Battery systems for commercial buildings with solar power

Control and operation strategies

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Abstract

In order to reach the climate targets, a sustainable energy system based on renewable energy generation is required. Battery storage systems are considered part of the solution, as electricity generation from renewable energy sources such as wind and solar does not match the energy consumption at all times.

This thesis investigates control and operation of battery storage systems for commercial buildings with and without photovoltaic installations. It was found in the literature review that the correct size of a battery system is important in order to have an optimal storage solution and avoid unnecessary costs. Therefore, a photovoltaic installation and battery storage system is simulated in the Hybrid Optimisation Model for Electrical Renewable (HOMER) Pro software. The power consumption user pattern in a commercial building is also studied. Further, the operation of a battery storage system is optimised using integer linear programming in MATLAB. The battery storage system was optimised in regard to day-ahead electricity spot prices and power consumption of a commercial building.

The net present cost of different system combinations is calculated with the HOMER software, and it was found that larger photovoltaic systems without battery storage was the more profitable solution. The optimisation based on the day-ahead spot prices was able to reduce costs based on energy fees, although it also increased the peaks in power consumption. This was due to low prices coinciding with hours of high power consumption, which in turn can increase the fees for power consumption. For the power consumption driven optimisation, the peaks are reduced during high demand periods and increased during low demand periods, thus balancing the power consumption of the commercial building. However, this does not reduce costs in terms of energy fees but power fees, and the profit is dependent on which fees that apply. The goal of installing a battery storage system should therefore be carefully evaluated so that it can be optimised with regard to the most profitable parameters for a given system and building.

Preface

This report is written as a part of the course ENE500 – Master thesis Renewable Energy at the faculty of Engineering and Science which is the final subject in the two-year master's programme in Renewable energy at the University of Agder (UiA).

My background for taking on the master thesis is a bachelor's degree in Energy Technology from Bergen University College. The bachelor thesis had the title "Ambitious renovation of old apartment buildings – Analysis of conditions and evaluation of potential improvements". The bachelor's degree is a multidiscipline degree with subjects within the field of mechanical, electrical and civil engineering in addition to a subject in renewable energy. The master thesis continues with the theme from the bachelor thesis on the energy consumption in buildings but with a renewed focus on energy generation and storage.

The motivation for writing the thesis is based upon the interest in renewable energy solutions and the transition towards a low carbon society. In my opinion, batteries will be a part of that transition and many are implementing battery storage with renewable energy solutions. Different parameters such as peak shaving, electrical spot prices or maximising self-consumption from photovoltaics can be used as input parameters for optimising and controlling battery energy storage systems. It is a relevant subject which requires more research to find the most energy and cost-efficient solutions.

The master thesis is based upon an ongoing project which is to be carried out by the Energy group in Sweco Bergen. I would like to thank Sweco for giving me the opportunity to write and learn about an ongoing and relevant project and my supervisor Asbjørn Orheim Stoveland for providing information and guidance. I would also like to thank my supervisor Professor Mohan Lal Kolhe for advice and Arvind Sharma for introducing me to the HOMER Pro software. Bernhard Fäßler has been a great support with input and explanations of his PhD thesis, MATLAB and valuable discussions and feedback.

My family and friends have been a great support during my studies. I am also grateful for invaluable discussions with fellow students. Last, but not least, my dear Øystein Rønneseth who has an eye for details and offers great support and highly valued opinions.

Bergen, 24.05.2019

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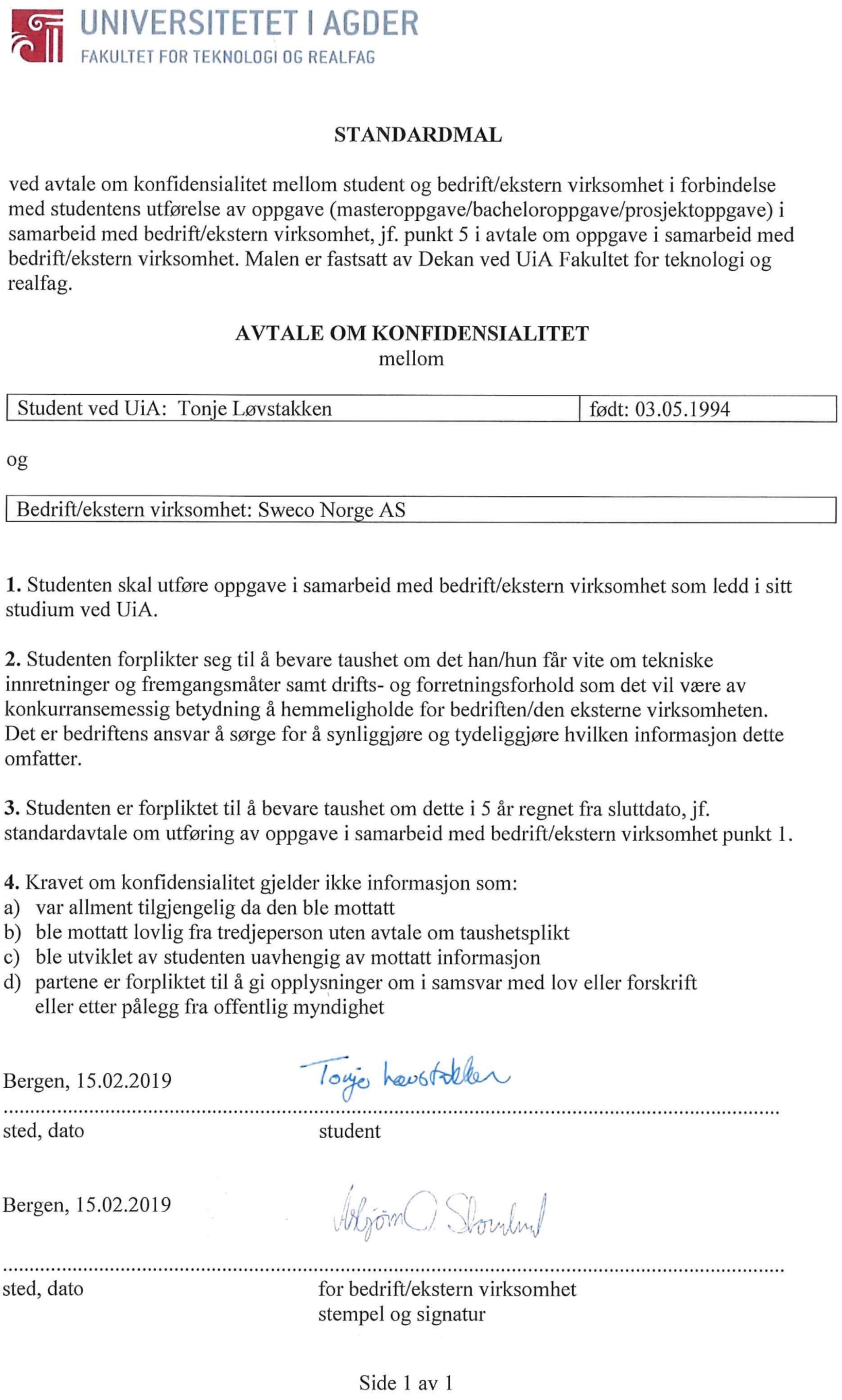

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Notation

$C_{ann,cap}$	Total Annualized Capital Cost (NOK/yr)
$C_{ann,tot}$	Total Annualized Cost of the System (NOK/yr)
c_{boiler}	Boiler Marginal Cost (NOK/kWh)
C_n	Nominal Capacity (Ah or kWh)
$C_{NPC,tot}$	Total Net Present Cost (NOK)
$c(t)$	Pseudo-cost Function (-)
E_{BL}	Energy from Battery (kWh)
E_{el}	Electrical Energy Content (Ws)
E_{PV}	Generated Energy from Photovoltaics (kWh)
$E_{PV\ SC}$	Directly Supplied Energy from Photvoltaics (kWh)
E_{served}	Total Electrical Load Served (kWh/yr)
E_{TOT}	Total Energy Use (kWh)
H_{served}	Total Thermal Load (kWh/yr)
$i(t)$	Current (A)
i	Discount rate (%)
P_{DC}	Direct Power (W)
$P_{DC,max}$	Maximum Power (W)
P_{loss}	Linear Battery Losses (W)
SOC	State of Charge (%)
u	Decision Variable (-)
η	Discharge Efficiency (%)
η_{in}	Charge Converter Efficiency (%)
η_{out}	Discharge Converter Efficiency (%)
R_{proj}	Project Lifetime (year)
$SOC(0)$	Initial State of Charge (%)
t	Time (s)

Abbreviations

AC	Alternating Current
BESS	Battery Energy Storage System
BMS	Battery Management System
CRF	Capital Recovery Factor
DC	Direct Current
DOD	Depth of Discharge
DSM	Demand Side Management
EMS	Energy Management System
ESS	Energy Storage Systems
EV	Electric Vehicle
LCOE	Levelised Cost of Energy
MIT	Massachusetts Institute of Technology
NPC	Net present cost
NVE	The Norwegian Water Resource and Energy Directorate
PCF	Pseudo-Cost Function
PV	Photovoltaic
SAM	System Advisory Model
SC	Self-consumption
SOC	State-of-charge
SOH	State-of-health
STC	Standardized Test Conditions
SS	Self-sufficiency

TEK	Building Regulations
TZ	Target Zero
V2G	Vehicle-to-Grid
UiA	University of Agder
ZEBRA	Zero Emission Battery Research Model

1 Introduction

1.1 Background

A new climate law was implemented in Norway from 01.01.2018. It states that the goal for Norway is to reduce its greenhouse gas emissions by 40% compared to 1990 levels by 2030 [1]. Further, it states that the overall goal is to become a low carbon society by 2050 and hence reduce emissions with 80–90%. The law is in accordance with the Paris agreement which Norway signed and ratified in 2016. In order to reach this goal, all sectors must be included. From investments in renewable energy generation to electrification of transportation and reducing energy demands in buildings.

According to Terje Jacobsen in SINTEF [2], the reduction in energy demand for buildings will make it possible to electrify the transportation sector by 2050, which in turn also reduces the emissions for the transportation sector. Buildings account for one-third of emissions [3] and 40% of the energy use in Norway [4]. Specific energy consumption in new buildings has been reduced during the last decades, as regulations have become stricter. The building regulations (TEK) [5] for new buildings is currently close to the passive house standard, and locally produced energy must be taken into account in order to further reduce emissions. The Energy Performance of Buildings Directive requires all new buildings in the EU to be nearly zero-energy by the end of 2020, while all new public buildings must be nearly zero-energy by 2018 [6]. After energy efficiency measures, the technologies to reach nearly zero-energy has typically been heat pumps and photovoltaics (PV) [7].

Bloomberg New Energy Finance predicts that wind and solar energy will cover 50% of the world's electricity demand by 2050, as the prices on the technologies continue to fall [8]. In Norway, the installed solar power increased by 366% from 2015 to 2016 [9]. From 2017 to 2018 the growth was lower but still, a 52% increase leading to a total of 68 MW peak installed [10]. The largest growth in installations of PV systems is for commercial buildings [11]. Reduced installation costs, electricity certificates and the plus-customer scheme allowing energy producers to sell energy to the grid [9] have led to PV projects becoming profitable for commercial buildings, and their large available roof areas hold potential for investments in solar energy.

The Norwegian Water Resources and Energy Directorate (NVE) has been tracking the electricity and power consumption in Norway. Since 1990 the trend is that the power consumption grows larger than the annual electricity consumption. This results in an undersized grid that does not have the available power for everyone to use at the same time [12]. Unless the power consumption is distributed over a larger time period and the peaks in power consumption are reduced, the grid operators are facing large investments to upgrade the grid. These investments are assumed to cost between 35–45 billion NOK and are planned to be finished in 2022 [13]. New pricing mechanisms are also discussed along with smart meters implemented in 2018, which are methods and technology encouraging customers to shift the time when they are using energy to avoid power peaks.

Storage solutions for electric energy have the potential to improve grid quality as it can be used to reduce peaks in the power consumption as well as reduce the mismatch between intermittent renewable energy generation and energy consumption. Such solutions are especially beneficial for commercial buildings with larger solar installations since the plus-customer scheme currently only allows 100 kW of power to be delivered to the grid at any time [14].

Battery technology has been in use for over 100 years and is still a technology under development [15]. In the transition to electrical solutions as part of the low carbon society, energy storage will play a crucial role. Innovation in the field is necessary in order to improve batteries regarding capacity, power, price and safety. Distributed energy storage is seen as part of the "smart grid" development, as it allows for flexibility in the energy flow in the grid. Battery technology is expected to be used for such applications [16, 17].

In 2017, the world surpassed 3 000 000 electric vehicles which is a growth by 1 000 000 from 2016 [18]. From 2011 to 2018 the market share of electric vehicles (EVs) in Norway has gone from 1% to 31% [19] resulting in close to 200 000 EVs on Norwegian roads [20]. The battery technology is in continuous development and the range of the EVs are increasing. Nevertheless, the battery performance is crucial, and the battery packs are recommended to be replaced when reaching 80% of the original capacity. Still, the batteries are far from fully utilized and should be repurposed or recycled as the materials used in the batteries are valuable and some can also be harmful to the environment [21]. As the first Nissan Leaf EVs were sold in Norway at the end of 2011, there is a large potential of used EV batteries becoming available during the next years [22].

Low energy buildings in combination with local renewable electricity generation reduce the power demand from buildings and thus strain on the grid. A battery system for storage can, in addition, distribute the load to reduce peak power demand which increases the exploitation of intermittent energy sources. These types of systems require a plan for operation and that the goal of the system is defined. Control algorithms can be created in order for the system to take into account the necessary parameters for efficient operation and maximising cost reduction.

1.2 Problem Definition and Research Questions

In this thesis, battery storage systems for commercial buildings are studied, focusing on the control and operation strategies for batteries. The following research questions are studied in this thesis:

1. What is the optimal size of a PV and battery storage system for a selected commercial building?
2. How does the power consumption for commercial buildings behave, what is the user pattern and how does it affect the operation of the battery storage system?
3. What is the optimal operation of a battery storage system in terms of electricity spot prices?
4. What is the optimal operation of a battery storage system for a commercial building in terms of electricity consumption?

2 Literature Study

Energy storage is used for saving energy for use at a later time. It can be done in many different ways, from storing kinetic energy in fly-wheel technology to potential energy in hydro-pumped storage, hot water tanks for heat energy storage and batteries which stores chemical energy [23]. The various types of storage have different qualities and are used depending on what type of storage is needed. The goal of research within the field of electric energy storage is to find a technology that can repeatedly store and discharge large quantities of energy with high efficiency and at low cost [16].

Batteries can be used to store excess electrical energy. This can reduce power fluctuations and provides a more flexible system when a higher percentage of intermittent renewable energy is connected to the grid. By storing and dispatching energy when necessary, peaks in power consumption can be reduced. Several types of batteries with different characteristics are on the market, and some of the most common are the lead-acid, nickel-cadmium, nickel-metal hydride and lithium-ion.

This chapter describes relevant theory about batteries and specifically lithium-ion batteries, energy consumption in commercial buildings, the electricity grid and prices as well as operation strategies and methods for battery energy storage which is necessary to understand the results and discussion of results. The theory chapter is based on the pre-study carried out in the autumn of 2018 in a report written for the subject ENE503 – Research Project, which was a pre-study for the master thesis. Another report was written in the subject ENE 506 – Smart grid systems and relevant theory have also been included from this report.

Literature was found in the IEEE Xplore digital library, ScienceDirect and with the library search motor at UiA, Oria. Keywords used were: lithium-ion, Li-ion, batteries, battery, recycled EV battery, modelling, mathematical, equivalent circuit, thermoelectrical, state of charge, SOC, estimation, energy storage, battery storage, recycled EV battery, photovoltaic, PV, battery management system, BMS, control, strategy, fuzzy logic, deterministic control, model predictive control, deterministic rule approach, demand side management, peak shaving, integer linear programming, linear programming, optimisation and operation.

Articles from 2010 until May 2019 were preferred as the literature for theoretical background in the master thesis. Some books have also been used for general theory about lithium-ion batteries, batteries in general and modelling of batteries. To supplement the scientific papers, some news articles and reports were used as well for statistics and relevant information retrieved from search in the Google search engine.

2.1 Battery Terminology

The *battery capacity* is the maximum amount of energy that can be extracted from a battery, measured in ampere-hours [Ah] or kilowatt-hours [kWh] at a constant discharge rate [24]. The *Depth-of-Discharge* (DOD) is the rated capacity withdrawn from the battery in percentage [24]. A DOD of 0% is, in other words, a fully charged battery.

There are especially two parameters which are of interest regarding batteries, the first is the *state of charge* (SOC). The SOC indicates how much energy is available in the battery compared to the maximum capacity, or the available charge, in percentage. It can be expressed mathematically as presented in Eq. (4) as the integration of the current *i* over time, where *SOC(0)* is the initial SOC, η is the discharge efficiency, *t* is the time and C_n is the nominal capacity of the battery [25].

$$SOC(t) = SOC(0) + \eta \int_0^t \frac{i(\tau)}{C_n} d\tau \qquad (1)$$

The second important parameter is the *state of health* (SOH). The SOH estimates the remaining lifetime of a battery by indicating the battery current condition compared to a new battery [26]. The condition of a battery will vary with how it is used, and it is thus harder to estimate than the SOC. An common practice for accurate but time-consuming measures of the SOH is to completely discharge the battery [27]. The method requires the battery to not be operated during the measurement period.

Another method to estimate the SOH is a system identification approach suggested by Giordano et al. [28]. The SOH is dependent on the internal resistance, which is dependent on the temperature, current and SOC. The suggested model and method are based on measures of the internal resistance and operating data from EVs. The internal resistance is found by applying a current pulse and measuring the response in voltage. It is measured for different SOC-values and temperature levels. Other methods which does not damage the batteries and which can be done while the batteries are operated, are for instance applicable to EVs [29].

The battery will lose storage capacity over time. Batteries have a certain number of cycles they can charge and recharge during their lifetime, called *cycle life*, but the cycles are dependent on how the batteries are operated [30]. The cycle life of a battery is mainly dependent on the anode and cathode materials used [29], but also on the use of the battery. Lithium-ion batteries will for example have around 3000 cycles at 100% DOD and over 20 000 cycles at 40% DOD [31].

The *calendar life* of a battery, which is another term describing the lifetime of a battery, is dependent on the degradation of the battery over time [30]. The term describes how long a battery is expected to last in terms of calendar years.

A battery storage system consists of batteries, a battery management system (BMS) and an inverter. The inverter, which is a power electronic converter, is a necessary interface between an electrical source and electrical load for conversion and control of electrical power. For battery storage systems the inverter transforms the direct current (DC) from the battery to alternating current (AC). The electricity grid supplies AC to residential and commercial buildings. A simple battery storage system is illustrated in Figure 1.

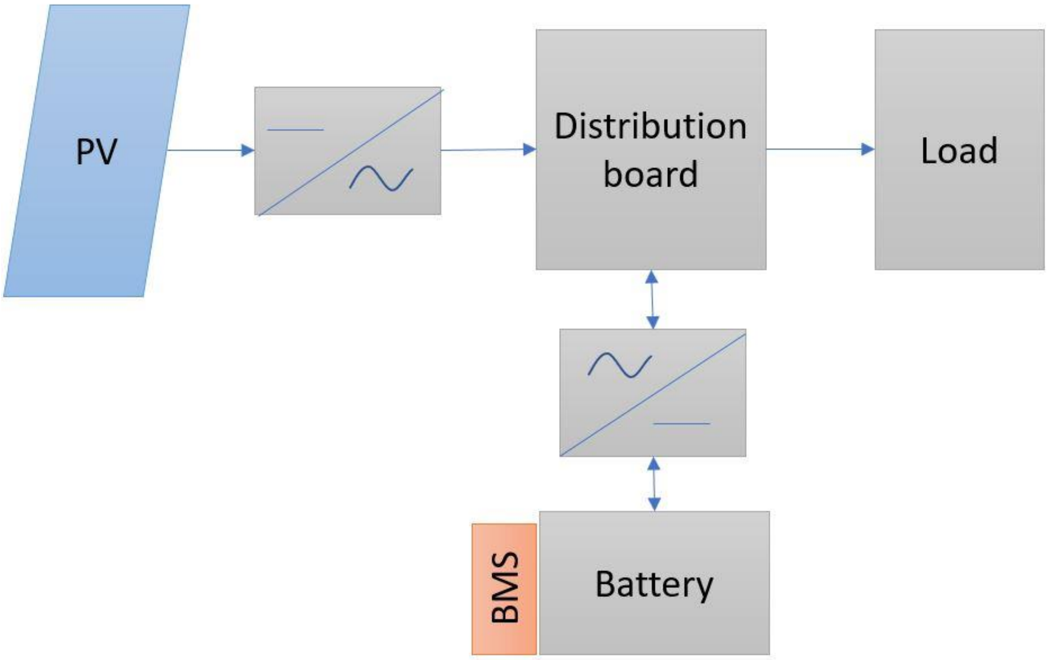

Figure 1 Illustration of a simple energy storage system.

The *round-trip efficiency* describes the efficiency of the system from the grid converted from AC to DC, stored in the battery and then converted from DC to AC again. This efficiency takes into account the losses that will occur from charging and discharging the battery through the inverter and is therefore, lower than the charge or discharge efficiency.

2.2 Comparison and Use of Batteries

A comparison of some common batteries can be seen in Table 1, based on [31-33]. The table shows the roundtrip efficiency, energy density, power density, expected charging and discharging cycles, the operating temperature range, the rate of self-discharging and the maximum depth of discharge for some rechargeable battery technologies. Depending on the purpose of the battery, different qualities are preferred, although the optimal battery would be one that was the best in every category. There is a lot of research on finding the best combination of anode and cathode materials to make a nearly reversible charge and discharge transformation, high specific energy, low resistance are the batteries that are

Table 1 Comparison of Different Battery Technologies

Type of battery	Lead-acid	Nickel-cadmium	Nickel-Metal-Hydride	Lithium-ion
η (%)	75	55–70	55–65	95
Energy density (Wh/kg)	35–50	30–60	60–80	80–180
Power density (W/kg)	150–400	80–150	200–300	200–1 000
Cycles	200–1 500	500–10 000	300–600	3 000
Operating temperature (^{o}C)	-40–60	-40–60	-20–50	-20–60
Self-discharge	2–8%/month	5–15%/month	15–25%/month	2–10%/month
Maximum Depth of Discharge	20–80%	60–80%	80-90%	80%

When comparing different battery technologies, the sustainability of batteries should also be taken into account. For example, Cadmium is one of the metals which are relatively rare and should therefore only be used in applications that are long-lasting or where high recyclability can be obtained in order to be sustainable [34]. Lithium is a relatively available and non-toxic metal, although its biggest challenge in terms of chemistry is that it is highly reactive and therefore requires a high degree of safety [35]. In terms of availability, there has been a focus on where and how lithium is mined. Many countries where this mineral is available uses child labour in mining which is a global ethical issue [36].

There are also other types of batteries in development in addition to those presented. For example, the Liquid metal battery developed by researchers at Massachusetts Institute of Technology (MIT) [37, 38] which has an ability to dispatch energy for longer time periods compared to other batteries. All three components in the battery; anode, cathode and electrolyte are liquid, which is a new concept. The battery is not compared with the others in this report, as it is not yet commercially available.

Lithium-ion batteries have become a popular solution in mobile applications like EVs and are considered suitable for energy storage applications as well [39]. This is due to the combination of high energy and power density, high energy efficiency and low self-discharge compared to other battery technologies presented in Table 1 [40]. The availability of lithium-ion batteries due to the increase in EVs on Norwegian roads makes a potential for energy storage solutions based on used EV batteries and are therefore further studied.

2.3 Lithium-ion Batteries

The lithium-ion battery is one of the most common rechargeable batteries used in electronic devices today, used in everything from cell phones to electric vehicles. The battery was developed due to a need for a battery with high energy density, small size and low weight [41]. A lithium-ion battery is an electrolyte cell which consists of an anode and cathode electrode, electrolyte and a separator in addition to a stainless-steel shell [21]. An illustration of a lithium-ion battery can be seen in Figure 2.

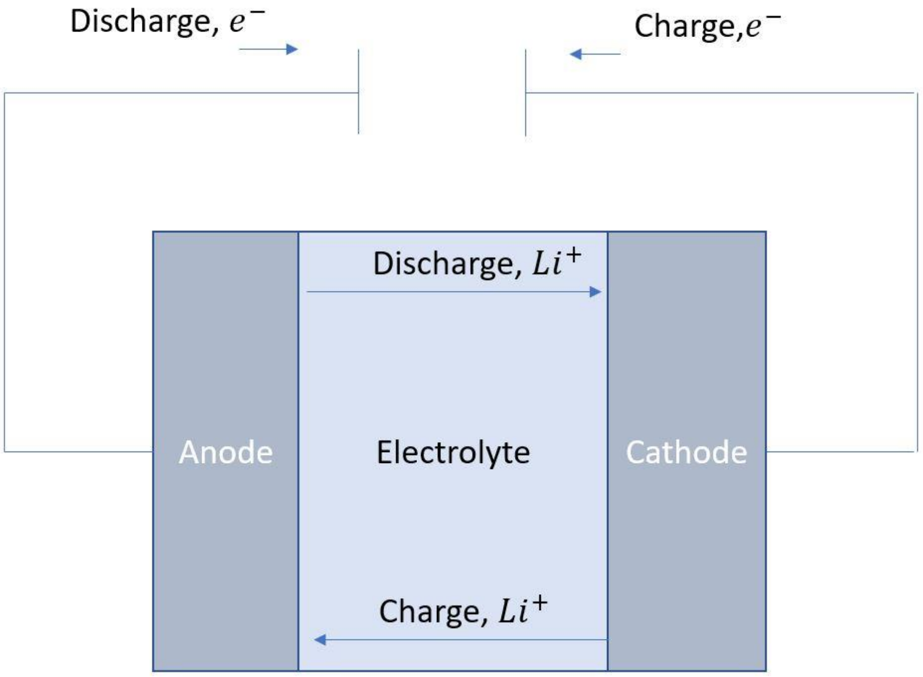

Figure 2 Principle Sketch of a Lithium-ion Battery.

The lithium-ion battery has unlike other batteries no reduction and oxidation (redox) reaction taking place but rather an intercalation reaction, where the ions travel back and forth between the anode and cathode causing the storage and discharging of energy [32, 42]. The reactions in the lithium-ion battery at the anode and cathode, which are almost completely reversible, can be seen in Eqs. (2) and (3).

$$6C + xLi^+ + xe^- \Leftrightarrow C_6Li_x \tag{2}$$

$$LiCoO_2 \Leftrightarrow Li_{1-x}CoO_2 + xLi^+ + xe^- \tag{3}$$

During a discharging cycle, the anode is the negatively charged electrode. The anode usually consists of carbon. The cathode, which usually consists of a lithium oxide, such as $LiCoO_2$, is the positively charged electrode during discharging. In addition to the electrodes, there is an electrolyte which usually is a lithium salt dissolved in an organic solvent. There is also a separator between the anode and cathode that only enables the lithium-ions to pass through.

2.4 Battery Management System

The smallest unit of a battery is a cell. For larger applications, single battery cells are coupled together in modules either connected in series or parallel and the modules can be further connected in series or parallel to form a battery pack. A BMS is needed in order to predict the battery performance and protecting the battery [43]. The system will monitor that the battery operates within its safe limits by using algorithms and monitoring the voltage, current and temperature. A BMS is installed on a module level.

To keep within the safety limits a lithium-ion battery should charge within a temperature of 0–60°C and discharge as well as store energy between 20–60°C [30]. The SOC should also be within the limit of 20–80% to maximize the lifetime of the battery. Overcharging by going beyond the cut-off voltage as well as deep discharging, will be damaging for the battery chemistry and can cause faster degradation as well as cause the battery to short circuit and release uncontrolled energy. A BMS is especially needed for lithium-ion batteries that require strict control but also for larger systems, for example in EVs where the battery pack can consist of hundreds of cells, or in battery storage systems in order to operate the system efficiently [41, 43].

Summarized, the most important tasks of a BMS is to [30]:

- Prevent overcharge
- Prevent overdischarge
- Monitor temperature
- Monitor the current
- Monitor the voltage
- Estimate the SOC and SOH

2.5 Repurposed Batteries from Electric Vehicles

For EVs the quality of the batteries is essential for the range of the cars. Therefore, it is estimated that the batteries should be replaced after 8–10 years of use when the capacity is degraded to 80% of the original value [44]. Although a reduction in the capacity of 20% affects the range of the cars, the batteries are far from not being able to store and dispatch energy [45]. This results in a potentially large amount of batteries that are available for recycling or that can be used in new applications – for example, stationary energy storage systems. The potential for this type of reuse is great, especially in countries like Norway where the market share of EVs is increasing fast. The batteries in the Nissan Leaf, which was one of the first batches of electric cars sold in Norway, are soon ready to be replaced based on the warranty.

A paper by Ahmadi et al. [17] presents data showing how a battery is expected to lose 20% of the original capacity during its first eight years while used in an EV, and 15% in a second-use application like energy storage over a period of 10 years. In the pre-study, it was found that repurposed EV batteries used as electric energy storage with the purpose of reducing peaks in power demand, reduced the CO_2 emissions by 56%.

The lifespan of second-use batteries is also discussed in a paper by Casals et al. [46]. The remaining battery capacity will vary depending on the application. The paper suggests that between fast EV charging, stationary energy storage, area regulation and transmission deferral, it is the fast EV charging and stationary storage which are the most promising applications. The batteries for these applications of second-use EV batteries are expected to last 30 and 12 years respectively.

According to the New Energy Outlook 2018 report by Bloomberg Energy Finance [8], the price for new lithium-ion batteries in 2017 was 200 $/kWh. The prediction is that towards 2030 the price will drop to 70 $/kWh. The numbers are based on a 79% drop in prices from 2010 to 2016. In Japan, Nissan launched an exchange program for Nissan LEAF bars where batteries can be exchanged for half the price of new batteries, while the used batteries are used for energy storage applications [47]. Little information about prices of repurposed EV batteries can be found, but for stationary energy storage, the batteries will have to be dismounted, collected, sorted and tested before they can be sold for second-time use which can add to the cost of the batteries [48]. As the prices for new batteries fall, an efficient way for testing etc. of batteries for second-time use must be implemented for the batteries to be economically feasible compared to new batteries [49].

2.6 Buildings with Battery Storage

A grocery distribution central in Sandnes will have solar cells on the roof (see Figure 3) and both thermal and electric storage installed [50]. The building of 26 000 m^2 will have a battery bank with a capacity of 460 kWh. The battery bank will be used to buy energy when prices are low, reduce peak power demand as well as improve grid stability. If the batteries are fully charged, excess energy will be converted to heat and stored in a hot water tank of 300 000 litres. In addition, the building will be operated based on weather forecast data as well as energy demand predictions and sensors.

Figure 3 Grocery Distribution Central in Sandnes with Photovoltaic Installation and Battery Storage [51].

Another grocery store, Kiwi Dalgård in Trondheim (see Figure 4), is also a building of interest. In addition to the solar installation on the roof, the walls are covered with building integrated thin-film technology [52]. This results in a total installation of 579 m^2 of solar cells. The production of electricity can be stored in a battery bank, and there will also be possibilities for EV and electric bicycle charging at the site.

Figure 4 Kiwi Dalgård in Trondheim with Facade Integrated Photovoltaic Panels [53].

Skagerak Arena in Skien is installing a test lab for PV and battery storage in collaboration with Skagerak Energy [54]. The football arena, as shown in Figure 5, will have an installation of 5 000 m^2 solar cells and a battery storage system that can deliver 400–600 kW of power in 2–3 hours. The project has been granted financial contribution from Enova SF since the project has a focus on testing new technology. The football stadium will have 10 times the usual need for energy during football games, in other words, a peak in power consumption for 2–3 hours, and the battery will otherwise be used in the local grid.

Figure 5 Skagerak Arena Football Stadium with Photovoltaic Panels and Battery Storage [55].

An office building named “Skipet” is currently under construction in Bergen, Norway [56]. The building is designed to be a passive house with energy class A and rated as a BREEAM-Nor Excellent building. Energy for space heating and domestic hot water heating will be from the district heating system in Bergen, cooling from sea water, electricity generation from PV panels and a battery system for storage. The building is also being constructed in cross-laminated timber. The battery storage system will consist of 10 used EV batteries from Nissan. The system will have a capacity of 150 kWh and discharge power of 50 kW. The building will have a heated floor area of 12 000 m^2 and 430 m^2 of PV panels on the roof, corresponding to an installation of 54 kWp which is estimated to produce close to 40 000 kWh of electricity annually. The building is used as a case for the analysis in this report.

Figure 6 Illustration of "Skipet" in Bergen [56].

2.7 Power consumption in Commercial Buildings

A report from 2013 by NVE analyses the energy and power consumption in Norwegian commercial buildings [57]. It states that the specific energy consumption in buildings (kWh/(m^2year)), is dependent on the building standard and the operation of the buildings. Insulation of the building envelope, equipment with low power demand and efficient control and operation strategies for the buildings are ways to reduce the energy consumption. With stricter building standards and regulations, the trend is that the heating demand for commercial buildings is reduced.

The power consumption varies with time, and a peak in power consumption is a result of large amounts of power consumed during a short time period. The energy consumption varies over the year. For example, during the winter the consumption is larger as there is a need for heating, but the energy consumption also varies during the day.

The energy and electricity use also vary depending on the type of building and how the user behaviour is. In Figure 7 the typical load of four different buildings is shown. It is the shape of the energy demand over the day which is of interest, not the difference in energy demand. Load profile (1) is a community building with a typically increasing load during the day and evening. The second is a commercial building where the load has a peak during the middle of the day but a high base load. The third is a residential building with more varying peaks, typically a peak during the morning and a larger peak in the evening after office hours. The fourth shows the load of an industrial building, which has a high but flat and steady energy demand.

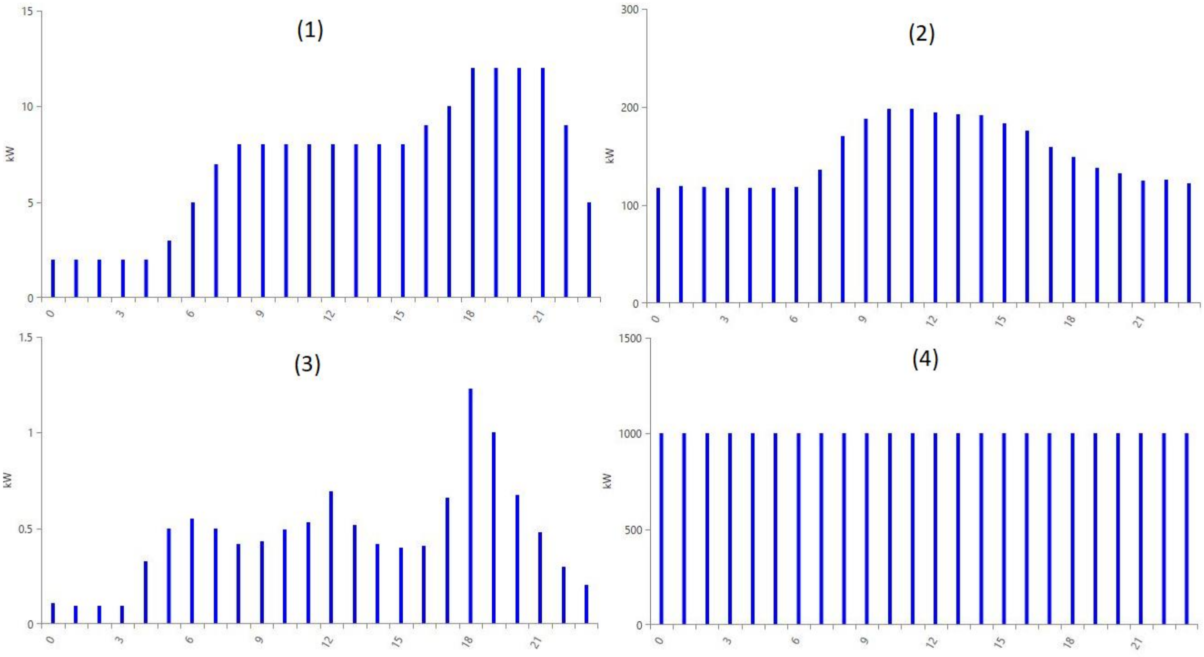

Figure 7 Load Profiles for a Community (1), Commercial (2), Residential (3) and Industrial (4) Building. From the HOMER Energy Pro Software.

2.8 Photovoltaic Installations

A PV installation on the roof can reduce the energy consumption in buildings. The solar insolation in Norway varies between 700–1000 W/m^2, and the number of hours with sun during a year varies. According to the online weather service YR [58], a collaboration between the Norwegian Metrological Institute and the Norwegian Broadcasting Corporation (NRK), the number of sunshine hours which can be expected in some cities in Norway is presented in Table 2. Sunshine hours are only a measure of direct sunlight which has a certain intensity, approximately 210 W/m^2 [24].

Table 2 Sunshine Duration in Norwegian Cities.

City	**Number of sunshine hours (h)**
Bergen	1184,4
Tromsø	1263,6
Trondheim	1346,5
Oslo	1669,0
Kristiansand	1777,6

Since a PV system produces electricity which can reduce the electricity bill, the cost of the system can be paid back over the years with reduced electricity bills. In a report by NVE from 2015 [59] PV installations and their costs are discussed. A typical wafer-based PV panel has a size of 1x1.6 m with efficiencies ranging from 14–18% for polycrystalline and 20–24% for monocrystalline solar cells. For commercial buildings, the typically installed power is from 10–100 kWp. The notation p stands for peak and the given power peak for a PV installation is the power under standardized test conditions (STC) which is the following:

- Solar irradiance of 1000 W/m^2
- Air mass of 1.5
- Cell temperature of 25^{o}C

To install a PV system PV panels, inverters, cables, and control systems are necessary. The installation costs is 30–40% of the total cost of a PV system [59], and systems with more PV modules can therefore be more profitable with a lower cost per kWp installed. Operation and maintenance costs are small, and for commercial buildings these are estimated to be 1.5% of the investment. Inverters have a shorter lifetime than the PV modules, which have a warranty of 25 years, and hence must be changed during the lifetime of the system. The lifetime of the PV panels will in most cases be longer than 25 years, which will affect the profit of the investment.

The levelised cost of energy (LCOE) of a system is defined by the microgrid modelling software company HOMER as the average cost per kWh of useful electrical energy produced by the system [60] For a system of 100 kWp with a solar irradiance of 876 kWh/m^{2}yr NVE defines a LCOE of 1.13 NOK/kWh as low, 1.55 NOK/kWh as medium and 1.69 NOK/kWh as a high investment cost [59]. The distributed energy sales and installer company Otovo, estimates that the pay-back time of PV systems are more than 12 years for most locations in Norway and 9–12 years for south-east locations [61].

2.9 The Electricity Grid

There are some regulations to consider when installing PV systems that are connected and delivers electricity to the grid. A limit of 100 kW electricity sold to the grid is set by NVE [14] for so-called plus-customers. The plus customer can sell the excess electricity to a power company if the generation is larger than the consumption in the building for certain hours. Large energy producers without energy storage systems have in periods with low energy consumption and excess energy been forced to “throw away” electricity due to the 100 kW rule by installing equipment that warns the system when the limit is approaching and turns the inverters off [62]. This is done to avoid the costs that apply when delivering more power than the limit as the producer is no longer considered a plus-customer but power producer.

Plus-customers are exempt from paying the constant fee due to the limit in feeding electricity to the grid. Digitalization in the power marked creates new opportunities, and distribution network operators are no longer obliged to receive excess energy from energy producers. They are, however, obliged to connect their customers to the grid. A new central IT system for the power market was in operation from February 18th, 2019. The IT system, called “El-hub”, will contribute to an effective power market and make information transfer easier between customers and producers [63]. With the new system, plus-customers must find an electricity supplier which is interested in buying excess energy from the PV system.

The Norwegian electricity grid as it is today is for the most part built between the years of 1975 and 2000 [64]. The grid has until now had the main purpose of transporting energy from large powerplants to the consumers. The Norwegian grid can be divided into three levels:

1. Transmission grid – high voltage which is usually 300–420 kV and has a length of 11 000 km. The transition system operator in Norway is Statnett.
2. Regional grid – links the transmission grid to the distribution grid, voltage of 33–132 kV and a length of 19 000 km.
3. Distribution grid – The local electricity grids that deliver electricity to the consumer. Lower voltage compared to the transmission grid, of up to 22 kV and is further divided into high voltage and low voltage distribution. Delivered electricity to the consumers carries 400 V or 230 V. The total length of the high voltage distribution grid is 100 000 km.

The grid must be able to deliver energy when needed. In other words, it must handle peaks in energy consumption and will have to be able to handle variations in electricity generation on both short and long term [64]. For Statnett as the transmission system operator, this means that the company must predict the power supply and demand in 24-hour periods. They are responsible to ensure the power quality of the grid and have to make adjustments in order to keep the balance between consumption and generation and thus controlling the frequency.

Electrification of the transport sector and more use of induction furnaces and other high-power consuming installations has led to more concentrated demands for peak power during the day. If these peaks cannot be reduced or better distributed over the day, large investments would be required to upgrade the Norwegian power grid [13], as the grid should be designed to meet the maximum power demand to avoid instability, fluctuations in voltage and blackouts [65].

The need for large investments is expected to be reduced by introducing technical solutions to distribute the peaks, such as batteries for energy storage or by changing the payment model for electricity, for example increasing the cost of electricity during the peak periods and reducing in other periods of the day.

It is NVE that regulates the fees customers pay for electricity, but the distribution network operator in each area set the network tariff for the transportation of power over the grid to the customers. A deal for the purchase of electricity with an electricity supplier must be made in addition. In Bergen where BKK is the network operator, the electricity bill for power measured electrical systems is made up of three parts as an example.

1. Constant yearly fee – Taxes, certificates, energy fund.
2. Energy fee – Based on the energy consumption (NOK/kWh)
3. Power fee – Based on the power consumption (NOK/kW)

Power prices vary from grid operator to grid operator. As an example the power fee for power measured electrical systems is 107 NOK/kW/month from 0–50 kW for systems connected to the grid of Agder Energi [66]. The fees for electricity in commercial buildings in Bergen with a main fuse above 330 A is presented in Table 3. The fees are in addition to an energy fee of 0.1583 NOK/kWh used, 800 NOK to the Enova fund and MVA of 25%.

Table 3 Electricity Fees in Bergen

Season	**Constant fee (NOK/yr)**	**Added energy fee (NOK/kWh)**	**Power fee 0–200 kW (NOK/kW/month)**	**Power fee above 200 kW (NOK/kW/month)**
Summer (1/4-30/9)	22 000	0.036	58,20	51,00
Winter (1/10-31/3)		0.042	67,70	57,00

Prices are expected to change and public hearings on the subject have been sent out from NVE several times and yet another discussion regarding this is expected in late 2019 [67]. The suggestion is to move from paying a constant fee, energy fee and power fee to a constant fee, energy fee and an overconsumption fee [68]. This will be done with a subscription of power as a constant fee with additional costs applying if consumption occurs over the limit, hence the overconsumption fee. The intention with a new model for electricity prices is to even the power consumption and reduce the strain on the grid, which would over time reduce costs.

2.10 The Nord Pool Market

Nord Pool is the leading European market for power trading and operates across nine European countries. Nord Pool AS is licenced by NVE and the Norwegian Ministry of Petroleum and Energy to organise and operate a market for power trading and facilitate the power market with foreign countries. Nord Pool spot prices are released day ahead and the prices can vary over the day, month and year. NVE predicts that the prices for electricity in Norway will slowly increase with 0,30 NOK/kWh over time towards 2030, even though there is also expected to be an increase in excess energy of 15 TWh [69]. Nord Pool electricity prices and how they have varied from 2015 to 2018 can be seen in Figure 8. The trend is that the prices are increasing for each year, although there are large variations.

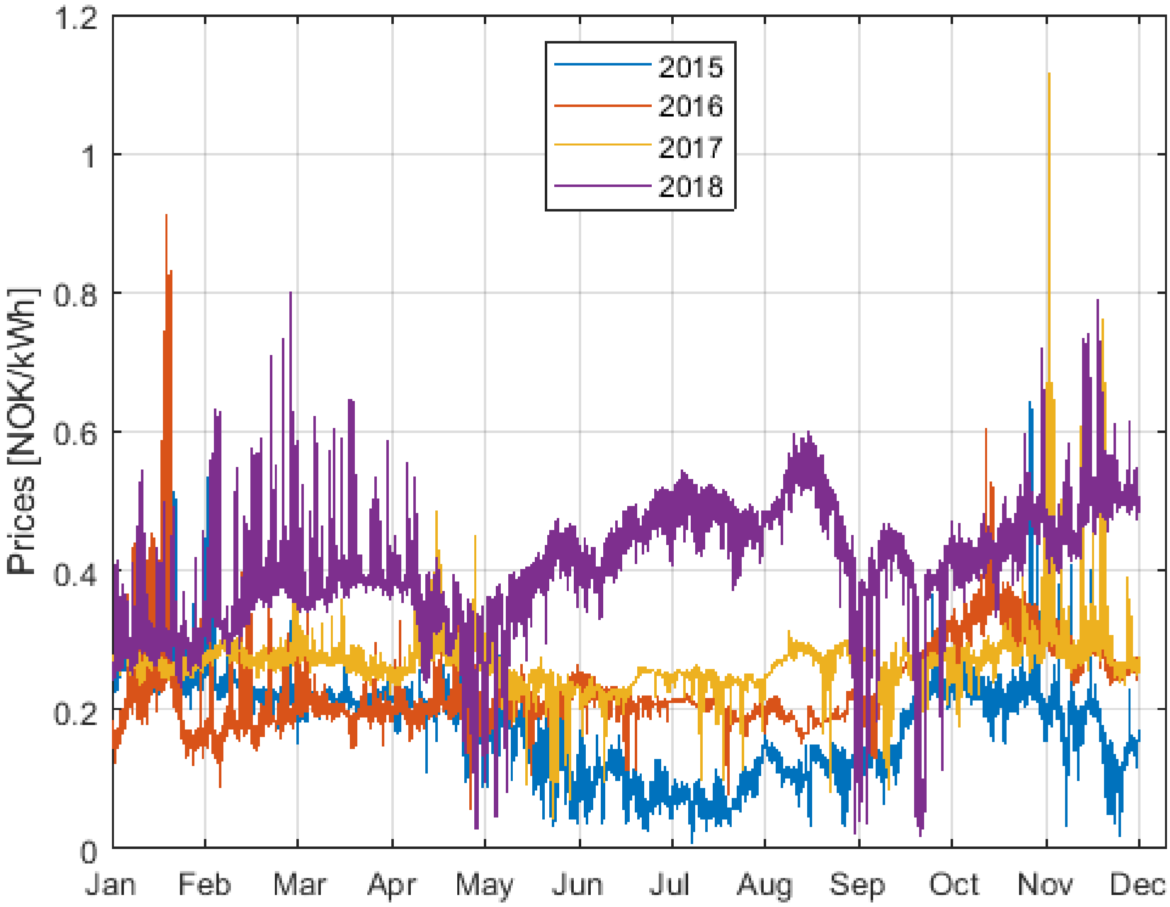

Figure 8 Nord Pool Electricity Spot Prices from 2015 to 2018 [70]. Plotted in MATLAB.

2.11 Control and Operation Strategies for Battery Storage

Demand side management is the optimisation of energy consumption on the consumer side [71]. It is defined as a plan or strategy to either reduce, increase or reschedule the consumers' energy demand in order to reduce the upgrading or increase in network capacity. Some demand-side management strategies are shown in Figure 9.

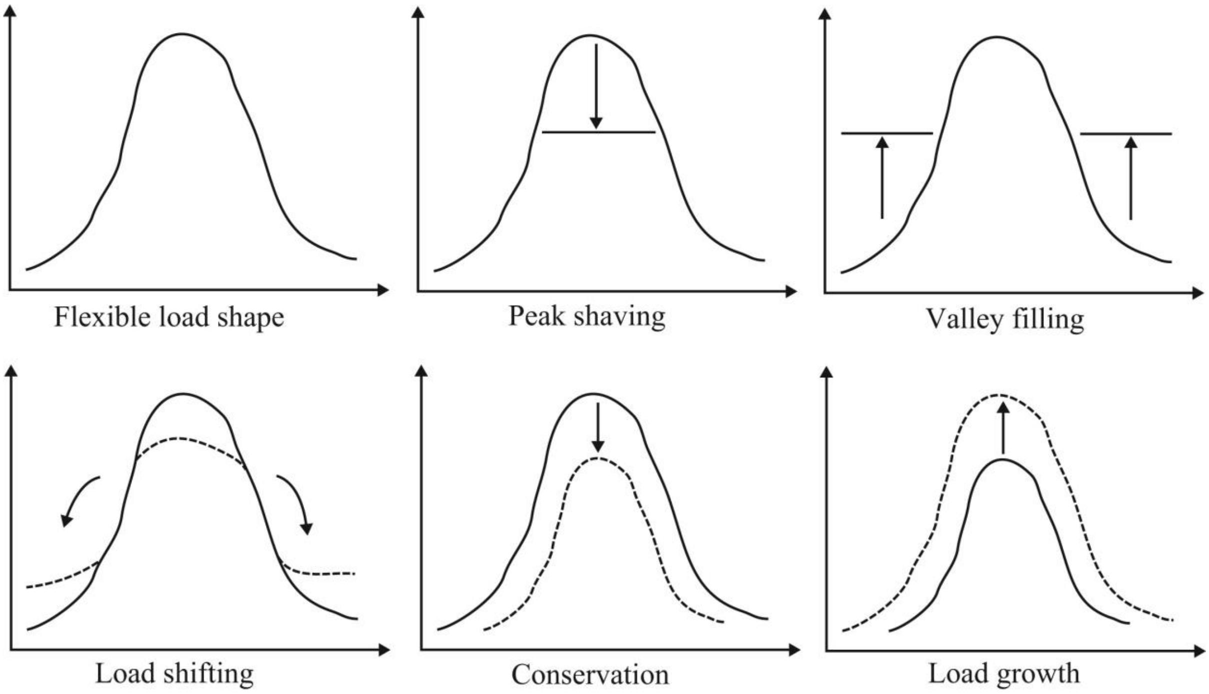

Figure 9 Demand Side Management Strategies, with Permission from Peter D. Lund [71].

Peak shaving is an operation strategy where the goal is to reduce the peaks in power demand. This reduces the electricity bill which is beneficial for the consumer, but also saves the grid operator for costs as the need for generation of power is reduced and investments in infrastructure can be delayed [72]. Load levelling or load shifting is another strategy similar to peak shaving, but where energy is stored during periods of low demand and dispatched during periods of high demand. This does not reduce the power demand but distributes it more evenly.

In a literature review by Uddin et al. [65] three strategies for reducing peaks in power demand are discussed:

1. Integration of Energy Storage Systems (ESS)
2. Integration of Electric Vehicle to Grid (V2G)
3. Demand Side Management (DSM)

In addition to the three strategies, peak shaving could also be achieved by using diesel generators, but as it has high emissions in addition to high operation and maintenance costs, it was not considered a good solution. Integration of ESS is considered the strategy with the most potential and can be used for peak shaving in residential buildings, industries and grids. The challenges of using ESS is:

- Optimum operation of ESS
- Optimal sizing of the storage system
- High capital cost

Several papers in the literature review in the study used demand power limits for optimum operation of the batteries. The correct sizing of the battery energy storage system (BESS) was found to balance the capital cost and electricity bill savings, and peak shaving was found to maximise the financial benefits. Correct operation from a grid perspective is dependent on an optimal sizing of a BESS. Otherwise, a system that is not optimised or has a random size can increase costs and system losses.

The economic savings from a BESS are divided into savings for the customer and savings for the utility company. For the customers perspective, the installations of a BESS used for peak shaving will reduce the monthly electricity bill depending on the electricity tariff system. In comparison the installations of BESS to reduce peaks in power demand for a utility company can be to replace expensive peaking plants, reduce the need to upgrade the grid, reduce the energy losses in the grid, contribute to maintaining the grid voltage by injecting or absorbing reactive power, reduce costs by taking advantage of differences in electricity prices and reduction in CO_2 emissions.

Another study conducted by Ollas et al. [73] compared three different battery dispatch algorithms for either peak power shaving or maximising self-consumption. Sizing of the battery storage system was also included. The study was made for a low energy single-family house in Sweden. The use of a residential building will differ from a commercial building, but the principles of operation strategies are transferable.

Eqs. (4), (5), (6) and (7) shows the ratios used for the calculations in the study for self-consumption (SC) and self-sufficiency (SS). This was done with a Target zero (TZ) method from the Fares and Webber study [74] and by using peak shaving algorithms from the system advisory model (SAM) software. In the equations E_{PV} is the generated energy from PV, E_{BL} is the energy from the battery, $E_{PV\ SC}$ is the directly supplied energy from PV and E_{TOT} is the total energy use.

$$SC_{TZ} = \int_{t1}^{t2} \frac{E_{PV\ SC} + E_{BL}}{E_{PV}} \tag{4}$$

$$SS_{TZ} = \int_{t1}^{t2} \frac{E_{PV\ SC} + E_{BL}}{E_{TOT}} \tag{5}$$

$$SC_{SAM} = \int_{t1}^{t2} \frac{E_{PV\ SC} + E_{BL} - E_{grid\ to\ battery}}{E_{PV}} \tag{6}$$

$$SS_{SAM} = \int_{t1}^{t2} \frac{E_{PV\ SC} + E_{BL} - E_{grid\ to\ battery}}{E_{TOT}} \tag{7}$$

The study found that the capacity of the battery should be carefully selected in order to have an optimal storage solution and avoid unnecessary costs.

Two operational methods are discussed in a study by Fares and Webber [74]. The target zero (TZ) operation is the first. This operation seeks to reduce the energy flow to and from the grid to zero, without future knowledge about electricity generation from PV or electricity demand. The second is the minimize power operation, where the battery is considered to have perfect prior knowledge about the future electricity demand and solar generation and can hence plan the operation to minimize the net power demand over a day. Figure 10 shows the performance of the two strategies, where the minimize power operation scheme has a better outcome in terms of reducing the electricity demand from the grid. This is illustrated with the blue line which shows the power from the grid, and the yellow line which shows the discharge (negative values) and charging (positive values) of the battery.

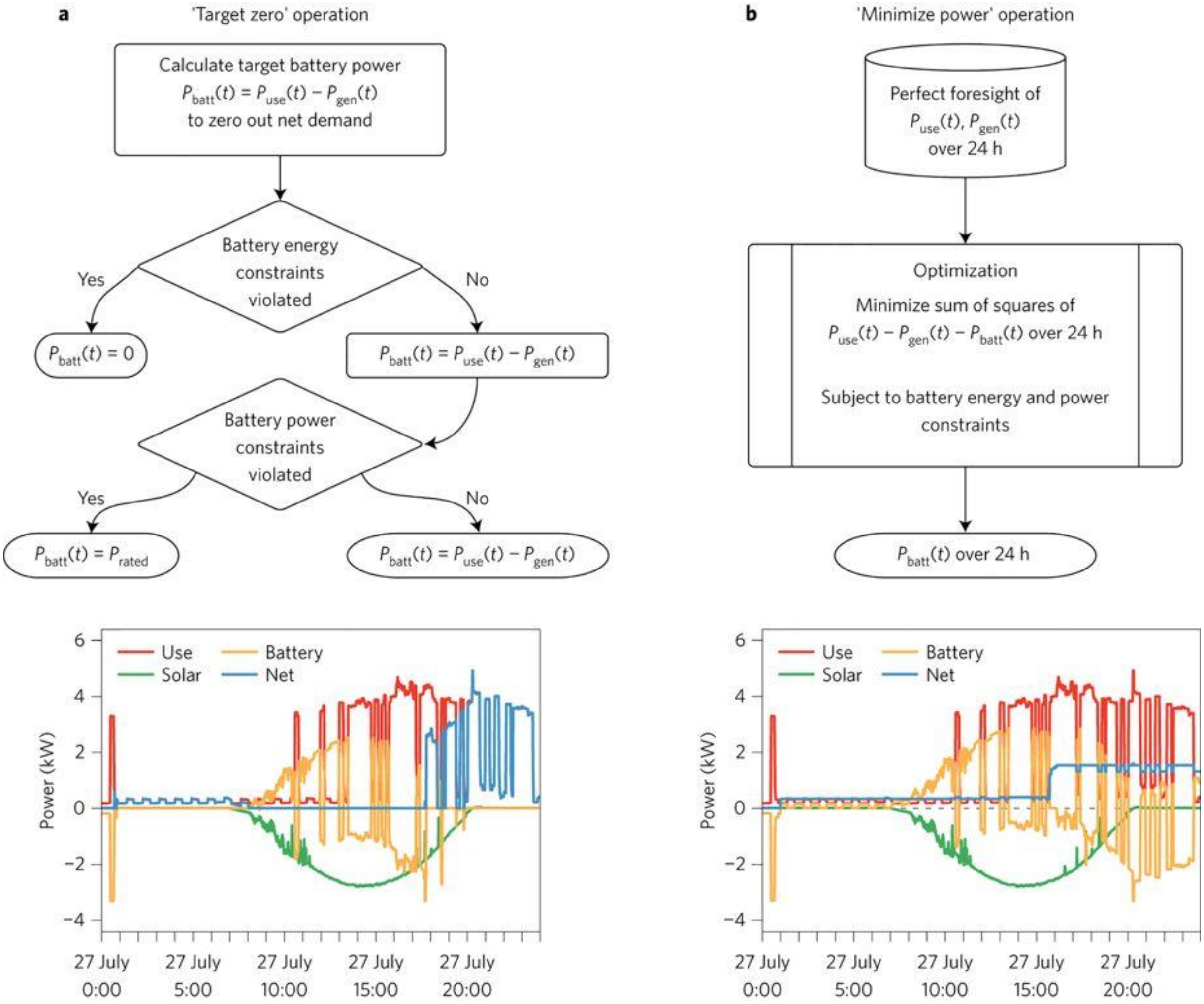

Figure 10 a) The Target Zero Method and b) Minimize Power Method. With Permission from Robert Fares [74].

In a paper by Yassin et al. [75] the sizing of battery storage for building integrated photovoltaic installations was studied. The paper presents two scenarios, the first a domestic house in Kristiansand and the other a university in New Delhi. The study was done for lead-acid batteries. For the residential house in Norway, it was found that the installation of an optimally sized battery storage system would reduce the annual electricity bill with 17.6%. For the university, the savings were only 0.4 % with the optimal size. The optimisation was done for flat energy prices.

In a PhD dissertation by Bernhard Fäßler [76] repurposed electric vehicle batteries used in stationary storage for grid balancing are studied. The dissertation consists of four technical publications and a Zero Emission Battery Research Activities (ZEBRA) battery is studied. The system is presented in Figure 11.

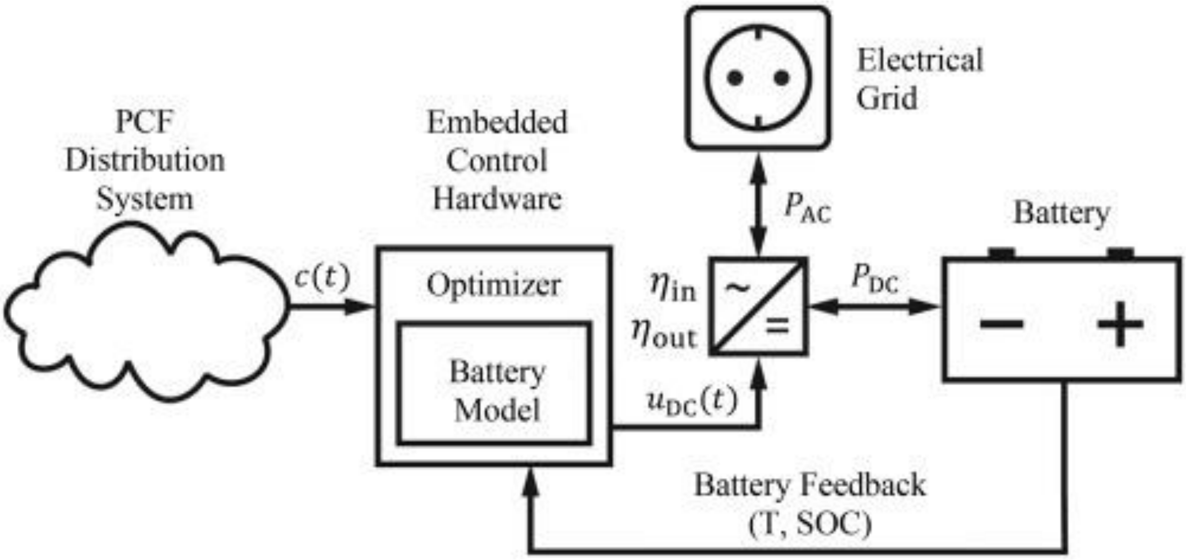

Figure 11 The Battery System of Interest in Dissertation [76].

In one of the papers by Fäßler et al. [77], sequential quadratic, dynamic and integer linear programming methods are compared for optimizing decentralized on-site battery storage used for grid balancing. Day-ahead electricity stock market prices are used as a pseudo-cost function (PCF).

The integer linear programming routine uses a linear battery model. The linear battery model is shown in Eq. (8) where E_{el} is the electrical energy content, $P_{DC}(t)$ is the DC power and P_{loss} are the linearized losses. Linear battery models can be used when the dynamics of the battery, which is dependent on the battery temperature, is not considered as the battery is studied over a larger time-frame.

$$\frac{dE_{el}}{dt} = P_{DC}(t) - P_{loss} \tag{8}$$

The operation of the battery is then optimised by using the *intlinprog* routine in MATLAB for Eq. (9) where *c(t)* is the PCF, *u(t)* is the decision variable, η_{in} is the charge efficiency, η_{out} is the discharge efficiency and $P_{DC,max}$ is the maximal DC power from the battery.

$$\min \int_{t_0}^{t_n} c(t) \cdot \left(u^+(t) \cdot \eta_{in}^{-1} \cdot P_{DC,max} - u^-(t) \cdot \eta_{out} \cdot P_{DC,max}\right) dt \tag{9}$$

The decision variable u, which is the integer variable, is limited to be either 1, 0 or -1 for battery charging at full power, idling state or discharging at full power.

The paper concludes that the sequential quadratic programming routine performs the best, although the integer linear programming has the shorter runtime with a good approximation of results. The latter was therefore further used to investigate the grid balancing potential and higher data resolutions of 15 minutes instead of one hour were found to give higher earnings.

In the same paper, the capacity-to-power ratio was investigated both for hourly and 15-minute based day-ahead prices. As can be seen in Figure 12, the capacity to power ratio is shown for earnings in (a) and losses in (b). It illustrates how a too high capacity to power ratio does not utilize the full capacity of the battery and a small ratio is not good for efficient operation with low earnings and high losses.

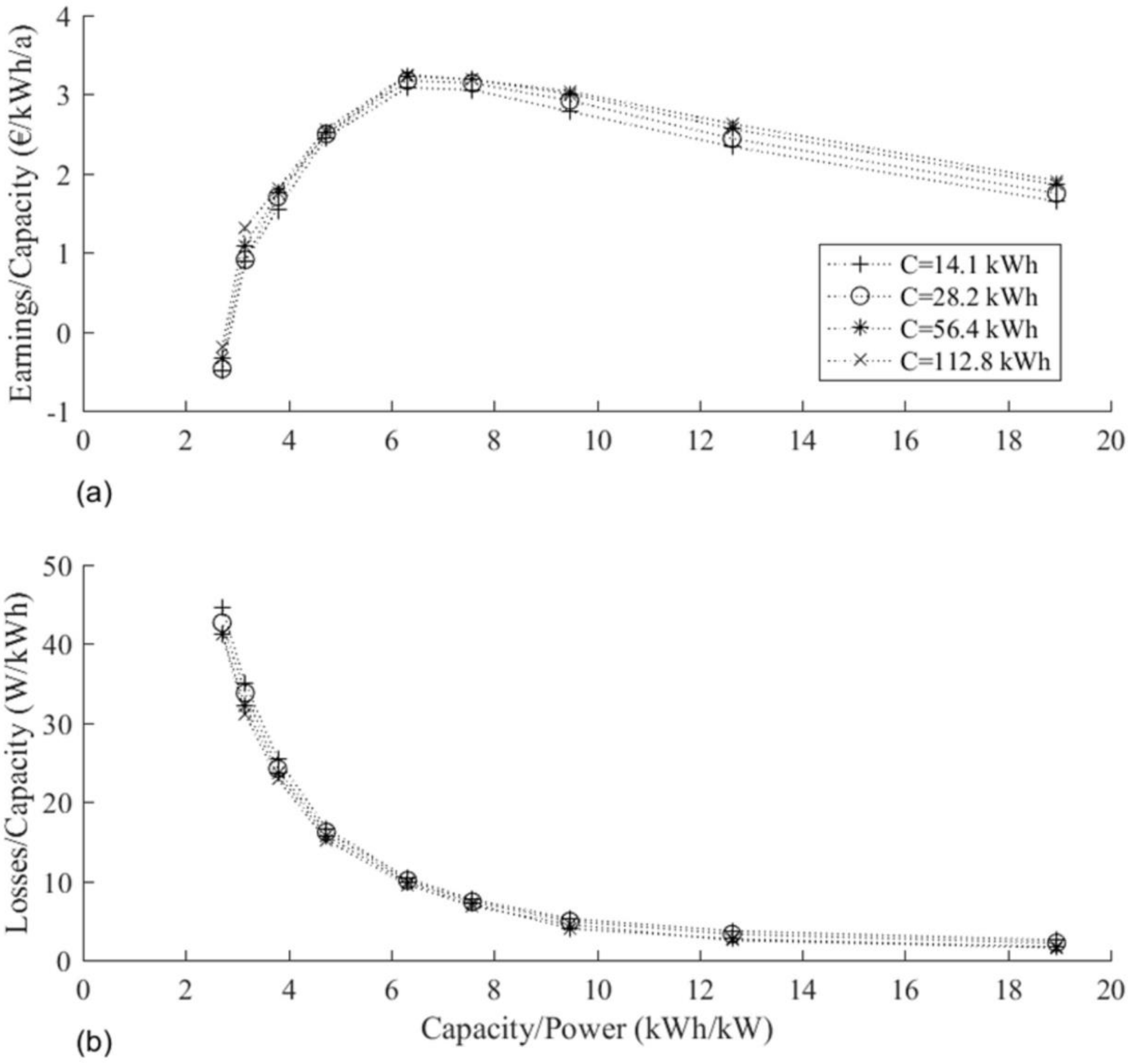

Figure 12 (a) Earnings and (b) Losses of Capacity-to-Power Ratio for Hourly Based Electricity Prices. [76].

As explained by Zhang et al. [78] there exists a lot of research regarding the scheduling and operation of battery storage systems using Energy Management System (EMS), dynamic programming or different algorithms. The weakness of the studies is that they rely on fixed and assumed sizes of the components, and rule-based operation control is proposed as an alternative approach.

It was found in the study by Zhang et al. [78] that the conventional operation strategy, which charges the battery when excess power is available from the PV system and exports to the grid when surplus power exists as well as discharges from the battery or uses grid power, is in conflict with peak shaving operation on rule-based control. This is due to the fact that with peak shaving, the SOC should be maintained at a high level, whereas for the conventional operation strategy the SOC varies with the generation of electricity from the PV system and the load from the building. A more complicated "Hybrid Operation Strategy" is therefore suggested and takes into account both strategies by using the optimisation toolbox in MATLAB.

Control strategies based on the deterministic rule approach are based on “If-else” rules applied to a system. The deterministic rule approach control strategy is for instance used in Hybrid EVs as mentioned in a study by Zulkifli et al. [79].

An example of a “if-else” system is presented in Figure 13. The figure is a combination of peak shaving strategy and maximising self-consumption, where the system plans ahead every evening. If the weather is clear the next day, it is the weekend and spring or summer and if the energy content in the battery is larger than the minimum, then power should be extracted. If the battery was under the limit, the grid must provide the power.

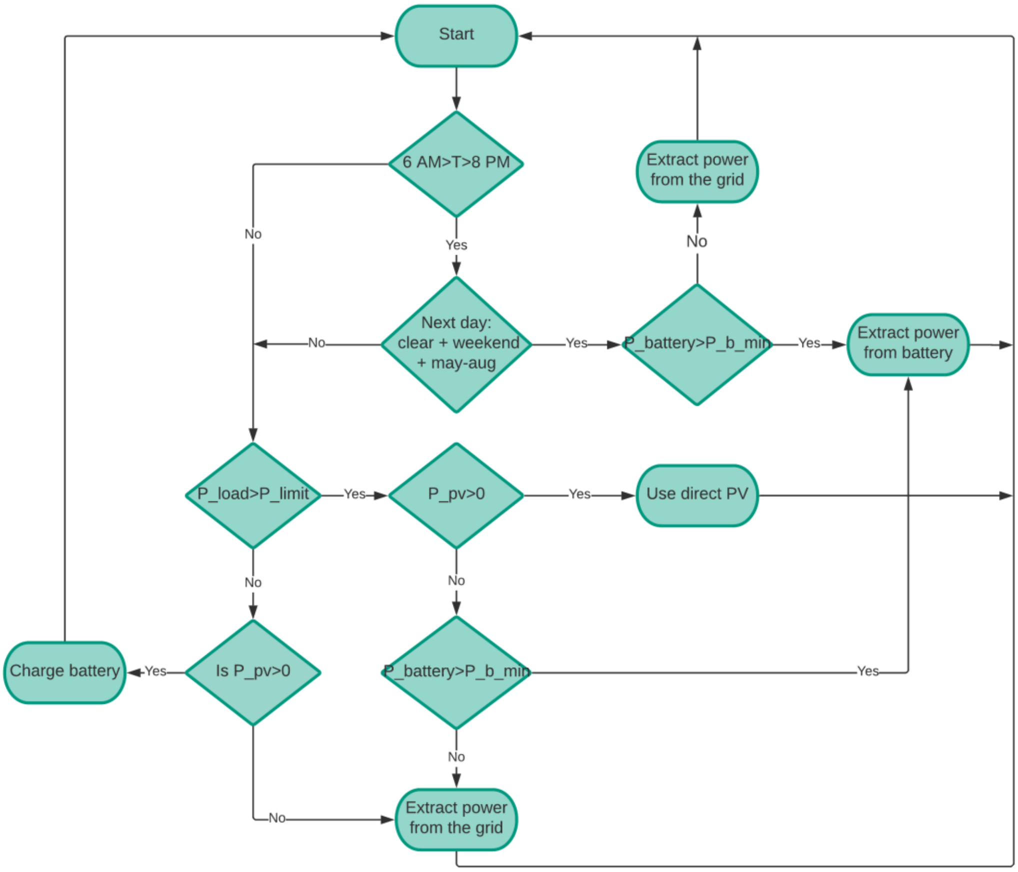

Figure 13 Flow-Diagram of Operation Strategy, Made with Lucidchart.

It is mentioned by Teleke et al. in [80] that a simple rule-based control method can be applied to a battery storage system which job is to reduce the intermittent behaviour of renewable energy so that it can be dispatched on an hourly basis. The method is also applicable to other storage types as it did not require a battery model in order to operate. The paper concluded that the sizing was important for an effective system and is depending on the limits of the battery system.

In a paper by Sevilla et al. [81], model-based predictive control is used to maximise self-consumption in a commercial building with PV installation and a battery storage system. A power balance based on the power flow of the system is first set up and then an equation describing the system as well as system constraints. The system is optimised with minimization constraints set to power from the grid, and maximisation to the power from the battery. Model predictive control is a control method divided into two systems, a base control and a supervisory control level.

3 Methods

3.1 Simulations in HOMER

The Hybrid Optimisation Model for Electrical Renewable (HOMER) Energy software, HOMER Pro, was used for simulations of a commercial building to find the optimal size of a PV installation with battery energy storage. The software is an optimisation tool for microgrids which will help decide which components are optimal for a system, and what size the system should be in terms of cost. Components like generators, PV, wind turbines, storage, hydropower, grid and load properties can be included. By adding prices of the components, the program calculates the net present cost (NPC) for different options. The NPC is defined as the present value of all costs of a system or project including installation and operation over the project lifetime minus the earnings over the project lifetime. This is calculated by summing up the cash flows, taking into account a discount factor, over the project lifetime.

The LCOE is calculated as well. As mentioned in Section 2.8, LCOE is defined as the average cost per kWh of useful electrical energy produced by the system. It is a common way to compare systems but is not used to rank them in HOMER. The equation for the levelised cost of energy is shown in Eq. 10, where $C_{ann,tot}$ is the total annualized cost of the system in (NOK/yr), c_{boiler} is the boiler marginal cost in (NOK/kWh), H_{served} is the total thermal load served in (kWh/yr) and E_{served} is the total electrical load served in (kWh/yr).

$$LCOE = \frac{C_{ann,tot} - c_{boiler} \cdot H_{served}}{E_{served}} \tag{10}$$

The total annualized cost can be calculated with Eq. 11. Here, the capital recovery factor (CRF) is a function of the annual real discount rate, *i* (%), and R_{proj} is the project lifetime in years. The $C_{NPC,tot}$ is the total net present cost in NOK.

$$C_{ann,tot} = CRF(i, R_{proj}) \cdot C_{NPC,tot} \tag{11}$$

The last calculation which can be used to compare systems is the operating cost. It is defined as the annualized value of all costs and revenues other than initial capital costs and can be seen in Eq. 12. It is the total annualized costs as calculated in Eq.11, minus the total annualized capital costs. Both are given in (NOK/yr). The total annualized capital cost is equal to the total initial capital cost multiplied by the capital recovery factor.

$$C_{operating} = C_{ann,tot} - C_{ann,cap} \tag{12}$$

To compare the different systems, HOMER calculates the NPC of each component and the system as a whole. The optimal solution will be the option with the lowest NPC and the other calculations are used for comparison. The principle of the system that was evaluated is shown in Figure 14.

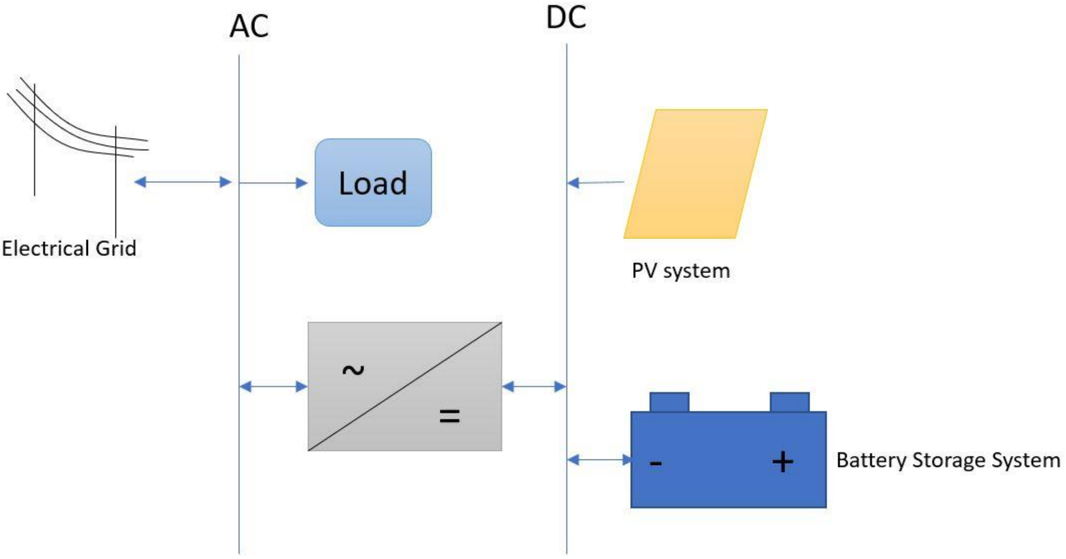

Figure 14 Energy System Studied with the HOMER Energy Pro Software.

To test the system and find the optimal size of the BESS and which variables affect the system, two scenarios is done with the HOMER software:

1. Simulation with PV with a lower limit of 0 and upper limit of 200 kW and battery between 0 and 300 kWh.
2. Simulation with peak power pricing in the morning and evening.

For the given system there are many variables that can be changed. Installation costs, operation and maintenance costs, the power consumption of the building and electricity prices are some of the most important. The simulation is done for a year, with 8760 time-steps of one hour. Optimiser settings were set to default.

The constraints set for the system are the following:

- The simulations were all done with the same electric load from the building "Bergen Stasjon Østsiden"[82], which is of similar size and type of building as "Skipet" presented in Section 2.6.
- The sale capacity of the grid was limited to 100 kW, which is the limit in Norway.
- Prices for PV are based on prices from Otovo [83], with a capital cost of PV set to 25 000 NOK/kW and a lifetime of 25 years.
- Cost of the converter was set to 1 100 NOK/kW based on prices from Solcellespesialisten [84].
- Operation and maintenance costs for PV and converter were set to 1.5% and the lifetime of the converter is set to 15 years, hence it must be changed once during the lifetime of the PV installation.
- Prices of the battery are set to 1 405 NOK for a 1 kWh lithium-ion battery with operation and maintenance costs of 140 NOK/year based on Bloomberg New Energy Finance predictions [8].
- Initial SOC was set to 50% and a minimum SOC was set to 20%.
- The grid was set with an average energy price of 1.06 NOK/kWh for the first quarter, 1.10 NOK/kWh for the second quarter and 1.2 NOK/kWh for the third and fourth quarter of the year based on numbers from statistics from Statistics Norway [85]. The sellback rate for energy sold to the grid is based on spot price statistics from Nord Pool [70].
- Solar data is based on the available data from NASA in the simulation program.

3.2 Simulations in MATLAB

In order to evaluate the operation of a BESS, the power consumption of a commercial building is evaluated. The power consumption is plotted in MATLAB to see how it changes throughout the day and if there are any distinctive patterns. Further, the goal is to find the optimal operation of a BESS for a commercial building based on different criteria.

First, the operation of the BESS is optimised based on the day-ahead electricity spot prices from Nord Pool. When the prices are low, the battery should charge and when prices are high, the battery should discharge. The second optimisation is done in terms of the electricity consumption of a commercial building. For this scenario, the opposite results should be achieved, and the battery should discharge when the consumption is high and charge when consumption is low.

An integer linear programming routine in MATLAB is considered for the optimisation of the battery storage system. The method is based on the work of Bernhard Fäßler [76] as mentioned in Section 2.11, but has been adapted to fit a battery system for a certain commercial building and is optimised in terms of Nord Pool electricity spot prices to fit the Norwegian market as well as the electricity consumption of the building. The MATLAB script is attached in the Appendices.

Linear optimisation is used to find a minimum or maximum of a function subject to a set of linear constraints. This is shown with Eq. (13) [86]. The inequality constraints are represented in Eq. (14), whereas the equality constraints are represented in Eq. (15). Lower and upper bounds are represented in Eq. (16) and Eq. (17) represents the integer variable. Mixed integer linear programming differs from linear programming with the integer constraint.

$$\min_{x}(f^T x) \tag{13}$$

$$Ax \leq b \tag{14}$$

$$A_{eq}x = b_{eq} \tag{15}$$

$$lb \leq x \leq ub \tag{16}$$

$$x_i \in \mathbb{Z} \tag{17}$$

The first optimisation is done with the same objective function presented in Eq. (18) as described in Section 2.11.

$$\min \int_{t_0}^{t_n} c(t) \cdot \left(u^+(t) \cdot \eta_{in}^{-1} \cdot P_{DC,max} - u^-(t) \cdot \eta_{out} \cdot P_{DC,max}\right) dt \tag{18}$$

The pseudo-cost function c(t) which is the price of electricity, is to be minimised. The goal is to simulate the charge and discharge of the battery based on minimising the cost of the system. The parameters used for the simulation is given in Table 4.

Table 4 Optimisation variables for the day-ahead spot price optimisation.

$E_{el\,max}$	150 (kW)
P_{max}	20/50 (kW)
P_{loss}	$0.01 \cdot P_{max}$(kW)
η_{in}	95%
η_{out}	95%
$SOC_{initial}$	50%
$SOC\ upper\ limit$	80%
$SOC\ lower\ limit$	20%
u	hei

First the maximum power of the battery is set to 50 kW, based on the battery installation in the building "Skipet". Secondly, it is set to 20 kW which gives a better power-to-capacity ratio according to Fäßler et al. [77]. The maximum energy is set to be 150 kWh and SOC of the battery is limited between 20–80% which is common for lithium-ion batteries. Another limitation is the decision variable u, which is the integer variable limited to be either 1, 0 or -1 for battery charging, idling or discharging respectively.

A battery has dynamic qualities as the characteristics can vary a lot with time. They are dependent on the SOC as well as the SOH. For the purpose of this thesis, a linear battery model with linear constraints is considered to calculate the SOC where the cyclic and calendric ageing is not considered. Otherwise, a complicated battery model with unavailable data would be required. The linear battery model in Eq. 19 as presented in Section 2.11 is considered. Losses are calculated based on the efficiency of lithium-ion batteries and is considered to be 1% [31].

$$\frac{dE_{el}}{dt} = P_{DC}(t) - P_{loss} \tag{19}$$

The roundtrip efficiency of the batteries in this system is given to be 90%. The charge and discharge efficiency η_{in} and η_{out} are set to 95%.

The second optimisation is done as the first but with hourly values of the electricity consumption of the building as input data in c(t). The electricity consumption data is historical data used to predict the future electricity consumption of the building and are considered perfect prior knowledge.

4 Results

For the results presented in this chapter, unless otherwise written, the building “Skipet” which was presented in Section 2.6 is considered as a case. The building is under planning and currently only calculated electricity demand is available. These are average hourly values calculated in SIMIEN, a program for simulations of energy demand and indoor environment in buildings. As hourly calculated values are not applicable to the evaluation of energy consumption in a building, measured electricity use from another building, “Bergen Stasjon Østsiden”[82], which is of similar size and type of building is used in the simulations in this thesis.

4.1 Optimal Size of Battery and Photovoltaic System Using HOMER Energy Pro

Several papers have stated that correct sizing of a BSS is crucial to get the economic savings as mentioned in Section 2.11. Therefore, it is interesting to simulate a battery storage system for a commercial building to find the optimal size of the battery and PV system.

The conditions set for the simulations are the ones presented in Section 3.1 and is the same for all scenarios. The following simulations were done:

1. Simulation with PV and converter with capacity varying between 0 and 200 kW and battery between 0 and 300 kWh. Demand rates from BKK of 53.90 NOK/kW/month for summer (01.04–30.09) and 62.70 NOK/kW/month during winter (01.10–31.03).
2. Simulation with added peak pricing in the morning and evening where prices are almost doubled from scenario 1.

4.1.1 Scenario 1

The results of the first scenario simulated are presented in Table 5. This first simulation suggested a PV installation of 168 kWp, a converter with the capacity of 132 kW and no battery storage as the lowest cost option. The second-best solution was a grid only system without PV and battery. The third solution for the first scenario suggested a PV installation of 186 kWp and a converter of 124 kW and a battery with nominal capacity of 102 kWh.

Table 5 Optimisation Results for Scenario 1.

System Ranking	PV capacity (kWp)	Battery capacity (kWh)	Converter (kW)	NPC (M NOK)	LCOE (NOK)
1.	168	-	132	26.8	1.26
2.	-	-	-	27.0	1.27
3.	186	102	124	27.2	1.28

4.1.2 Scenario 2

The second simulation is based on the first, but in addition, peak pricing has been introduced and prices for power has also been included. The prices of electricity are increased to 100 NOK/kW/month between 6 am to 10 am, and from 4 pm to 8 pm. The scenario is based on future predictions of peak pricing [68] and to see if the system is affected by an almost doubling in power prices during certain hours. The simulation results are presented in Table 6. The most profitable solution suggested is to maximise the PV installation. Secondly a battery storage system is included, and the third option is to only use the grid.

Table 6 Optimisation Results for Scenario 2.

System Ranking	PV capacity (kWp)	Battery capacity (kWh)	Converter (kW)	NPC (M NOK)	LCOE (NOK)
1.	200	-	158	31.0	1.46
2.	199	102	144	31.4	1.48
3.	-	-	-	31.4	1.48

4.2 Power Consumption in Commercial Buildings

In Figure 15 and Figure 16 the measured electricity use for some typical Mondays and Wednesdays of the building “Bergen Stasjon Østsiden” are plotted. The figures show how the range in power consumption varies significantly through the year, but that there is a distinctive increase in power consumption from 7 am with a peak around 12 pm and slowly decreasing during the evening. One exception is in Figure 16 where the 17th of May does not follow the trend as it is a National holiday and clearly not a typical Wednesday, hence the energy consumption is lower compared to the 15th of May showed in Figure 15. During the week the base load of the building varies between 80–140 kW, whereas the peak load varies between 160–240 kW between summer and winter. Figure 17 shows the energy consumption for Saturdays through a calendar year. Still, the power consumption varies a lot between summer and winter between around 90–152 kW, although there is no distinctive peak curve for the power consumption during certain hours as for the weekdays.

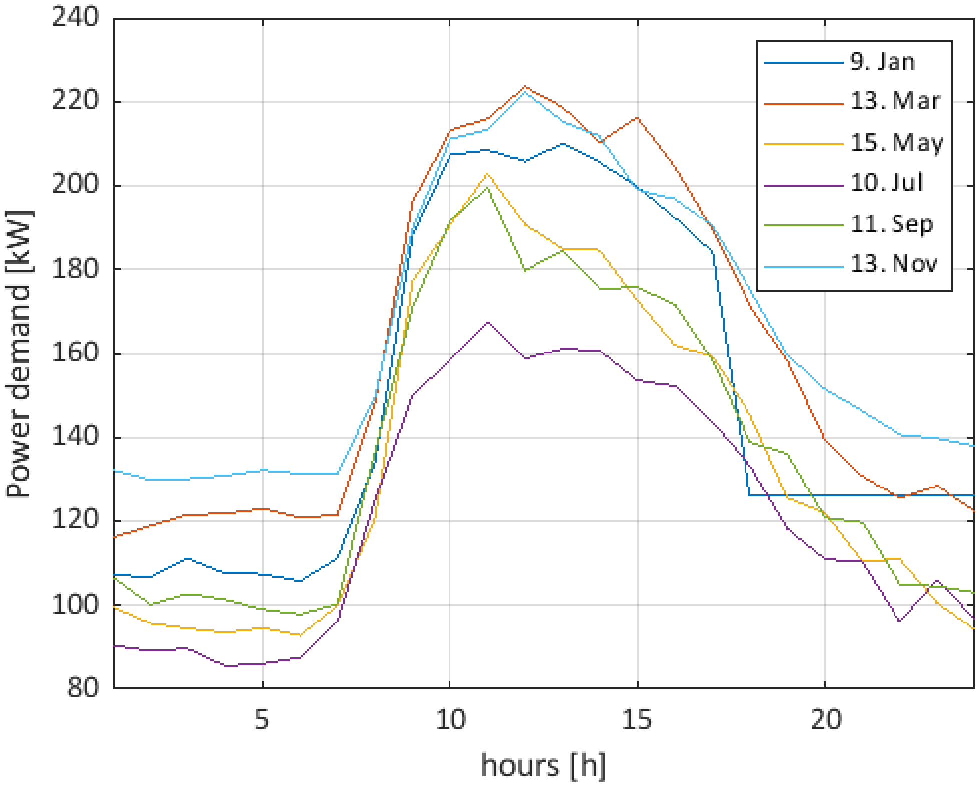

Figure 15 Power Consumption for Typical Mondays Through a Calendar Year.

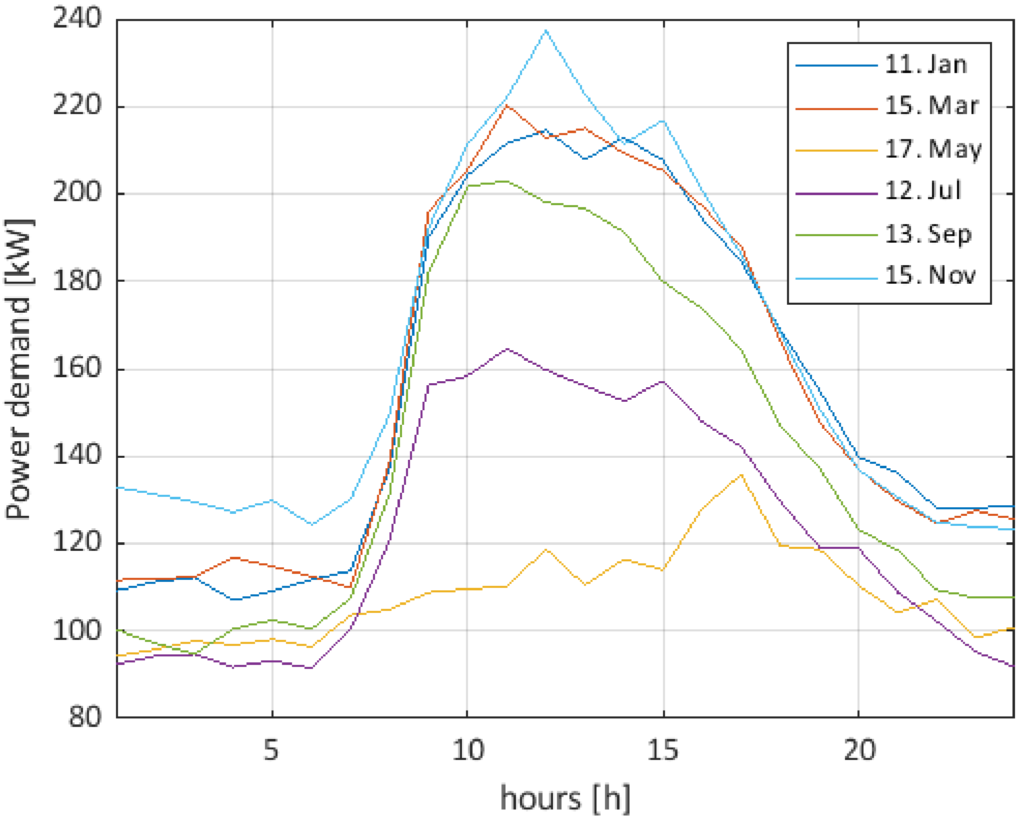

Figure 16 Power Consumption for Typical Wednesdays Through a Calendar Year.

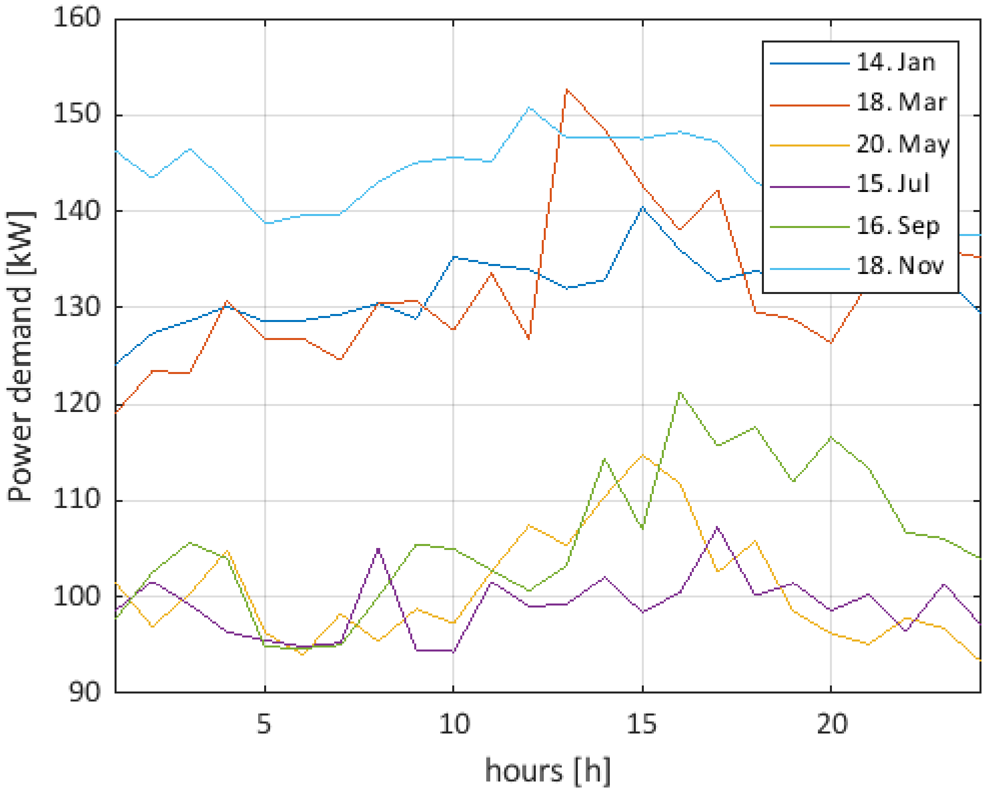

Figure 17 Power Consumption for Typical Saturdays During a Calendar Year.

4.3 Optimisation of Battery in MATLAB Using Spot Prices

The integer linear optimisation routine in MATLAB was first used to optimise the battery storage system to operate such that the costs were minimised in terms of electricity spot prices. In Figure 18, the electricity consumption with and without a battery storage system compared to the electricity spot prices for a Tuesday in March 2017 is presented. The figure shows how the battery charges during the first hour, then charge when prices are at a minimum at hour 16, followed by a discharge at hour 21 when the price is at a peak. The battery charges in the beginning since the initial SOC was set to 50% for the simulation and there are some losses when the battery is in idle state.

The peak in power consumption is increased from 229 kW to 265 kW due to the minimum in price occurring at hour 16, hence making the battery charge when the power consumption is already high. The peak in electricity price at hour 21 is making the battery discharge. With the increase in power consumption and the electricity prices presented in Section 2.9, there will be a 2 024 NOK increase in payment that month based on the power consumption for the selected day with this operation scheme.

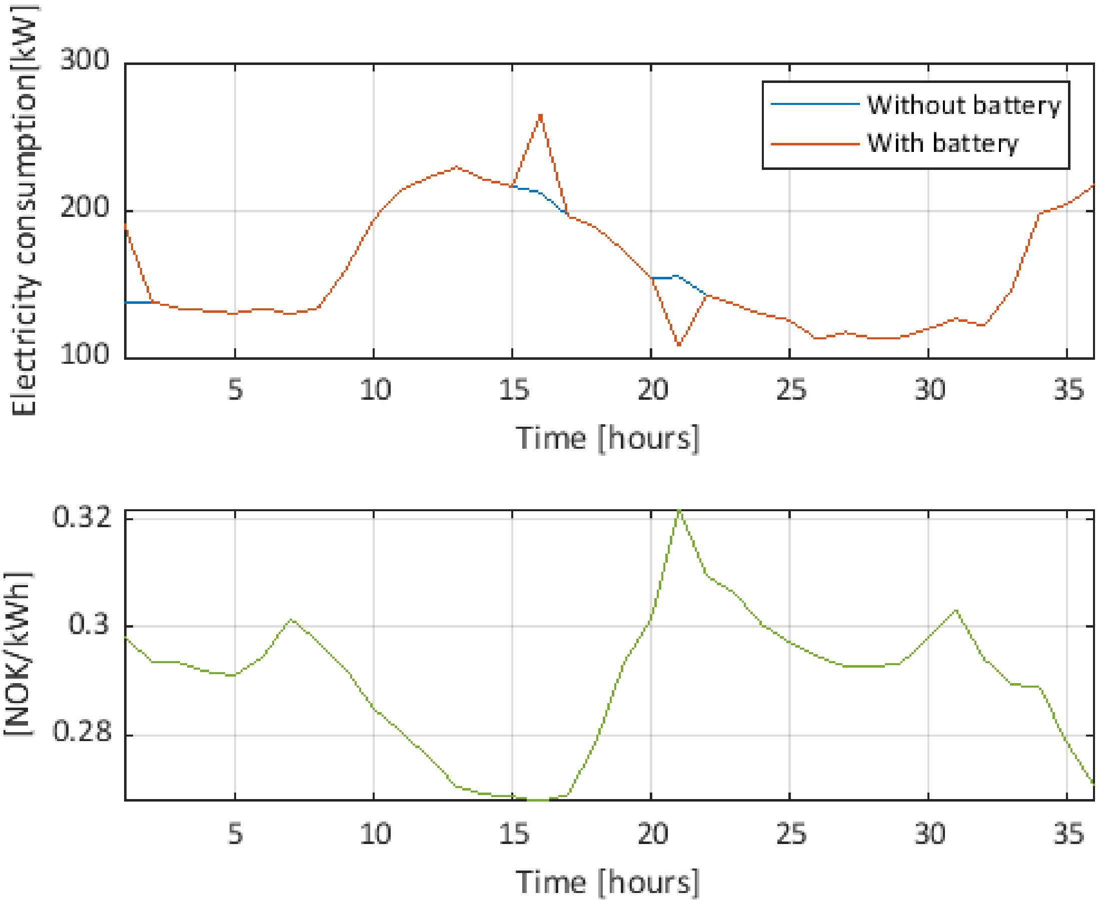

Figure 18 Electricity Use with and without Battery Storage and Electricity Spot Prices for $P_{max} = 50\ kW$.

By summing up the cost of the electricity over a year based on the electricity spot prices with and without battery, the effect of the battery can be shown as presented in Table 7. With the battery system, the electricity consumption has increased with 12 100 kWh. The increase is expected, as there are losses related to the charging and discharging of the battery storage. The table also shows the increase in the cost of 2 480 NOK over the year.

Table 7 Comparison of Costs with and without Battery for Spot Price Optimisation with 50 kW Battery.

	Electricity Consumption (kWh)	**Cost (NOK)**
Without battery	1 206 700	324 430
With battery	1 218 800	326 910
Difference	12 100	2 480

Based on the findings in [77] by Fäßler et al., the optimisation was also done with lower power for a better power-to-capacity ratio, setting the maximum power of the battery to 20 kW instead of 50 kW. The result is shown in Figure 19. With the reduced maximum power, the battery charges and discharges more often. It starts with discharging as the initial capacity of the battery is 50%, and also discharges at the second peak in electricity prices at hour 7. Then the battery charges during low prices around hour 15 increasing the peak in power consumption, followed by discharging starting at hour 20 when the prices reach a peak. Still, the battery is not able to discharge during all the peaks in the spot prices for electricity, but more often than when the maximum power from the battery was set to 50 kW.

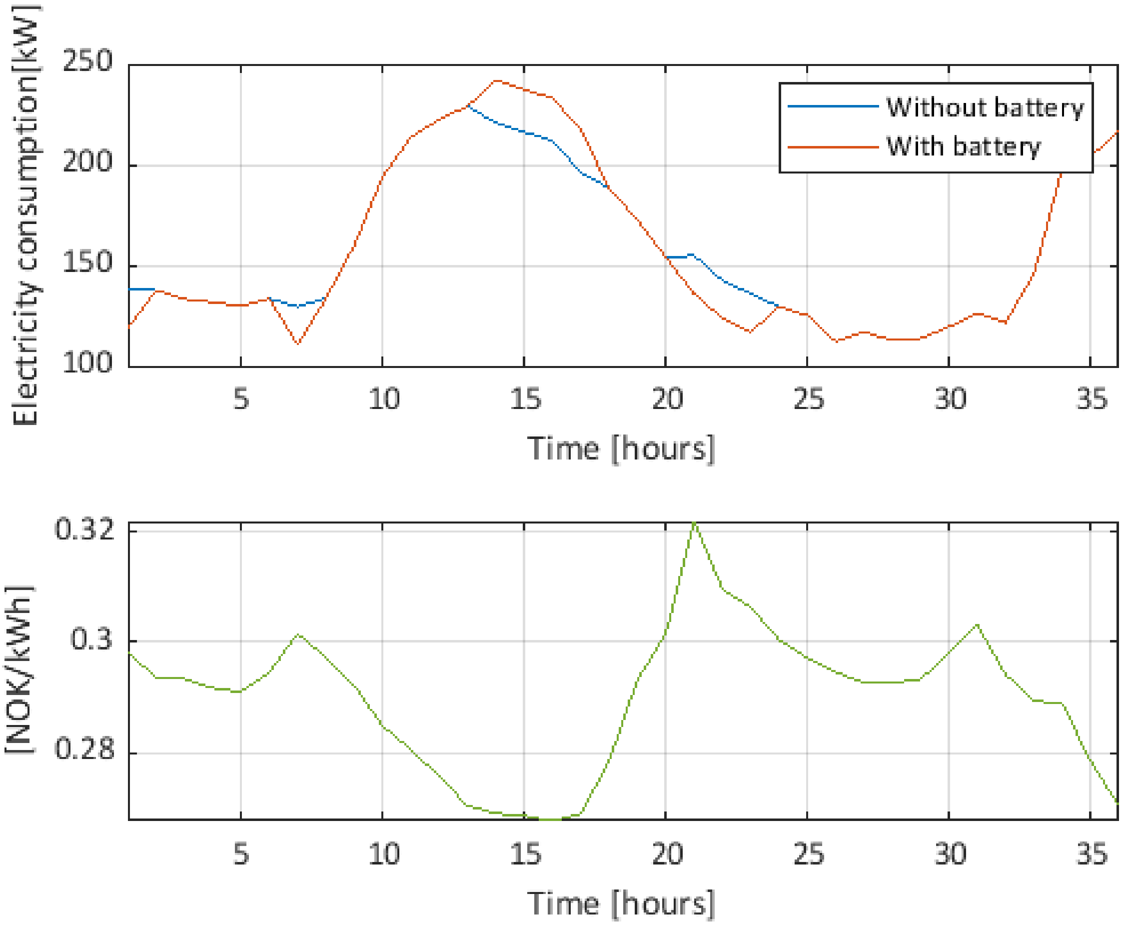

Figure 19 Electricity Use with and without Battery Storage and Electricity Spot Prices $P_{max} = 20\ kW$.

The peak in power consumption is still increased with a lower maximum power, from 229 kW to 242 kW due to the minimum in price occurring at hour 16, hence making the battery charge when the power consumption is already high. The peak in electricity price at hour 21 is making the battery discharge. With the increase in power consumption and the electricity prices presented in Section 2.9 there will be a 730 NOK increase in payment that month based on the power consumption for the selected day with this operation scheme.

Table 8 shows the result of a cost calculation and the electricity consumption in the building for the optimization done over a year, with and without battery storage. In this scenario, the costs are slightly reduced with the battery storage, although the electricity consumption is still higher due to the losses from storing and dispatching energy in a battery.

Table 8 Comparison of Costs with and without Battery for Spot Price Optimisation with 20 kW Battery.

	Electricity Consumption (kWh)	**Cost (NOK)**
Without battery	1 206 700	329 840
With battery	1 209 800	329 710
Difference	3 100	-130

4.4 Optimisation of Battery Using Power Demand

Secondly, the integer linear optimisation routine was used to optimise the battery storage system to operate such that the costs were minimised in terms of the electricity consumption of the commercial building. In Figure 20, the electricity demand with and without a battery storage system with a maximum power of 50 kW for a Tuesday in March 2017 is presented.

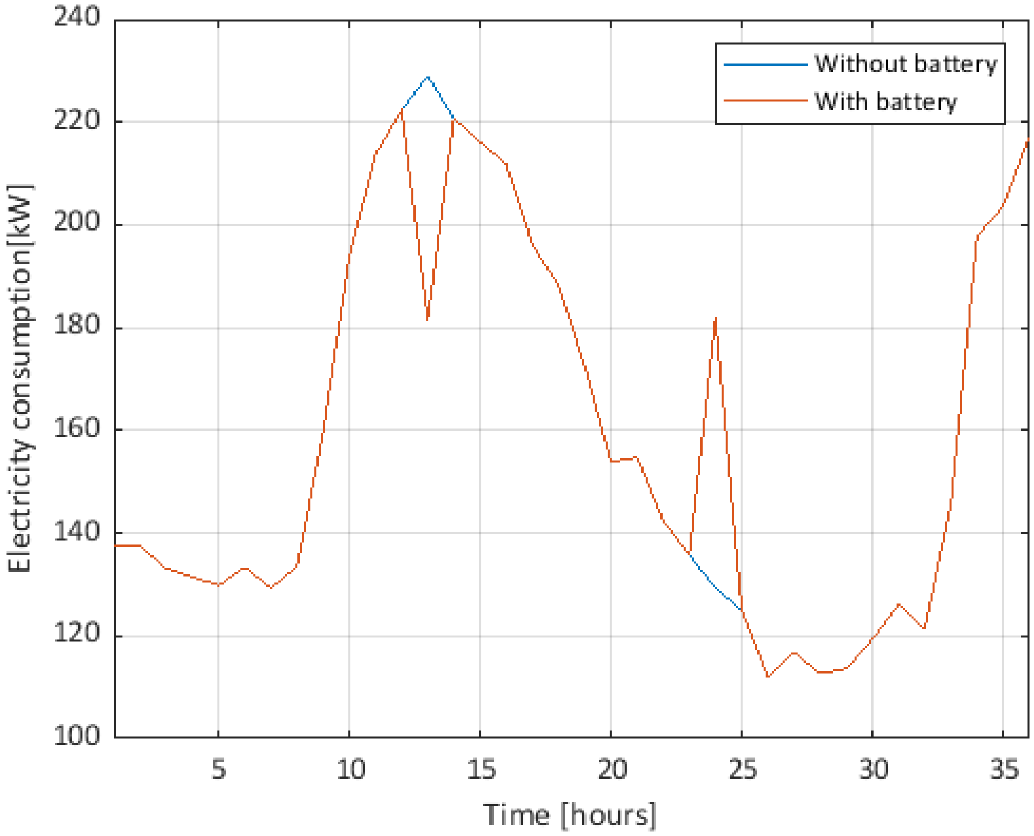

Figure 20 Electricity Use with and without Battery Storage for P_{max} = 50 kW.

The figure shows how the battery discharges during the peak in power consumption around hour 12–14, reducing the peak from 229 kW to 222 kW. The battery then charges from hour 23–25 when the power consumption is lower. The charging of the battery creates a peak, but not during the hours when the power consumption is already high. With the reduction in power consumption and the electricity prices presented in Section 2.9 there will be a 376 NOK reduction in payment that month based on the power consumption for the selected day with this operation scheme.

The costs and electricity consumption are simulated over a year and presented in Table 9. With the battery system, the electricity consumption has increased as expected, but the total costs based on the spot prices have also increased.

Table 9 Comparison of Costs with and without Battery for Energy Demand Optimisation with 50 kW Battery.

	Electricity Consumption (kWh)	**Cost (NOK)**
Without battery	1 206 700	329 840
With battery	1 212 700	331 110
Difference	6 000	1 270

Similar to the spot price optimisation, a simulation with lower maximum power set to 20 kW was also done for the optimisation based on electricity consumption as input data. The result is presented in Figure 21. The battery charges during the first hours when there is a low electricity consumption and discharges from hour 12 to 17 during the peak in power consumption. The battery then charges again from hour 22 to 26. With a lower maximum power, the reduction in power consumption is more even than when the maximum power was 50 kW.

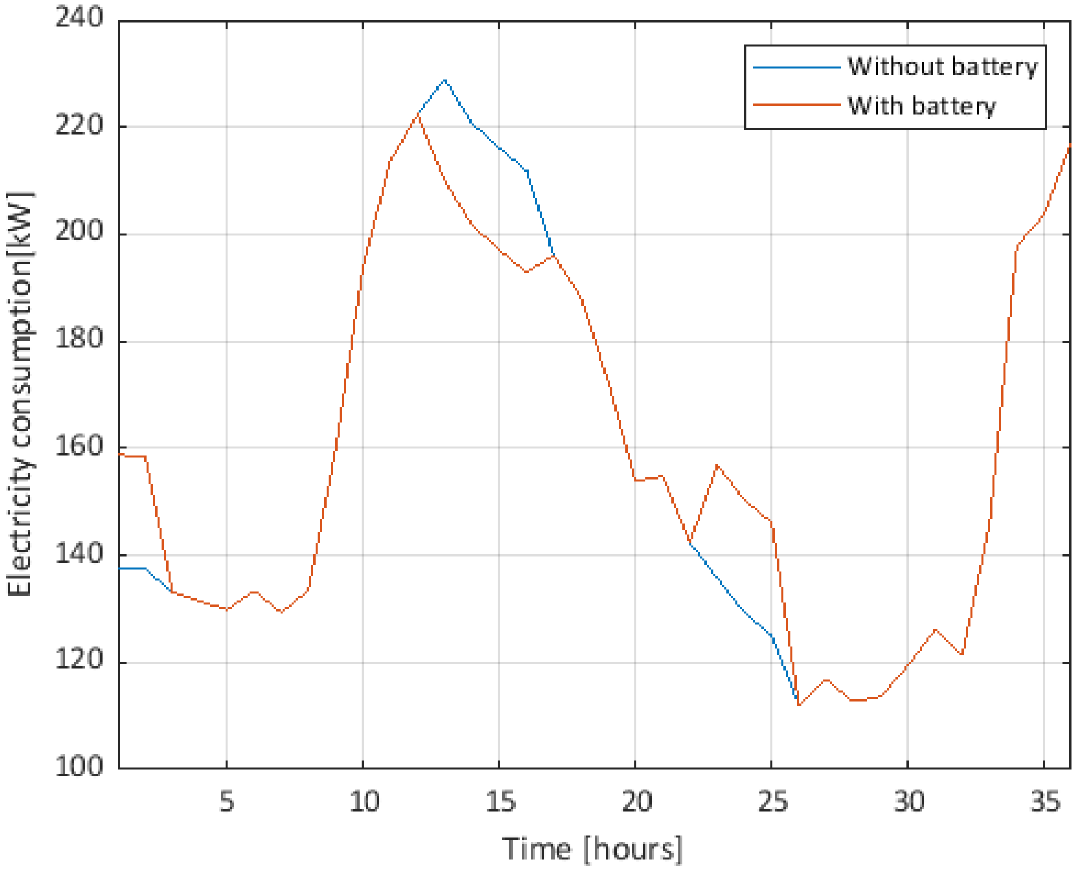

Figure 21 Electricity Consumption with and without Battery Storage on the 7th of March 2017.

A full year simulation was also done for the optimisation based on power consumption with 20 kW maximum power and the electricity consumption and calculated costs are presented in Table 10. With a lower maximum power, the electricity consumption still increases, but the increase is lower compared to when the maximum power was 50 kW. The same is the case for the cost.

Table 10 Comparison of Costs with and without Battery for Energy Consumption Optimisation with 20 kW Battery.

	Electricity Consumption (kWh)	**Cost (NOK)**
Without battery	1 206 700	329 840
With battery	1 210 900	330 390
Difference	4200	550

5 Discussion

5.1 Simulation of Optimal Size of Battery and Photovoltaic System in HOMER

The building “Skipet” is designed to install 430 m^2 of PV, 54 kWp power installed, corresponding to a production of almost 40 000 kWh/year of electricity and a battery with a capacity of 150 kWh. The installation of second-life batteries from electric vehicles is mostly a decision to test new technology in an environmentally friendly building and is not from an economic point of view [56].

The simulations in HOMER based on the energy consumption in the building “Bergen Stasjon Østsiden” showed that a larger photovoltaic installation was considered a more profitable solution. Since HOMER calculated the cost over the lifetime of a system, a photovoltaic installation will often be a profitable solution as the investment is paid back with the production of electricity. Since the payback time for photovoltaic installations in Norway is more than 12 years [61] but less than the lifetime of the photovoltaic installation, it will become profitable over time. Therefore, the calculations in HOMER suggest a large photovoltaic installation since the installation cost will evidently be paid back. For inverters, the lifetime is shorter than the lifetime of the PV panels and they will have to be changed at least once, hence double in cost over the lifetime.

The size of photovoltaic installations is usually limited by the available roof area on the considered building, unless it is also installed on the facades. Nevertheless, the simulation shows that for the given input variables, a large photovoltaic installation will be a cost-effective solution over time and the installation on “Skipet” could be more than doubled in size based on both scenarios simulated. A limitation to the simulation is the solar data, and a more accurate simulation of electricity generation from the photovoltaic installation can be achieved by using actual solar data from the exact location.

Simulations in HOMER showed that the battery storage was not the most profitable solution but was considered the second-best option with the peak pricing in the second scenario. From the grid operation perspective however, peak shaving is an important demand side management strategy [72]. With future pricing mechanisms to reduce power consumption from the grid, battery energy storage systems might be a more economically feasible solution.

The building “Skipet” is planning to install a battery storage system with a capacity of 150 kWh. In the literature it was found in several papers [65, 73, 75, 80] that the correct size was important for whether or not a system is profitable. The simulations in HOMER did not suggest a system with battery as the option with lowest net present cost, but the simulations will depend on the prices for each component and will change depending on the variables included in the simulation like the real discount rate, inflation rate and lifetime of the components. The Norwegian Water Resources and Energy Directorate defined a project with a levelised cost of energy of 1.13 NOK/kWh as low and 1.55 NOK/kWh to be a project with medium investment cost [59]. Both scenarios simulated are below the definition of medium investment cost. As the prices of batteries have been significantly reduced during the last years and further reductions are expected [8], it will also affect the profitability of battery storage systems in the future.

5.2 Power Consumption in Commercial Buildings

The power consumption in the commercial building studied, follows the expected curve for commercial buildings as presented in Section 2.7 where the power demand of different buildings was presented. The user behaviour plays an important role in planning an operation scheme for a commercial building. The electric power consumption for a working day in the building varies between 165 kW to 240 kW between summer and winter. For commercial buildings, these peaks are occurring during the working hours between 7 am and 5 pm. This range in power suggests that it would be beneficial with a control system which is able to adjust based on predictions in power demand data.

By operating the battery storage system in terms of peak shaving, the goal is to reduce the peaks in power use. Load shifting operation differs from peak shaving in that the battery will charge from the grid when prices are low, typically when there is a lower load on the grid, and discharge when prices are higher.

For commercial buildings with battery storage systems that also have photovoltaic installations this should also be included in the operation and control of the battery storage. During the winter months when there is less solar insolation it might be a better idea to use the battery for load shifting in terms of saving costs. The limits of the system and when it should charge and discharge, will depend on the time of year as well as whether it is a weekday or weekend.

5.3 MATLAB Optimisation

The operation of a battery storage system will also affect the cost, and an effective operation scheme should also be considered in addition to correct sizing of a storage system. The optimisation in MATLAB only accounts for the operational costs of a battery storage system which is illustrated with the historical electricity spot prices available from Nord Pool. Optimisation in terms of day-ahead electricity spot prices does only illustrate the effect of fluctuations in the prices per kWh used and does not show the total cost of the electricity consumption or the cost of a battery storage system in total.

The results show how the control of the battery by setting the maximum power of the battery to 20 kW will reduce the electricity bill in terms of paying for the number of kWh used. However, the simulation also showed that if prices are low during peak demand hours it can create additional peaks in power consumption and hence potentially increase the electricity bill for commercial buildings, which mainly pay according to the power consumption and not the energy consumption.

Variations in electricity spot prices will influence the effect of a battery storage system which is optimised based on day-ahead electricity spot prices. With large fluctuations, higher earnings can be expected compared to flat prices or small fluctuations which would make a battery storage system an unnecessary investment.

For the optimisation based on the electricity consumption in the building, the results show that the battery storage system can reduce the peaks in power consumption, although the costs in terms of energy used are not reduced. For commercial buildings which pay for electricity based on the maximum peak of power used each month, it can create an additional reduction in costs.

The integer linear optimisation routine used in this thesis does not illustrate a dynamic system. The integer variable limits the battery to either stay idle, fully charge or fully discharge. With the optimisation in terms of day-ahead spot prices, this creates larger peaks in the power consumption than earlier. With a linear programming routine, the decision variable is a continuous variable between -1 and 1 which allows the battery to charge and discharge with less than full power, creating a more dynamic system.

In the study by Fares and Webber [74] the operation of the battery storage system which planned the operation based on predictions in power consumption and electricity generation from the photovoltaic installation reduced the grid demand the most. Hence, an operation scheme for a battery storage system for a commercial building with a photovoltaic installation which is based on power consumption data, weather forecasting and day-ahead electricity prices have the potential to reduce costs the most.

6 Conclusion

The simulations in HOMER to find the optimal size of a photovoltaic installation and battery storage system for a commercial building showed that a large photovoltaic installation without a battery storage system was the most profitable solution. The simulations calculated the net present cost of the systems, which is dependent on economic parameters like inflation rate and nominal discount rate as well as other input variables like solar insolation data, prices for photovoltaics, inverters and batteries, electricity fees and electricity coinsumption which all influence the result. With an optimised operation, higher electricity fees and reduced costs, batteries can be profitable in the future.

The power use in the commercial building was found to have an increase in the load between 7 am and 4 pm with a peak around 12 pm During weekends, the load does not have a distinctive peak in power consumption. During office hours in commercial buildings there is a potential to reduce peaks in power consumption.

The first optimisation showed that in terms of spot prices, the peak in power consumption could potentially increase when the battery was optimised in terms of electricity spot prices, which in turn can increase the total costs of electricity since commercial buildings pay for power peaks.

The second optimisation based on the power consumption as input data, showed that the battery was able to reduce peaks in power consumption. However, the battery storage system should always be sized according to the operation it should follow, whether that is reducing peaks or reducing costs based on day-ahead stock market prices.

The limits of integer linear programming were investigated, and it was found that the integer variable creates a non-dynamic system. A lower maximum power from the battery which gave a more optimal power-to-capacity ratio, allowed for a more dynamic system but other optimization routines like linear programming can be a better option.

When designing a battery storage system, it is important to know what the goal and limitations to such a system is to understand how it affects the outcome. The results show how two different inputs for the optimisation each have the potential to reduce costs, although they also can increase them. The goal of installing a battery storage system should therefore be carefully evaluated so that it can be optimised with regard to the most profitable parameters.

7 Recommendations for Further Work

A well-designed battery system with effective and well-planned operation have the potential to save electricity cost. Therefore, creating a system that can adjust and consider several parameters like power consumption data, solar insolation/weather forecast and changes in electricity prices is an interesting task. Based on the scientific papers presented in this thesis, it is possible to optimise for either peak shaving, to increase self-consumption of generated electricity from PV or reduce costs based on spot-prices, but not all simultaneously. The effects of the two optimisations done in this thesis showed that such parameters can have opposite effects and making them work together by taking into account the spot prices while not creating new peaks in power demand and finding the optimal combination is as far as the author is concerned currently not solved and require further research.

The ratio between optimal sizing and optimal operation should also be investigated, to find which has the most effect on a storage system. The operation of a battery storage system which includes a photovoltaic installation should also be done to see the effect of such an installation.

Machine learning algorithms like Artificial Neural Networks would be applicable and could forecast the operation of a storage system based on such parameters. This would require available historical data of all the parameters in order to train, test and validate the algorithms.

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Appendices

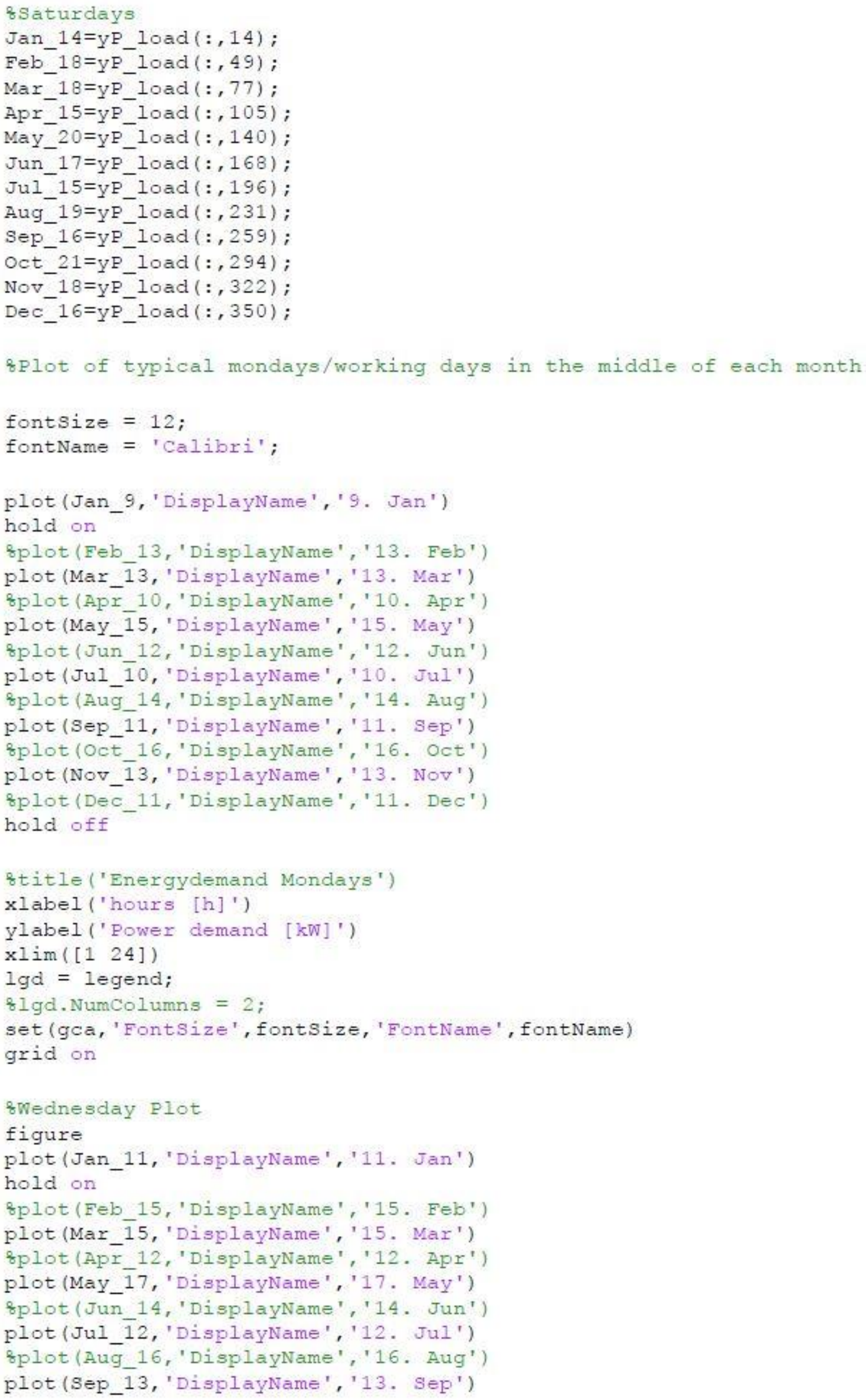
MATLAB Code

Spotprices

```
%Spot price plots

close;
clear;
clc;

data=xlsread('Priser_matlab.xlsx');
[~, headers] = xlsread('Priser_matlab.xlsx','A1:D1');
tbl=array2table(data,'variableNames',headers);

% Arrays
Time_h=(1:1:8760)';
t=1:8760;
El_2015=data(:,1);
El_2016=data(:,2);
El_2017=data(:,3);
El_2018=data(:,4);

plot(El_2015)
hold on
plot(El_2016)
plot(El_2017)
plot(El_2018)
set(gca,'xtick',linspace(t(1),t(end),12))
month =
{'Jan','Feb','Mar','Apr','May','Jun','Jul','Aug','Sep','Oct','Nov','Dec'};
xticklabels(month)
%title('\fontsize{16} Nord Pool electricity spotprices')
%xlabel('hours [h]')
ylabel('Prices [NOK/kWh]')
legend('2015','2016','2017','2018','Location','north')
grid on

% Splitting data into sub-arrays - 24 values in 365 rows
p2015= reshape(El_2015,[24,365]);
p2016= reshape(El_2016,[24,365]);
p2017= reshape(El_2017,[24,365]);
p2018= reshape(El_2018,[24,365]);

save price p2015 p2016 p2017 p2018

load price
```

Electricity demand

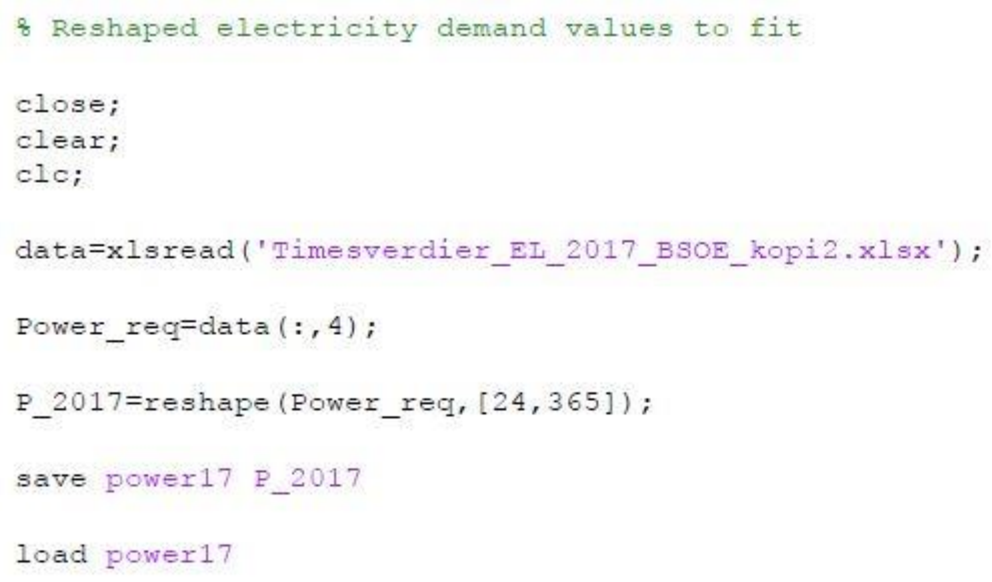
```
%% Electricity demand plots
close;
clear;
clc;

data=xlsread('Timesverdier_EL_2017_BSOE_kopi2.xlsx');
[~, headers] = xlsread('Timesverdier_EL_2017_BSOE_kopi2.xlsx','A1:J1');
tbl=array2table(data,'variableNames',headers);

% Data for a year - 8769 values in a row
xTime_h=(1:1:8760)';
xPV_production=data(:,6);
xP_load=data(:,4);
xPeak_only=data(:,8); %Peak load, minus 200 kWh as a limit
xEl_B=data(:,10);

save pload xP_load
load pload

% Splitting data into sub-arrays - 24 values in 365 rows

yTime_h = reshape(xTime_h,[24,365]);
yPV_production = reshape(xPV_production,[24,365]);
yP_load = reshape(xP_load,[24,365]);
yPeak_only = reshape(xPeak_only,[24,365]);
yEl_B = reshape(xEl_B,[24,365]);

% Day number: https://www.epochconverter.com/days/2017
%Mondays
Jan_9=yP_load(:,9);
Feb_13=yP_load(:,44);
Mar_13=yP_load(:,72);
Apr_10=yP_load(:,100);
May_15=yP_load(:,135);
Jun_12=yP_load(:,163);
Jul_10=yP_load(:,191);
Aug_14=yP_load(:,226);
Sep_11=yP_load(:,254);
Oct_16=yP_load(:,289);
Nov_13=yP_load(:,317);
Dec_11=yP_load(:,345);

%Wednesdays
Jan_11=yP_load(:,11);
Feb_15=yP_load(:,46);
Mar_15=yP_load(:,74);
Apr_12=yP_load(:,102);
May_17=yP_load(:,137);
Jun_14=yP_load(:,165);
Jul_12=yP_load(:,193);
Aug_16=yP_load(:,228);
Sep_13=yP_load(:,256);
Oct_18=yP_load(:,291);
Nov_15=yP_load(:,319);
Dec_13=yP_load(:,347);
```



```
%Saturdays
Jan_14=yP_load(:,14);
Feb_18=yP_load(:,49);
Mar_18=yP_load(:,77);
Apr_15=yP_load(:,105);
May_20=yP_load(:,140);
Jun_17=yP_load(:,168);
Jul_15=yP_load(:,196);
Aug_19=yP_load(:,231);
Sep_16=yP_load(:,259);
Oct_21=yP_load(:,294);
Nov_18=yP_load(:,322);
Dec_16=yP_load(:,350);

%Plot of typical mondays/working days in the middle of each month

fontSize = 12;
fontName = 'Calibri';

plot(Jan_9,'DisplayName','9. Jan')
hold on
%plot(Feb_13,'DisplayName','13. Feb')
plot(Mar_13,'DisplayName','13. Mar')
%plot(Apr_10,'DisplayName','10. Apr')
plot(May_15,'DisplayName','15. May')
%plot(Jun_12,'DisplayName','12. Jun')
plot(Jul_10,'DisplayName','10. Jul')
%plot(Aug_14,'DisplayName','14. Aug')
plot(Sep_11,'DisplayName','11. Sep')
%plot(Oct_16,'DisplayName','16. Oct')
plot(Nov_13,'DisplayName','13. Nov')
%plot(Dec_11,'DisplayName','11. Dec')
hold off

%title('Energydemand Mondays')
xlabel('hours [h]')
ylabel('Power demand [kW]')
xlim([1 24])
lgd = legend;
%lgd.NumColumns = 2;
set(gca,'FontSize',fontSize,'FontName',fontName)
grid on

%Wednesday Plot
figure
plot(Jan_11,'DisplayName','11. Jan')
hold on
%plot(Feb_15,'DisplayName','15. Feb')
plot(Mar_15,'DisplayName','15. Mar')
%plot(Apr_12,'DisplayName','12. Apr')
plot(May_17,'DisplayName','17. May')
%plot(Jun_14,'DisplayName','14. Jun')
plot(Jul_12,'DisplayName','12. Jul')
%plot(Aug_16,'DisplayName','16. Aug')
plot(Sep_13,'DisplayName','13. Sep')
```

```
%plot(Oct_18,'DisplayName','17. Oct')
plot(Nov_15,'DisplayName','15. Nov')
%plot(Dec_13,'DisplayName','13. Dec')
hold off

%title('Energydemand Wednesdays')
xlabel('hours [h]')
ylabel('Power demand [kW]')
xlim([1 24])
lgd = legend;
%lgd.NumColumns = 2;
set(gca,'FontSize',fontSize,'FontName',fontName)
grid on

%Saturday plot
figure
plot(Jan_14,'DisplayName','14. Jan')
hold on
%plot(Feb_18,'DisplayName','18. Feb')
plot(Mar_18,'DisplayName','18. Mar')
%plot(Apr_15,'DisplayName','15. Apr')
plot(May_20,'DisplayName','20. May')
%plot(Jun_17,'DisplayName','17. Jun')
plot(Jul_15,'DisplayName','15. Jul')
%plot(Aug_19,'DisplayName','19. Aug')
plot(Sep_16,'DisplayName','16. Sep')
%plot(Oct_21,'DisplayName','21. Oct')
plot(Nov_18,'DisplayName','18. Nov')
%plot(Dec_16,'DisplayName','16. Dec')
hold off

%title('Energydemand Saturdays')
xlabel('hours [h]')
ylabel('Power demand [kW]')
xlim([1 24])
lgd = legend;
%lgd.NumColumns = 2;
set(gca,'FontSize',fontSize,'FontName',fontName)
grid on
```

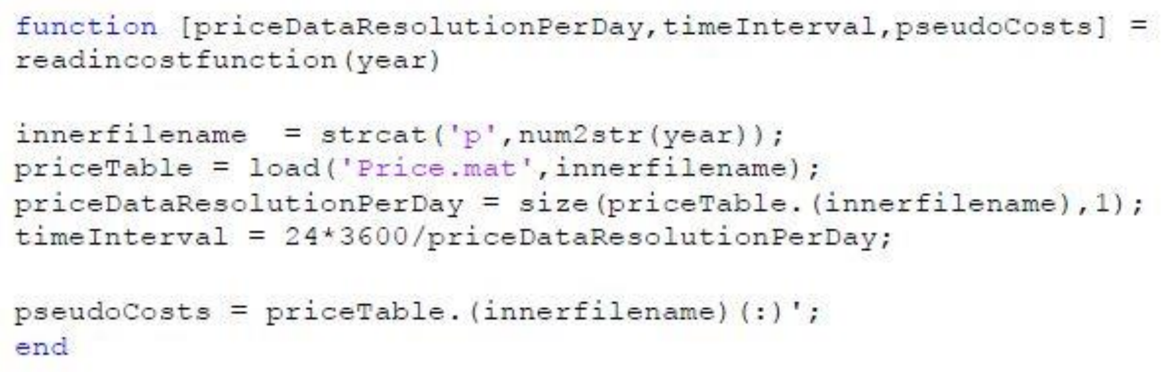
Reshaped El-demand



```
% Reshaped electricity demand values to fit

close;
clear;
clc;

data=xlsread('Timesverdier_EL_2017_BSOE_kopi2.xlsx');

Power_req=data(:,4);

P_2017=reshape(Power_req,[24,365]);

save power17 P_2017

load power17
```

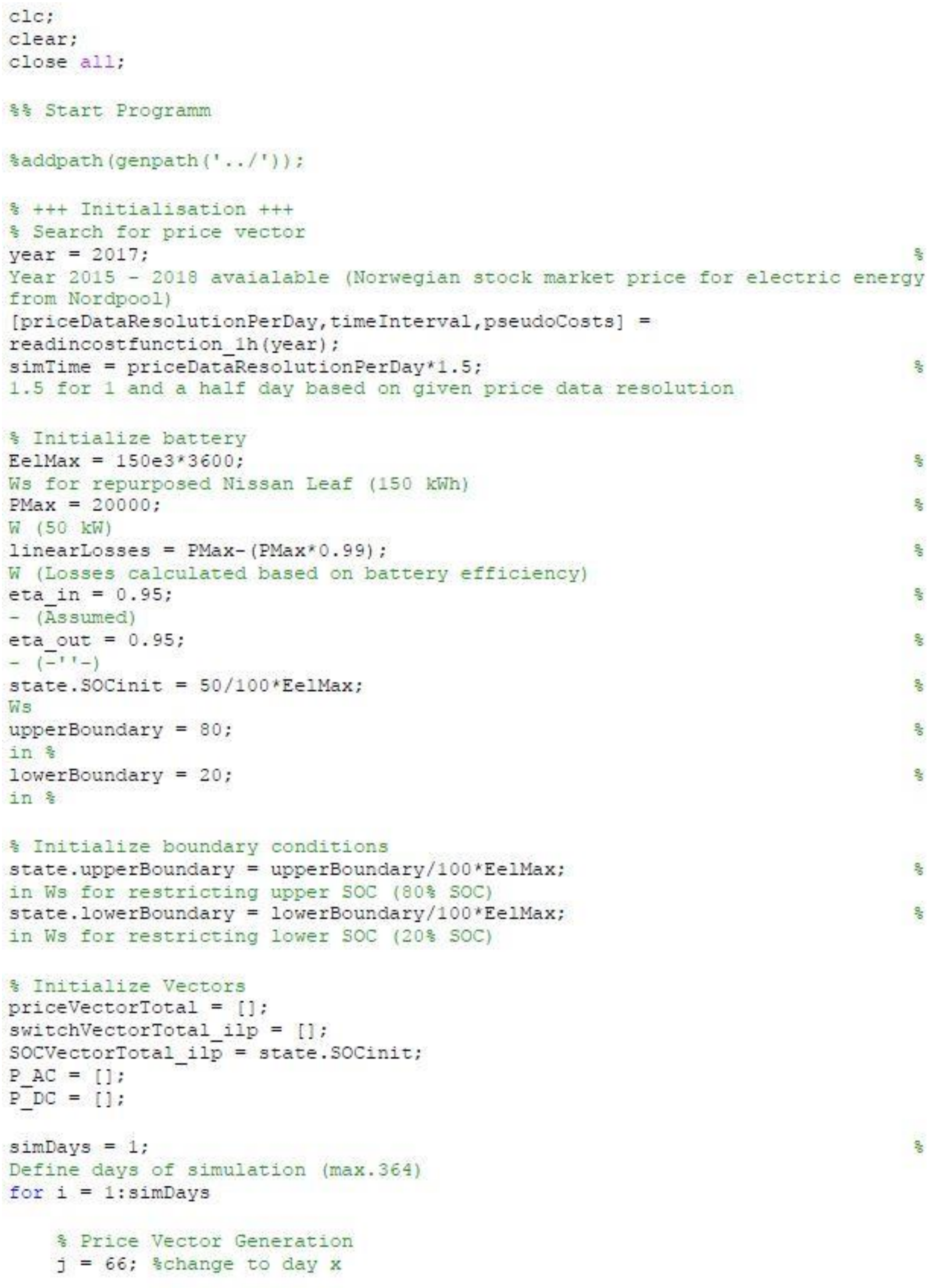
Cost function

The optimisation is similar for the day-ahead spot price and power demand, hence only the day-ahead spot price optimisation is shown here.

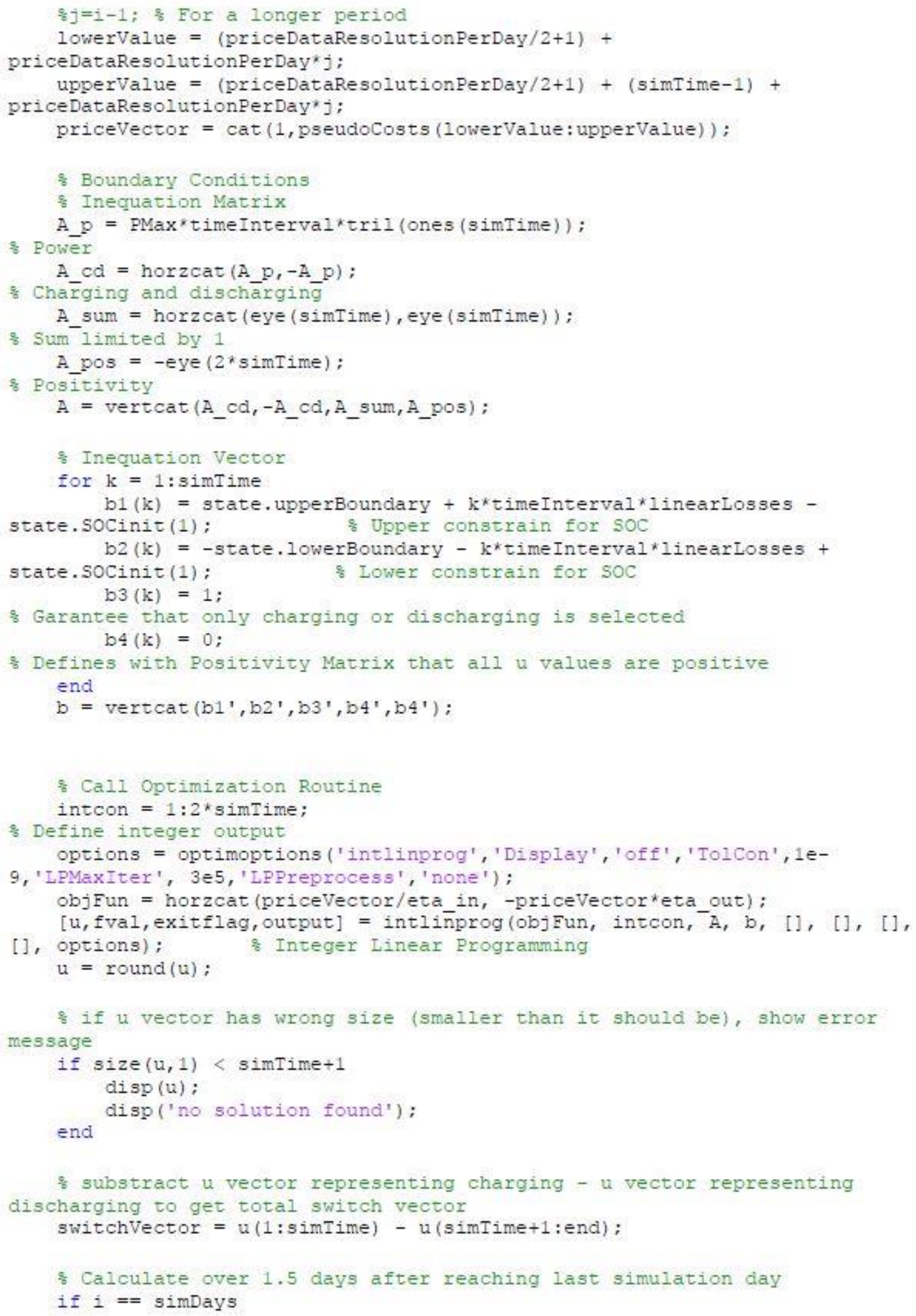


```
function [priceDataResolutionPerDay,timeInterval,pseudoCosts] =
readincostfunction(year)

innerfilename  = strcat('p',num2str(year));
priceTable = load('Price.mat',innerfilename);
priceDataResolutionPerDay = size(priceTable.(innerfilename),1);
timeInterval = 24*3600/priceDataResolutionPerDay;

pseudoCosts = priceTable.(innerfilename)(:)';
end
```

Cost optimisation



```
clc;
clear;
close all;

%% Start Programm

%addpath(genpath('../'));

% +++ Initialisation +++
% Search for price vector
year = 2017;                                                         %
Year 2015 - 2018 avaialable (Norwegian stock market price for electric energy
from Nordpool)
[priceDataResolutionPerDay,timeInterval,pseudoCosts] =
readincostfunction_1h(year);
simTime = priceDataResolutionPerDay*1.5;                             %
1.5 for 1 and a half day based on given price data resolution

% Initialize battery
EelMax = 150e3*3600;                                                 %
Ws for repurposed Nissan Leaf (150 kWh)
PMax = 20000;                                                        %
W (50 kW)
linearLosses = PMax-(PMax*0.99);                                     %
W (Losses calculated based on battery efficiency)
eta_in = 0.95;                                                       %
- (Assumed)
eta_out = 0.95;                                                      %
- (-''-)
state.SOCinit = 50/100*EelMax;                                       %
Ws
upperBoundary = 80;                                                  %
in %
lowerBoundary = 20;                                                  %
in %

% Initialize boundary conditions
state.upperBoundary = upperBoundary/100*EelMax;                      %
in Ws for restricting upper SOC (80% SOC)
state.lowerBoundary = lowerBoundary/100*EelMax;                      %
in Ws for restricting lower SOC (20% SOC)

% Initialize Vectors
priceVectorTotal = [];
switchVectorTotal_ilp = [];
SOCVectorTotal_ilp = state.SOCinit;
P_AC = [];
P_DC = [];

simDays = 1;                                                         %
Define days of simulation (max.364)
for i = 1:simDays

    % Price Vector Generation
    j = 66; %change to day x
```



```
    %j=i-1; % For a longer period
    lowerValue = (priceDataResolutionPerDay/2+1) +
priceDataResolutionPerDay*j;
    upperValue = (priceDataResolutionPerDay/2+1) + (simTime-1) +
priceDataResolutionPerDay*j;
    priceVector = cat(1,pseudoCosts(lowerValue:upperValue));

    % Boundary Conditions
    % Inequation Matrix
    A_p = PMax*timeInterval*tril(ones(simTime));
% Power
    A_cd = horzcat(A_p,-A_p);
% Charging and discharging
    A_sum = horzcat(eye(simTime),eye(simTime));
% Sum limited by 1
    A_pos = -eye(2*simTime);
% Positivity
    A = vertcat(A_cd,-A_cd,A_sum,A_pos);

    % Inequation Vector
    for k = 1:simTime
        b1(k) = state.upperBoundary + k*timeInterval*linearLosses -
state.SOCinit(1);            % Upper constrain for SOC
        b2(k) = -state.lowerBoundary - k*timeInterval*linearLosses +
state.SOCinit(1);           % Lower constrain for SOC
        b3(k) = 1;
% Garantee that only charging or discharging is selected
        b4(k) = 0;
% Defines with Positivity Matrix that all u values are positive
    end
    b = vertcat(b1',b2',b3',b4',b4');


    % Call Optimization Routine
    intcon = 1:2*simTime;
% Define integer output
    options = optimoptions('intlinprog','Display','off','TolCon',1e-
9,'LPMaxIter', 3e5,'LPPreprocess','none');
    objFun = horzcat(priceVector/eta_in, -priceVector*eta_out);
    [u,fval,exitflag,output] = intlinprog(objFun, intcon, A, b, [], [], [],
[], options);       % Integer Linear Programming
    u = round(u);

    % if u vector has wrong size (smaller than it should be), show error
message
    if size(u,1) < simTime+1
        disp(u);
        disp('no solution found');
    end

    % substract u vector representing charging - u vector representing
discharging to get total switch vector
    switchVector = u(1:simTime) - u(simTime+1:end);

    % Calculate over 1.5 days after reaching last simulation day
    if i == simDays
```

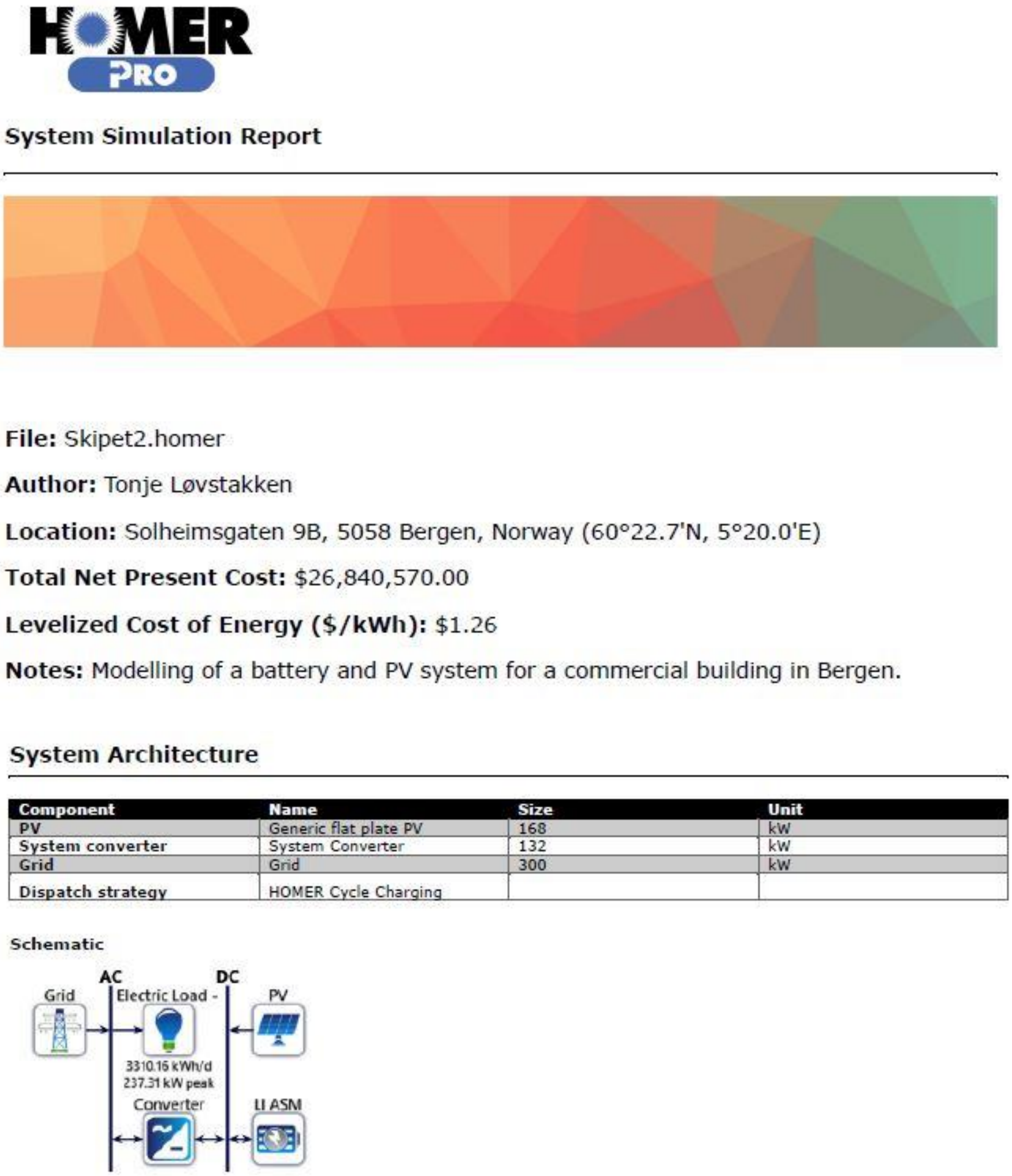
```
        priceDataResolutionPerDay = simTime;
    end


    % Model Backcalculation
    % using the same linear battery model as in the optimization
    for l = 1:priceDataResolutionPerDay
        % SOC
        state.SOCinit(l+1) = state.SOCinit(l) + (PMax*switchVector(l) -
linearLosses)*timeInterval;

        % P_DC
        state.P_DC(l) = PMax*switchVector(l);

        % P_AC
        if switchVector(l) < 0
% Define eta for AC depending on if battery gets charged or discharged
            eta = eta_out;
        else
            eta = 1/eta_in;
        end
        state.P_AC(l) = PMax*switchVector(l)*eta;
    end

    % Add results to output vectors
    priceVectorTotal = [priceVectorTotal,
priceVector(1:priceDataResolutionPerDay)];
    switchVectorTotal_ilp = [switchVectorTotal_ilp,
switchVector(1:priceDataResolutionPerDay)'];
    SOCVectorTotal_ilp = [SOCVectorTotal_ilp, state.SOCinit(2:end)];
    P_AC = [P_AC, state.P_AC];
    P_DC = [P_DC, state.P_DC];

    % Use the last SOC state as the new initial SOC state
    state.SOCinit = state.SOCinit(end);
end

% Devide SOC vectors (in Ws) by the may capacity of the battery time 100 to
get % values
SOCVectorTotal_ilp = SOCVectorTotal_ilp./EelMax.*100;


%% Simulation Analysis

% Earnings
resulting_cost = P_AC*timeInterval/(3600*1e6)*priceVectorTotal(1:end)';

%Ideling
ideling = find(~switchVectorTotal_ilp(1:end));
ideling = size(ideling,2);
% Number of ideling times
idle_states = length(find(switchVectorTotal_ilp ==
0))/length(switchVectorTotal_ilp);              % Percent ideling

% SOC
```

```
average_soc = mean(SOCVectorTotal_ilp(1:end));
std_average_soc = std(SOCVectorTotal_ilp(1:end));
soc_max = max(SOCVectorTotal_ilp(1:end));
soc_min = min(SOCVectorTotal_ilp(1:end));
range_average_soc = soc_max - soc_min;

% System efficiency (inkl. converters)
u_soc_huge = find(abs(SOCVectorTotal_ilp(1:end-1)-SOCVectorTotal_ilp(1)) < 5);
soc_stop = u_soc_huge(end);
u_opt = P_AC(1:soc_stop);
u_ab = find(u_opt < 0);
u_zu = find(u_opt >= 0);
eta = abs(sum(u_opt(u_ab)))/sum(u_opt(u_zu));


% +++ Display results +++
% Display performance results
disp(['Battery performance values']);
disp([resulting_cost, ideling, average_soc, std_average_soc, soc_max, soc_min,
range_average_soc, idle_states, eta]);
% Display max, min, and average SOC
disp(['Max, min, and average SOC']);
disp([max(SOCVectorTotal_ilp(1:end)), min(SOCVectorTotal_ilp(1:end)),
max(SOCVectorTotal_ilp(1:end))-min(SOCVectorTotal_ilp(1:end))]);

%% Electricity price - spotprice on the day of simulation
priceVector_kr=priceVector./100;

%% Power calculations
data=xlsread('Timesverdier_EL_2017_BSOE_kopi2.xlsx');                      %
load power demand
Power_req=data(:,4);                                                        %
extract right column
power=Power_req(1584:1619);                                                 %
Power demand witout battery day 66
P_w_bat=(power'+(P_AC./1000));                                              %
Power demand -  with battery

%% Plot
fontSize = 11;
fontName = 'Calibri';

% Subplot
figure
subplot(2,1,1);
plot(power')
hold on;
plot(P_w_bat)
%plot(P_AC./1000)
set(gca,'FontSize',fontSize,'FontName',fontName)
xlim([1 36])
xlabel('Time [hours]')
ylabel('Electricity consumption[kW]')
legend('Without battery','With battery')
grid on
```

```
% Cost function plot
subplot(2,1,2);
plot(priceVector_kr,'Color',[0.4660, 0.6740, 0.1880])
set(gca,'FontSize',fontSize,'FontName',fontName)
xlim([1 36])
%ylim([0.2 0.4])
%title('Pseudo cost function')
xlabel('Time [hours]')
ylabel('[NOK/kWh]')
grid on
```

HOMER reports

The following are exstractions from a PDF report created in HOMER for each of the possible solutions presented in Chapter 4. This is an example of one of the 6 reports.



System Simulation Report

File: Skipet2.homer

Author: Tonje Løvstakken

Location: Solheimsgaten 9B, 5058 Bergen, Norway (60°22.7'N, 5°20.0'E)

Total Net Present Cost: $26,840,570.00

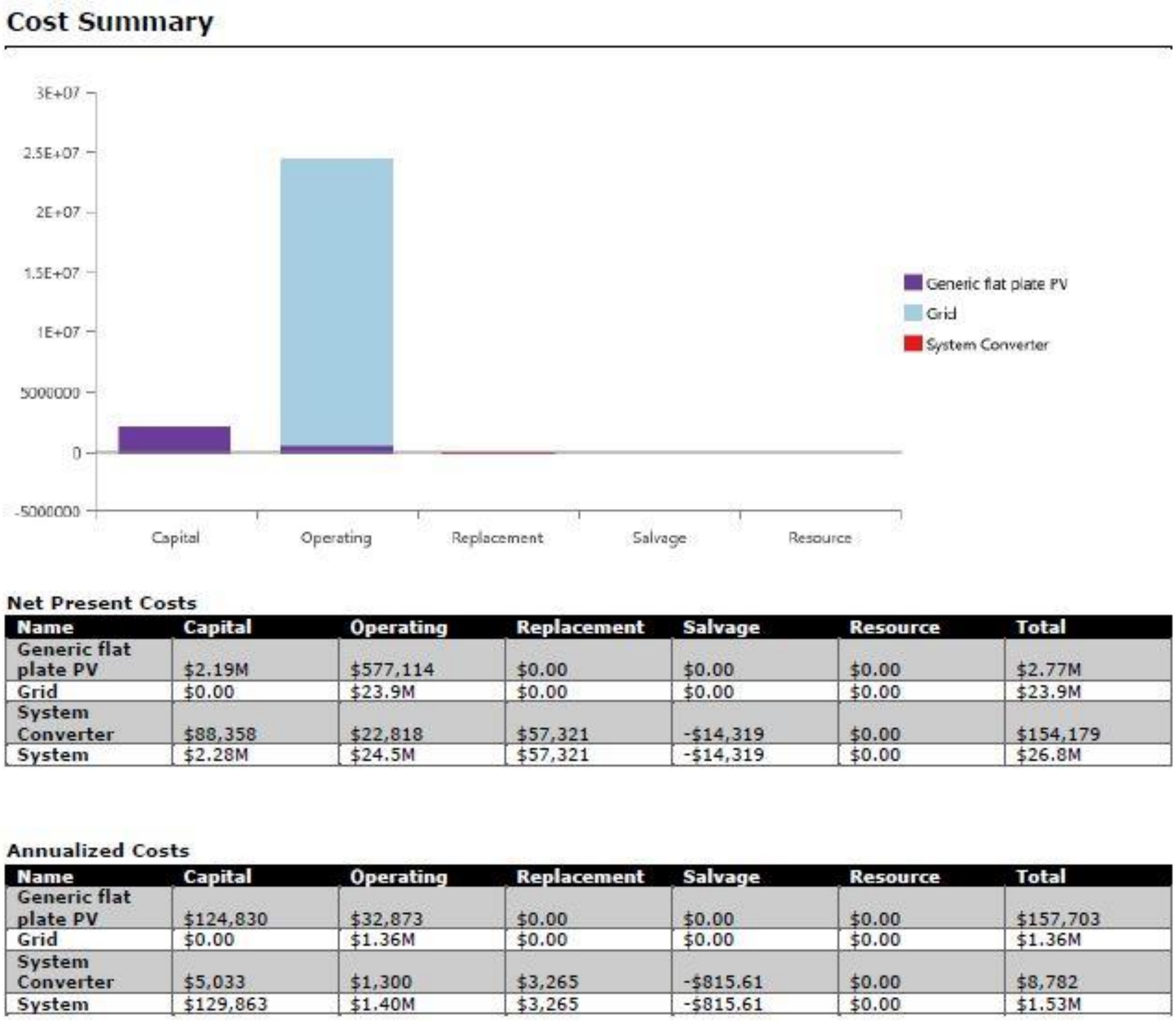
Levelized Cost of Energy ($/kWh): $1.26

Notes: Modelling of a battery and PV system for a commercial building in Bergen.

System Architecture

Component	Name	Size	Unit
PV	Generic flat plate PV	168	kW
System converter	System Converter	132	kW
Grid	Grid	300	kW
Dispatch strategy	HOMER Cycle Charging		

Schematic



Cost Summary

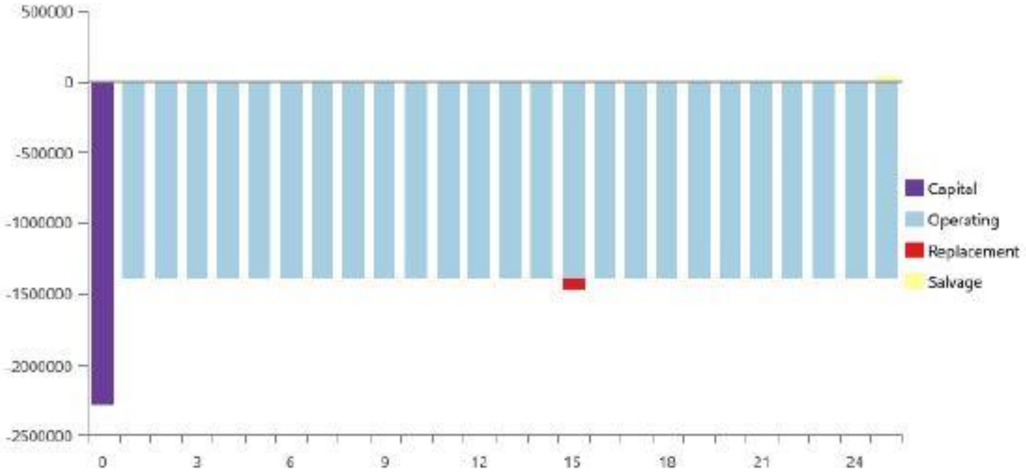
Net Present Costs

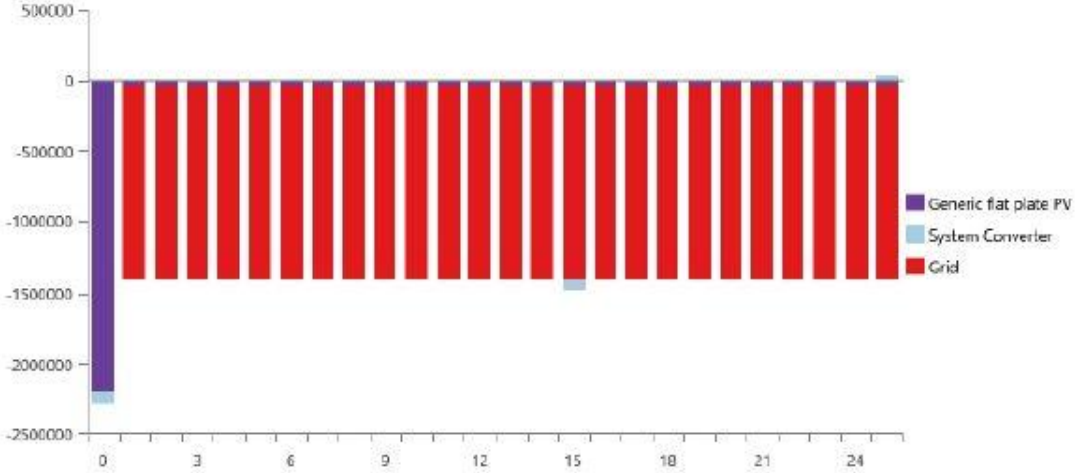
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Generic flat plate PV	$2.19M	$577,114	$0.00	$0.00	$0.00	$2.77M
Grid	$0.00	$23.9M	$0.00	$0.00	$0.00	$23.9M
System Converter	$88,358	$22,818	$57,321	-$14,319	$0.00	$154,179
System	$2.28M	$24.5M	$57,321	-$14,319	$0.00	$26.8M

Annualized Costs

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Generic flat plate PV	$124,830	$32,873	$0.00	$0.00	$0.00	$157,703
Grid	$0.00	$1.36M	$0.00	$0.00	$0.00	$1.36M
System Converter	$5,033	$1,300	$3,265	-$815.61	$0.00	$8,782
System	$129,863	$1.40M	$3,265	-$815.61	$0.00	$1.53M

Cash Flow





Electrical Summary

Excess and Unmet

Quantity	Value	Units
Excess Electricity	440	kWh/yr
Unmet Electric Load	0	kWh/yr
Capacity Shortage	0	kWh/yr

Production Summary

Component	Production (kWh/yr)	Percent
Generic flat plate PV	151,479	12.4
Grid Purchases	1,065,577	87.6
Total	1,217,056	100

Consumption Summary

Component	Consumption (kWh/yr)	Percent
AC Primary Load	1,208,210	99.9
DC Primary Load	0	0
Deferrable Load	0	0
Grid Sales	854	0.0706
Total	1,209,064	100

PV: Generic flat plate PV

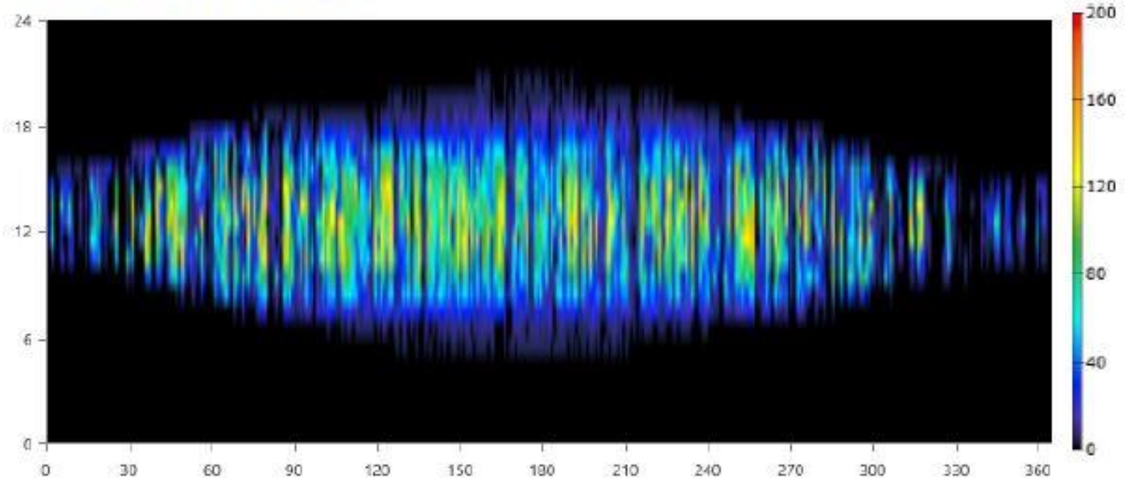
Generic flat plate PV Electrical Summary

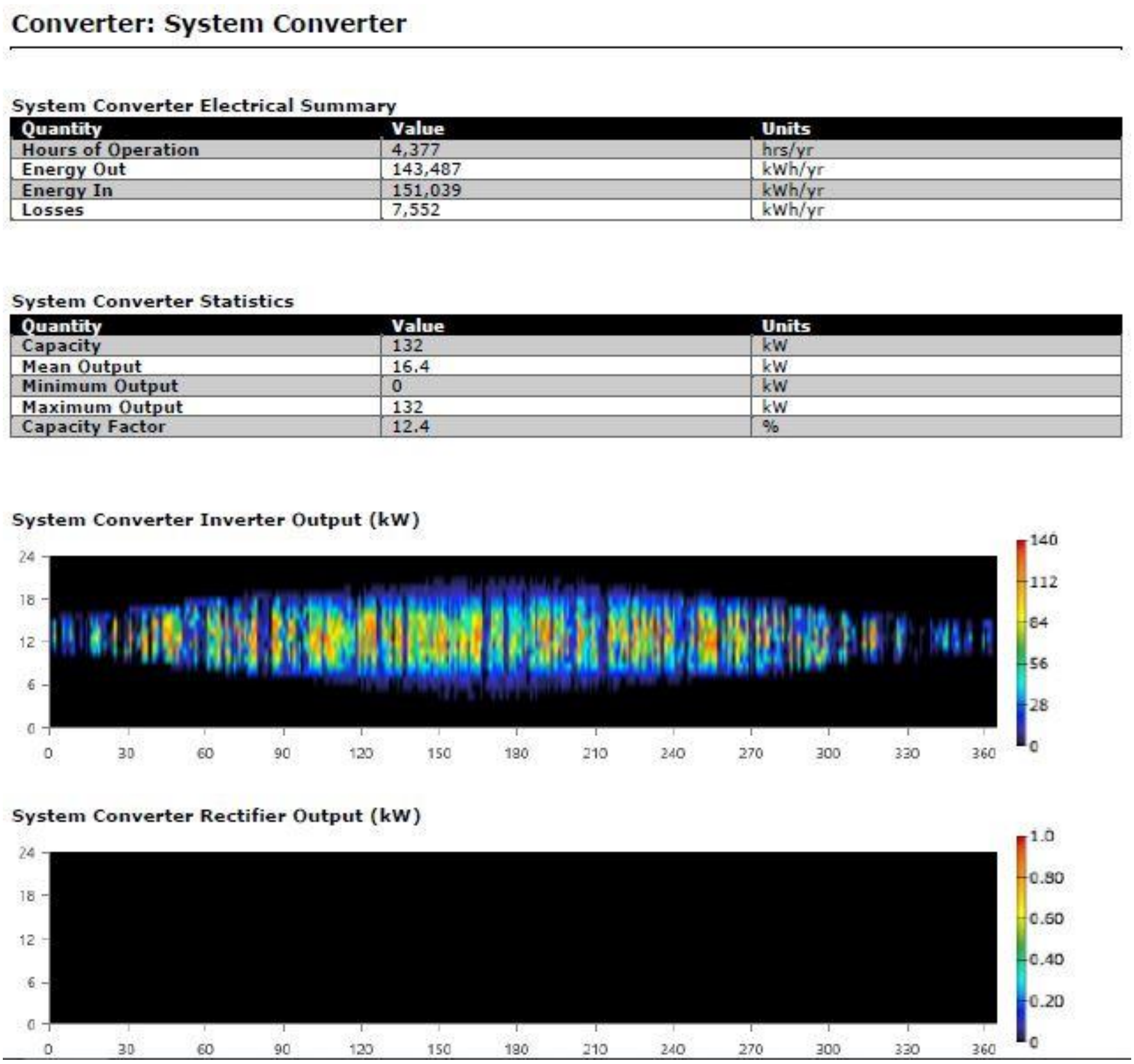
Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	163	kW
PV Penetration	12.5	%
Hours of Operation	4,377	hrs/yr
Levelized Cost	1.04	$/kWh

Generic flat plate PV Statistics

Quantity	Value	Units
Rated Capacity	168	kW
Mean Output	17.3	kW
Mean Output	415	kWh/d
Capacity Factor	10.3	%
Total Production	151,479	kWh/yr

Generic flat plate PV Output (kW)





Converter: System Converter

System Converter Electrical Summary

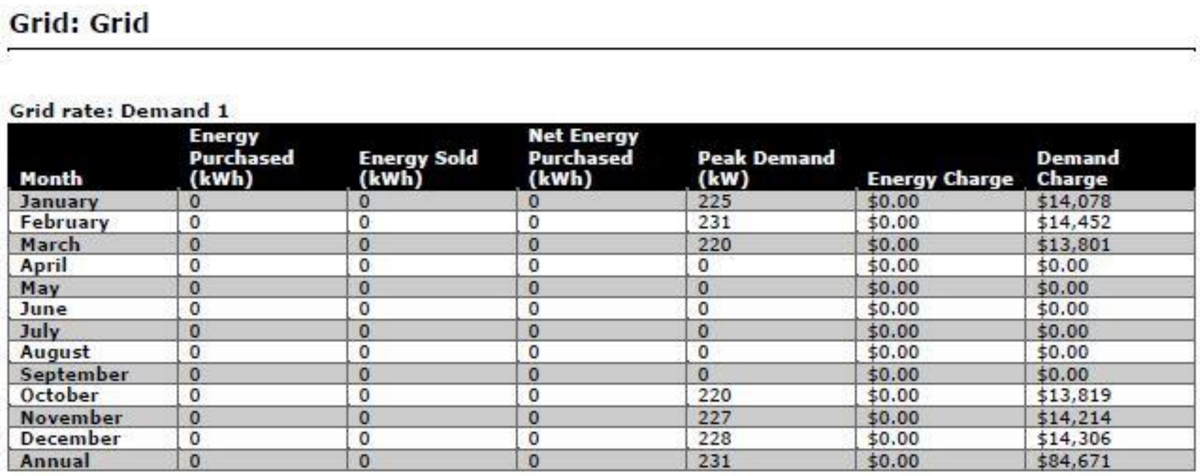
Quantity	Value	Units
Hours of Operation	4,377	hrs/yr
Energy Out	143,487	kWh/yr
Energy In	151,039	kWh/yr
Losses	7,552	kWh/yr

System Converter Statistics

Quantity	Value	Units
Capacity	132	kW
Mean Output	16.4	kW
Minimum Output	0	kW
Maximum Output	132	kW
Capacity Factor	12.4	%

System Converter Inverter Output (kW)

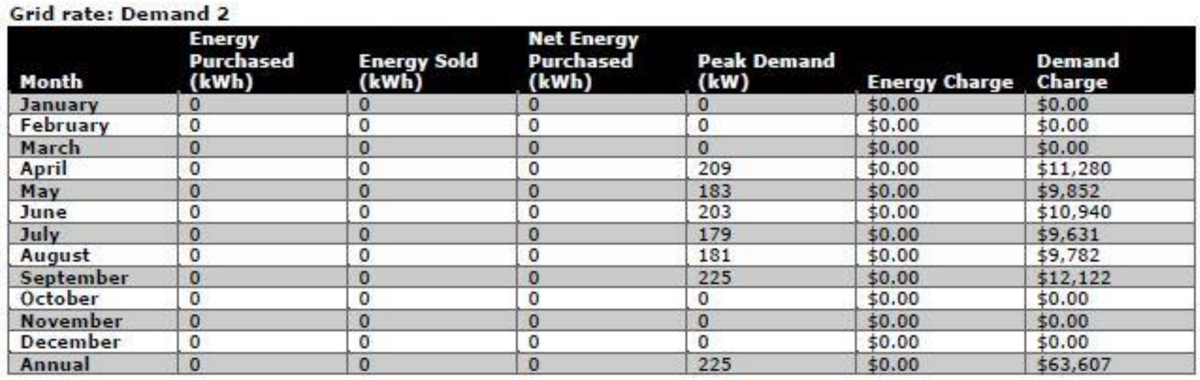
System Converter Rectifier Output (kW)



Grid: Grid

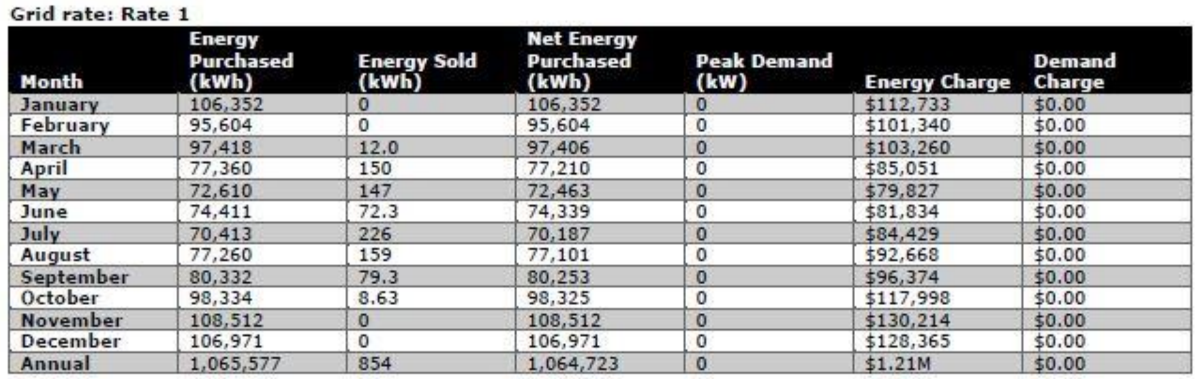
Grid rate: Demand 1

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	0	0	0	225	$0.00	$14,078
February	0	0	0	231	$0.00	$14,452
March	0	0	0	220	$0.00	$13,801
April	0	0	0	0	$0.00	$0.00
May	0	0	0	0	$0.00	$0.00
June	0	0	0	0	$0.00	$0.00
July	0	0	0	0	$0.00	$0.00
August	0	0	0	0	$0.00	$0.00
September	0	0	0	0	$0.00	$0.00
October	0	0	0	220	$0.00	$13,819
November	0	0	0	227	$0.00	$14,214
December	0	0	0	228	$0.00	$14,306
Annual	0	0	0	231	$0.00	$84,671



Grid rate: Demand 2

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	0	0	0	0	$0.00	$0.00
February	0	0	0	0	$0.00	$0.00
March	0	0	0	0	$0.00	$0.00
April	0	0	0	209	$0.00	$11,280
May	0	0	0	183	$0.00	$9,852
June	0	0	0	203	$0.00	$10,940
July	0	0	0	179	$0.00	$9,631
August	0	0	0	181	$0.00	$9,782
September	0	0	0	225	$0.00	$12,122
October	0	0	0	0	$0.00	$0.00
November	0	0	0	0	$0.00	$0.00
December	0	0	0	0	$0.00	$0.00
Annual	0	0	0	225	$0.00	$63,607



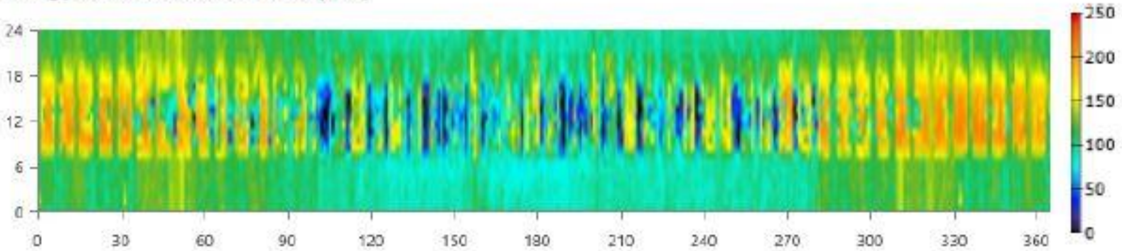
Grid rate: Rate 1

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	106,352	0	106,352	0	$112,733	$0.00
February	95,604	0	95,604	0	$101,340	$0.00
March	97,418	12.0	97,406	0	$103,260	$0.00
April	77,360	150	77,210	0	$85,051	$0.00
May	72,610	147	72,463	0	$79,827	$0.00
June	74,411	72.3	74,339	0	$81,834	$0.00
July	70,413	226	70,187	0	$84,429	$0.00
August	77,260	159	77,101	0	$92,668	$0.00
September	80,332	79.3	80,253	0	$96,374	$0.00
October	98,334	8.63	98,325	0	$117,998	$0.00
November	108,512	0	108,512	0	$130,214	$0.00
December	106,971	0	106,971	0	$128,365	$0.00
Annual	1,065,577	854	1,064,723	0	$1.21M	$0.00

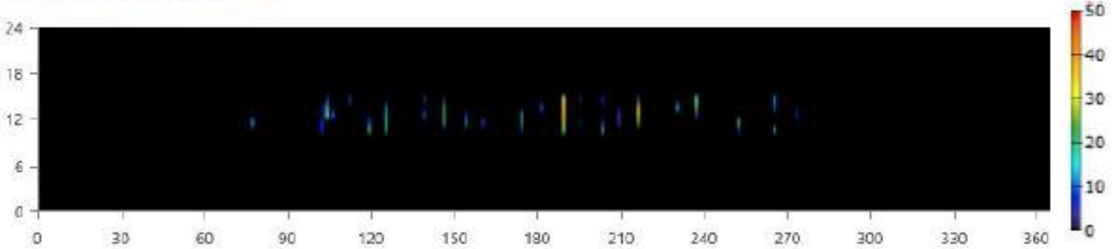
Grid rate: All

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	106,352	0	106,352	225	$112,733	$14,078
February	95,604	0	95,604	231	$101,340	$14,452
March	97,418	12.0	97,406	220	$103,260	$13,801
April	77,360	150	77,210	209	$85,051	$11,280
May	72,610	147	72,463	183	$79,827	$9,852
June	74,411	72.3	74,339	203	$81,834	$10,940
July	70,413	226	70,187	179	$84,429	$9,631
August	77,260	159	77,101	181	$92,668	$9,782
September	80,332	79.3	80,253	225	$96,374	$12,122
October	98,334	8.63	98,325	220	$117,998	$13,819
November	108,512	0	108,512	227	$130,214	$14,214
December	106,971	0	106,971	228	$128,365	$14,306
Annual	1,065,577	854	1,064,723	231	$1.21M	$148,278

Energy Purchased From Grid (kW)



Energy Sold To Grid (kW)



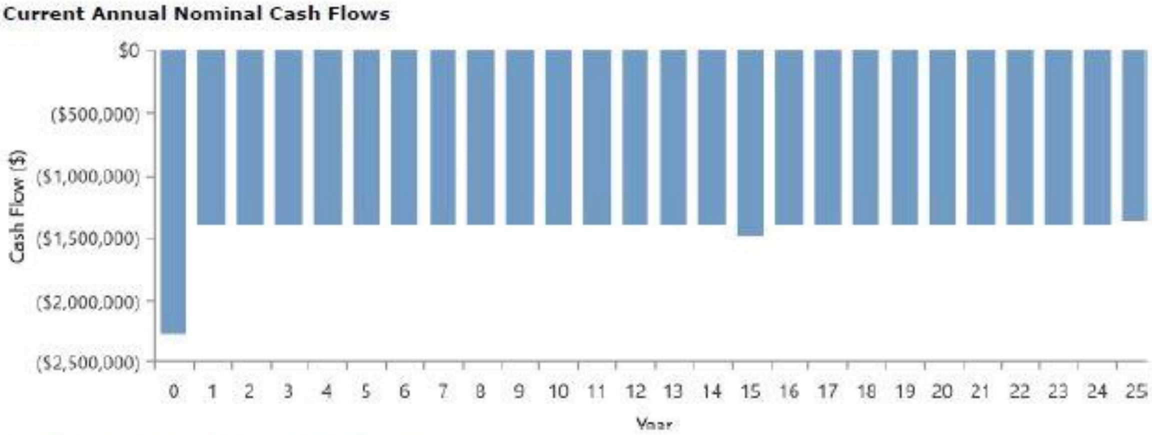
Compare Economics

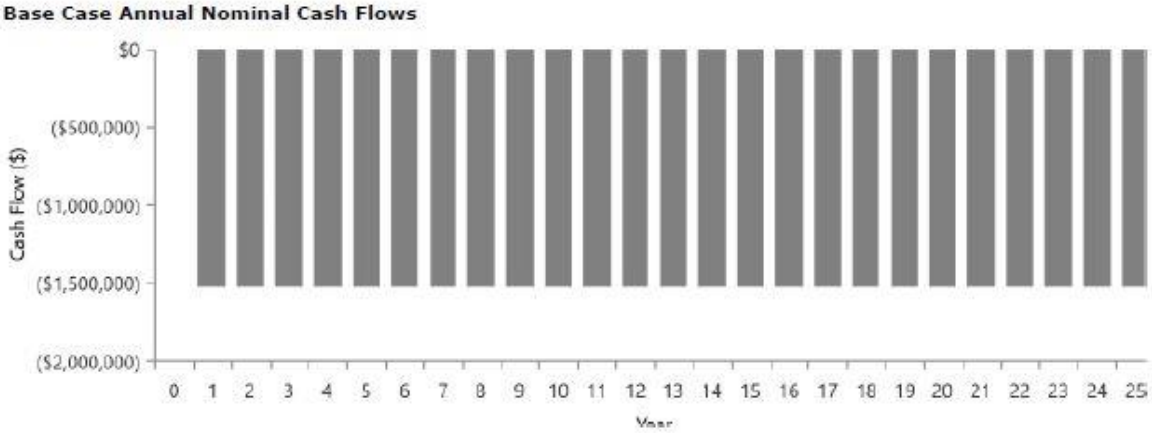
IRR (%):**3.39**

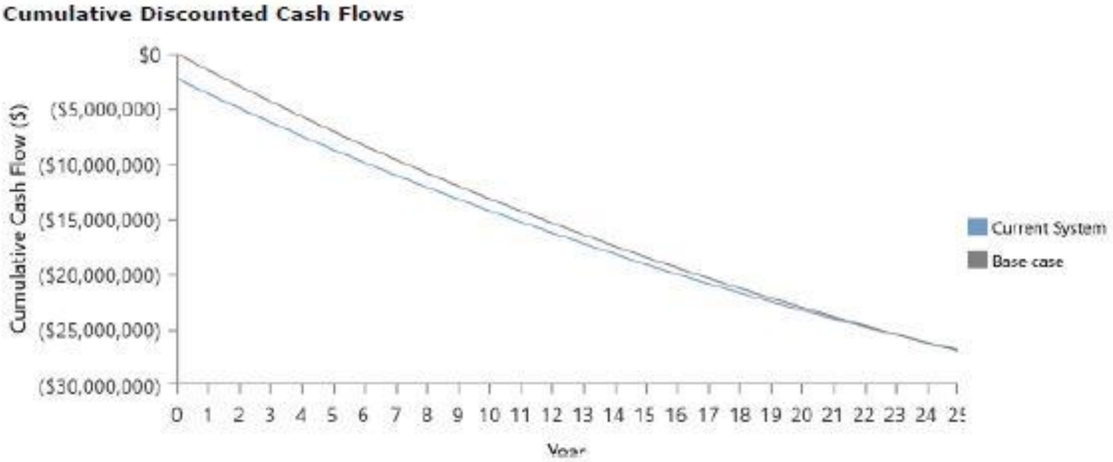
Discounted payback (yr):**23.5**

Simple payback (yr):**17.0**

	Base Case	Current System
Net Present Cost	$27.0M	$26.8M
CAPEX	$0.00	$2.28M
OPEX	$1.54M	$1.40M
LCOE (per kWh)	$1.27	$1.26
CO2 Emitted (kg/yr)	763,589	673,445
Fuel Consumption (L/yr)	0	0


Current Annual Nominal Cash Flows


Base Case Annual Nominal Cash Flows


Cumulative Discounted Cash Flows