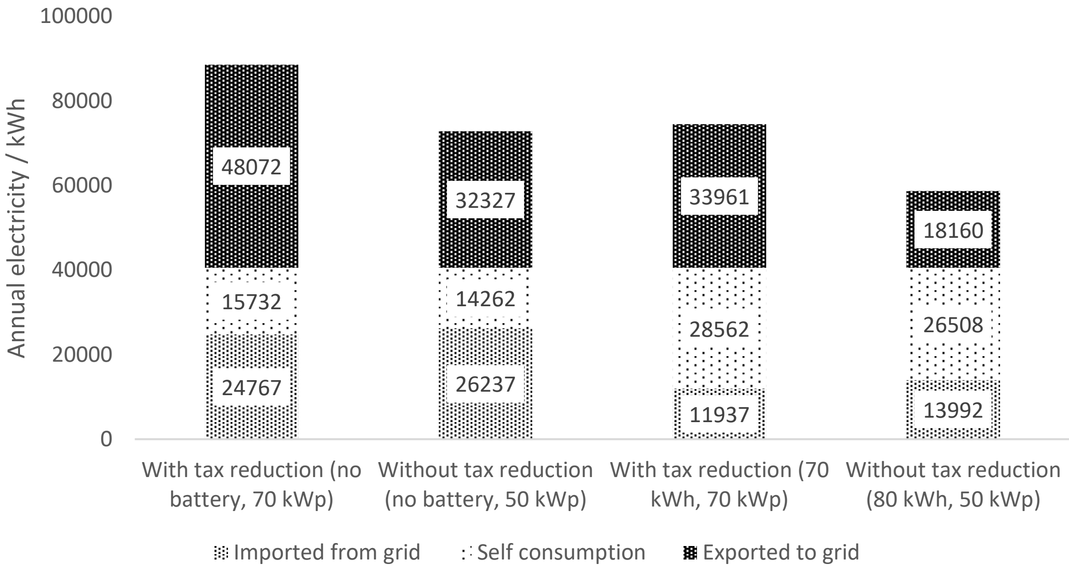

Figure 46. Annual imported, exported and self-consumed electricity while utilizing the most profitable battery, with and without tax reduction as well as without the use of a battery for both system sizes (70 kWp and 50 kWp)

The variations of economical parameters show results according to figure Figure 47 in the case of excluding and including the tax reduction for sold electricity. For both cases, a negative LCP is shown while the economical parameters are set to a worst-case scenario. For the majority of cases, however, a positive LCP is achieved.

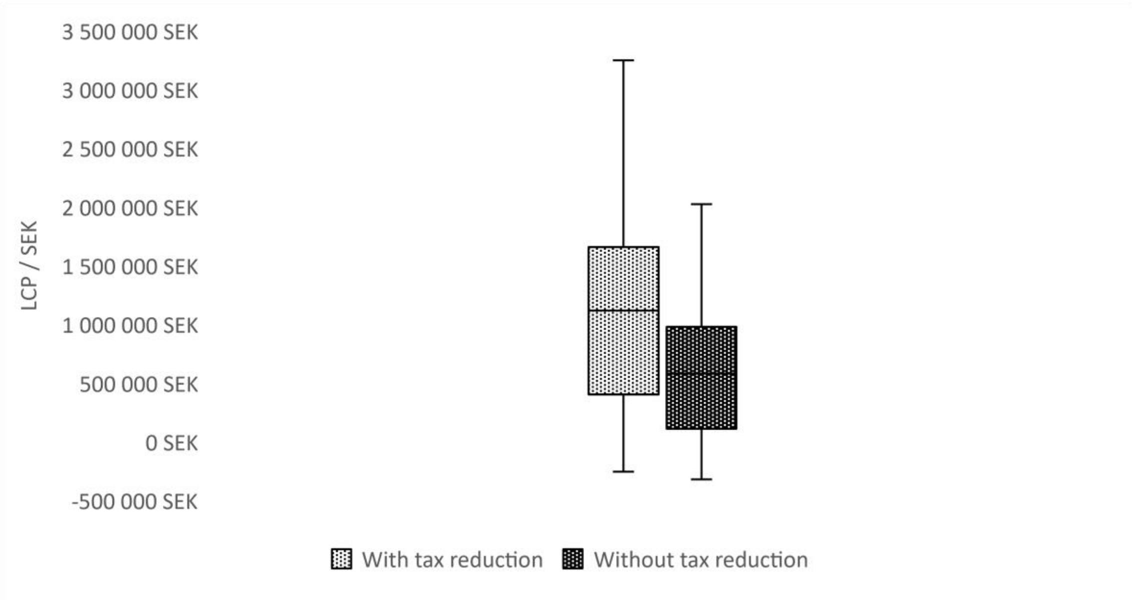

Figure 47. LCP of the PV system while utilizing the most profitable battery during various economical scenarios, with and without tax reduction.

As opposed to the previous cases, the highest battery prices are in this case possible while including the tax reduction, as shown in Figure 48. This is another indication that due to the PV system size, a battery will add significantly more value as it helps limiting the amount of sold electricity exceeding 30 000 kWh annually and thus maximizing the profit of selling electricity. Both cases do however show a maximum battery price of more than 1500 SEK/kWh.

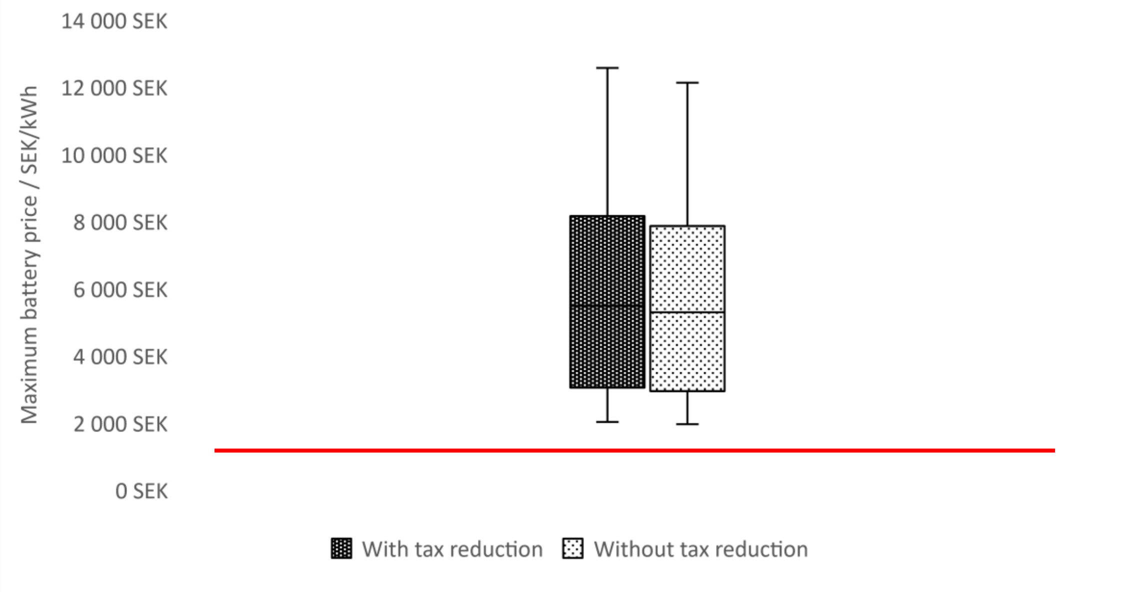

Figure 48. Maximum battery price in SEK/kWh for the most profitable battery during various economical scenarios for maintaining profitability, with and without tax reduction. The red horizontal line represents the current battery price of 1500 SEK/kWh

The LCP for all cases is summarized in Figure 49 below, including the LCP of the renovation itself. Again, the renovation shows negative profitability even while using the lowest investment costs found in previous studies. The PV systems do however show positive profitability in most cases and lower profitability variations.

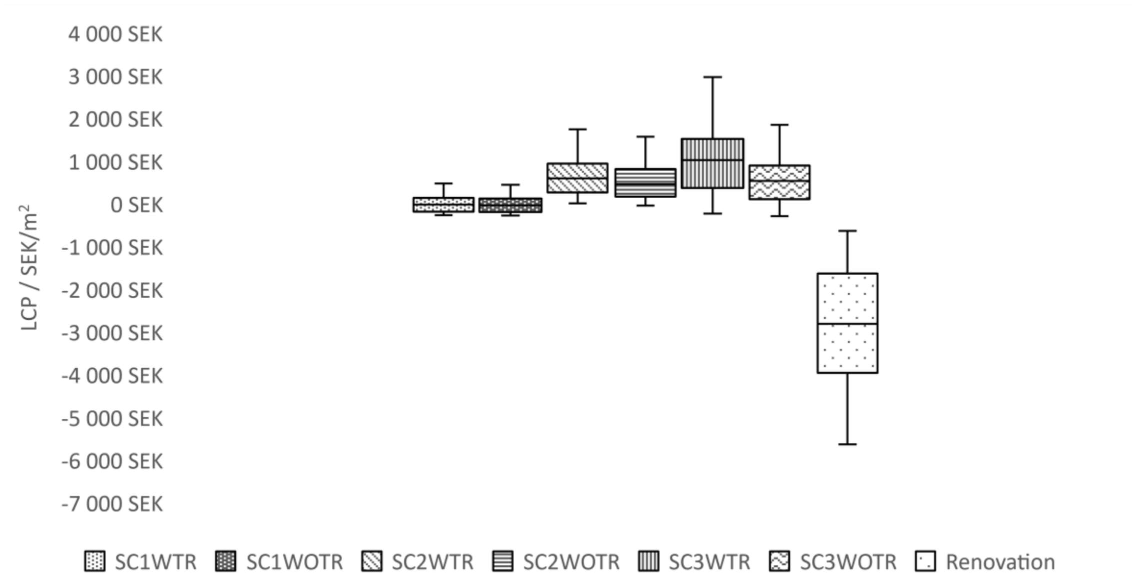

Figure 49. Comparison of the LCP between the two cases, with and without tax reduction. The right-most box plot represents the profitability of the energy renovation alone.

5 Conclusion

If economic profitability is pursued, the Swedish NZEB definition showed to be somewhat contradictory. As shown in both case-studies, the passive energy renovations towards passive house standard (required by the Swedish NZEB definition) were not profitable contrarily to installing a PV system , even in the worst economical scenarios. If aiming for maximum profitability, a suitable strategy for achieving a net-zero energy balance between energy load and production is to maximize the use of the highest yielding roof surfaces for PV. Thereafter, adjust the level of ambition of the passive energy renovation measures to reach an annual balance between energy need and production.

Regarding design of batteries, three energy dispatch strategies were analysed. It was found that the strategy that prioritizes *PV-self consumption* was the most profitable. *Demand change reduction* was less profitable as the electricity peak loads in the evaluated buildings are not high enough to justify a reduced fuse size with the utilization of batteries. *Time-of-use optimization*. Moreover, as the hourly electricity price variations were found to be relatively small, the *Time-of-use optimization* strategy seems inadequate to make up for the energy storage losses brought by storing the energy during long periods.

As for the battery size, the results generally imply an optimal size large enough to cover the night load and part of the morning and afternoon peaks as well. The exact daily time-interval to be considered depends on whether tax reduction is considered or not. Generally, it was found that the optimal battery size should cover the electricity load from approximately 5 pm to 6 am with tax reduction and somewhat longer without tax reduction. Nevertheless, this is a first approximation that will need further detailed evaluation.

A discontinuation of the tax reduction would imply lower overall profitability for the PV systems evaluated in this study. However, without tax reduction, the majority of the PV systems with optimal batteries are still maintaining profitability even in the least preferred economical scenarios. The most significant effect of removing the tax reduction is the significant increase of profitability of using batteries. On average, the increased profit brought by utilizing batteries showed to be 25 % while including the tax reduction. While excluding the tax reduction, using batteries will, on average, yield a 108 % increase in profit. Arguably, the added profit of using batteries in a scenario with tax reduction might therefore not always be substantial enough to justify the increased complexity of installing such a system. Moreover, in some economical scenarios with tax reduction, the marginal gains of using batteries are not enough to maintain profitability. The declining trend in battery prices may however completely diminish this risk in a near future. In the case of excluding the tax reduction however, profitability is positive for all scenarios and the added value is often substantial and therefore, a battery would be a preferable option.

All in all, regarding energy renovation and from a profitability point of view only, the requirements of NZEB should put more focus on on-site renewable energy production rather than ambitious passive energy renovation as it induces higher chances of profitability and may therefore be a more attractive option for building owners. From an economic perspective, and given the results of this study, it seems doubtful to renovate far beyond what is required by the building code regarding heat losses. However, as the investment costs used for the renovations were not specific to this study and other parameters such as the added value of thermal comfort and increased market value were not taken into account, further analysis on this topic is needed.

6 Summary

The building industry in Sweden is currently responsible for 19 % of domestic green house gas emissions as well as a third of the energy use. Primarily caused by heating of the buildings, this is an indication that energy related measures must be taken in order to reach the future energy goals. As 80 % of the buildings that will exist in 2050 have already been built, the greatest potential for theses measures lies in the existing building stock, as opposed to new construction. In this study, existing buildings belonging to the Million Program were specifically targeted as these buildings are due for renovation and compose a significant portion of the current Swedish building stock.

The aim of this study was to assess the economic feasibility of energy renovation and implementation of photovoltaic systems towards the Swedish Net-Zero Energy Building definition (NZEB). The economic impact of removing the currently granted tax reduction for sold electricity was furthermore investigated due to the possibility of it being discontinued in a near future. Using energy simulation software, previously measured data and guidelines from the industry, one single-family building and one multi-family building were modelled and assessed in regards to their potential of energy renovation. Furthermore, the potential of implementing photovoltaic systems with energy storing batteries was evaluated and designed to reach the Swedish Net-Zero Energy Building definition. The energy renovation and the photovoltaic systems were assessed based on economic feasibility using life-cycle cost (LCC) methodology in various economic scenarios.

A key finding was that following the Swedish NZEB definition, which includes achieving passive house standard, is not the most economically preferable strategy towards reaching NZEB. The life cycle cost calculations showed consistently negative economic results while the evaluated PV systems showed profitability in the majority of economic scenarios. Furthermore it became clear that implementing energy storing batteries in PV systems will yield even higher profitability, particularly in cases where the tax reduction for sold electricity is removed. More specifically, the added profitability of implementing batteries showed, on average, an additional 25 % while including the tax reduction and 108 % while excluding it.

By disregarding the NZEB requirements and primarily focusing on the PV systems, it was discovered that initially optimizing the PV system size, in regards to economic profitability, and subsequently adjusting the energy renovation ambitions to reach Net-Zero Energy Balance, a higher profitability can be achieved. For the buildings specifically investigated in this study, optimizing the PV systems involved fully covering the highest yielding roof surfaces in PV panels. Therefore, if profitability is the primary desire in a renovation project towards NZEB, a suitable strategy might be to disregard the requirement of reaching passive house standard and instead focus on merely reaching a Net-Zero Energy Balance.

To further assess these conclusions however, future studies might include the added value in terms of thermal comfort and market value that is generally brought while renovating to passive house. Additionally, looking at a longer analysis period, more suitable for an energy renovation might also affect the results as energy renovation measures generally have a longer life span than a PV system.

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Appendix A

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	1.648	1.653	1.620	1.622	1.630	1.605	1.655	1.649	1.672	1.673	1.658	1.638
1	1.642	1.644	1.612	1.612	1.614	1.582	1.636	1.633	1.662	1.602	1.659	1.645
2	1.639	1.641	1.596	1.608	1.608	1.566	1.625	1.622	1.656	1.597	1.650	1.633
3	1.639	1.641	1.611	1.608	1.604	1.556	1.618	1.615	1.656	1.598	1.645	1.627
4	1.648	1.653	1.628	1.617	1.609	1.552	1.613	1.611	1.663	1.608	1.643	1.627
5	1.658	1.666	1.652	1.634	1.624	1.578	1.625	1.626	1.677	1.630	1.656	1.639
6	1.674	1.687	1.677	1.661	1.656	1.639	1.653	1.674	1.717	1.677	1.670	1.648
7	1.733	1.768	1.720	1.712	1.713	1.697	1.690	1.757	1.779	1.743	1.702	1.681
8	1.760	1.792	1.741	1.734	1.737	1.719	1.722	1.801	1.834	1.803	1.771	1.730
9	1.748	1.785	1.729	1.726	1.728	1.712	1.731	1.805	1.838	1.775	1.814	1.763
10	1.762	1.775	1.712	1.711	1.710	1.698	1.731	1.809	1.835	1.755	1.770	1.762
11	1.760	1.742	1.696	1.694	1.706	1.694	1.723	1.802	1.832	1.737	1.765	1.736
12	1.746	1.720	1.685	1.678	1.693	1.677	1.707	1.778	1.818	1.719	1.761	1.744
13	1.745	1.727	1.677	1.668	1.682	1.664	1.693	1.765	1.769	1.706	1.746	1.743
14	1.736	1.724	1.672	1.650	1.668	1.654	1.681	1.747	1.759	1.701	1.774	1.743
15	1.738	1.725	1.670	1.644	1.663	1.649	1.679	1.729	1.754	1.706	1.771	1.741
16	1.794	1.754	1.675	1.645	1.663	1.657	1.679	1.705	1.760	1.709	1.799	1.767
17	1.863	1.801	1.696	1.654	1.686	1.677	1.697	1.736	1.773	1.753	1.844	1.798
18	1.788	1.792	1.727	1.671	1.702	1.700	1.708	1.738	1.785	1.810	1.904	1.806
19	1.726	1.737	1.712	1.686	1.706	1.712	1.715	1.745	1.833	1.797	1.818	1.771
20	1.692	1.706	1.690	1.682	1.685	1.679	1.702	1.736	1.800	1.720	1.763	1.729
21	1.676	1.688	1.676	1.674	1.689	1.674	1.697	1.726	1.743	1.676	1.712	1.695
22	1.667	1.675	1.662	1.652	1.667	1.673	1.689	1.692	1.703	1.651	1.690	1.673
23	1.657	1.601	1.638	1.626	1.642	1.628	1.661	1.655	1.677	1.625	1.673	1.656

Figure 50. Average electricity prices of hour 1 to 24 in each month during 2019

Appendix B

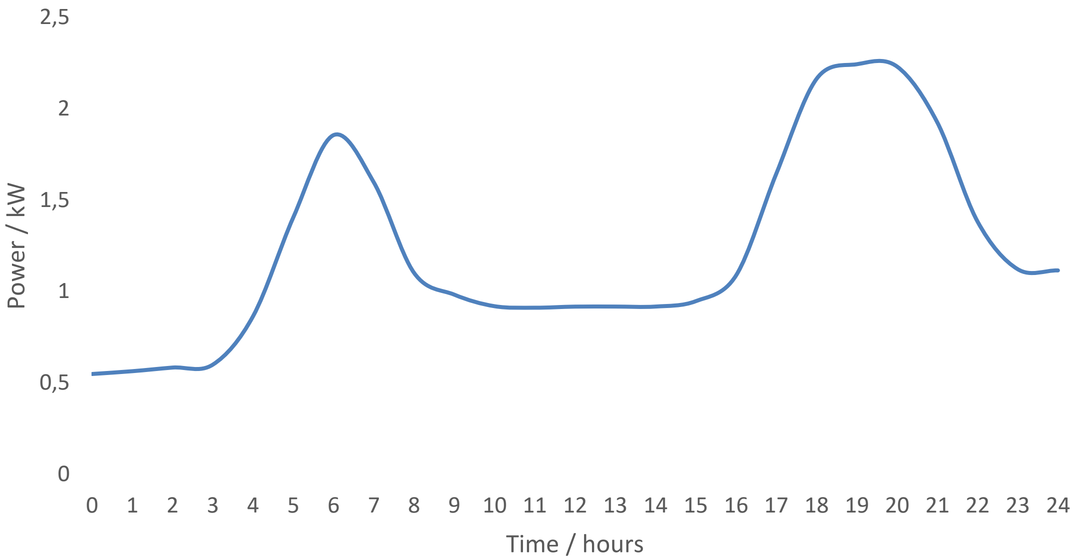

Figure 51. Electricity load for the single family building during a cold day (3 feb)

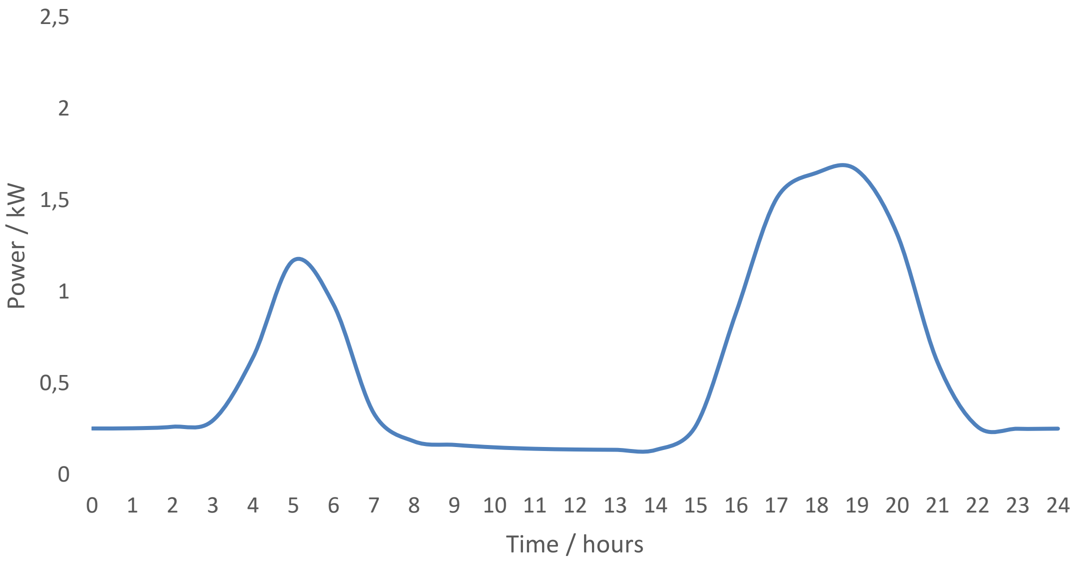

Figure 52. Electricity load for the single family building during a warm day (Jul 7)

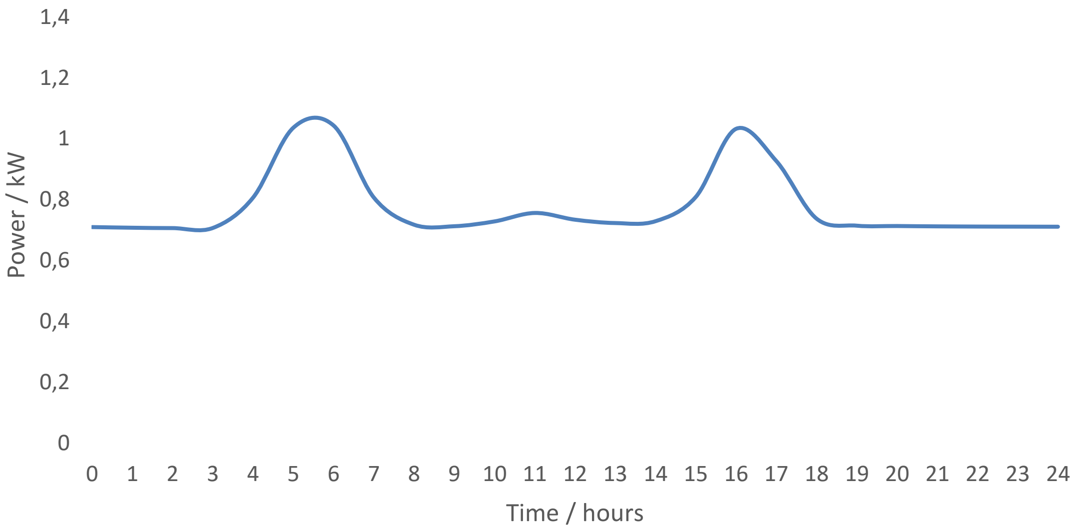

Figure 53. Electricity load for the multifamily building (excluding household electricity). The same profile is seen for cold and warm months as no heat pump is being used

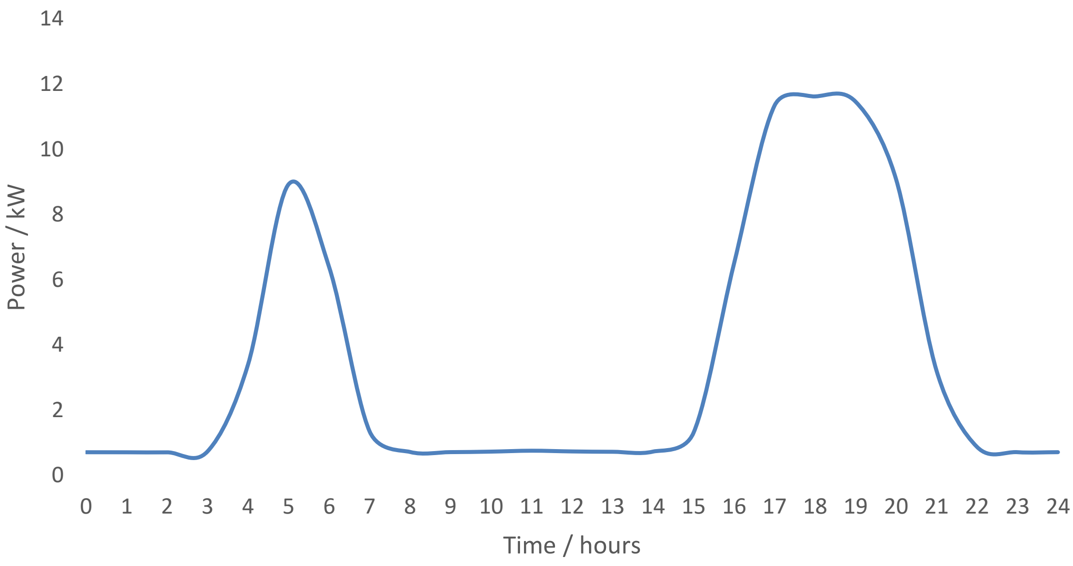

Figure 54. Electricity load for the multi family building (including household electricity). The same profile is seen for cold and warm months as no heat pump is being used

Appendix C

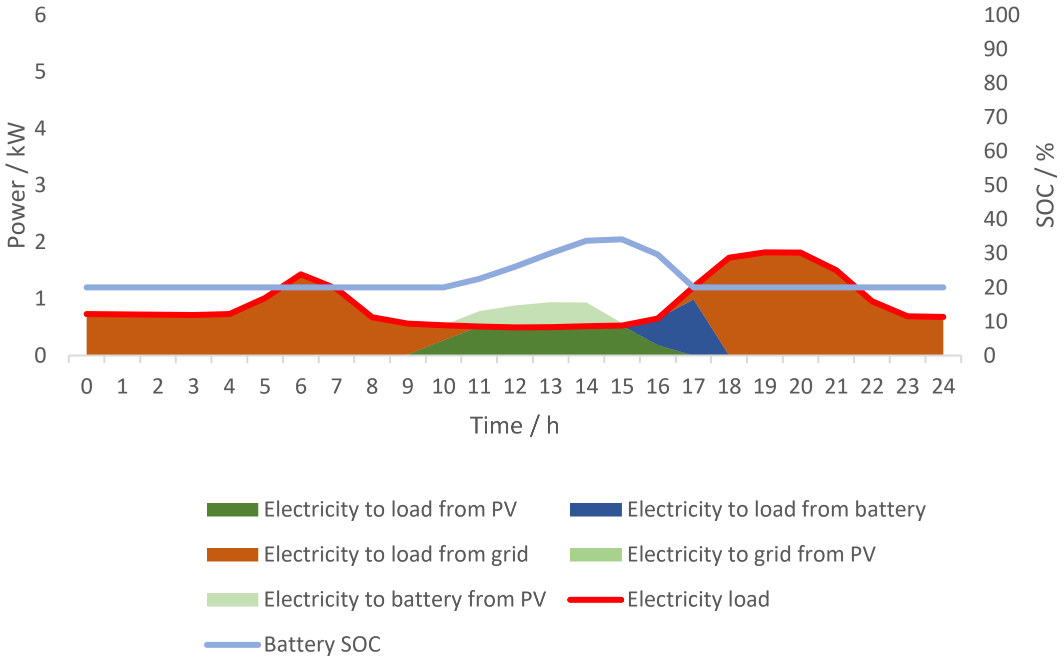

Figure 55. A sunny winter day (Feb 3) showing the 10 kWh (Scenario 1 SFH with/without tax reduction) battery state of charge, allocations of PV electricity production, battery dispatch and sold/purchased electricity from the grid while using a 3.3 kWp PV system. The x-axis represents the hours of a full day and night (24 h).

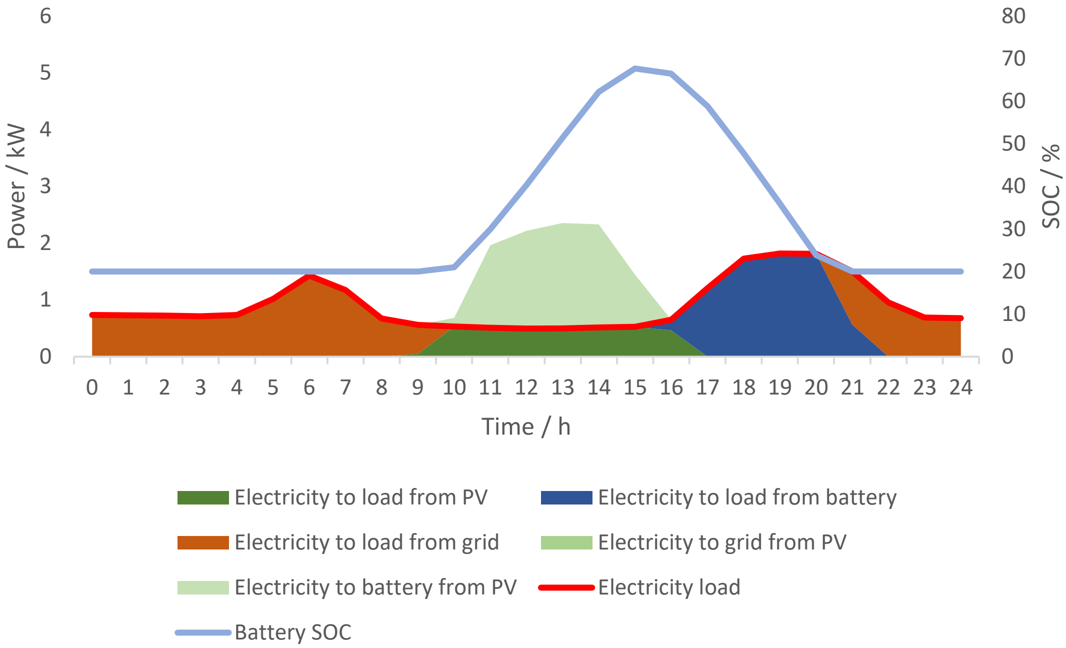

Figure 56. A sunny winter day (Feb 3) showing the 10 kWh (Scenario 2 SFH with tax reduction) battery state of charge, allocations of PV electricity production, battery dispatch and sold/purchased electricity from the grid while using an 8.25 kWp PV system. The x-axis represents the hours of a full day and night (24 h).

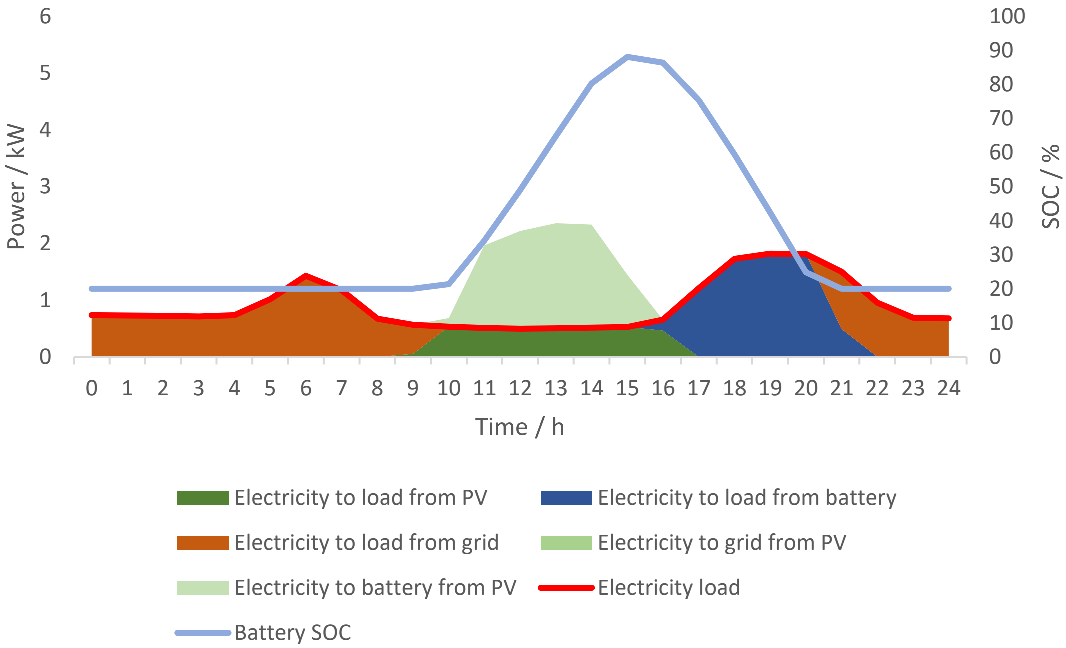

Figure 57. A sunny winter day (Feb 3) showing the 10 kWh (Scenario 2 SFH without tax reduction) battery state of charge, allocations of PV electricity production, battery dispatch and sold/purchased electricity from the grid while using an 8.25 kWp PV system. The x-axis represents the hours of a full day and night (24 h).

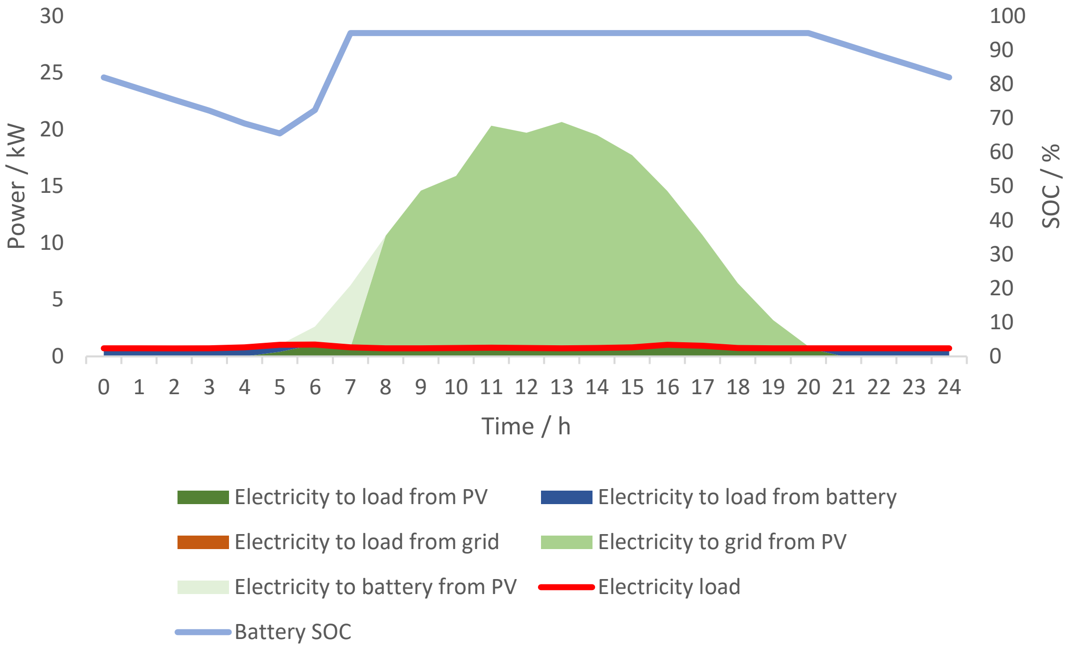

Figure 58. A sunny summer day (Jul 7) showing the 20 kWh (Scenario 1 MFH with/without tax reduction) battery state of charge, allocations of PV electricity production, battery dispatch and sold/purchased electricity from the grid while using a 34.2 kWp PV system. The x-axis represents the hours of a full day and night (24 h).

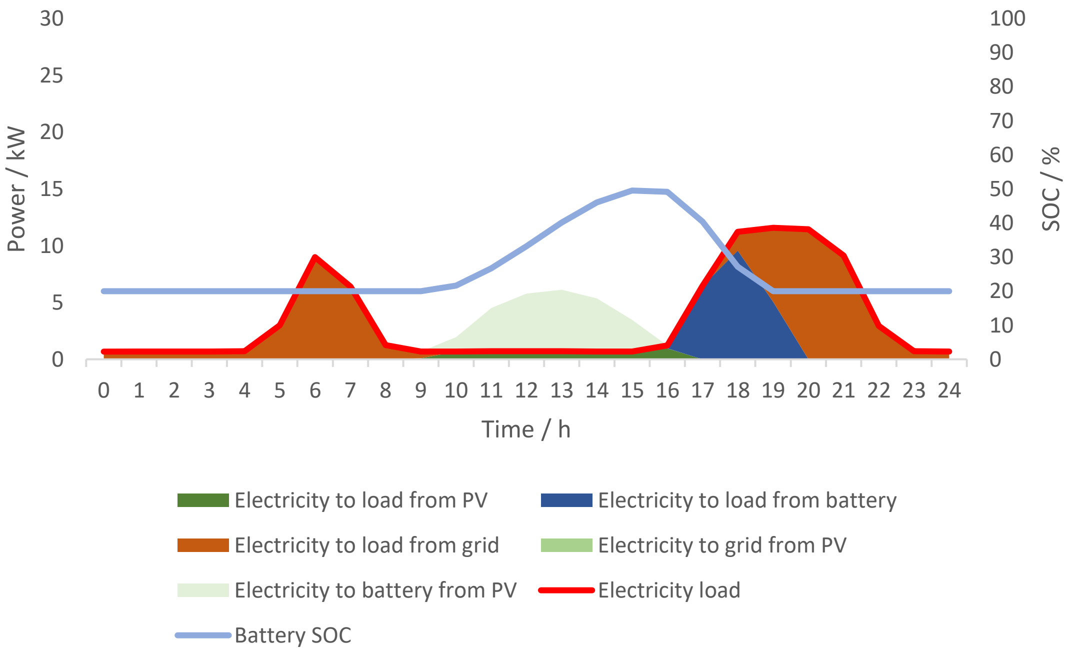

Figure 59. A sunny winter day (Feb 3) showing the 70 kWh (Scenario 2 MFH with tax reduction) battery state of charge, allocations of PV electricity production, battery dispatch and sold/purchased electricity from the grid while using a 34.2 kWp PV system. The x-axis represents the hours of a full day and night (24 h).

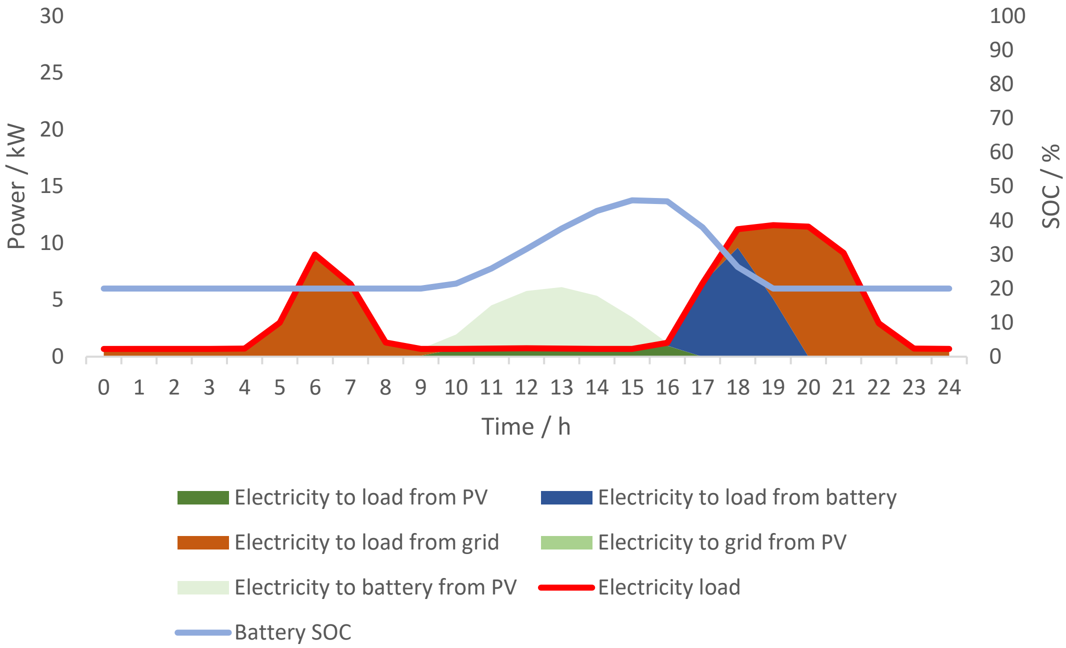

Figure 60. A sunny winter day (Feb 3) showing the 80 kWh (Scenario 2 MFH without tax reduction) battery state of charge, allocations of PV electricity production, battery dispatch and sold/purchased electricity from the grid while using a 34.2 kWp PV system. The x-axis represents the hours of a full day and night (24 h).

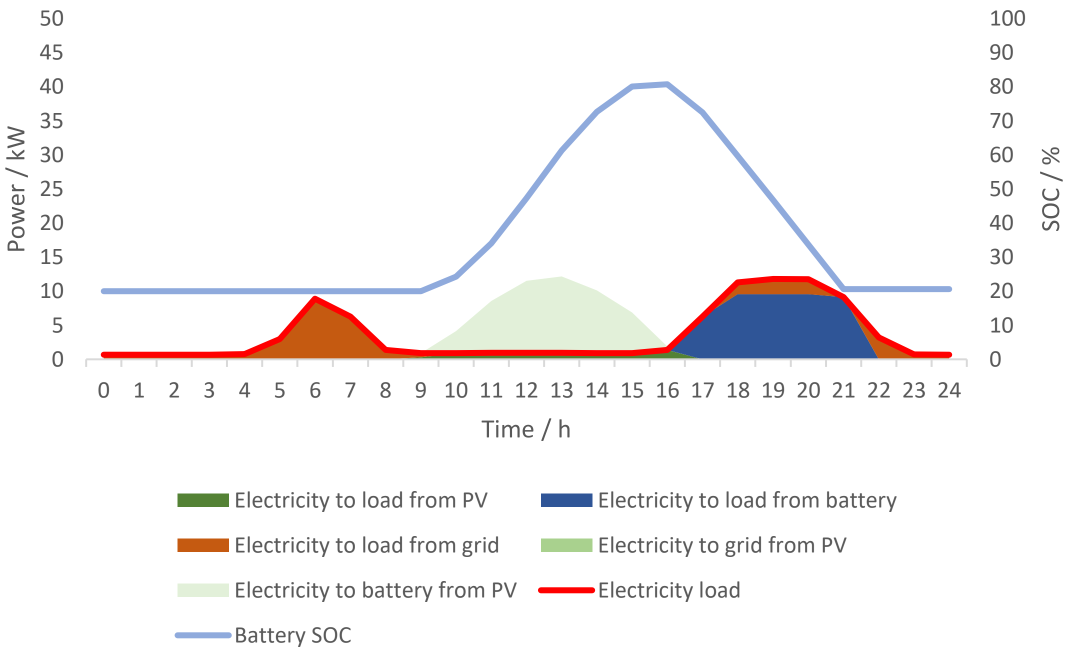

Figure 61. A sunny winter day (Feb 3) showing the 70 kWh (Scenario 3 MFH with tax reduction) battery state of charge, allocations of PV electricity production, battery dispatch and sold/purchased electricity from the grid while using a 70 kWp PV system. The x-axis represents the hours of a full day and night (24 h).

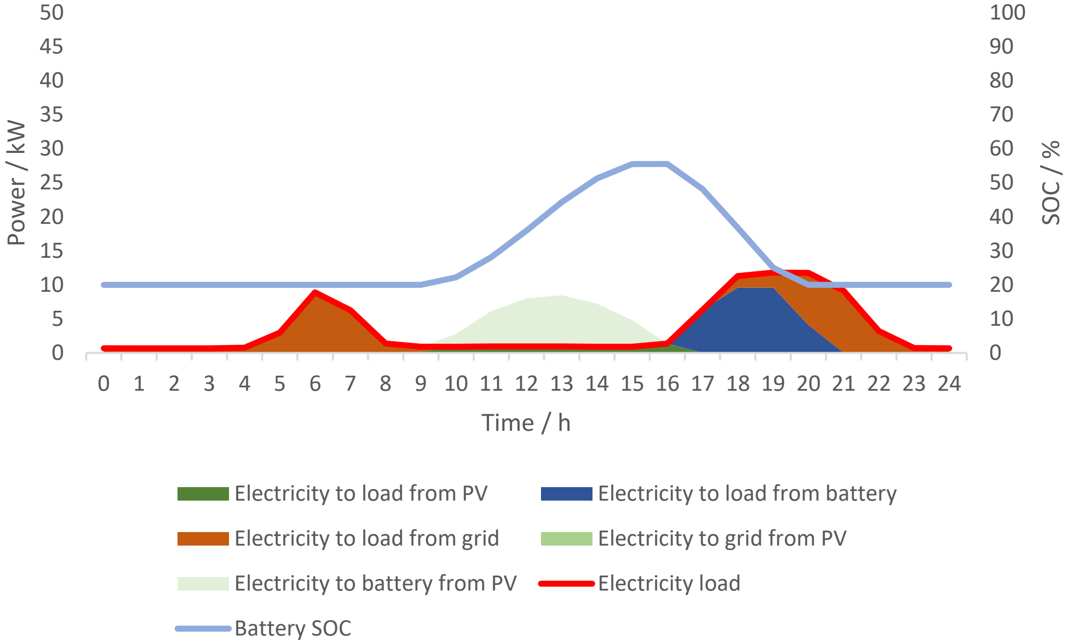

Figure 62. A sunny winter day (Feb 3) showing the 80 kWh (Scenario 3 MFH without tax reduction) battery state of charge, allocations of PV electricity production, battery dispatch and sold/purchased electricity from the grid while using a 50 kWp PV system. The x-axis represents the hours of a full day and night (24 h).

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