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Simulation and Design of Strategies to Control the Energy Flow in a Multi-Function Power Converter

Master of Science Thesis

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Division of Electric Power Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
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Abstract

In this thesis work a simulation model of a PV-system with a connected BESS has been built and three strategies has been designed to control the energy flow between the different power units in order to increase the economical return with a BESS. The power units were the local load, the energy production from the PV-modules, the battery energy storage and the grid. In strategy 1 and strategy 2 the main purpose is to increase the usage of self produced energy. In strategy 2 the charge and discharge of the battery is also controlled to certain hours. In the night, when the energy price is at its lowest, the battery is charged and in the morning, when the energy price is at its highest, the battery is discharged. During the day the battery is charged from the overproduced energy from the PV-modules and in the afternoon, the stored energy in the battery is controlled to be used from the time when the energy price is highest. Strategy 3 was, instead of increasing the self usage of the own produced energy, designed to reduce the highest power peaks over the month.

Under the given circumstances, it could be seen that by using strategy 2 and 3 the economical return compared to strategy 1 were increased. The highest increase was to use strategy 3. However, the strategies did not increase the economical return as much in order for the BESS to be economically beneficial except for the lead acid battery in strategy 3, which had almost the same economical return at different energy sizes of the battery.

Index Terms: PV-system, BESS, Management, Energy flow, Converter, Strategy.

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Stefan Schleeh
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List of symbols

A_{PV}	Area of PV-modules.	[m^2]
B	Variable	[degree]
$Buytime$	Time when energy should be bought to charge the battery with	
C	Capacity	[Ah]
$C_{Bat,full}$	Capacity of a fully charged battery	[Ah]
$\mathrm{C_D}$	With $\mathrm{R_{ct}}$ it represent the transient behaviour of the battery cell	[F]
C_N	Nominal capacity	[Ah]
D	Diffuse irradiation	[kW/m^2]
DB	Direct beam irradiation	[kW/m^2]
DHI	Diffuse horizontal irradiation	[kW/m^2]
DNI	Direct normal irradiation	[kW/m^2]
DOD	Depth-of-discharge	[%]
d	Day number of the year	
E	Energy	[kWh]
$E_{Bat,usable}$	The available energy of a fully charged battery	[kWh]
E_{BH}	Bought energy during the hour	[kWh]
$E_{Bougth,year}$	Annual bought energy from the grid	[kWh]
E_{Load}	Energy consumption in the house	[kWh]
E_{Net}	The net consumption of E_{load} and E_{PV} during a specified time interval	[kWh]
E_N	Nominal energy of the battery	[kWh]
E_{PV}	Energy produced from PV-modules	[kWh]
$E_{Sold,year}$	Annual sold energy to the grid	[kWh]
EOT	Equation of Time	[degree]
G	Irradiation on the modules	[kW/m^2]
GHI	Global horizontal irradiation	[kW/m^2]
HRA	Hour angle	[degree]
L	Cycle life	
$Limit$	Limit to keep $P_{Bought,hourly}$ beneath	[kW]
LST	Local Solar Time	[degree]
$LSTM$	Local Standard Time Meridian	[degree]
LT	Local Time	[degree]
P_{Bought}	Power bought from the grid	[kW]
$P_{Bought,hourly}$	Bought hourly mean power	[kW]
$P_{Compensate}$	The amount of power that has to be discharged from the battery in order to keep $P_{Bought,hourly}$ beneath $Limit$	[kW]
P_{Fuse}	The rated power of the fuse	[kW]
P_{Load}	Power consumption in the house	[kW]
$P_{Max,charge}$	The maximal power that can charge the battery	[kW]
$P_{Max,discharge}$	The maximal power that can discharge the battery	[kW]
$P_{Missing}$	The amount of energy missing in the local load after P_{PV} has provided its power	[kW]
$P_{Overprod}$	Over produced power after the P_{load} has used as much as possible	[kW]

P_{PV}	Estimated power production	[kW]
$P_{PV,peak}$	Installed power of PV-modules	[kW_{Peak}]
P_{Sold}	Power sold to the grid	[kW]
$P_{Sold,hourly}$	Sold hourly mean power	[kW]
R_{ct}	With C_D it represent the transient behaviour of the battery cell	[Ω]
R_{int}	Internal resistances in the battery cell	[Ω]
$R_{self\text{-}discharge}$	Capacity loss when storing a battery during a longer time.	[Ω]
SOC	State-of-charge	[%]
SOC_kWh	State-of-charge	[kWh]
SOC_{Max}	The upper limit in the SOC operation window corrected after $E_{bat,full}$	[%]
SOC_{Min}	The lower limit in the SOC operation window fixed set after E_N	[%]
SOH	State-of-health	[%]
Spotprice	Spotprice for a specific spot area	[SEK/kWh]
TCF	Time correction factor	[degree]
time	A time array	
$t_{PV,start}$	The hour when PV-modules starts to produce energy in the morning	
$t_{PV,stop}$	The hour after when PV-modules stops to produce energy in the evening	
U	Voltage	[V]
U_{batt}	Output voltage of the battery cell.	[V]
U_N	Nominal battery voltage	[V]
U_{OC}	Open circuit voltage of the battery cell	[V]
$UseAM$	Start time when energy should be used from the battery in the morning	
$UsePM$	Start time when energy should be used from the battery in the afternoon	
$Usetime$	Time when energy should be used from the battery	
α	Elevation angle of the sun	[degree]
β	Tilting angle of PV-modules	[degree]
η_{Bat}	Efficiency of battery	[%]
η_{PV}	Efficiency of PV-modules	[%]
ΔT_{GMT}	The difference in hours between the LT and the GMT	[Hours]
δ	Declination angle	[degree]
Γ	Amount for capacity or energy throughput of a battery before EOL	[Ah or kWh]
Γ_A	Actual amount of capacity or energy throughput of a battery	[Ah or kWh]
$\Gamma_{A,year}$	The annual capacity or energy throughput of a battery	[Ah or kWh]
Ψ	Azimuth angle of PV-modules	[degree]
θ_s	The angle between the DB and the normal of the surface	[degree]

Abbreviations

AC	Alternating current
Anode	Negative electrode
BESS	Battery Energy Storage System
Cathode	Positive electrode
CET	Current Equalizing Technology
DC	Direct current
EOL	End-of-life
GMT	Greenwich Mean Time
Li-ion	Lithium ion
NaS	Sodium sulphur
NiCD	Nickel cadmium
NiMH	Nickel metal hydrid
Primary batteries	Non-rechargeable batteries
PV	Photovoltaic
Secondary batteries	Rechargeable batteries
STC	Stadard test condition
VAT	Value-added tax
$ZnCl_2$	Zinc-Chlorine

Contents

Chapter 1

Introduction

An interesting topic about today's energy system is to increase the amount of renewable energy sources and reduce the amount of fossil fuels. In the last years the amount of power produced by photovoltaic cells (PV-cells) has increased in the electrical power grids of the developed world and have made the costs to install them to fall [1, 2]. This has opened a new market where the electricity consumers have the opportunity to become small electricity producers. The produced electricity can then be used for self-usage or sold to an electricity supplier.

1.1 Background

Ferroamp Elektonik AB develops a converter for PV-systems with a connection to a battery energy storage system (BESS), called EnergyHub [3]. In this thesis the PV-system with a BESS is refereed to the system set-up with the power units of PV-cells, local loads, the grid and a BESS. The EnergyHub has an integrated control system in order to control the energy flow between the different power units connected to it. The control system also has a Current Equalizing Technology (CET) which equalizes the current in the three phases from the grid connected to the PV-system with a BESS.

The EnergyHub consists of two DC-DC converters, one bidirectional DC/AC and a control system which controls the energy flow and the CET. One of the DC-DC converters is connected to the PV-cells, the second to the battery storage and the DC/AC converter is connected to the distribution board. In Appendix A.1 a single line diagram of the EnergyHub can be seen.

In the control system of the EnergyHub, different strategies to control the energy flow between the power units in the PV-system with a BESS can be implemented. These strategies can have different approaches depending on what improvements that are requested. In this thesis the economical return with an EnergyHub is wanted to be increased.

1.2 Previous work

There are different companies that are developing converter solutions for PV-systems with a BESS [4]. Some companies have external converters for batteries and PV-cells with a control unit that controls the energy flow, like the one from SMA Solar Technology [5]. Other companies have all the converters integrated in one unit, as the PowerRouter from Nedap [6]. The PowerRouter is similar to the EnergyHub except from that it is only a single phase converter, when the EnergyHub can be connected up to three phases [3, 4].

The main principle of the control system strategies that the PowerRouter uses is to increase the self-usage as much as possible. This means that the overproduced electricity, which is not consumed in the PV-system with a BESS, is stored in the batteries instead of sold to the grid. By the systems from SMA Solar Technology, it can be noted that it uses the same type of control strategies as the PowerRouter [5]. Considering the strategies implemented into the two systems an easy solution seems to be to increase the self-usage as much as possible.

1.3 Problem description

Ferroamp Elektronik AB's aim is to develop an EnergyHub which is able to control the energy flow in a PV-system with a BESS in order to increase the economical return. In the development of the EnergyHub so far, the main focus has been to design and improve the stability of the converters. Little effort has been dedicated to investigate and design strategies for the control of the energy flow.

1.3.1 Purpose

The main purpose of the thesis is to design and investigate strategies to control the energy flow in the EnergyHub in order to increase the economic return of a PV-system with a BESS. An other goal is to quantify the cost consequences using the various control strategies. Furthermore, the impact of future cost reductions of batteries and PV-system as well as future increase in electricity prices will be investigated. The thesis will also answer two main questions:

1. Are there any economical benefits for a certain costumer with an EnergyHub and connected BESS?
2. What should the rated energy of the battery be for a certain costumer in order to maximize the economical return when using an EnergyHub?

1.3.2 Limitations

The project is restricted in the constraints for a master thesis and therefore some limitations had to be set.

- Only strategies towards private electricity consumers will be developed.
- The strategies will be designed for Swedish conditions, i.e. the input data like solar irradiation, grid and electricity prices will be to the Swedish system perspective.
- Only the Swedish support system will be studied.
- Most of the biggest PV-cells producers leave a warranty performance of 80 % after 25 years of their PV-cells and therefore the battery wear will be based on 25 years [7–9].

1.4 Outline of thesis

This report aims to present the thesis work. The report is written with the intention that the reader has a basic electrotechnical understanding. The report contains of another three chapters, with the following content:

Chapter 2 - Collection of known theories
In Chapter 2 a theory review has been done in order to give a deeper understanding about the different power units. Firs, theories about battery models and battery types are given. Second, it is explained how the energy production from PV-modules can be estimated from the incoming irradiation. Last, the principle of the electricity market in Sweden is explained.

Chapter 3 - Case Set-up
The simulation model and the different strategies are described in Chapter 3. The simulation model has been developed with the different power units in mind. With the simulation model as a tool, three strategies were developed.

Chapter 4 - Analysis
Chapter 4 contains analysis of each strategy. First a the behaviour of the strategies are described and then an economical analysis is performed. In the end a critical review of the work is given.

Chapter 5 - Conclusion
In Chapter 5 the project is summarized and conclusions that has been made are given. A recommendation for future work is given as well.

Chapter 2

Collection of known theories

This chapter aims to give a deeper understanding about the different power units in the PV-system with a BESS.

2.1 Known theories about batteries

In this sub-chapter the basics of batteries will be reviewed as a simplified life model of the battery in order to predict the lifetime of the batteries. Also different types of batteries suitable for BESS will be studied.

2.1.1 Battery basics

Batteries are classified into two types; non-rechargeable (primary) and rechargeable (secondary) batteries [10]. In this thesis the secondary batteries will be in focus and explanations will be done regarding to those. The battery consists of one or several cells where electrochemical process can arise. By applying a load over the battery the electrochemical process starts and the chemical energy stored in the batteries is converted to electrical energy. If energy is fed into a secondary battery the conversion is reversed and the energy is stored in the battery until a load is applied over it again. The cells can either be connected in series or in parallel depending on what the requested nominal voltage or capacity of the battery should be. In basic a cell is composed of three components:

1. The negative electrode (anode) that supply the cell with electrons due to oxidation in the electrochemical process.
2. The positive electrode (cathode) that collects the electrons from the cell due to reduction in the electrochemical process.
3. The electrolyte that transports the charge between the anode and the cathode.

Due to the oxidation there is a potential at the anode as well as at the cathode due to the reduction. The difference of these potentials results in the voltage over the cell. In Table 2.1 the electrochemical reaction at the different electrodes of a zinc-chlorine ($ZnCl_2$) battery are shown with the corresponding arising potential.

Table 2.1: Chemical potential for a zinc-chlorine cell.

Electrode	Chemical process	Resulting potential
Anode	$Zn \rightarrow Zn^{2+} + 2e$	-0,76 V
Cathode	$Cl_2 \rightarrow 2Cl^- - 2e$	1,36 V

Using the result from Table 2.1 the voltage (U) over one cell is calculated as

$$U = 1,36V - (-0,76V) = 2,12V. \tag{2.1}$$

The theoretical capacity (C) of a cell is given by the quantity of the material of the electrodes. Different materials has different electrochemical equivalences and, for example, Zn and Cl_2 in the $ZnCl_2$ battery has electrochemical equivalences of 1,22 g/Ah and 1,32 g/Ah respectively [10]. The total electrochemical equivalence is 2,54 g/Ah and if the weight of the electrodes would be 1 g in total, the resulting capacity would be 0,394 Ah. By knowing U and C the theoretical energy (E) delivered from a cell can be calculated as

$$E[Wh] = U * C\ [VAh]. \tag{2.2}$$

The theoretical maximal energy that could be delivered from 1 g of $ZnCl_2$ electrode would be 0,835 Wh.

During usage of the battery the charge level of the battery can either be expressed as state-of-charge (SOC) or depth-of-discharge (DOD). SOC is the ratio between the nominal capacity (C_N) and the amount of stored capacity in the battery [11]. DOD is the ratio between C_N and the amount of discharged capacity, i.e. 1-SOC [12]. State-of-health (SOH) is used to define how well a battery can perform and is the ratio between C_N and a fully charged battery ($C_{Bat,full}$).

2.1.2 Battery types suitable for BESS

There are several technologies of batteries and the difference lies in the combination of the anode and the cathode. The different combinations give different energy densities and properties of the battery like cycle-life and discharge rates. Secondary battery types, that are suitable for BESS, are deep cycle batteries and the mostly used are listed below with a short explanation. The list is a summary of the information in the reports from [10, 13–16] and therefore are the specified references to [10, 13–16] not given in the list.

- **Lead acid** batteries are one of the oldest battery technology, which have been used for over 100 years and are well established in the electrical storage systems. The components of the cell are lead dioxide as the cathode, metallic lead as the anode and a sulphuric acid solution as the electrolyte. Lead acid batteries are robust, not sensitive to charge and discharge patterns and has a low cost per kWh compared to other battery technologies. Its disadvantages are that during high power discharges the available capacity is limited to 50-70 % of C_N, it has a low cycle-life value and a low energy density. The efficiency of the battery is around 86 % [4]. An important feature to consider when managing lead acid batteries is not to let them be discharged during a longer time since it can lead to sulfation of the electrodes and reduce the performance of them. In the electrochemical process of the battery, hydrogen is a by-product which has to be considered when selecting the location of the battery energy storage since hydrogen is explosive.

- **Nickel based** batteries are, as lead acid batteries, a technology used for over 100 years and are the second most used battery technology after lead acid. The first nickel based batteries was nickel cadmium (NiCd) but cadmium is toxic and therefore was the nickel metal hydrid (NiMH) battery developed to replace NiCd. Other nickel based batteries have been developed but NiCd and NiMH are the most used. Compared NiCd with lead acid and Li-ion batteries, NiCd is between them seen to energy density, energy power and cycle-life value. A great advantage of nickel based batteries is that they work better than other battery technologies in critical environments with low temperature and are safer than Li-ion batteries. The biggest drawback is that nickel based batteries cost almost as much as Li-ion batteries.

- **Lithium ion** (Li-ion) batteries are a fairly new technology first commercialised in the early 90s and has taken over a great deal of the battery market, for example in year 2000, 50 % of the small portable market where supplied with Li-ion batteries. The technology is based on Li-ions that are working as electron carrier in the electrolyte between the two electrodes. The electrode and electrolyte materials can be of different chemistries depending on which type of Li-ion battery that is used. The reason why the Li-ion batteries have become so popular is its high energy density, high cycle-life values and high efficiency, 95-98 %. The Li-ion batteries are a relatively new battery technology and a researches are going on about different Li-ion types and the management systems. Therefore, the prices are relatively high but are decreasing due to higher production rates and that the technology is getting more mature. The management systems are a very important feature since the Li-ion batteries can catch fire or explode if it is not charged under controlled conditions.

- **Sodium sulphur** (NaS) is a relative new battery technology with molten liquefied sodium and sulphur as electrolytes. The NaS batteries are well suited for larger energy storages systems, the smallest are about 6 MWh. They have a high cycle-life level, high energy density and a quick response when the sodium and sulphur are molten. The problem with this battery technology is to keep the sodium and sulphur molten, which is at a temperature of 300 - 360 °C. To maintain the temperature the battery has to be well isolated and use stored energy. If the batteries are used daily and the size is adequate the temperature can almost be maintained due to its own reaction heat.

2.1.3 The equivalent circuit of a battery

One purpose of modelling a battery is to understand its behaviour during its lifetime. The battery models can be classified into four different categories; physical, empirical, mixed and abstract models [17]. The physical models describes the electrochemical processes with base in the battery basics described in Chapter 2.1.1. They are very detailed and describe the physical phenomena in a large extent. They need a large number of parameters and are therefore of limited usage in practice. The empirical models describe the battery's behaviour with simple mathematical expression where the parameters have been derived to fit experimental tests. The mixed model uses methodologies from both the physical models and the empirical models. They are developed to reduce the number of parameters but at the same time have a high accuracy. The abstract models have been developed to describe the battery by electrical circuits like the thevenin equivalent circuit in Figure 2.1 and stochastic processes [10]. In Figure 2.1 U_{OC} represent the open circuit voltage of the cell, R_{int} is the resistances inside the cell due to the voltage drop when the charges are transported through the electrolyte and contact resistances etc. R_{ct} and C_D represent the transient behaviour of the cell during changes in the charge or discharge levels [18]. When a charged battery is not discharged for a long time most batteries loses some capacity which $R_{self\text{-}discharge}$ is representing. U_{batt} is the output voltage of the battery. The variables of the circuit are set to fit the experimental results from different battery types.

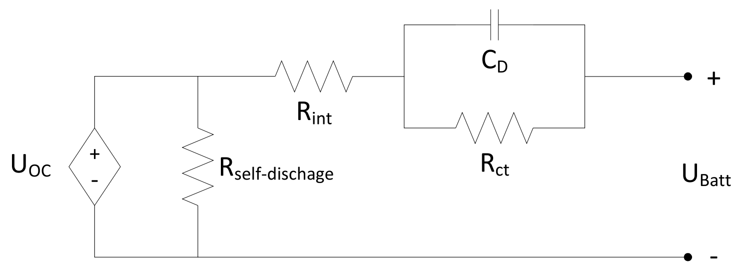


Fig. 2.1 Thevenin eqvivalent circuit of a battery.

Depending on the SOC of the battery U_{batt} will change [10]. For a Li-ion battery U_{batt} will have some decrease between 100-90 % SOC, between 90-20 % U_{batt} is almost constant and in the last 20 %, U_{batt} will decrease exponential. For lead-acid batteries it looks almost the same but the decreases are not as high as for Li-ion.

2.1.4 Battery life-model

One of the reasons to develop battery models is to understand the future performance and do a life prediction of the battery [10]. The performance of batteries depends on different stress factors, like discharge rates, discharge patterns, Ah-throughput and temperatures [19]. To simulate when it is time to replace a battery a simple model of Ah-throughput can be used. The Ah-throughput model only counts the amount of capacity (Γ_A) and compares it with the amount of capacity that can be put through the battery before end-of-life (EOL). When $\Gamma_A = \Gamma$ the battery should be replaces. Manufactures normally give one or more cycle-life (L) at a certain DOD. L is usually measured at a constant temperature of 25 °C and EOL is reached when SOH is 80 %. The relationship between different L and DOD is not always linear and since a battery connected to PV-modules do not have a certain discharge pattern with a specific DOD, Γ can be assumed to be

$$\Gamma = average\{C_N DOD_i L_i\}_Y^X \ [Ah] \tag{2.3}$$

where i stands for the certain value given by the manufacturer and X and Y are the operation range of the battery where L with corresponding DOD are given. Assuming the battery will operate within the range where U_{batt} is constant, 20-90 % of SOC, Γ can be calculated by

$$\Gamma = average\{E_N DOD_i L_i\}_Y^X \ [Wh] \tag{2.4}$$

where E_N is the nominal energy of the battery. In [19] the Ah-throughput model has been compared with a true lead-acid battery and the highest error was about ± 17 % for a profile from a wind power plant and for a profile from a PV-plant it was about 10 %. The Ah-throughput model do not say anything about the SOH after a certain Γ_A but using a certain discharge pattern with a specific DOD it can be assumed that the SOH decreases linearly with the number of cycles [10].

2.2 Solar irradiation on PV-modules

This section has been written with inspiration from [20]. Due to this, specified references to [20] are not given in the section.

To simulate the electrical energy production from the PV-modules the solar irradiation on them has to be estimated. The irradiation are measured in weather stations and two types of irradiation data are of interest in the simulations; the diffuse horizontal irradiation (DHI) and the direct normal irradiation (DNI). DNI is the irradiation vertical to the sun's rays and DHI is the indirect irradiation on a horizontal surface, like reflections from clouds and the earth etc. PV-modules are normally installed with a tilting angle (β), an azimuth angle (Ψ) and due to these angles the irradiation data has to be recalculated to the surface on the PV-modules. β is an angle compared to the horizontal plane and Ψ is the cardinal angle where north is $0°$. The elevation angle (α) will also affect the irradiation on the modules and is the angle between the sun's rays and a horizontal plane. Figure 2.2 shows an clarification of the angles β, Ψ and α that is used to calculate the energy production from the PV-modules.

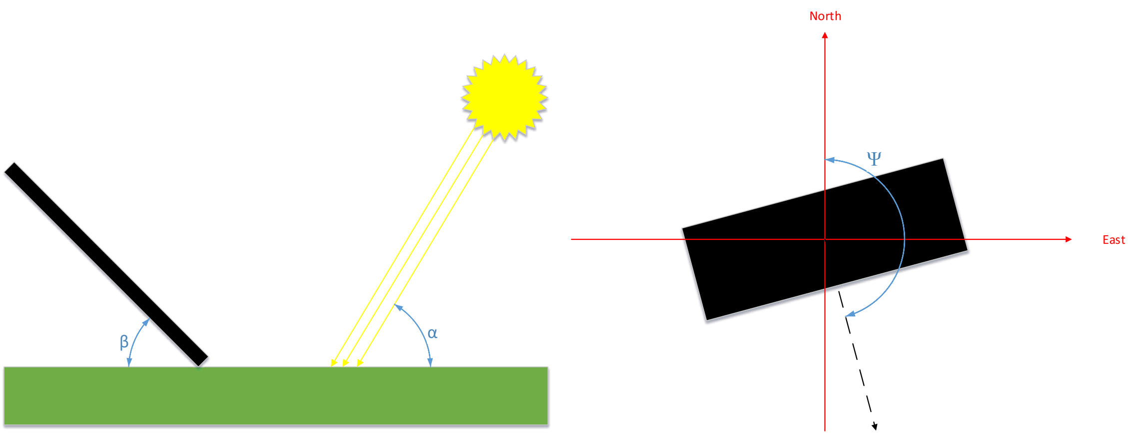


Figure 2.2: The angles β, Ψ and α. The black dashed line is the direction the PV-modules are facing.

α is changing over time and is determined from the coordinates of the PV-modules location, the hour angle (HRA) and the declination angle (δ). HRA is the angle which tells where the sun is positioned with $0°$ at noon. δ is the angle between the line from the centre of the sun to the centre of the earth and the line from the centre of the earth to the equator. These two angles is calculated from the time of the day and the day of the year.

The earth is both rotating around the sun in an ellipse shaped orbit and is spinning around its own axis. Due to that the earth's axis is tilted compared to the rotation around the sun δ varies during the year with

$$sin\delta = sin(23,45°)sin(B) \tag{2.5}$$

where the angle 23,45° is the tilting angle of the earth compared to the plane of the ellipse orbit around the sun [21]. The variable B is given by

$$B = \frac{360}{365}(d - 81)\ [degree] \tag{2.6}$$

where d is the day number of the year with January 1 as $d = 1$. From (2.5) and (2.6) it can be seen that it is assumed that the declination angle is constant over a day but in reality it varies with 0,5°. To calculate the sun's position a correction in time has to be done due to the earth's ellipse shaped orbit around the sun and the tilt of the axis. This is done by Equation of Time

$$EoT = 9,87sin(2B) - 7,53cos(B) - 1,5sin(B)\ [degree]. \tag{2.7}$$

Further the Local Standard Time Meridian ($LSTM$), which is a recalculation of the Prime Meridian to the Local time (LT) zone, is determined by

$$LSTM = 15^\circ \Delta T_{GMT}\ [degree] \tag{2.8}$$

where ΔT_{GMT} is the difference in hours between the LT and the reference time in Greenwich Mean Time (GMT). 1° change in longitude is 4 minutes change in time which means that the time varies within a LT zone. Since LT is the same within a LT zone the time correction factor (TCF) is a correction in order to determine the local solar time (LST). TCF is therefore expressed as

$$TCF = 4(Longitude - LSTM) + EOT\ [degree] \tag{2.9}$$

where Longitude is in degrees. LST is then found by using LT and TCF recalculated to hours.

$$LST = LT + \frac{TCF}{60}\ [degree]. \tag{2.10}$$

HRA is, as mentioned earlier, the angular representation of LST and due to that the earth is rotating with a speed of 15° per hour and HRA should be 0 at noon it is defined as

$$HRA = 15^\circ(LST - 12)\ [degree] \tag{2.11}$$

By knowing δ and HRA, α can be determined as

$$sin\alpha = sin\delta sin(Latitude) + cos\delta cos(Latitude)cos(HRA). \tag{2.12}$$

The irradiation (G) that the PV-modules can use for electrical power production is divided into two types of irradiation. The first type is the direct beam irradiation (DB) which is the same as DNI but recalculated on the surface of the PV-modules with

$$DB = DNIcos(\theta_s)\ [kW/m^2]. \tag{2.13}$$

where θ_s is the angle between the DNI and the normal of the surface. θ_s is calculated by

$$\begin{aligned} cos\theta_s = {} & sin(\delta)sin(Latitude)cos(\beta) - \\ & - sin(\delta)cos(Latitude)sin(\beta)cos(\Psi - 180^\circ) + \\ & + cos(\delta)cos(Latitude)cos(\beta)cos(HRA) + \\ & + cos(\delta)sin(Latitude)sin(\beta)cos(\Psi - 180^\circ)cos(HRA) + \\ & + cos(\delta)sin(\Psi - 180^\circ)sin(HRA)sin(\beta) \end{aligned} \tag{2.14}$$

The second type is the diffuse irradiation (D) which is the indirect irradiation hitting the modules which can be calculated from the DHI. If DHI is not measured in the meteorological measuring it can be estimated as

$$DHI = GHI - DNIsin(\alpha)\ [kW/m^2] \tag{2.15}$$

where GHI is the global horizontal irradiation which is all irradiation from both the sun and the surroundings on a horizontal surface. If assuming that the diffuse irradiation is equally distributed from all around the sky, D can be determined by

$$D = DHI\frac{180° - \beta}{180°}\ [kW/m^2]. \tag{2.16}$$

The total amount of irradiation on the modules (G) is then

$$G = DB + D\ [kW/m^2]. \tag{2.17}$$

By knowing G, the area (A_{PV}) and efficiency (η_{PV}) of the PV-modules the power production from the PV-modules can be estimated by

$$P_{PV} = GA_{PV}\eta_{PV}\ [kW]. \tag{2.18}$$

2.3 Electricity market

When having a PV-plant there is three parts of the electricity market that is of interest to deal with; the grid owners, the electricity traders and electricity certificates. The grid owners' task is to deliver the electricity from the producers to the consumers. Normally, the electricity traders purchase the electricity from producers on Nord Pool Spot and sell it to the consumers. As a consumer there are therefore two services to pay for which are the grid fees to the grid owner and the amount of bought electricity from the electricity traders.

2.3.1 Grid fees

The grid is divided into the national grid, the regional grid and the local grid and a grid owner is responsible for the distribution of the electricity [22]. As a private electricity consumer the building is normally connected to the local grid, meaning the grid fees are paid to the local grid owner. The grid fee is divided into two prices, a fixed price and a transmission price [23], called fuse subscription. The fixed price is dependent on the fuse level and the transmission price is dependent on the amount of energy bought from the grid. Some grid owners also have a power price, which is then called capacity subscription [24, 25]. The power price is dependent on the mean value of a specified numbers of consumed power peaks within a month. With capacity subscription the fixed price is usually lower and the possibility to affect the grid fees increases.

2.3.2 Electricity trade

Electricity trade companies are those who buy electricity from the producers and sell it to the consumers [22]. Seen from a consumer's point of view, one big difference with an electricity trader compared to an grid company is that the consumer can choose any electricity trader from Sweden to buy the electricity from. The electricity price depends on the annual fee, the purchase price for the electricity trader, the mark-up, the electricity taxes, the electricity certificates and the value-added tax (VAT) [26]. The purchase price depends on the spot price from Nord Pool Spot which differs from spot area to spot area and is presented at 13.00 each day for the next 24 hours [27].

There are normally three types of contract types, one with fixed prices, one with variable price and one with a mix of the fixed and variable price contracts [26]. The fixed price contract does an averaging approximation of the spot price during the period of the contract. The variable price contract takes an averaging price dependent on the spot price over the month and the standard settlement area. Hour metering can also be chosen in the variable price contract meaning the purchase price will be the same as the spot price. The annual fee and the mark-up is also depended on the type of contract but is set by the electricity trader. The electricity taxes and the VAT is regulated by the government and the electricity certificates are marked driven.

2.3.3 Electricity certificates

To increase the renewable electricity sources in Sweden, the government has implemented a marked driven subsidy, called electricity certificate [28]. Renewable electricity sources are wind power, solar power, wave power, geothermal power, some biomass fuel, some hydro power and peat in combined heat and power plants. The principle is that renewable electricity producers get a certificate for each produced MWh and those who are quota obligated must buy certificates to fulfill a specific quota for that year. The quota obligated are the electricity supplier, the electricity users, registered electricity intensive industries and those who produces electricity for self-usage with a production higher than 60 MWh or a power plant bigger than 50 kW. The renewable electricity producers are not counted to the quota obligated and the period a power plant can get certificates for is maximum 15 years or until 2035.

To get electricity certificates the renewable electricity producer must first do an application to Energimyndigheten [28]. Approved as a certificate taker a Cesar account has to be opened at Svenska Kraftnät where the amount of entitled produced electricity is submitted and a certificate is given for each MWh of entitled produced electricity. The cost for a Cesar account is 0,07 SEK per certificate counted for the highest amount of certificate on the account during a quarter. Svenska Kraftnät also takes an administrative fee if they are responsible for the trade for the certificates on the account. The entitled produced electricity is the electricity passing through the measuring equipment. If the main fuse is lower than 63 A, the power output to the grid is lower than 43,5 kW and the annual consumption from the grid is higher than the output, the installation of the measuring equipment connected to the grid and the measuring shall be paid by the grid owner [29]. This measuring can be used for the Cesar account, but then electricity certificates are only given to the electricity put into the grid. To get electricity certificates for all the electricity produced an extra measuring equipment has to be installed in the connection to the PV-plant and the measuring equipment and measuring will be paid by the electricity producer.

The electricity certificates can then be sold to the quota obligated and the price is negotiated between the seller and buyer. In Figure 2.3 the average price for a certificate at each month is presented between June 2003 to September 2013 [30]. The prices are not inflation-adjusted and depends on the exchange between EUR and SEK on the date the data are downloaded from [30]. The fluctuations in the price are due to the demand of certificates and the average price over the whole period is about 225 SEK per certificate.

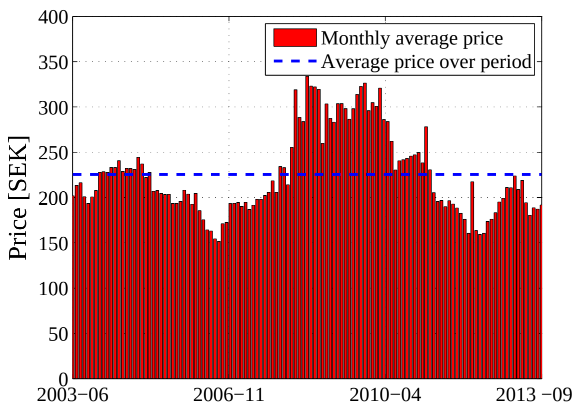


Fig. 2.3 The bars represent the average price for one electricity certificate at each month and the dashed blue line represent the average price over the whole period [30].

2.3.4 Selling electricity as a micro producer

As a producer of small amounts of power there are three ways to earn money from the produced energy; by selling electricity to an electricity trader, by compensation from the grid owner and by selling electricity certificates for the produced electricity. When selling electricity to a electricity trader a contract has to be negotiated and there are no legislations today that defines the contract conditions, meaning the selling is on the electricity trader terms. The compensation from the grid owner is due to the decrease of energy losses in the grid and for the decrease of fees to connecting grid owners that the power plant causes [29].

Chapter 3

Case Set-up

The main purpose of the thesis, as explained in Chapter 1.3, is to design and evaluate one or more strategies to control the power flow in the EnergyHub in order to increase the economic return of a PV-system with a connected BESS. The design of the strategies was developed in a simulation model, which was preformed in MATLAB [31]. Since the primary function of the simulation model is to be a tool in the development of the strategies in the EnergyHub it will be based on historical values. The power units in the smart house are the local load, the energy production from the PV-modules, the BESS and the grid which is represented as the electricity market. In Figure 3.1 a schematic schedule of the simulation model can be seen with the different power units and the directions of the power between them and the EnergyHub. The strategies are implemented in the EnergyHub where the power flow is controlled. In the following section it is described how the simulation model and the strategies were developed.

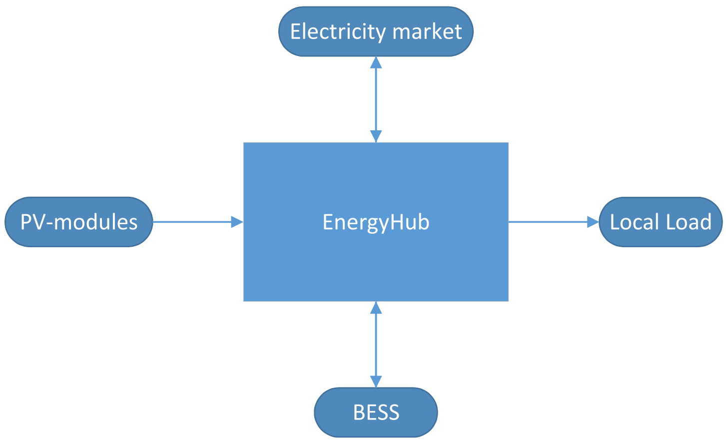


Fig. 3.1 Overview of the EnergyHub with the directions of the energy flows between the different power units.

3.1 Simulation model

In the simulation model different profiles such as load, irradiation and spot price profiles are read from different files. These profiles have different sampling intervals but in the strategies the sampling interval should be the same for all different profiles. That is why a time array ($time$) is created as in Figure 3.2. In this thesis the sampling interval of $time$ is in minutes.

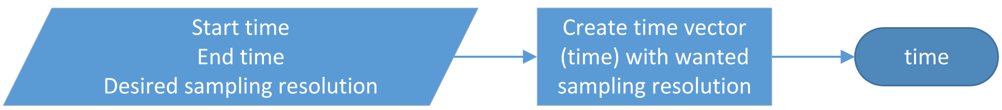


Fig. 3.2 Flowchart of how $time$, with wanted time resolution, is created.

3.1.1 Local load

The local load is based on historical load profiles. In Figure 3.3 it can be seen how the E_{Load} array with the desired sampling interval is created from the load profile.

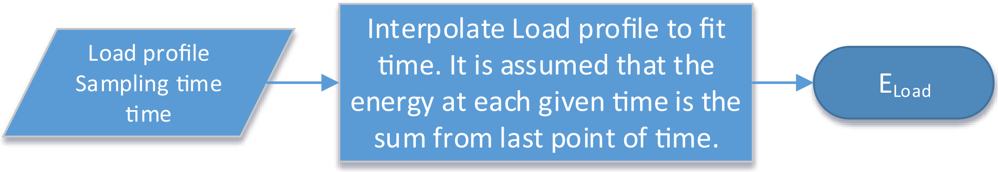


Fig. 3.3 Flowchart of how E_{Load} is created.

Two functions were built in MATLAB to manage the two types of load profiles shown in Table 3.1 and Table 3.2. In Table 3.3 the structure of the E_{Load} array is presented where date number is a number given by MATLAB for a specific time. The sampling interval of E_{Load} in the table is in minutes.

Table 3.1: Structure of one of the load profile types.

Time stamp	Consumed energy [kWh]
2012-01-01 01:00:00	2,05
2012-01-01 02:00:00	1,55
2012-01-01 03:00:00	1,44

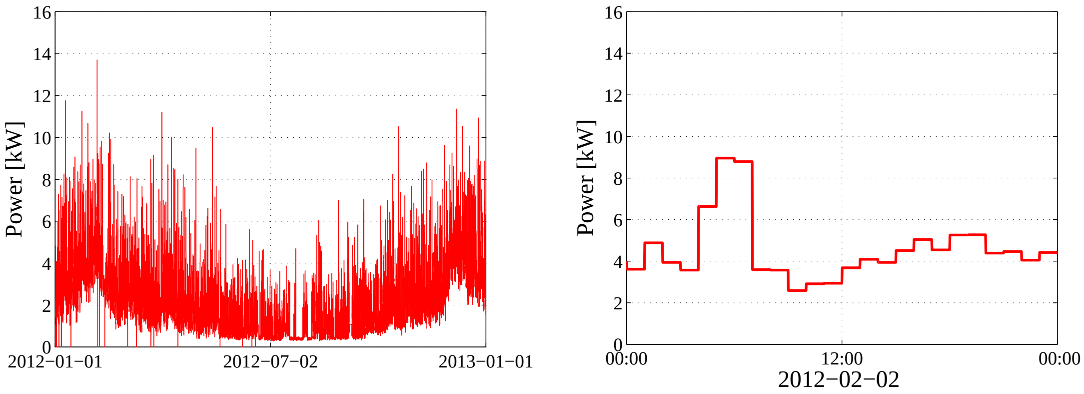
Table 3.2: Structure of the other load profile type.

Year	Month	Day	Hour	Minute	Second	Consumed energy [kWh]
2012	5	24	10	13	0	1,8922
2012	5	24	10	14	0	1,7044
2012	5	24	10	15	0	1,3845

Table 3.3: Structure the E_{Load} array after the sequence in Figure 3.3 has been performed.

Date number	Consumed energy [kWh]
734869,0006944444	0,0342
734869,0013888889	0,0342
734869,0020833333	0,0342

Figure 3.4(a) shows the power consumption (P_{Load}) of a load profile for a residential with a heating pump during 2012 provided by Göteborg Energi [32]. P_{Load} is a recalculation of E_{Load} where it is assumed that the consumed energy during the sampling time is constant. Figure 3.4(b) shows a day of the load. In the graphs it can be seen that the electricity consumption is higher during the winter than the summer and there is normally a peak in the morning and in the evening. The sampling interval of the load profile is in hours and the annual energy consumption is about 18000 kWh. The highest peak consumption was about 13,7 kW which corresponds to a total current of about 35 A in all three phases together at a phase voltage level of 230 V.



(a) P_{Load} over a year.

(b) P_{Load} over a day.

Figure 3.4: P_{Load} for a house with a heating pump and a annual energy demand of about 18000 kWh.

3.1.2 Energy production from PV-cells

The energy production from the PV-modules is based on the solar irradiation on the PV-modules. There are several methods to extract the solar irradiation and one of them are to use historical irradiation data from meteorological measuring where direct (DNI), diffuse (DHI) or global (GHI) irradiations are collected [20]. The irradiation profiles for the simulation model should have the same structure as in Table 3.2 but with irradiation in the last column with the unit W/m^2. Figure 3.5 shows the flowchart of how the E_{PV} array is estimated and the resulting array looks like the example of the E_{Load} array in Table 3.3.

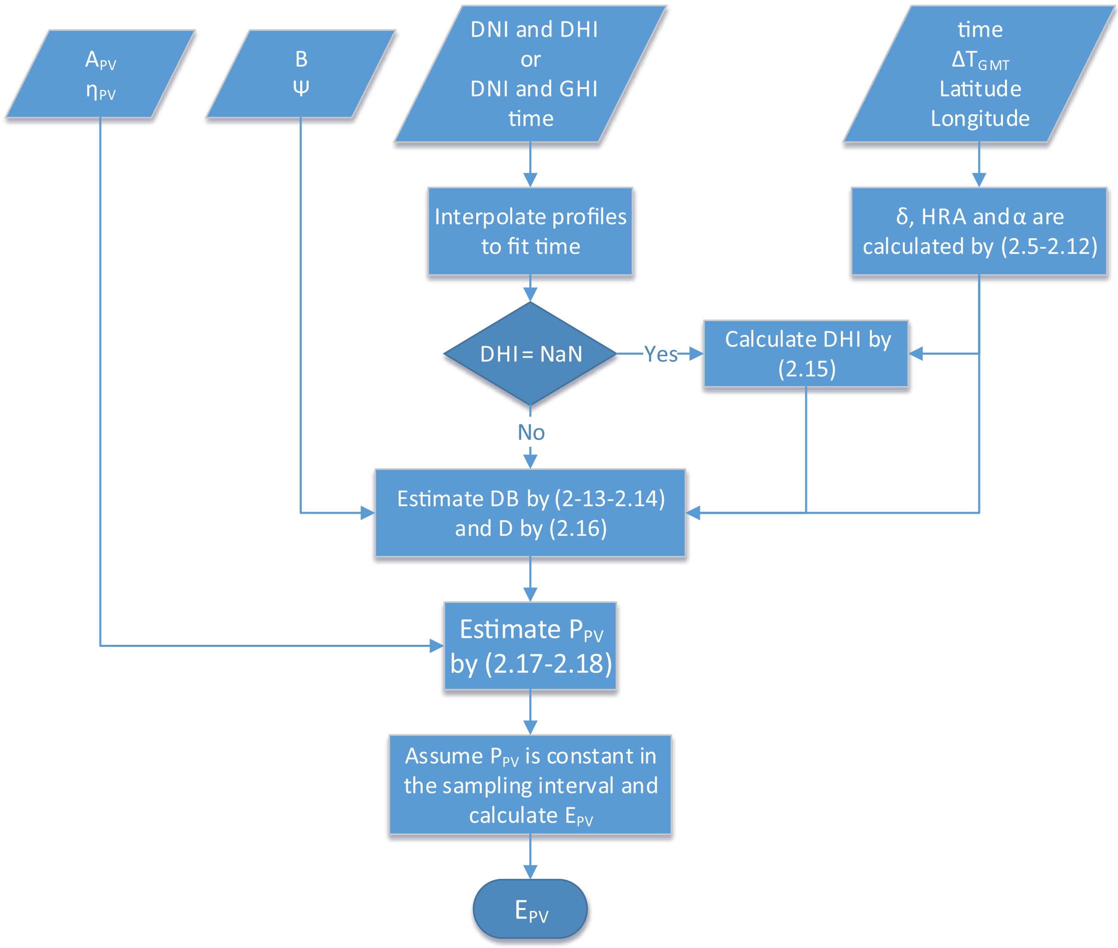
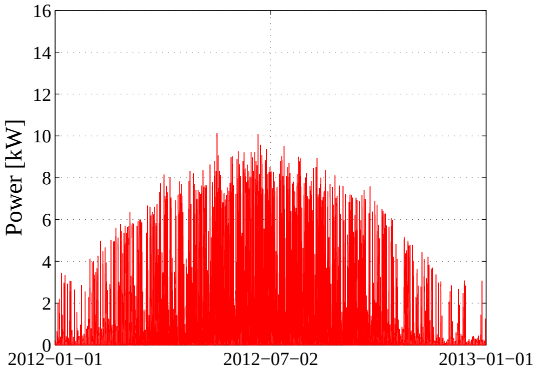
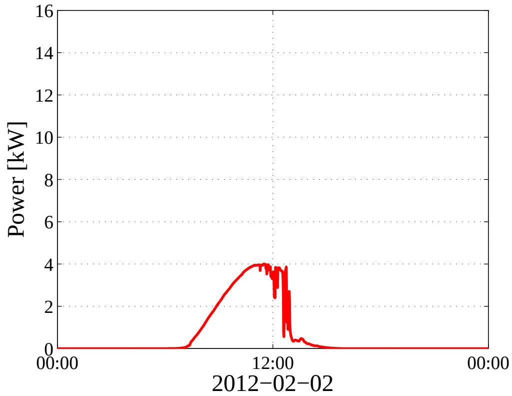


Fig. 3.5 Flowchart of how E_{PV} is estimated.

Figure 3.6(a) shows the estimated power production (P_{PV}) for 2012 from a 50 m^2 PV-plant located in Norrköping with an efficiency (η_{PV}) of 15 %, β of 30°, Ψ of 180°, Latitude and Longitude of 58.58° and 16.15°. Figure 3.6(b) shows the power production during the same days as P_{Load}. The irradiation data for the figures has been provided by SMHI's meteorological measuring in Norrköping with a sampling interval in minutes [33]. It can be seen in the graphs that the PV-production is dependent on what time of the year it is, time of the day and the irradiation on the modules due to the weather.



(a) P_{PV} over a year



(b) P_{PV} over a day

Figure 3.6: P_{PV} from a 50 m^2 PV-plant located in Norrköping with an efficiency of 15 %, β of 30° and Ψ of 180°.

3.1.3 Electricity market

The electricity market section is built on prices in the trade with the electricity market participates. In the simulations, the grid will be seen as an infinite source and it is only of interest how much energy that is bought from and sold to the grid. First an array with the spot price (Spotprice) is created for the spot area where the PV-system with the BESS is located. This is performed as shown in the flowchart in Figure 3.7. A monthly average value is calculated in order to be used if a monthly variable price contract is used. In reality the monthly variable price is both dependent on the standard settlement area and the spot price but in the simulations it is assumed that it is only an average of the spot price.

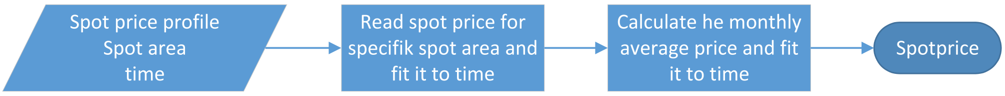


Fig. 3.7 Flowchart of how the spot price vector is created.

The spot price profile is historical spot prices from Nord Pool Spot saved in excel sheets where an extraction of the profile can be seen in Table 3.4 [27]. SYS is a system price and SE and SE1-4 are the spot prices of interest. It can be seen that from 1st of November 2011 the spot prices was divided into 4 different spot areas where 1 is in the north and 4 in the south. An extraction of the resulting Spotprice array is shown in Table 3.5

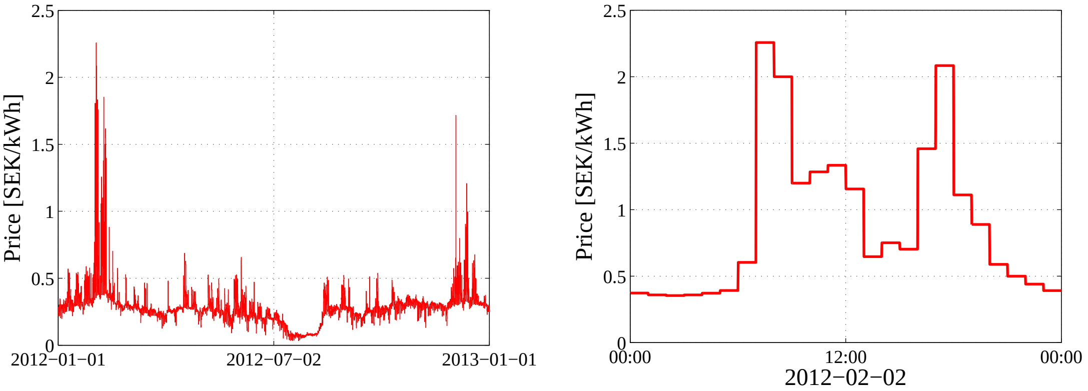
Table 3.4: Extraction from spot price profile [27].

Time stamp	SYS [SEK/MWh]	SE [SEK/MWh]	SE1 [SEK/MWh]	SE2 [SEK/MWh]	SE3 [SEK/MWh]	SE4 [SEK/MWh]
2011-10-31 22:00:00	352,69	352,51				
2011-10-31 23:00:00	337,88	337,79				
2011-11-01 00:00:00	338,99		338,99	338,99	338,99	338,99
2011-11-01 01:00:00	335,2		335,2	335,2	335,2	335,2

Table 3.5: An extraction of how the Spotprice array looks like after the sequence in Figure 3.7 has been performed.

Date number	SYS [SEK/kWh]	Spot price [SEK/kWh]	Monthly average spot price [SEK/kWh]
734869,0006944444	0.28360	0.28565	0.33796
734869,0013888889	0.28360	0.28565	0.33796
734869,0020833333	0.28360	0.28565	0.33796

Figure 3.8(a) shows the spot price of 2012 in spot area 3 and Figure 3.8(b) shows the spot prices during the same days as P_{Load}. From the figures it can be seen that the prices are higher in the winter. Moreover, they are rising in the morning and in the afternoon, similar to P_{Load}.



(a) The spot price over a year

(b) The spot price over a day

Figure 3.8: The spot prices of 2012.

The outgoings in the simulation of the electricity market are the grid fees and the bought electricity from the electricity trade. The inputs for the grid fees are

- annual grid fee
- electricity price
- power price

all given with VAT. For the power price, an array is created with the same sampling time as $time$ and with the changes of the power price over the year. For the electricity trade the inputs are;

- annual electricity fee.
- purchase price.
- mark-up.
- electricity tax.
- electricity certificate.
- VAT.

The purchase price is either a fixed price given by the electricity trader, the average monthly spot price or the spot price seen in Table 3.5. If electricity certificates are thought to be traded with, the account costs for the Cesar account and the costs for the measuring is added to the outgoings. Costs for the measuring is only in the case where measuring equipment is installed at the PV-modules.

Other costs of interest are the installation costs of the PV-modules and the BESS. In 2012 the average installation cost in Sweden was 22000 SEK/kW$_{\text{Peak}}$ where all installation and components costs were accounted for [2]. The EnergyHub will cost about the same as other converters and can therefore be accounted for in the average price [34]. The nominal power for a PV-module is usually defined at standard test condition (STC) which is at an irradiation of 1 kW/m^2, an airmass of 1,5 and a temperature of 25°C [7–9]. By assuming the PV-modules has the stated efficiency (η_{PV}) the installed power can be calculated by

$$P_{PV,peak} = A_{PV} * \eta_{PV} \; [kW_{Peak}] \tag{3.1}$$

where η_{PV} is around 11-19 %. The costs for a Li-ion battery storage is about 10000 SEK/kWh$_{E_N}$ and for a lead-acid battery storage about 1500 SEK/kWh$_{E_N}$ [34, 35]. The subscript $_{E_N}$ stands for the rated energy of the battery.

The incomes in the simulations are based on the negotiated price with the electricity trader, the compensation from the grid owner and the amount of sold electricity certificates. In the simulations the electricity certificate price is assumed to be the average price from Figure 2.3 which is 225 SEK per certificate.

In Table 3.6 three types of grid subscription are presented. The prices are collected from the grid company's homepage and the prices are for private consumers except for the compensation from the grid owner [24, 25, 36–39]. Number of power peaks refers to the number of power peaks that is used in the calculations of the power price. Göteborg Energi has 0 at number of power peaks since they are not using the capacity subscription.

Table 3.6: Three types of grid subscriptions

	Falbygdens Energi [24,36]	Göteborg Energi [37,38]	Sollentuna Energi [25,39]
Main fuse [A]	63	63	16/20/25
Annual grid price [SEK/year]	990	1245	1500/ 7410/10630/14300
Electricity price [öre/kWh]	21,5	26,5	0
Power price [SEK/kW]	30	0	87/43,5[1]
Number of power peaks	1	0	3
Compensation from grid owner [öre/kWh]	2,4	6,5	100

In Table 3.7 one price example is given from a electricity trader's homepage [40,41]. The prices are for variable price contracts where both monthly average purchase price as hourly purchase price can be used. In the tables the hourly price is used.

Table 3.7: Electricity trade prices

	Fortum Market [40,41]
Annual electricity price including VAT [SEK/year]	828
Spot price 2012 in area 3 (min/mean/max) [öre/kWh]	3,31/28,17/225,76
Mark up [öre/kWh]	0
Electricity tax [öre/kWh]	29,3
Electricity certificate [öre/kWh]	22,5
VAT [%]	25
Buy price (min/mean/max) [öre/kWh]	96,89/100,96/352,95
Sell price excluding VAT [öre/kWh]	Spot price - 0,205

[1] Monday - Friday 07-19 o'clock except general holidays and some days around the change between normal time and summer time, which will not be considered since the support did not know the dates from earlier years. High price in January, February, Mars, November and December/Low price in the other months

3.1.4 Battery storage

The battery storage is seen as a state-of-charge (SOC) in the simulations and depends on what action is decide to be performed; to charge the battery, discharge it or do nothing. The inputs of the battery storage are nominal battery capacity (C_N), battery voltage (U_N), life cycle (L) with corresponding depth-of-discharge (DOD), the maximal charge and discharge currents, the battery efficiency (η_{Bat}) and the numbers of batteries. The batteries are assumed to be put in series, in order to have as high voltage as possible and therefore is the nominal energy of the battery

$$E_N = C_N U_N * Number\ of\ batteries\ [kWh]. \tag{3.2}$$

The operation window of SOC will be in the range where U_N is constant and therefore, it can be assumed that E_N is constant as well. The SOC is calculated after each operation by

$$SOC = 100\frac{SOC_{kWh}}{E_N}\ [\%] \tag{3.3}$$

where SOC_{kWh} is the amount of energy stored in the battery. In Chapter 2.1.4 a battery life model, Ah-throughput model, is described in order to simulate how long a lead acid battery can be in use before end-of-life (EOL) and it is assumed that this model also can be implemented on a Li-ion battery. The amount of energy (Γ) that can pass through the battery before EOL is calculated by (2.4). The state-of-health (SOH) is assumed to decrease linearly with Γ and is calculated as

$$SOH = 100(1 - 0,2\frac{\Gamma_A}{\Gamma})\ [\%] \tag{3.4}$$

where Γ_A is the sum of energy past through the battery and 0,2 comes from that when Γ_A = Γ SOH should be 80 %. When the SOH has reached 80 % the battery storage is replaced with a new one. In the development of the strategies only a lead acid and Li-ion battery type will be used because NaS batteries are only suitable for bigger BESS. The NaS batteries also has lower energy density than Li-ion but costs as much. In Table 3.8, U_N, C_N, η_{Bat}, L and corresponding DOD of a lead acid and a Li-ion battery is presented. The example of lead acid battery is ”SBS B14” from Enersys and of the Li-ion battery is ”Swing 5300” by Boston Power. The information in the table is provided by [42, 43] except for the efficiencies which are given in Chapter 2.1.2.

Table 3.8: Battery data example

Battery	U_N [V/Battery]	C_N [Ah/Battery]	η_{Bat} [%]	L [Cycles]	DOD [%]
Lead acid [42]	12	62	86	3200/2500/1900/1500	20/30/40/50
Li-ion [43]	3,65	10	95	3000/2000	80/90

The charge and discharge currents are limited by both the batteries and the converter. For the Li-ion battery the charge and discharge limitation currents are 10,6 A and 13 A respectively and for the lead acid battery there are no such limitations on the current [43,43]. For the converter the limitation currents are 10 A both at charge and discharge which means that the converter sets the limitations [34]. The SOC windows for the Li-ion batteries are 20-90 % due to that the batteries are sensitive for over charge and the voltage is almost constant in that area. For lead acid the recommended SOC window is 50-80 % [35]. Since SOH is decreasing during usage of the battery, it is assumed that the upper SOC limit will decrease with the SOH. The lower SOC limit will remain the same the whole time since the SOH is not an absolute value and to be on the safe side it will remain the same.

3.1.5 Output

The outputs from the simulations will be of relevance to answer the questions in Chapter 1.3.1 and to analyse the strategies. To answer both the questions the economic return over one year is calculated as well as the equivalent battery unit wear after 25 years. To calculate the first year's return, the outgoings, incomes and outgoings without PV-modules, EnergyHub and BESS are calculated. The subscript $_{Without}$ stands for without PV-modules, EnergyHub and BESS. The incomes are calculated as

$$Income = \sum(E_{Sold} * Sell\, price) + Certificate\ income\ [SEK] \tag{3.5}$$

where E_{Sold} and $Sell\, price$ are arrays with sold energy and sell prices for one year. Each MWh of entitled produced electricity is assumed to give 225 SEK, which is the $Certificate\ income$. The outgoings are calculated as

$$\begin{aligned} Outgoings = \sum(E_{Bought} * Buy\, price) + Certificate\ costs+ \\ + Annual\ costs + Power\ costs\ [SEK] \end{aligned} \tag{3.6}$$

where E_{Bought} and $Buy\, price$ are arrays with bought energy and buy prices for one year. $Certificate\ costs$ are the costs for the electricity certificates, which is 0,07 SEK per certificate counted for the highest amount of certificate on the Cesar account during a quarter and it is assumed that after each quarter the certificates are sold. $Annual\ costs$ are the annual fees from the grid owner and the electricity trader and $Power\ costs$ are the costs for the capacity subscription for one year. $Outgoings_{Without}$ is calculated as

$$\begin{aligned} Outgoings_{Without} = \sum(E_{Bought,without} * Buy\, price)+ \\ + Annual\ costs + Power\ costs_{Without}\ [SEK]. \end{aligned} \tag{3.7}$$

The $Increased\ revenue$ from the system is

$$Increased\ revenue = Outgoings_{Without} + Income - Outgoings\ [SEK]. \tag{3.8}$$

The return is calculated by

$$Return = \frac{Increased\ revenue}{Investment\ costs}\ [\%] \tag{3.9}$$

where $investment\ costs$ are the costs for PV-modules and BESS. The equivalent battery unit wear after 25 years is calculated as

$$Equivalent\ unit\ wear = 25\frac{\Gamma_{A,year}}{\Gamma} \tag{3.10}$$

where $\Gamma_{A,year}$ is the amount of energy gone through the battery over one year. The integer of the $Equivalen\ unit\ wear$ is the number of times the battery storage has to be replaced during a 25 year period.

3.2 Strategy development

In the development of the strategies the examples of the local load, PV-production, electricity market and battery storage in Chapter 3.1 was used. As can be seen in Table 3.7 the mean price for electricity is around 1 SEK/kWh, meaning the profit is higher by using as much of the own produced electricity as possible and therefore is the basic hierarchy of the strategies to

1. use as much energy from the PV-modules as possible in the local load.
2. charge the batteries with remaining energy from PV-modules or discharge the battery to use in the local load if the energy from PV-modules is not enough.
3. sell remaining electricity to the grid or buy the missing electricity.

The differences between the strategies are the methods to increase the economic return of the EnergyHub. From Table 3.7 and Table 3.6 it can be seen that the prices that can affect the economic return, by implementing a control strategy, are the electricity price, the power price and the purchase price. The purchase price are dependent on time as can be seen in Figure 3.8(a) and the power price is dependent on the consumed power peaks from the grid. This means that by controlling the energy flow to buy and store electricity when it is cheap and use it when the price is high or keeping the consumed power peaks as low as possible could affect the economical outcomes. In the developing of following strategies these prices has been kept in mind.

Overproduction is handled in a similar way for the three strategies and can be seen in Figure 3.9. The inputs of the strategies are different for each strategy and is stated for each strategy. t in the flowchart stands for the sampling time, $P_{Load}(i)$ is the power from the E_{Load} array at the specific time and $P_{PV}(i)$ is the power from the E_{PV} array. $P_{Overprod}$ is the amount of power that is left after P_{Load} is satisfied and $P_{Bat,discharged}$ is the amount of power needed to charge the battery during one time sample.

$SOC(i)$ represents what the SOC level would be if the specific amount of energy would charge or discharge the battery. SOC_{Max} and SOC_{Min} are the limits of the battery operation window. SOC_{Min} is set after E_N and SOC_{Max} is set after $E_{Bat,full}$ which is the product of E_N and SOH. The initial SOC is set to SOC_{Max} since the simulation model only deals with SOC within the SOC window. $P_{Max,charge}$ and $P_{Max,discharge}$ are the maximal amount of energy that can charge or discharge the batteries due to the limitation currents from either the battery or converter. In the process boxes at the end, it can be seen how the different parameters of interest changes. P_{Bought} and P_{Sold} are the power bought and sold during the operation. It is assumed that the losses are only present during charging of the battery.

3.2.1 Strategy 1

Strategy 1 controls the energy flow by only considering the electrical statuses of the different power units and is the reference strategy in the development of the other strategies. In Figure 3.10 the flowchart of strategy 1 is shown when $P_{Load}(i) > P_{PV}(i)$. The inputs for the strategy are P_{Load}, P_{PV} and the $SOC(i-1)$ of the battery where (i-1) stands for the previous state. $P_{Missing}$ is the missing power in order to provide enough power to P_{Load}.

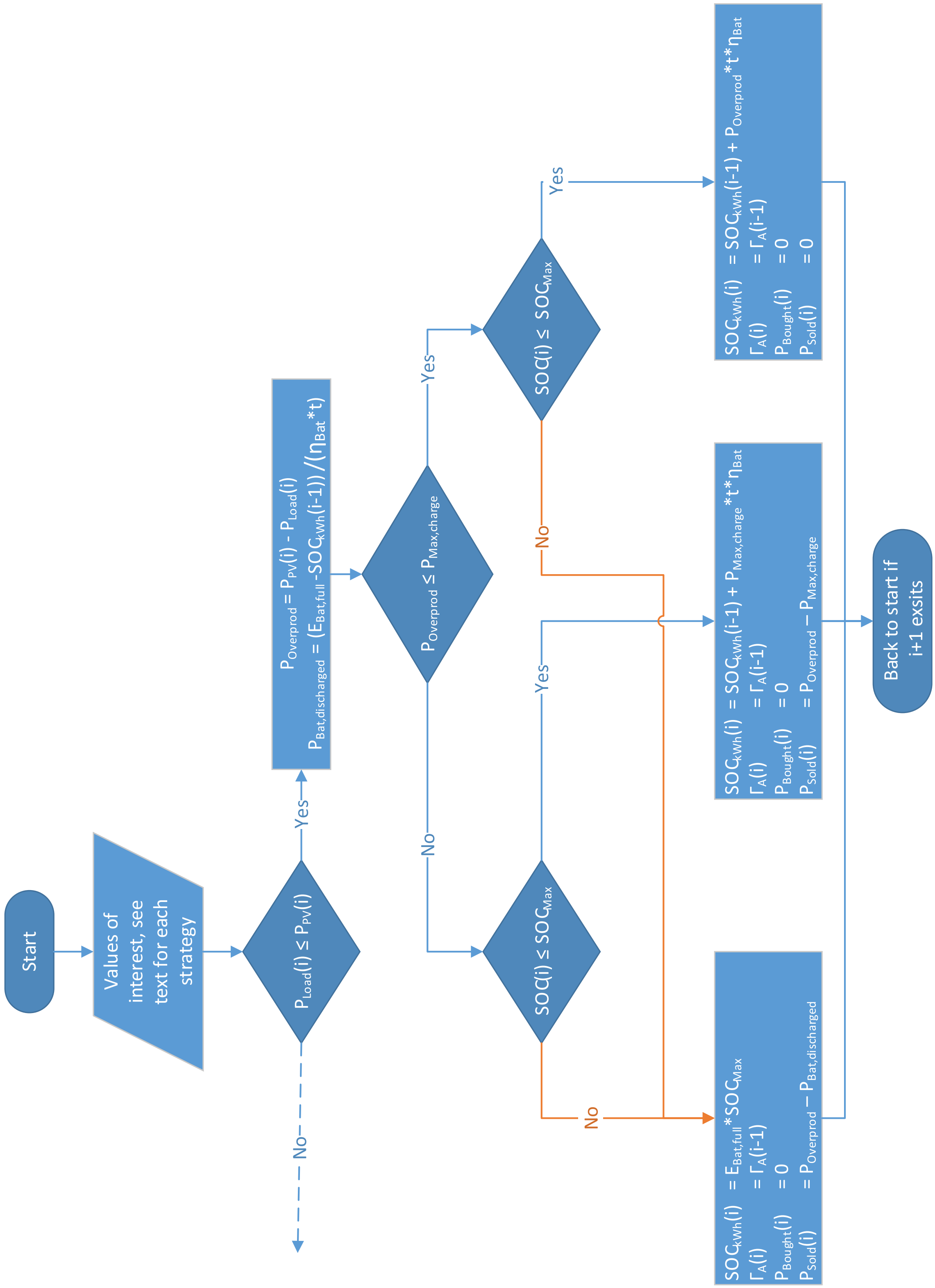


Fig. 3.9 Flowchart of the overproduction of the strategies.

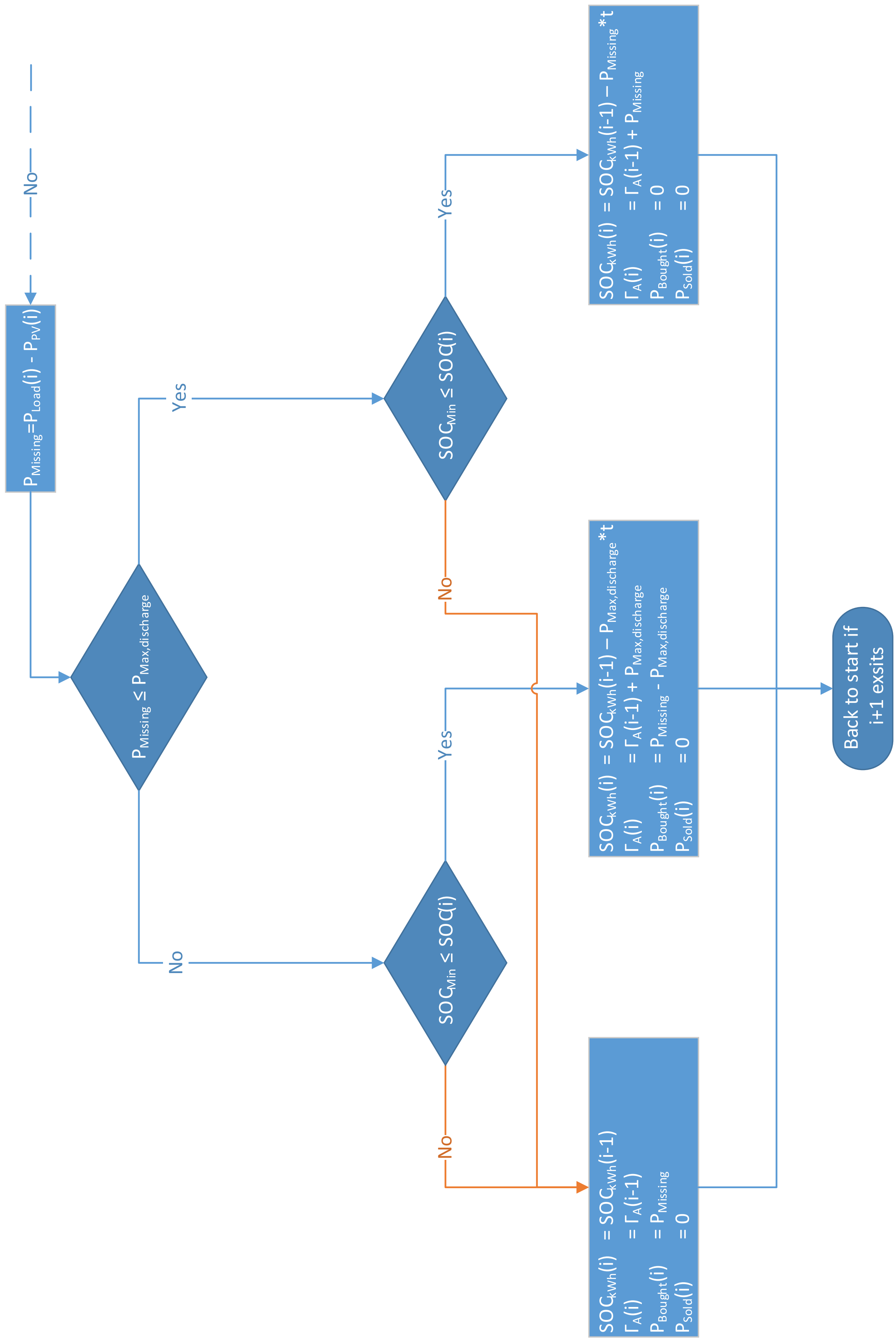


Fig. 3.10 Flowchart of strategy 1.

3.2.2 Strategy 2

Strategy 2 deals with the fact of changing electricity prices over the day. Therefore does this strategy require a variable hourly price contract with an electricity trader. At 13.00 each day the spot prices are decided on Nord Pool Spot for the next 24 hours. There is usually a price drop during the night and a price increase during the morning and afternoon. The objective of strategy 2 is to buy electricity to charge the batteries during the night when the prices are low ($Buytime$) and use the energy from the batteries in the morning when the price is high ($UseAM$). During the day the battery is charged with energy from the PV-modules and in the afternoon when the price is high the stored energy is used ($UsePM$).

Figure 3.11 shows the flowchart of strategy 2 when $P_{Load}(i) > P_{PV}(i)$ and Figure 3.9 shows when $P_{Load}(i) <= P_{PV}(i)$. The inputs for the strategy are P_{Load}, P_{PV}, the $SOC(i-1)$, $Buytime$, $Usetime$ and P_{Fuse}. P_{Fuse} is the maximal amount of power that can be bought from the grid because of the main fuse. The main difference from strategy 1 is the usage of $Buytime$ and $Usetime$. At 13.00 the spot prices for the next 24 hours are read from the third column of the Spotprice array ($Spotprice_{+24}$) and $Buytime$ and $Usetime$ are decided like in the flowchart in Figure 3.12. $Buytime$ and $Usetime$ are only defined if the energy stored in the battery will be consumed in the morning or in the afternoon. If $Buytime$ becomes NaN it means that extra energy to charge the battery with will not be bought during the night. If $UseAM$ or $UsePM$ becomes $always$, the energy stored in the battery will not be controlled to be used at a specific time in the morning or the afternoon respectively. $E_{Bat,usable}$ is the available energy of a fully charge battery and is calculated as

$$E_{Bat,usable} = E_N * SOH * (SOC_{Max} - SOC_{Min})\ [kWh]. \tag{3.11}$$

In the flowchart in Figure 3.12 $E_{Load,-24}$, and $E_{PV,-24}$ are the section of E_{Load} and E_{PV} for the previous 24 hours. $t_{PV,stop}$ is the first full hour where the PV-modules have stopped producing energy previous night and $t_{PV,start}$ is the hour the PV-modules have started producing energy this morning. E_{Net} represents the net consumption of E_{Load} and E_{PV} during a specific time interval. $Buytime$ and $Usetime$ are first defined when there is a whole section of $E_{Load,-24}$, and $E_{PV,-24}$ and are stopped defined when there is not a whole section of $Spotprice_{+24}$ left.

3.2.3 Strategy 3

Strategy 3 is based on reducing the consumed power peaks from the grid. The flowchart of the strategy when $P_{Load}(i) > P_{PV}(i)$ is presented in Figure 3.13 and Figure 3.9 shows when $P_{Load}(i) <= P_{PV}(i)$. In this strategy the battery is used to keep the hourly mean power ($P_{Bought,hourly}$) beneath a limit ($Limit$). As can be seen in Chapter 3.1.3 the power price is decided on different numbers of power peaks for the different grid owners. If $P_{Bought,hourly}$ has exceeded $Limit$ the number of power peaks, $Limit$ is set to the lowest power peak of the power peaks counted for. It does this by calculating what $P_{Bought,hourly}$ would be if the consumed power right now would be constant the hour out. If $P_{Bought,hourly}$ will exceed $Limit$, the stored energy in the battery is used to reduce $P_{Bought,hourly}$ to either $Limit$ or to low as possible. Otherwise, if $P_{Bought,hourly}$ is lower than $Limit$, the battery is charged under the criteria that $P_{Bought,hourly}$ will not exceed $Limit$.

The inputs to the strategy are P_{Load}, P_{PV}, the $SOC(i-1)$, t_{Left}, E_{BH} and $Limit$ where, t_{Left} is the time left of the full hour and E_{BH} is the already bought energy this hour. In the end of the hour E_{BH} is the same as $P_{Bought,hourly}$ since the hourly mean power is the same as energy during that hour. $P_{Compensate}$ is the amount of power that has to be discharged from the battery in order to keep $P_{Bought,hourly}$ beneath $Limit$. If the power prices are only during specific hours, as for Sollentuna Energi, $Limit$ is set to infinity during these hours.

One of the critical decision in strategy 3 is to decide the initial value for $Limit$ in each month. If the grid owner decides the power price only on the highest power peak, the initial value for $Limit$ of the month is the same as from the month before. Furthermore, it is assumed that the power consumption during the night is lower compared to during the day, which could be seen in Figure 3.4(b). Therefore is $Limit$, after the first hour of the month, set to $P_{Bought,hourly}$ of that hour. In the case where the number of power peaks counted for is more than one $Limit$ is set to 0 initially of each month. These decisions has to do with that the price is more dependent on $P_{Bought,hourly}$ exceeding $Limit$ when only one power peak is counted for than when severel power peaks are counted for.

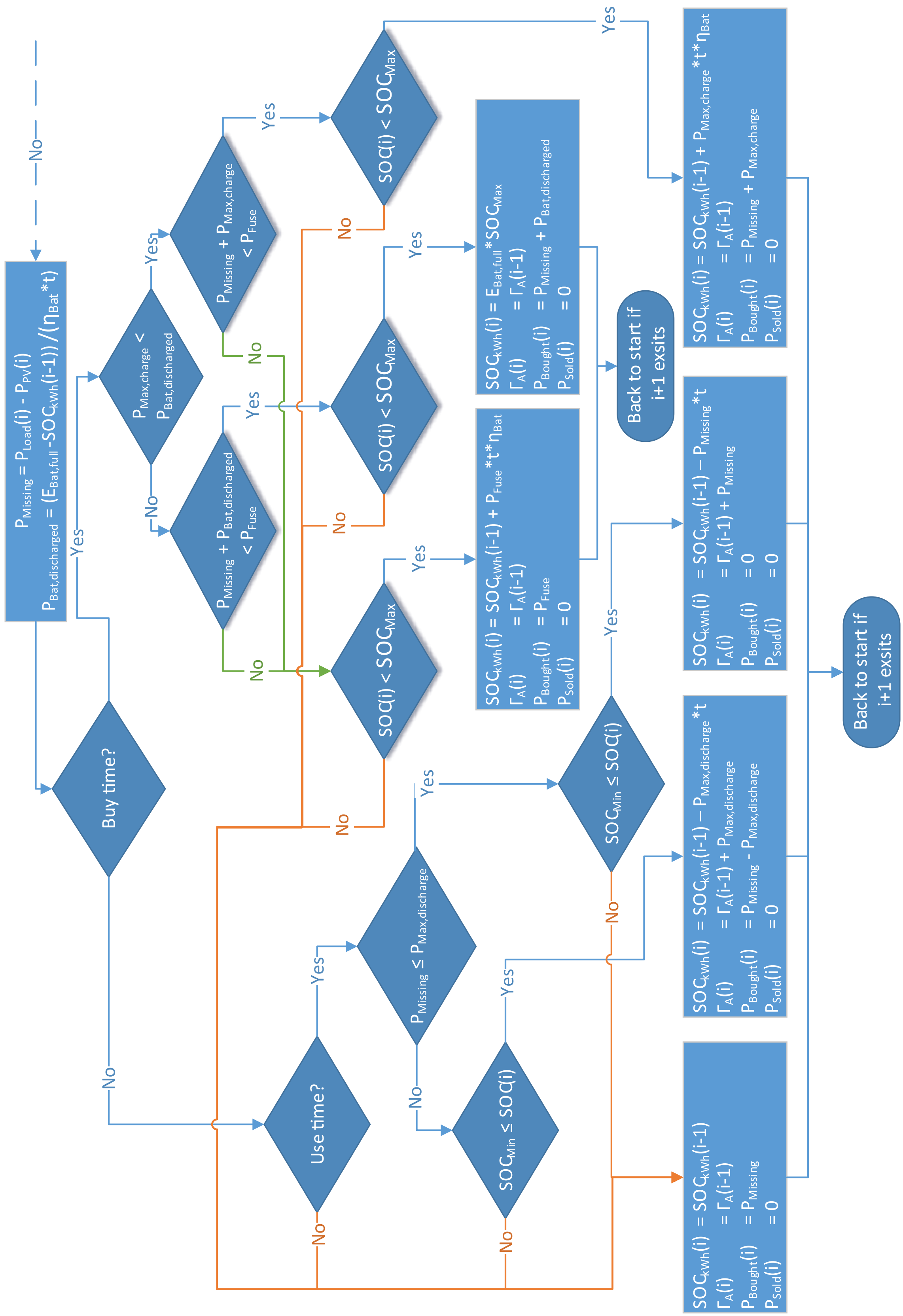


Fig. 3.11 Flowchart of strategy 2.

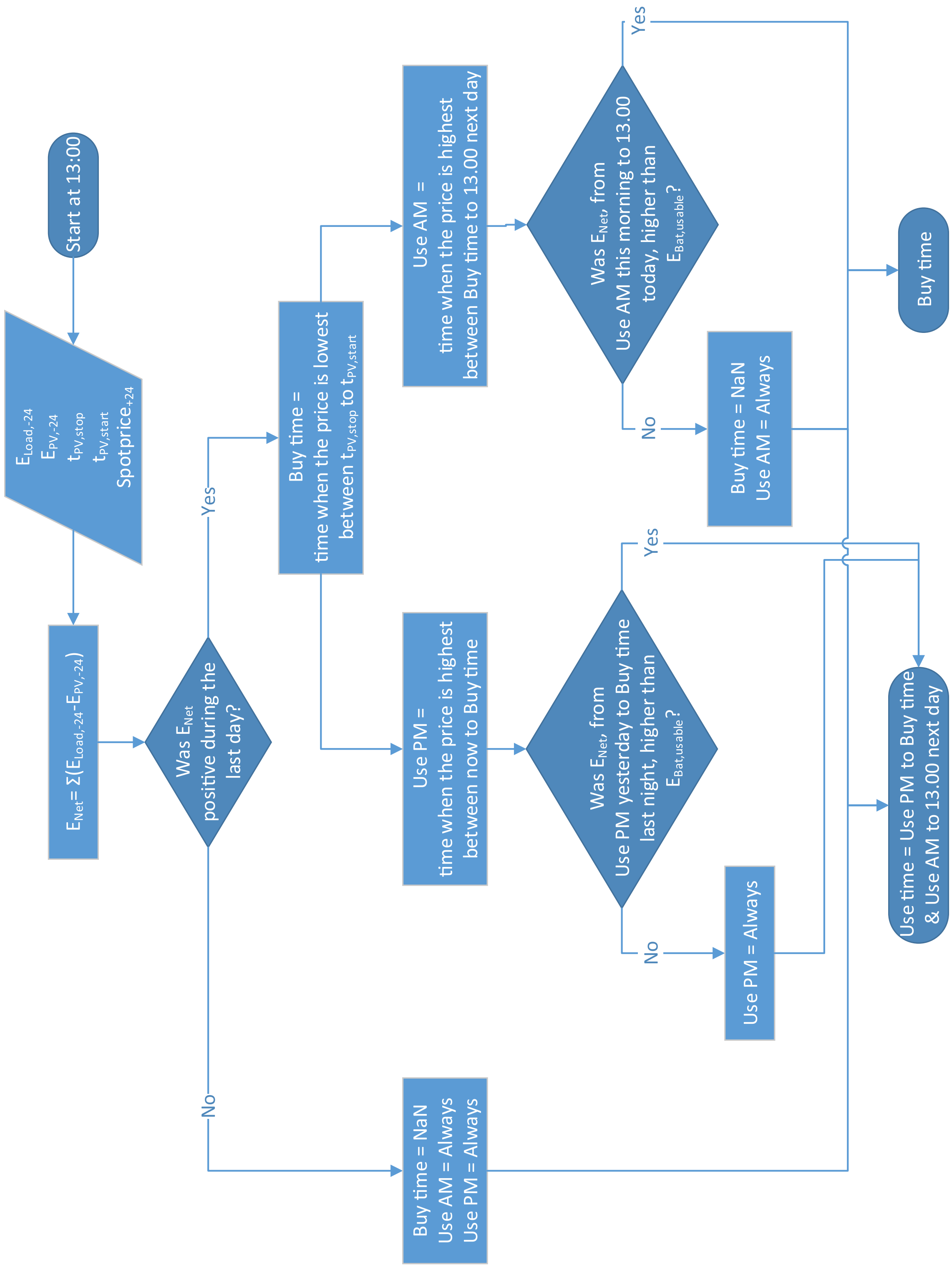


Fig. 3.12 Flowchart to decide Buy time and Use time.

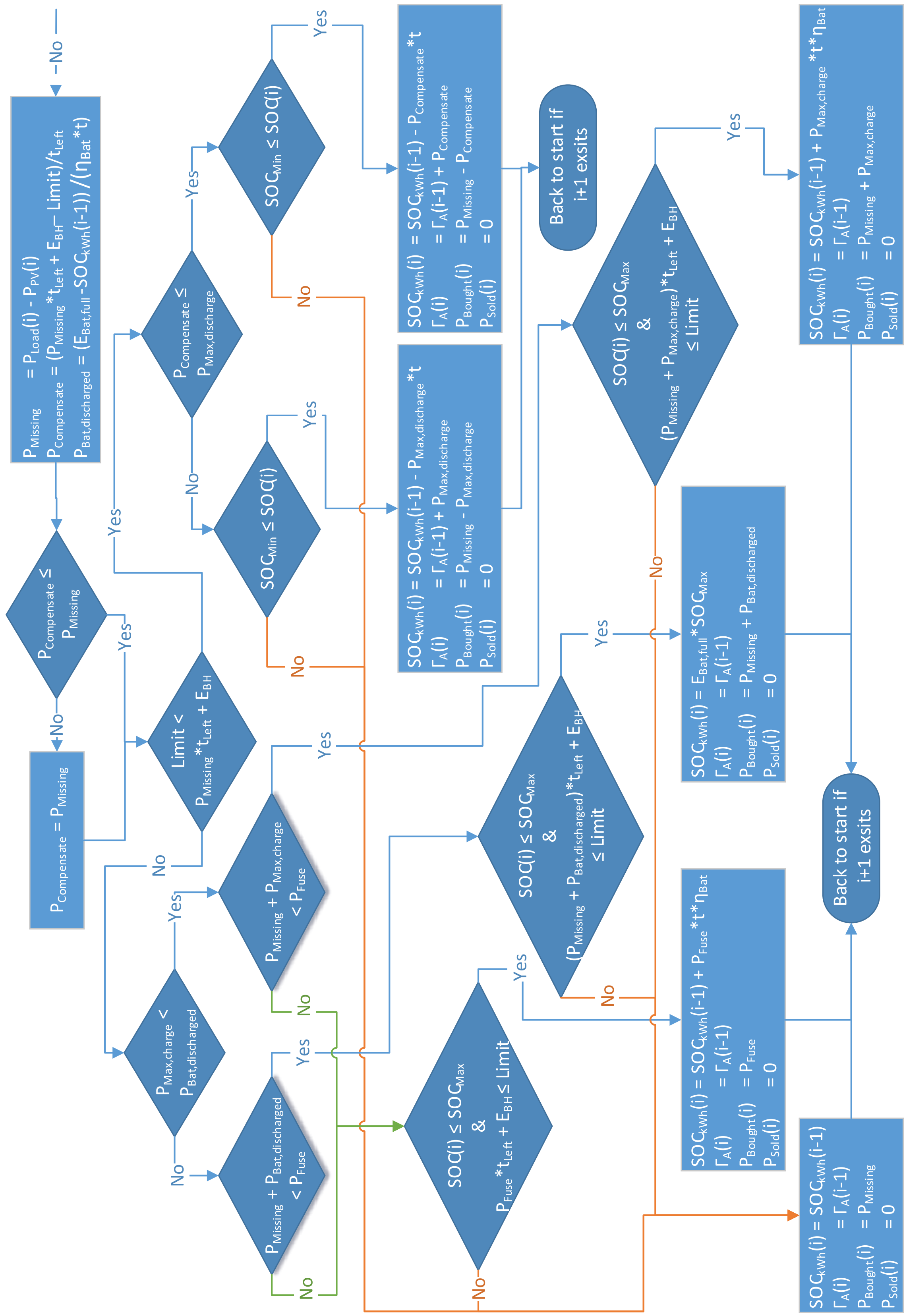


Fig. 3.13 Flowchart of strategy 3.

Chapter 4

Analysis

The analysis of the strategies has been done with the P_{Load}, the P_{PV} and Fortum Market as electricity trader given in Chapter 3.1. As purchase price the spot price given in that chapter will be used. For the electricity certificate it is assumed that the measuring is at the connection to the grid. Both the lead acid and Li-ion battery from Chapter 3.1 will be analysed as will the three different grid owner's grid subscription.

4.1 Strategy 1

Strategy 1 is developed to control the energy flow considering the electrical statuses of the different power units. First, the behaviour of strategy 1 is described and furthermore, an economical analysis has been performed where the increased revenue and return after the first year and the equivalent battery unit wear after 25 years are presented.

4.1.1 Behaviour of strategy 1

In Figure 4.1 and Figure 4.2 the behaviour of strategy 1 is presented for the Li-ion battery. In Appendix A.2 the behaviour of strategy 1 with a lead acid battery can be observed. The information about Figure 4.1 and Figure 4.2 is also for the lead acid battery. The graphs to the left in the figures show the results with E_N of 2,112 kWh and to the right with E_N of 14,976 kWh. These sizes was chosen to show the behaviour of a small battery and a big battery. For strategy 1, the behaviour will be the same for all the three grid subscriptions since it only considers the electrical statuses of the power units.

In Figure 4.1(a) and Figure 4.1(b) SOC of the battery is shown and it can be observed that the battery is operating within the stated SOC window. Furthermore, the upper SOC limit is decreasing and the lower SOC limit is constant, as explained in Chapter 3.1.4. In Figure 4.1(c) and Figure 4.1(d) the mean hourly bought power ($P_{Bought,hourly}$) and the mean hourly sold power ($P_{Sold,hourly}$) to the grid is shown. From these four figures, it can be observed that during the summer the daily peak power productions from the PV-modules must be higher than the consumed power in the house. This can also be observed by the fact that the battery is charged more often and that more electricity is sold during summertime. During wintertime the power production is lower than the consumed power in the house and therefore there is no or little power left to charge the battery with or sell to the grid. Comparing this with P_{Load} and P_{PV} in Figure 3.3 and Figure 3.5 in Chapter 3.1 it can be seen that the observations are true, there is higher daily peak power productions than consumed power in the house during summer and the other way around in the winter.

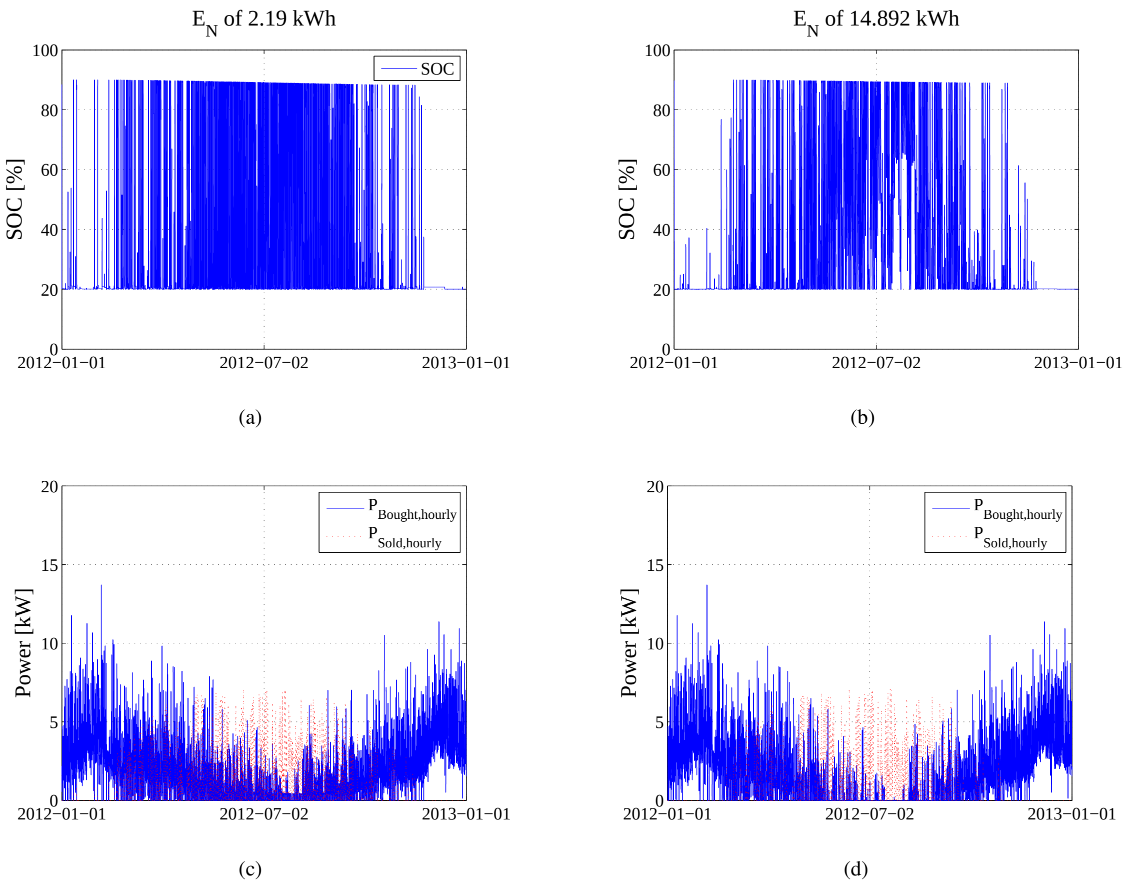
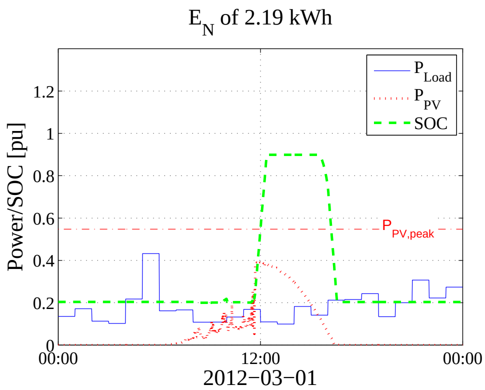
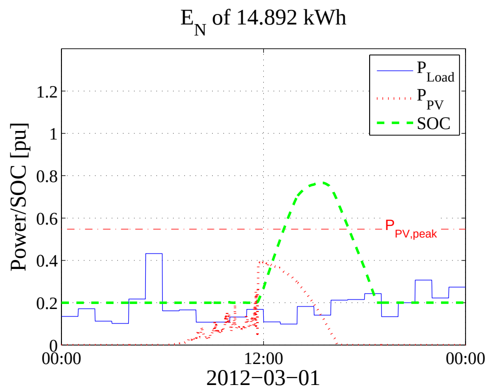


Figure 4.1: SOC, $P_{Bought,hourly}$ and $P_{Sold,hourly}$ of strategy 1 with the Li-ion battery over the time period of 2012. In the graphs to the left E_N is 2,112 kWh and to the right E_N is 14,976 kWh.

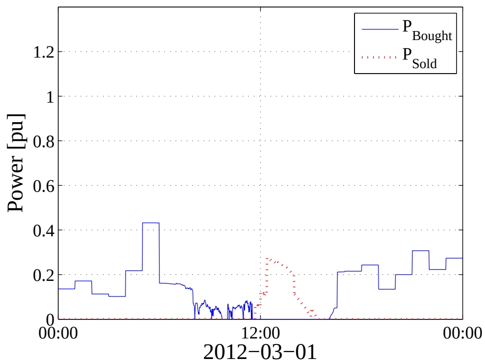
Figure 4.2(a)-Figure 4.2(d) shows the behaviour of Strategy 1 over one day in per unit (pu). 1 pu for SOC corresponds to E_N, 1 pu of P_{Load}, P_{PV}, P_{Bought} and P_{Sold} corresponds to the highest P_{Load} over the year which for this local load is 13,7 kW. P_{Bought} is the bought power from the grid, P_{Sold} is the sold power to the grid and $P_{PV,peak}$ is the installed peak power of the PV-modules. In the beginning of this day all the consumed power in the house is bought from the grid because the battery is discharged at the lower SOC limit and can not be used. In the morning the PV-modules starts to produce power but it seems the irradiation on the modules are inhibited by the angle of the sun and the weather. At noon the P_{PV} becomes higher than P_{Load} and the battery starts to charge. The reason the SOC is not increasing to 80 % directly and instead energy is sold to the grid, is due to the charging current limitation of the converter. The overproduced power from P_{PV} is charging the battery and the rest is sold to the grid. When the battery is charged to the upper SOC limit all the overproduced power is sold to the grid. When P_{PV} becomes less than P_{Load} the battery is discharged to the lower SOC limit and after the lower SOC limit is reached the power is bought from the grid. The main difference between a battery of 2,112 kWh and 14,976 kWh is that less energy is sold to and bought from the grid for the 14,976 kWh battery. This can specially be observed between Figure 4.2(c) and Figure 4.2(d).



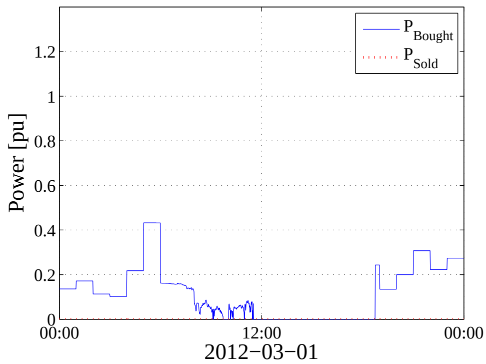
(a)



(b)



(c)

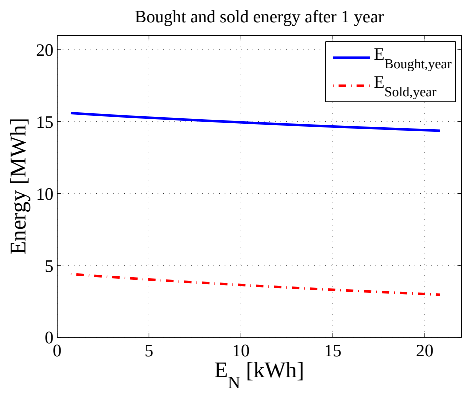


(d)

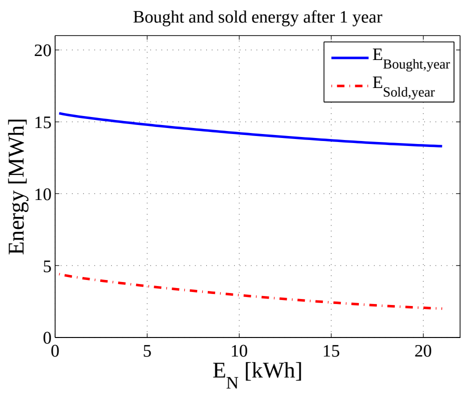
Figure 4.2: Behaviour of strategy 1 with the Li-ion battery over a day. In the graphs to the left is 2,112 kWh and to the right is 14,976 kWh. 1 pu for the powers corresponds to 13,7 kW and for the SOC to E_N

Comparing the lead acid battery with the Li-ion battery, the operation window of the SOC for the lead acid battery is between 50-80 % and for Li-ion 20-90 %. For the same E_N this results in more usable energy available with a Li-ion battery than with a lead acid battery, 1,4 kWh and 0,6 kWh respectively, for E_N of 2 kWh. Another difference between the battery types, which comes from the series connection of the batteries, are the maximal amount of power that can charge ($P_{Max,charge}$) or discharge ($P_{Max,discharge}$) them. The slope of SOC is steeper for the Li-ion than for the lead acid battery for the given constrains. The reason is that, for example, the output voltage of a 15 kWh battery is about 240 V and 1500 V for the lead acid and Li-ion battery respectively. With a charge and discharge current limitation of 10 A the maximal amount of power that can charge or discharge the batteries is about 2.4 kW and 15 kW, respectively. Because of this no comparison between the batteries can be done since they behaves different.

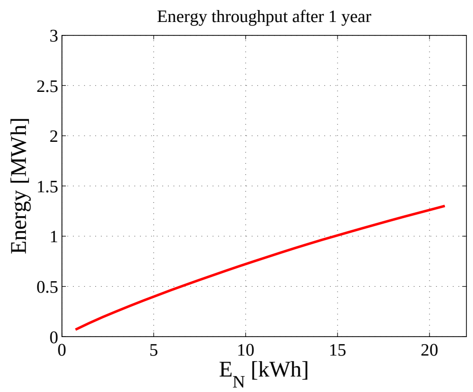
Figure 4.3 shows the yearly bought energy from the grid $E_{Bougth,year}$, the yearly sold energy to the grid $E_{Sold,year}$ and the yearly energy throughput (Γ_A) of the battery at different battery sizes. The graphs to the left shows the results for the lead acid battery and those to the right shows the results for the Li-ion battery. It can be observed that $E_{Bougth,year}$ and $E_{Sold,year}$ is decreasing linearly and Γ_A has an logarithmic increase. This means that there is a higher energy throughput of a bigger battery than for a smaller but the bigger battery is used less seen to its size. This can also be observed in Figure 4.1(a) and 4.1(b), the bigger battery is not always charged to the upper limiter and in the summer there are days that the battery is not discharged to the lower limiter.



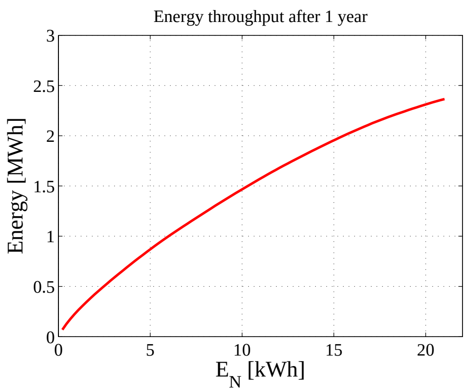
(a)



(b)



(c)



(d)

Figure 4.3: The bought energy from the grid, the sold energy to the grid and the energy throughput of the battery after 1 year for strategy 1. The graphs to the left show the results with the lead acid battery and to the right with the Li-ion battery.

4.1.2 Economic analysis of Strategy 1

Figure 4.4 shows the economical results for strategy 1 with the different grid owners and the equivalent battery unit wear after 25 years. The graphs to the left shows the results with the lead acid battery and to the right with the Li-ion battery. Fig 4.4(a)-Fig 4.4(d) shows the increased revenues and the return after one year. The economical results are calculated as explained in Chapter 3.1.5. The return is in percentage and is calculated on the investment cost of 165000 SEK for the installation of the PV-system and 1500 SEK/kWh$_{E_N}$ or 10000 SEK/kWh$_{E_N}$ for the lead acid and the Li-ion battery respectively. GE, SOL and FE, in the legend, stands for Göteborg Energi, Sollentuna Energi and Falbygdens Energi respectively and the number is the strategy number.

It can be observed that for Göteborg Energi and Falbygdens Energi the increased revenues increases with E_N but the return is decreasing. This means that the increase rate of the increased revenues are lower than the increase rate of the investments of the PV-system with a BESS. For Sollentuna Energi, on the other hand, the increased revenues decreased with E_N and this results in a higher decrease for the return. The variation between the different grid owners in the economical return mainly depends on the differences in compensation. Sollentuna Energi is giving 1 SEK/kWh in compensation but the return would be about the same as for the other grid owners if a few Ã¶re would be used instead.

By studying these graphs conclusions can be made that the economical return is very dependent on the prices from the grid owners. This means that the conditions of installing PV-modules are different from place to place since the grid owner can not be chosen.

One interesting thing in the graphs are the small decreasing steps that are at E_N of about 5 kWh and 19 kWh for the lead acid battery and at about 2 kWh and 9 kWh for Li-ion battery. These steps are due to that an electricity certificate is lost when $E_{Sold,year}$ is decreasing beneath an integer, which can be observed in Figure 4.3(a) and Figure 4.3(b). This means that 225 SEK is lost and this affects the economical results. That the steps are steeper for Li-ion is only due to that the increase of E_N for the Li-ion battery is smaller in the simulations.

Figure 4.4(a)-Figure 4.4(d) only shows what the economical results are after the first year, but in the long run there are components in the PV-system that has to be changed. The converter is assumed to be changed at least one time during a 25 year period. Figure 4.4(e) and Figure 4.4(f) shows the equivalent battery unit wear after 25 years for different E_N of the lead acid and the Li-ion battery. This means that for smaller batteries the battery has to be changed about 2-3 times and with bigger batteries the wear is lower and the battery does not need to be replaced as often. This has to do with the ratio between Γ_A and Γ. With a bigger battery, Γ has a higher value but Γ_A is less seen to the corresponding E_N. This can also be observed in the energy throughput for the Li-ion battery in Figure 4.3 and in the SOC graph in Figure 4.1 where the battery is cycled more for the smaller E_N than for the bigger. The replacement of the batteries has not been included in the economical calculations and has to also be considered in the comparison of the different strategies.

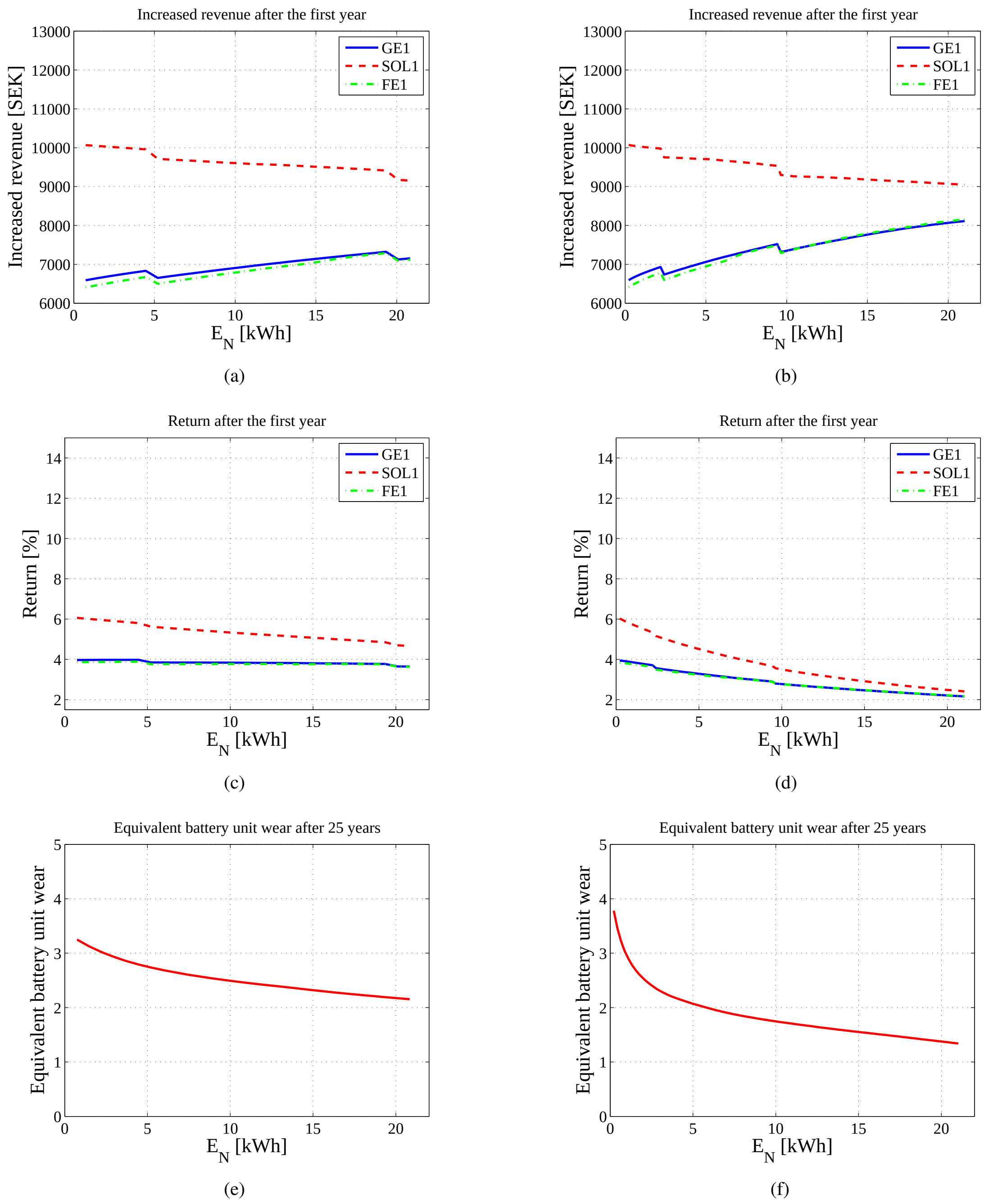


Figure 4.4: The economical return of the PV-system with battery after the first year both in SEK and percentage and also the equivalent battery unit wear after 25 years with strategy 1 for different E_N. The graphs to the left show the results with the lead acid battery and to the right with the Li-ion battery.

4.2 Strategy 2

Strategy 2 is developed to buy energy in the night to charge the battery when the electricity price is low and to use the charged energy in the battery when the price is high in the morning and the afternoon. First, the behaviour of strategy 2 is described and furthermore, an economical analysis has been performed where the increased revenue and return after the first year and the equivalent battery unit wear after 25 years are presented. At last an economical sensitivity analysis is presented where different prices has been changed.

4.2.1 Behaviour of strategy 2

In Figure 4.5 and Figure 4.6 the behaviour of strategy 2 is presented for the Li-ion battery. In Appendix A.3 the behaviour of strategy 2 with a lead acid battery can be observed. The information about Figure 4.5 and Figure 4.6 is the same for the lead acid battery. The graphs to the left in the figures show the results with E_N of 2,112 kWh and to the right with E_N of 14,976 kWh. To be noticed is that the zoomed in days in Figure 4.6 is not the same as in Figure 4.2 since these days gives more interesting information. To see the same days as for Figure 4.2, see Appendix A.4. In the figures Göteborg Energi has been used as grid owner.

The SOC in Figure 4.5(a) and Figure 4.5(b) is similar to the SOC in Figure 4.1(a) and Figure 4.1(b), from strategy 1, with the exception from that the battery is used more often during the winter period. In Figure 4.5(c) and Figure 4.5(d) $P_{Bought,hourly}$ and $P_{Sold,hourly}$ is shown. As in strategy 1 it can be observed that there is more power sold during the summer than in the winter. When there is an overproduction, which is either higher than $P_{Max,charge}$ or when the battery is charged to the upper SOC limit, this is also sold to the grid.

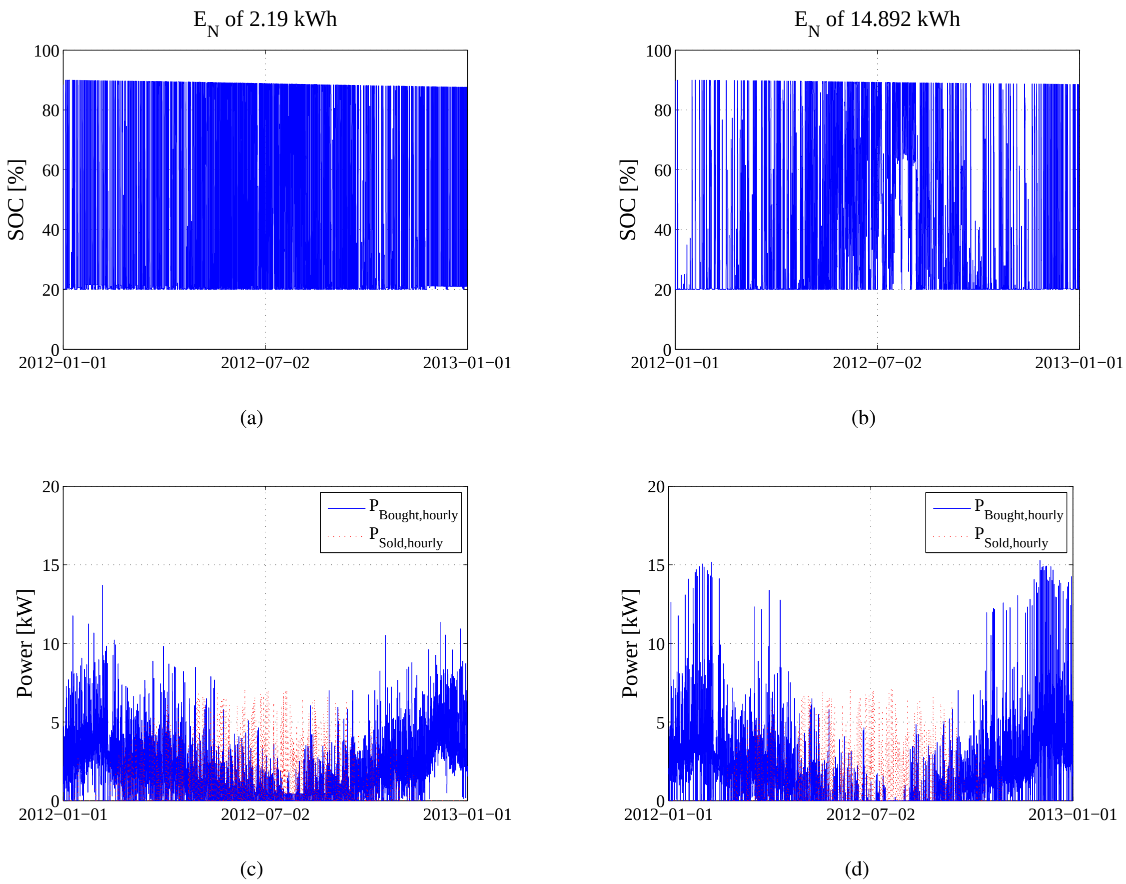


Figure 4.5: SOC, $P_{Bought,hourly}$ and $P_{Sold,hourly}$ of strategy 2 with the Li-ion battery and Göteborg Energi as grid owner over the time period of 2012. In the graphs to the left E_N is 2,112 kWh and to the right E_N is 14,976 kWh.

In Figure 4.6 the behaviour of strategy 2 is shown over one day. 13.00 the day before it was decided that during the night between 02.00-03.00 energy should be bought from the grid to charge the battery and be used with start from 07.00. This was performed because E_{Net} was positive between 07.00-13.00 the day before and the lowest price in the night was between 02.00-03.00.

At 09.20 the PV-modules starts to produce more power than is consumed and the battery is being charged. Between 12.00-13.00, P_{PV} is mainly less than P_{Load} and the battery is being discharged during this time. At 13.00 the new spot prices are downloaded and it is decided that the stored energy in the battery should be used first after 17.00 because E_{Net} was positive between 17.00-13.00 the day before and the highest price in the afternoon was between 17.00-18.00. The time period 17.00-13.00 comes from that it was decided not to define $Buytime$ during the coming night, which is not illustrated in the figures. In the graphs it can also be observed that, as for strategy 1, when there is an overproduction, which is either higher than $P_{Max,charge}$ or when the battery is charged to the upper SOC limit, this is also sold to the grid.

One difference between the lead acid and the Li-ion battery, except the SOC window, is that the battery is not charged to the upper SOC limiter for the lead acid battery during $Buytime$. This is because $P_{Max,charge}$ is to small too charge the battery to the upper SOC limit during one hour.

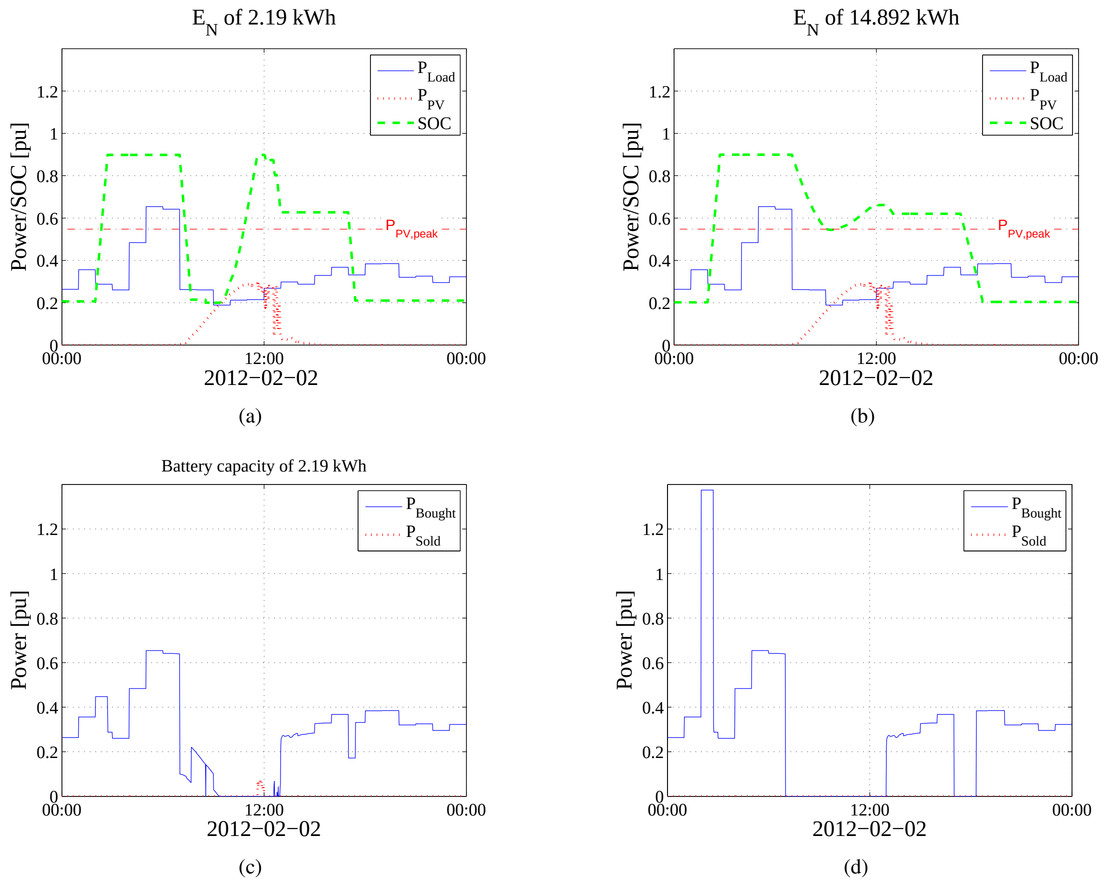


Figure 4.6: Behaviour of strategy 2 with the Li-ion battery and Göteborg Energi as grid owner over a day. In the graphs to the left E_N is 2,112 kWh and to the right E_N is 14,976 kWh. 1 pu for the powers corresponds to 13,7 kW and for the SOC to E_N.

Figure 4.7 shows $E_{Bougth,year}$, $E_{Sold,year}$ and Γ_A of the battery after one year, at different capcity sizes. The graphs to the left shows the results for the lead acid battery and those to the right shows the results for the Li-ion battery. Comparing these graphs with those in Figure 4.3 there is only a slightly increase of $E_{Bougth,year}$ and $E_{Sold,year}$, which can not be observed in the graphs, and a higher increase for Γ_A. $E_{Bougth,year}$ and $E_{Sold,year}$ should almost be the same since bought energy is only at another time and the battery should be empty when the PV-modules are producing. The energy throughput of the battery should also increase due to that energy is bought to charge the battery.

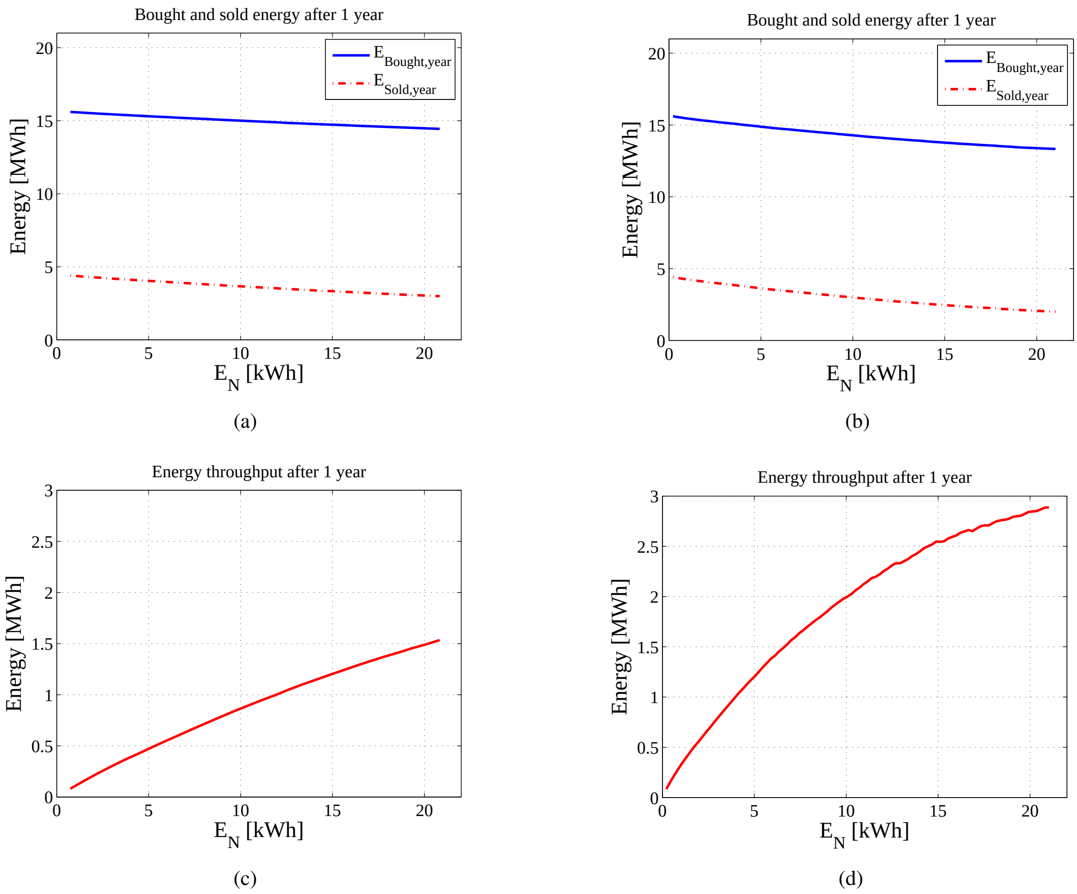


Figure 4.7: The bought and the sold energy to the grid and the energy throughput of the battery after 1 year for strategy 2. The graphs to the left show the results with the lead acid battery and to the right with the Li-ion battery.

4.2.2 Economic analysis of Strategy 2

Figure 4.8 shows the economical results for strategy 1 (GE1) and strategy 2 (GE2) with Göteborg Energi as grid owner and the equivalent battery unit wear after 25 years for strategy 2. The graphs to the left shows the results with the lead acid battery and to the right with the Li-ion battery. The return is in percentage and is calculated on the investment cost of 165000 SEK for the installation of the PV-system and 1500 SEK/kWh$_{E_N}$ or 10000 SEK/kWh$_{E_N}$ for the lead acid and the Li-ion battery respectively.

In the graphs it can be observed that there is a slight increase of the economical results for strategy 2 compared to strategy 1. On the other hand, the equivalent battery unit wear has after 25 years also increased which was expected since the battery is used more in strategy 2 compared to strategy 1. This makes it difficult to define if there is an economical benefit after 25 years since it is unknown what the prices will be in the future and the replace batteries are not included in the economical results. If the battery prices will decrease it can be economically feasible to use the battery more in order to make a small increase of the economical result.

Furthermore, it can be observed in Figure 4.8 that there are decreasing steps in the economical results for different E_N. These are due to the loss of an electricity certificate as was explained in Chapter 4.1.2. One difference is that the steps are a bit displaced to a bigger E_N. This is connected with the small increase of $E_{Sold,year}$ for strategy 2 compared to strategy 1.

Economical results for strategy 2 with Falbyggdens Energi and Sollentuna Energi was also calculated. It was observed that differences between strategy 1 and strategy 2 for the grid owners were as the difference between the strategies for Götgeborg Energi.

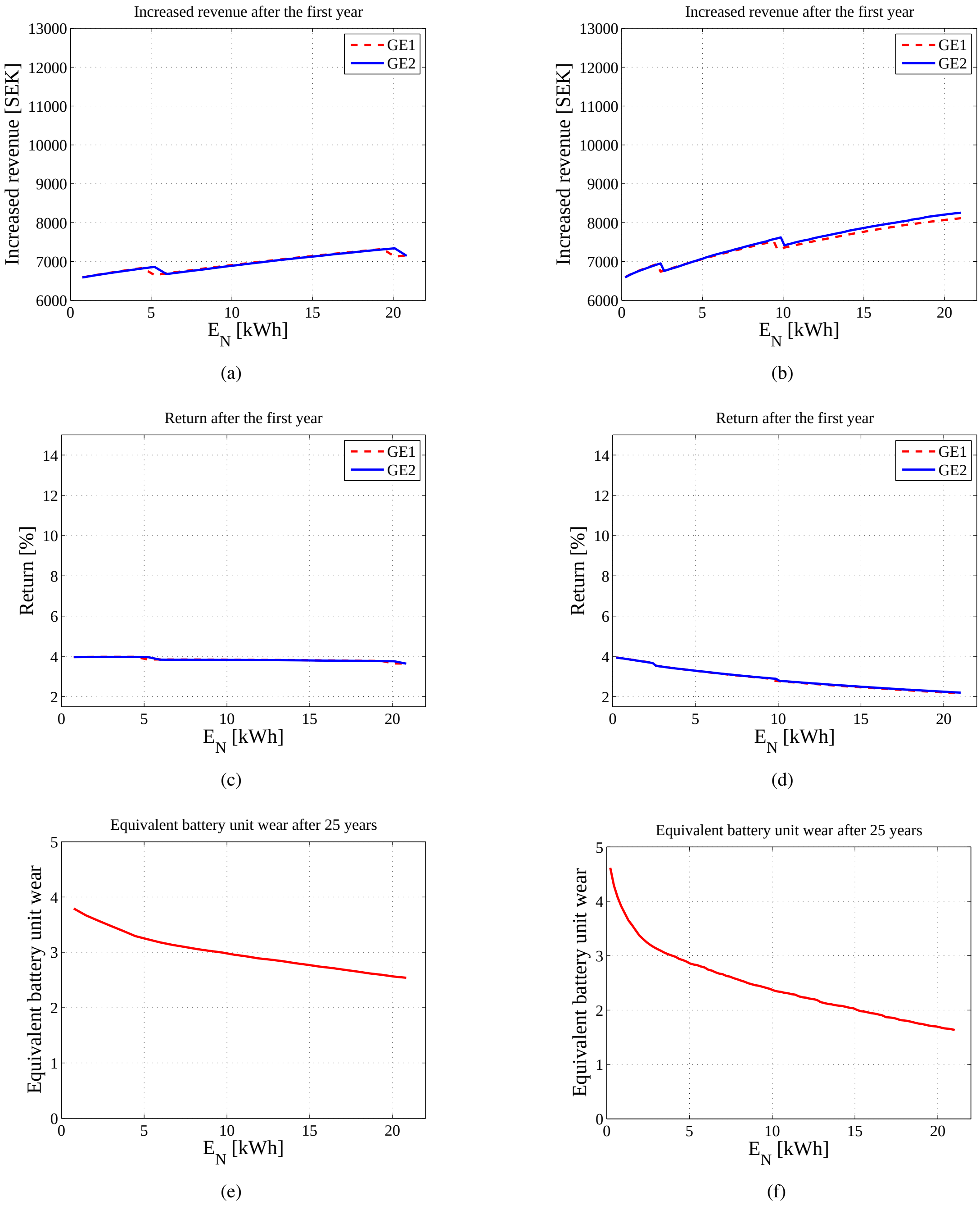


Figure 4.8: The economical return of the PV-system with battery after the first year both in SEK and percentage and also the equivalent battery unit wear after 25 years with strategy 2 for different E_N. The graphs to the left show the results with the lead acid battery and to the right with the Li-ion battery.

Figure 4.9 shows the economical results when different prices has been changed with Göteborg Energi as grid owner. The default graph is the graph from Figure 4.8 for strategy 2 and the value in the legend is the factor the default price has been changed with. In Figure 4.9(a) and Figure 4.9(b) only the battery price has been changed. The default battery price is 1500 SEK/kWh$_{E_N}$ and 10000 SEK/kWh$_{E_N}$ for the lead acid and the Li-ion battery respectively. It can be observed that changing the battery price will mainly affect the economical results for bigger E_N. This is as expected since the investment cost will be more affected for higher E_N.

In Figure 4.9(c) and Figure 4.9(d) the installation costs for the PV-modules has been set to half and then the battery price has been changed. The default price for the PV-modules was 165000 SEK. It can be observed that changing the price for the PV-modules will almost double the return for small E_N, which is expected due to that the main costs are the installations costs for the PV-modules. For bigger E_N the battery cost has more impact on the investment costs, than for small E_N, and the return goes down.

In Figure 4.9(e) and Figure 4.9(f) the spot price has been changed in order to see the impact of the PV-system with a BESS. It can be observed that changing the spot price mainly affect the offset of the return. The small changing in steepness of the curves are due to the combination of the increase of investment costs and that less is sold and bought from the grid for bigger E_N.

$Buytime$ and $Usetime$, in strategy 2, is defined on the E_{Load} and E_{PV} from the last 24 hours. An analysis was performed to see what the economical results would be if it was know exactly how E_{Load} and E_{PV} would be for the next 24 hours. The results was almost the same as for the default graph with minor changes, both positive and negative. An analysis was also performed with changing the variance of the spot price which gave about the same result as for the default graph.

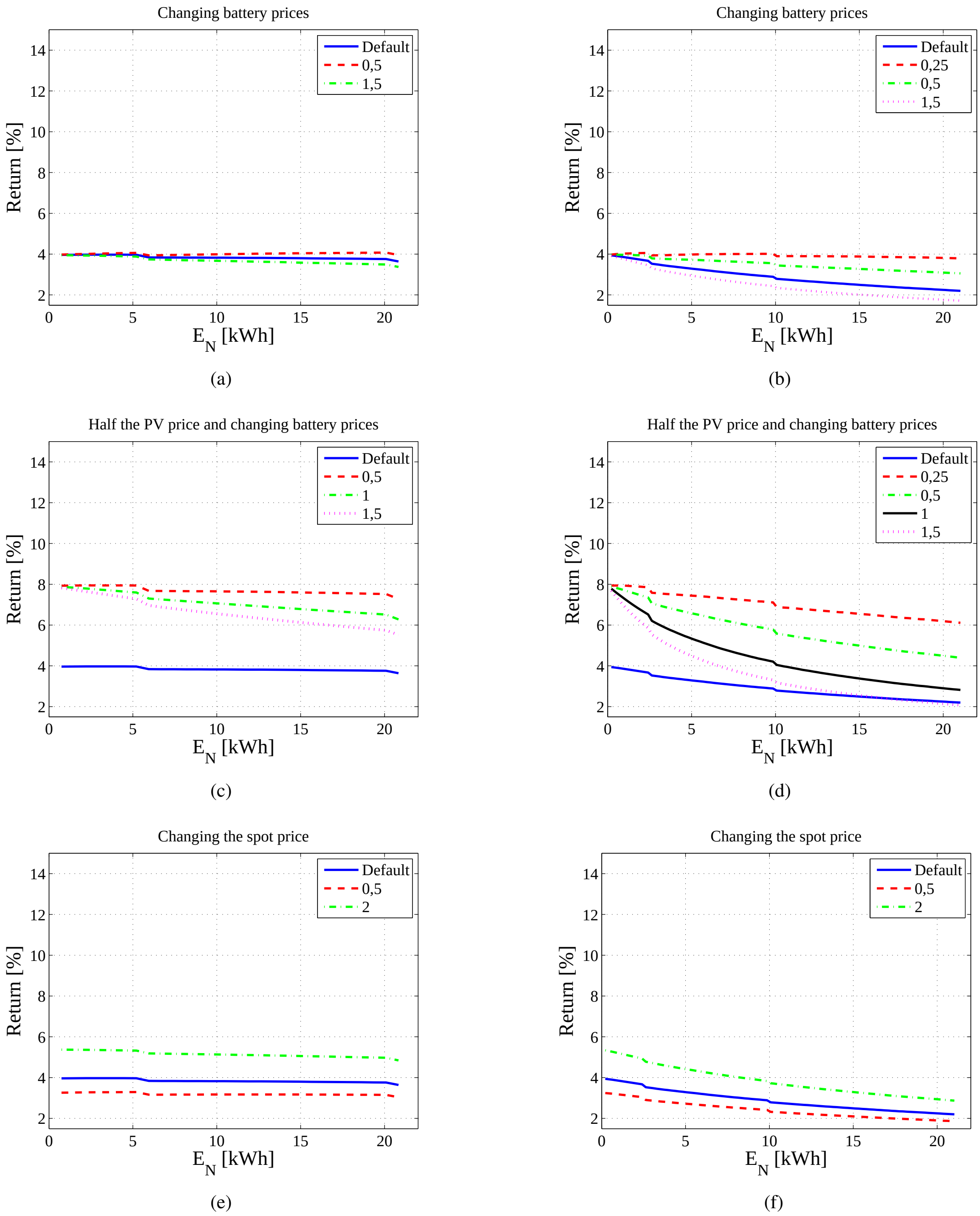


Figure 4.9: Analysis where different prices has been changed. The default graph is the resulting return with the prices described earlier with Göteborg Energi as grid owner. The graphs to the left is the resulting return for the lead acid battery and to the right for the Li-ion battery.

4.3 Strategy 3

Strategy 3 is developed to keep the hourly mean power consumption from the grid ($P_{Bought,hourly}$) beneath a limitation ($Limit$). First, the behaviour of strategy 3 is described and furthermore, an economical analysis has been performed where the increased revenue and return after the first year and the equivalent battery unit wear after 25 years are presented. One economical sensitivity analysis is presented where different prices has been changed.

4.3.1 Behaviour of strategy 3

In Figure 4.10 and Figure 4.11 the behaviour of strategy 3 is presented for the Li-ion battery. In Appendix A.2 the behaviour of strategy 3 with a lead acid battery can be observed. The information about Figure 4.10 and Figure 4.11 is the same for the lead acid battery. The graphs to the left in the figures show the results with E_N of 2,112 kWh and to the right with E_N of 14,976 kWh. The zoomed days are the same days as for Figure 4.2. In the figures, Falbygdens Energi has been used as grid owner.

Figure 4.10(a) and Figure 4.10(b) show the SOC over the year and it can be observed that the battery is used in a different way compared to the corresponding figures for strategy 1 and 2. Instead of using the battery in order to store as much of the own produced energy it is used to reduce $P_{Bought,hourly}$. In Figure 4.10(c) and Figure 4.10(d) it can be observed that $Limit$ is set after $P_{Bought,hourly}$, when $P_{Bought,hourly}$ has exceeded $Limit$. Falbygdens Energi is deciding their power prices on the highest power peak each month and therefore is $Limit$ set to that power peak.

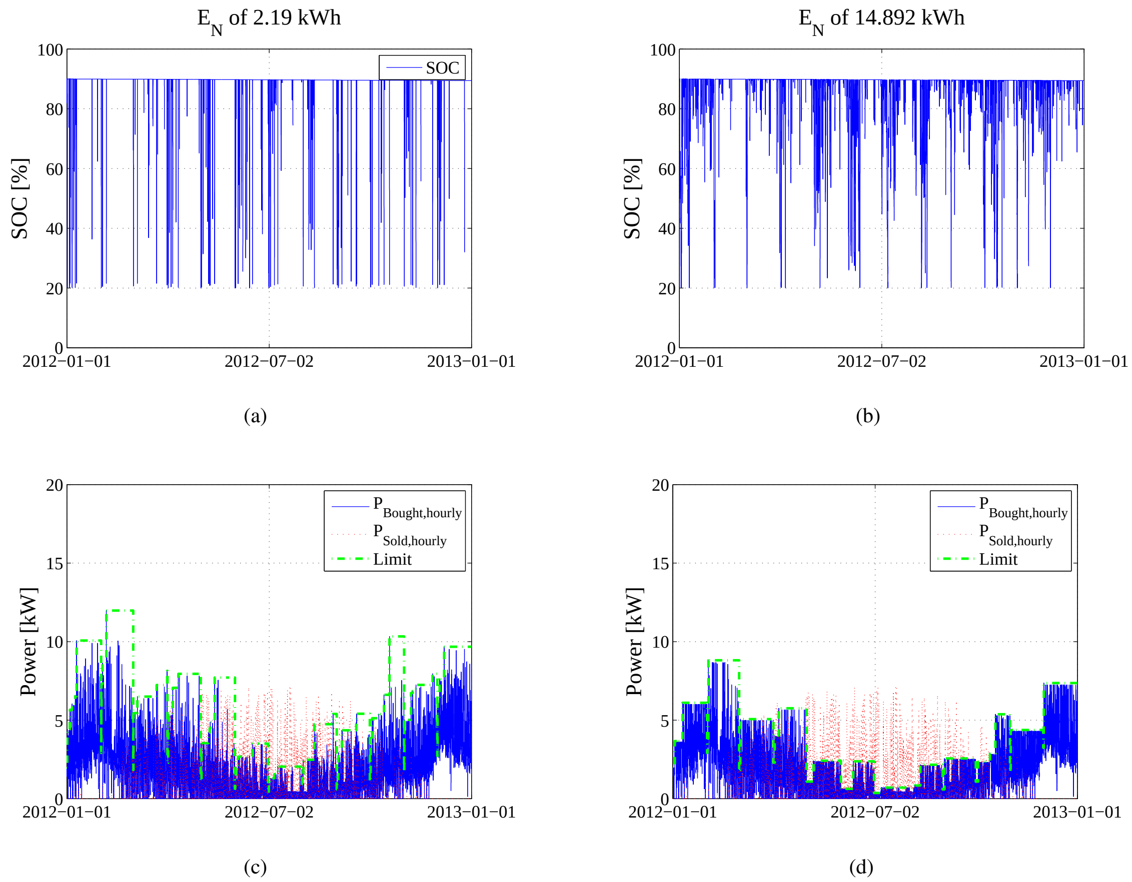


Figure 4.10: SOC, $P_{Bought,hourly}$ and $P_{Sold,hourly}$ of strategy 3 with the Li-ion battery and Falbygdens Energi as grid owner over the time period of 2012. In the graphs to the left E_N is 2,112 kWh and to the right is 14,976 kWh.

In Figure 4.11(a)-Figure 4.11(d) it can be observed how strategy 3 performs during the first day of the month. Initially of the day, $Limit$ is kept the same as earlier. After the first hour, $P_{Bought,hourly}$ was lower than $Limit$ and therefore is $Limit$ getting the value of $P_{Bought,hourly}$. The next hour P_{Load} exceed Limit and the stored energy in the battery is used to keep $P_{Bought,hourly}$ at $Limit$. In the morning P_{Load} is too high, for a too long time, in order for $P_{Bought,hourly}$ to be kept at $Limit$ and therefore does $Limit$ get a new value. In Figure4.11(d) it can be observed at this peak, that even if there is energy left in the battery, $P_{Bought,hourly}$ could not be kept at $Limit$. This was because more energy could not have been discharged from the battery during this time due to $P_{Max,discharge}$. The reason that P_{bought} can exceed $Limit$ is because of the design of the strategy; If the battery can be charged but not make $P_{Bought,hourly}$ to exceed $Limit$, the battery should be charged. The main differences between the lead acid and the Li-ion battery is that, as with the other strategies, more energy is available during one cycle and $P_{Max,charge}$ and $P_{Max,discharge}$ are higher for the Li-ion battery due to the differences in voltage.

Figure A.10 - Figure A.13 in Appendix A.6 show the behaviour of strategy 3 with Sollentuna Energi as grid owner. Sollentuna Energi decides their power price on the mean value of the three highest power peaks during the month. They also only measure the power peaks Monday-Friday between 7.00-19.00 and has some days where they do not measure. This can also be observed in the Figure A.12(c) and Figure A.12(d). $Limit$ is not set after each power peak, it is instead set after the third highest power peak during the measuring time of the month.

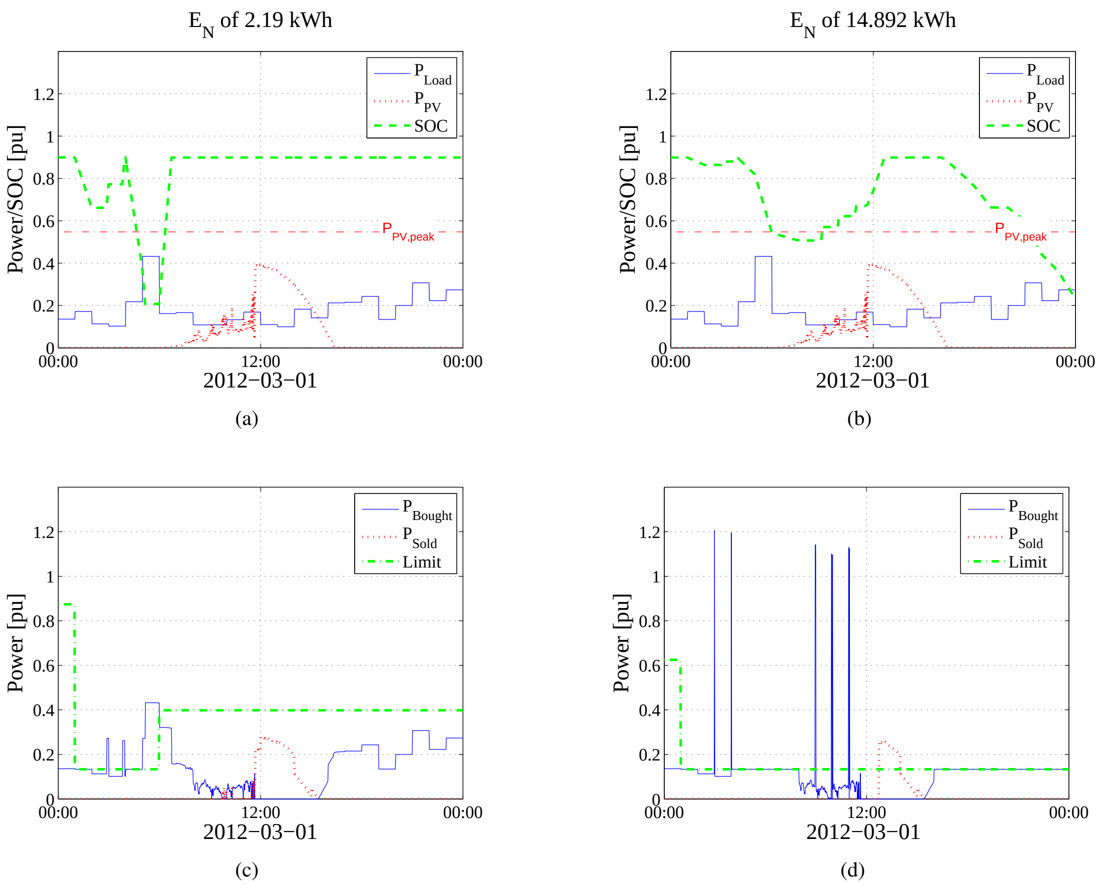


Figure 4.11: Behaviour of strategy 3 with the Li-ion battery and Falbygdens Energi as grid owner over the same day as strategy 1. In the graphs to the left E_N is about 2,112 kWh and to the right E_N is about 14,976 kWh. 1 pu for the powers corresponds to 13,7 kW and for the SOC to E_N.

Figure 4.12 shows $E_{Bougth,year}$, $E_{Sold,year}$ and Γ_A of the battery after one year, at different capacities. The graphs to the left shows the results for the lead acid battery and those to the right shows the results for the Li-ion battery. In these graphs it can be observed that $E_{Bougth,year}$ and $E_{Sold,year}$ is almost constant for the different battery sizes except for Li-ion that has a small decrease for the bigger capacities. This has to do with that strategy 3 only tries to keep $Limit$ as low as possible and therefore the battery will not be used that often as with strategy 1 and 2. This can also be observed for the energy throughput which is roughly half the amount of energy as for strategy 1 and 2. The uneven shape of Γ_A for the Li-ion battery is mainly because of the increase of the E_N, $Limit$ will be affected. With changing E_N, some power peaks that has not been limited earlier could be limited. This could on the other hand lead to that the battery is discharged when a higher power peak comes which gives the irregular shape.

In Figure A.14 in Appendix A.6 the same type of graphs are shown. In these graphs the same principle can be applied and the reason that Γ_A for the Li-ion battery is more smooth is that $Limit$ is based on the third exceeded power peak. This makes the results less dependent on if $P_{Bought,hourly}$ could have been kept beneath $Limit$.

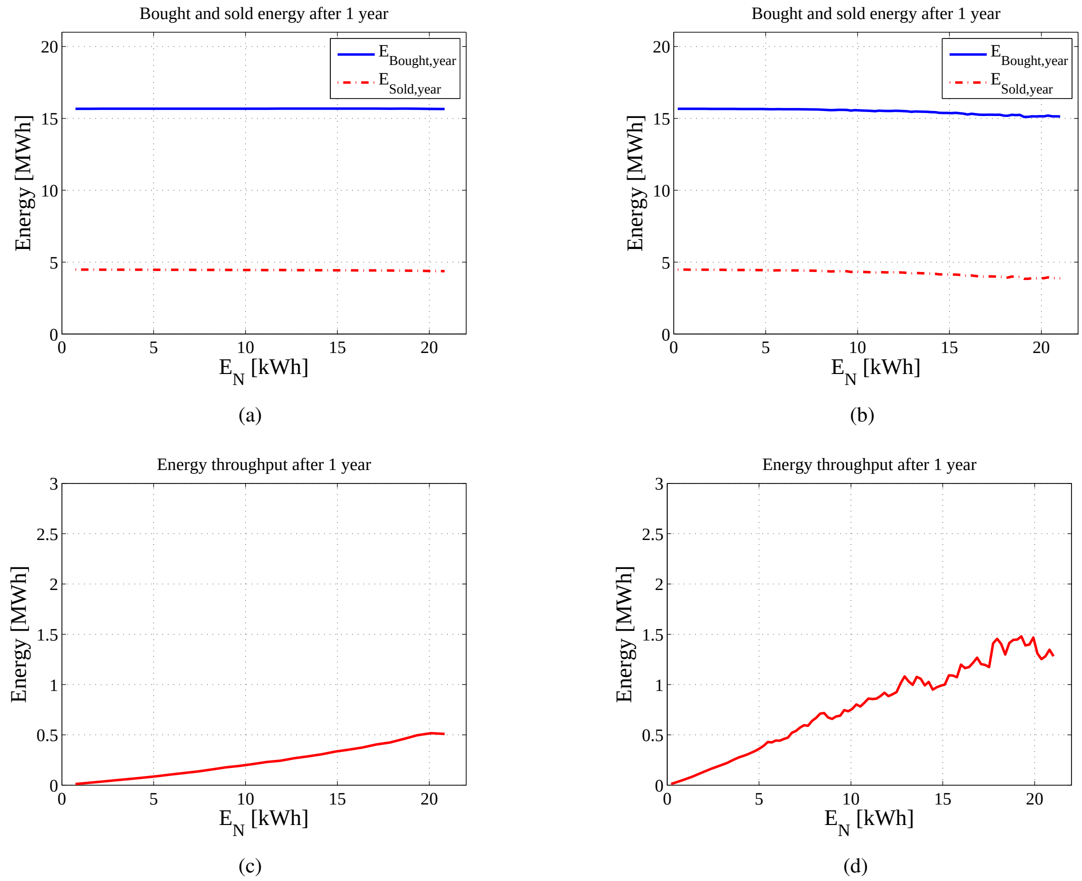


Figure 4.12: The bought and the sold energy to the grid and the energy throughput of the battery after 1 year for strategy 3 with Falbygdens Energi as grid owner. The graphs to the left show the results with the lead acid battery and to the right with the Li-ion battery.

4.3.2 Economic analysis of Strategy 3

Figure 4.13 shows the economical results for strategy 1 (FE1) and strategy 3 (FE2) with Falbygdens Energi as grid owner and the equivalent battery unit wear after 25 years for strategy 3. The graphs to the left shows the results with the lead acid battery and to the right with the Li-ion battery. The return in percentage is calculated on the investment cost of 165000 SEK for the installation of the PV-system and 1500 SEK/kWh$_{E_N}$ or 10000 SEK/kWh$_{E_N}$ for the lead acid and the Li-ion battery respectively.

As in strategy 2 there is a small increase of the increased revenues as the return. It can be observed that there are no steps in the results for strategy 3, except at about 17,5 kWh for the Li-ion battery, as it was for strategy 1. This is because $E_{Sold,year}$ does not decrease that much that electricity certificates are lost, as was the case for strategy 1. The irregular shape of the curves are, as for the energy throughput in Figure 4.12, due to that the power price is set after the maximal amount of power consumed during one month, which changes with increased E_N. The logaritmic increase in the increase revenues, which can specially be seen for the Li-ion batteries, is due to that $Limit$ can be kept down more for smaller batteries, seen to E_N.

Figure 4.14 shows the economical results for strategy 1 (SOL1) and strategy 3 (SOL2) with Sollentuna Energi as grid owner and the equivalent battery unit wear after 25 years for strategy 3. As for Figure 4.13, the graphs to the left are the results with the lead acid battery and to the right with the Li-ion battery. In this case, compared with the other cases, there is a large increase of the increased revenues and return with the increase of E_N. This depends on that the power prices are fairly high, the price is set after the three highest consumed power peaks, the measurements are only done during the day between 7.00-19.00 and that Sollentuna Energi give a compensation price of 1 SEK/kWh. That the power prices is only set during the days results in that the battery is guaranteed charged to the upper SOC limiter in the beginning of the day. The fact that Sollentuna Energi calculate the power price on the three highest power peaks gives that even if a consumed power peak was lost, the $Limit$ will still try to reduce the $P_{bought,hourly}$.

In both Figure 4.13 and Figure 4.14 the equivalent battery unit wear after 25 years are just below 1, meaning that due to the wear of the battery it must be replaced about one time during a 25 year period. Comparing this with the equivalent battery unit wear after 25 years for strategy 1 in Figure 4.4 it can be observed that it is much lower for strategy 3. This has to do with that the battery is only used to reduce the consumed power peaks from the grid and as can be observed in, for example, Figure 4.10(b) it is used much less than for corresponding graph for strategy 1, Figure 4.1(b).

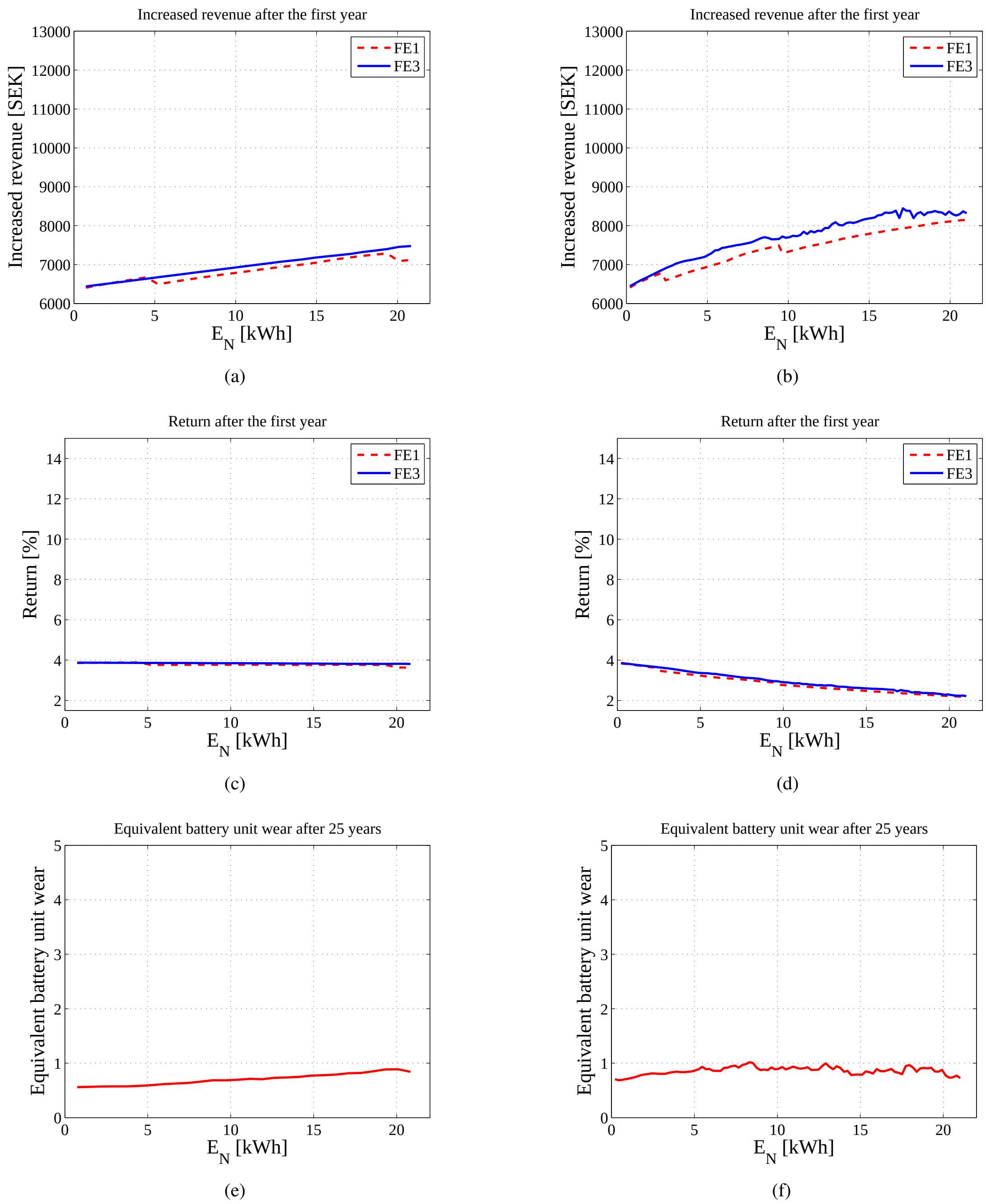


Figure 4.13: The economical return of the PV-system with battery after the first year both in SEK and percentage and also the equivalent battery unit wear after 25 years with strategy 3 for different E_N. The graphs to the left show the results with the lead acid battery and to the right with the Li-ion battery.

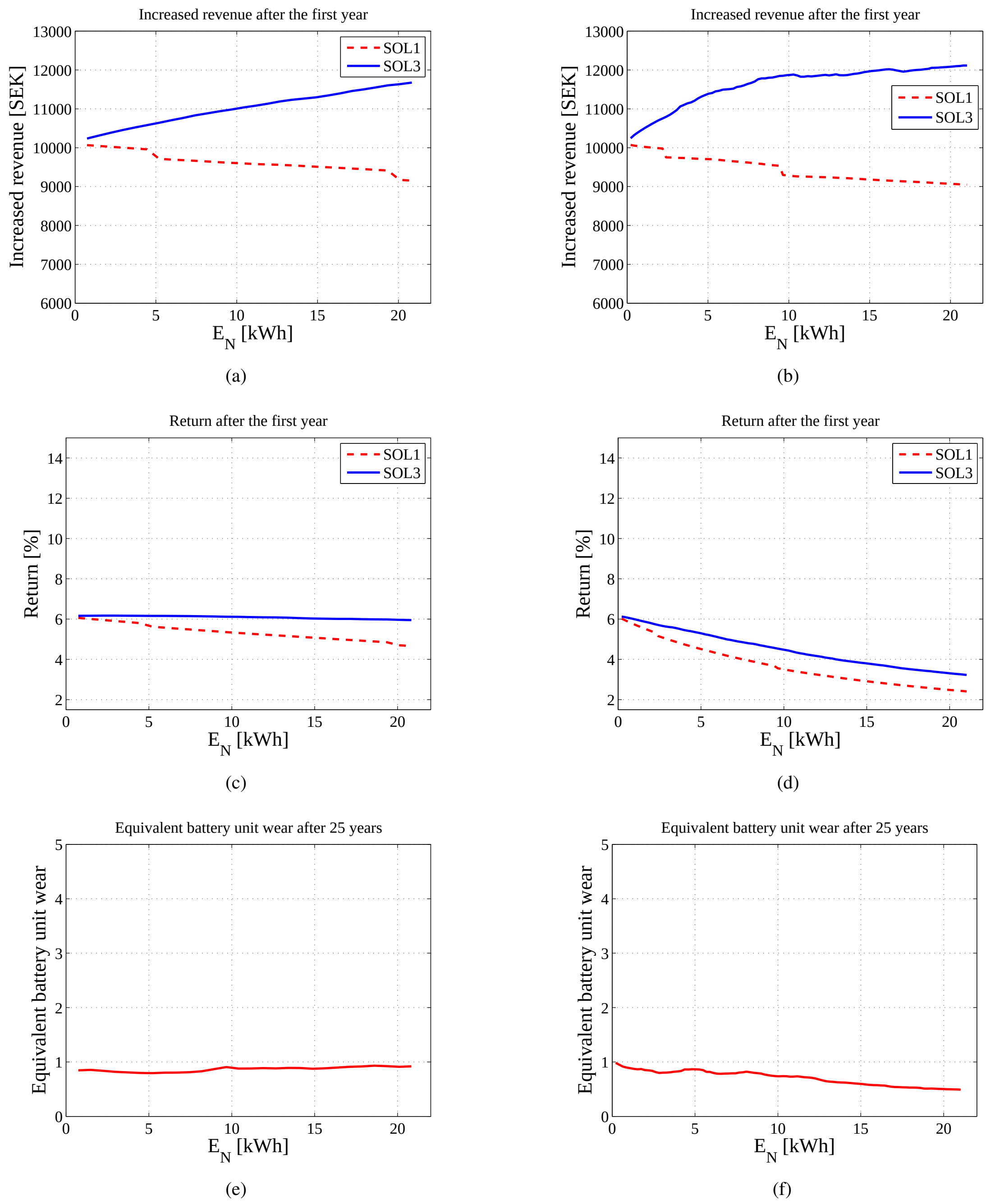


Figure 4.14: The economical return of the PV-system with battery after the first year both in SEK and percentage and also the equivalent battery unit wear after 25 years with strategy 3 for different E_N. The graphs to the left shows the results with the lead acid battery and to the right with the Li-ion battery.

Figure 4.15 and Figure 4.16 shows the economical results when different prices has been changed with Falbygdens energi and Sollentuna energi as grid owner respectively. The default graphs is the graphs from Figure 4.13 and Figure 4.14 for strategy 3 and the value in the legend is the factor the default price has been changed with. It can be observed that by lowering the battery prices the return could eventually increase or be increased at a certain E_N. If the installation of the PV-modules would also decrease, the battery price must decrease even more in order to get an increase of the return.

As for strategy 2, the spot prices will only change the offset of the return. The rate of change is because the bought and sold energy to the grid is a bit reduced with increased E_N and that the costs of the battery will affect the return more. An analysis was also performed where the spot price variance was changed, but as for strategy 2 this gave only a very small change of the return.

Changing the power prices will have small impact on the return. This differences in the return for Sollentuna Energi and Falbygdens Energi is mainly because of the number of power peaks, that the measurements are only done during the day between 7.00-19.00 for Sollentuna energi and that Sollentuna Energi gives a higher compensation price.

4.4 Critical review

In this thesis work the aim has been to develop simulation model as accurate to the reality as possible. However, some assumptions had to be done that affects the result of the different strategies. The power unit that had the most assumptions was the battery. The battery model used a constant battery voltage, linearly degradation of the SOH and a constant efficiency where the losses was only present during charging of the battery. These assumptions could affect the results by that the battery is used to another extend and that the losses would be either higher or lower. However, the economical results would probably not be affected in that big extend because the battery is probably working almost as it would in the reality.

The biggest impact on the economical results is probably that only one profile for each power unit, with one year's values, and limited amount of electricity traders and grid owners was used. If, for example, other load profiles or other prices would have been used the economical results would have been different. Since the main task was to design strategies, only the economical results of the first year was calculated and therefore was the assumptions reduced as well.

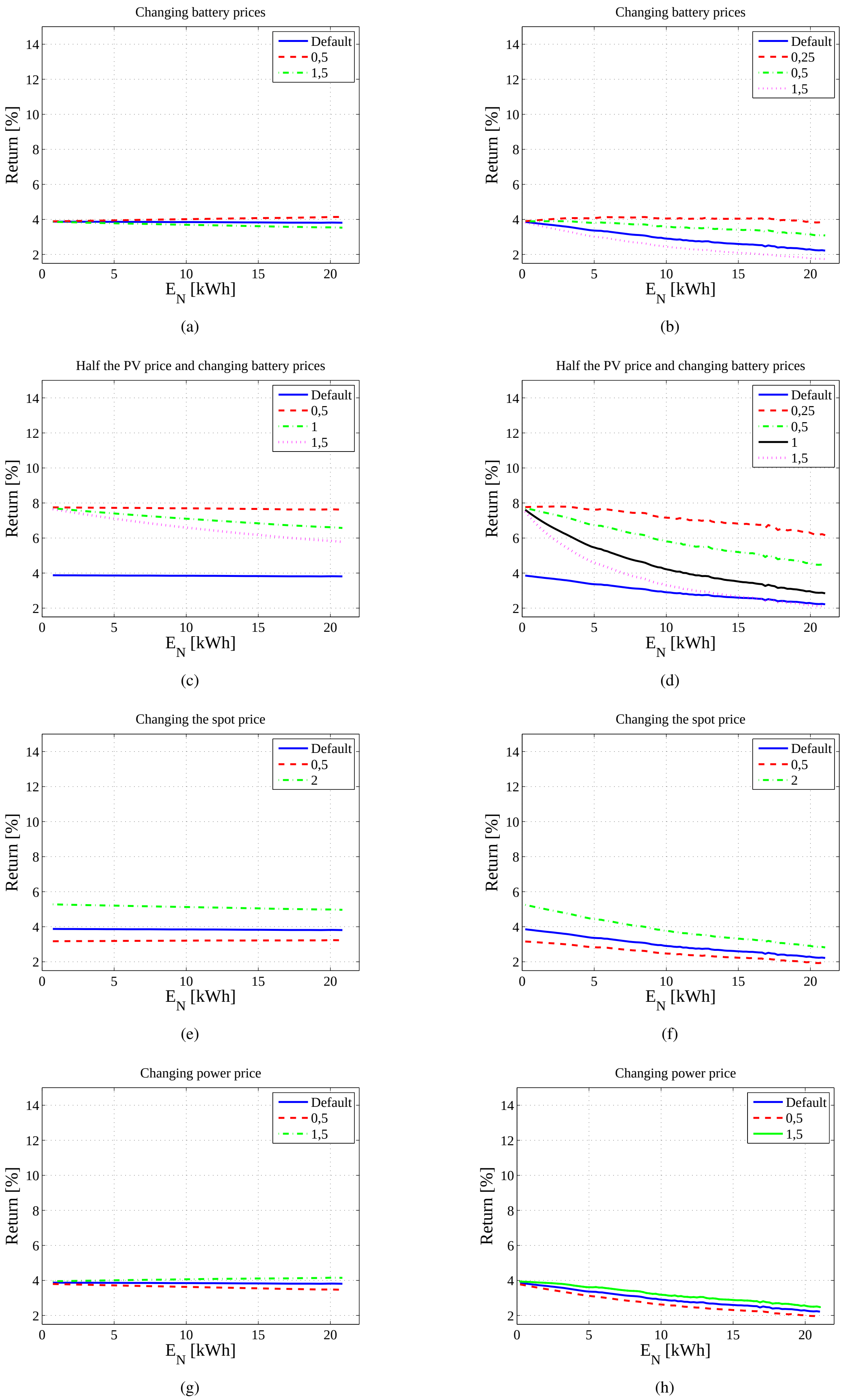


Figure 4.15: Analysis where different prices has been changed. The default graph is the resulting return with the prices described earlier with Fallbygdens Energi as grid owner. The graphs to the left is the resulting return for the lead acid battery and to the right for the Li-ion battery.

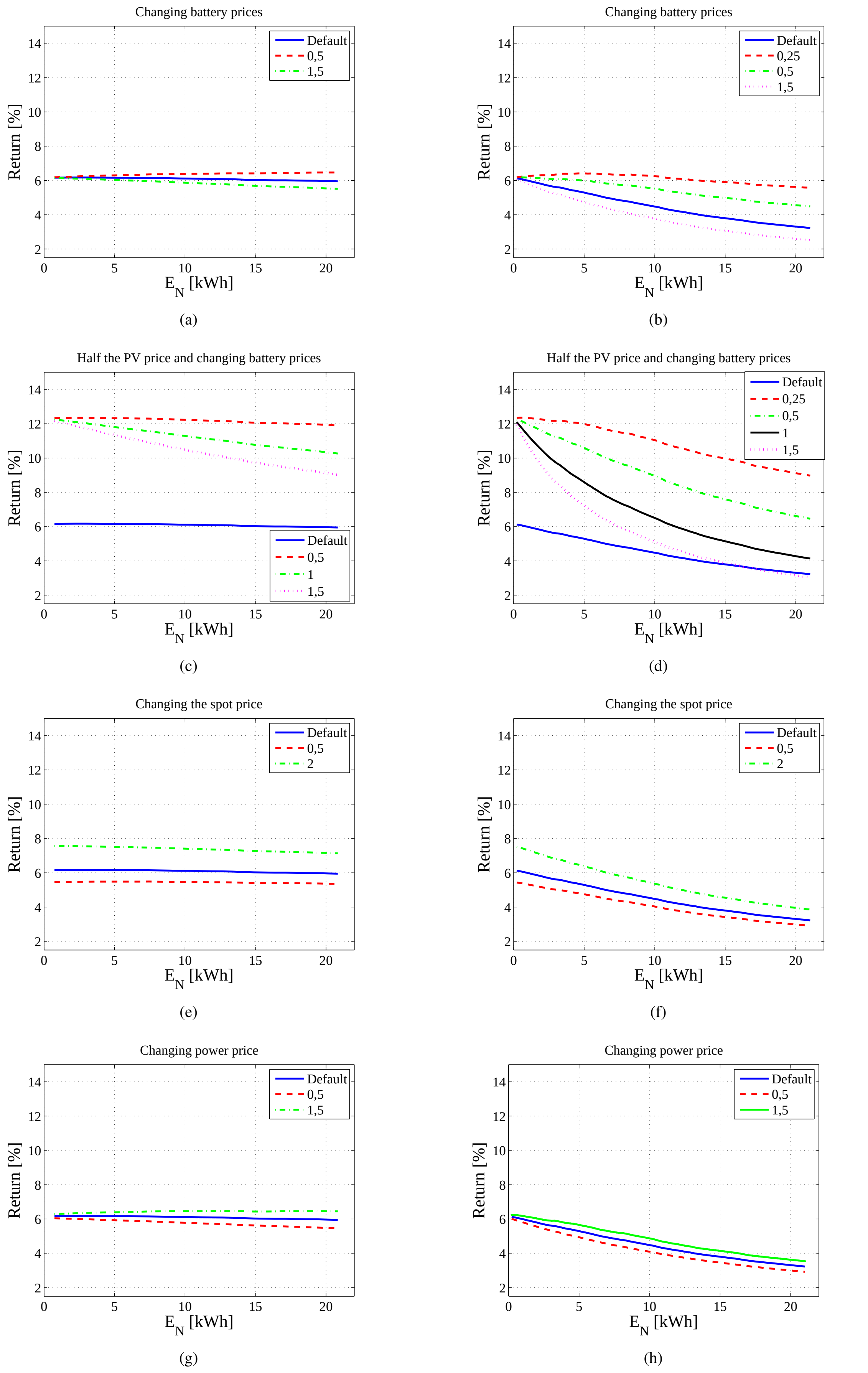


Figure 4.16: Analysis where different prices has been changed. The default graph is the resulting return with the prices described earlier with Sollentuna Energi as grid owner. The graphs to the left is the resulting return for the lead acid battery and to the right for the Li-ion battery.

Chapter 5

Conclusions

The following chapter aims to summarize the work that has been performed and make conclusions considering the given analysis in Chapter 4. The chapter also gives proposals of future work that could be done to improve results.

5.1 Results from present work

An analysis of the behaviour in the different strategies were performed. In the analysis it could be observed that the battery was used different in the strategies as for the two battery types. For the same E_N of the lead acid and the Li-ion battery, more energy were available for usage during one cycle with the Li-ion battery. This gave different results for how the system performed.

Regarding the economics of the strategies it could be seen that with increased E_N of the battery the first year's return mainly decreased. For the Li-ion battery the slop of the decrease in the return was higher than for the lead-acid battery. This was mainly because the price for the Li-ion battery was much higher. What also was accounted for in the economics was the equivalent battery unit wear after 25 years. This gave an indication of how many times the battery had to be replaced with a new one due to the wear. For strategy 1 and 2 the equivalent wear decreased with increased E_N. This was mainly because an increase of E_N does not give an increase of the energy production and for bigger E_N the battery was not always charged to the upper limiter. For strategy 3 the battery was used for an other purpose, to reduce the consumed power peaks, and the equivalent wear was about 1.

From the economical results for all the three strategies, it can be concluded that Sollentuna Energi is the grid owner that is most economical beneficial for the whole system. The main reason Sollentuna Energi gave higher economical results was that they gave 1 SEK/kWh in compensation.

Comparing strategy 1 and 2, in terms of economics, it was found that there was a small increase in the return after the first year for strategy 2. In the same time there was also an increase of the equivalent wear of the battery. Comparing strategy 1 and 3 on the other hand, gave both an increase of the return after the first year as an decrease of the equivalent wear of the battery for strategy 3. By these results it can be concluded that strategy 3, with these given constrains, gives a higher economical return compared to the other strategies.

An sensitivity analysis of the strategies was also performed. In these analysis it could be seen that the economical return of the PV-system was very dependent on the spot price and the installation cost of the PV-modules. When changing these prices the offset of the return was mainly affected. In order for the BESS to become economical beneficial the battery price had to be reduced. For the lead acid battery, half the battery price could make the BESS economical beneficial at some E_N. For the Li-ion battery on the other hand the price has to decrease to at least 75 % of the default price in order fro the BESS to become economical beneficial.

To answer the first question in Chapter 1.3.1 it can be concluded that a BESS is not economical beneficial for a PV-system with the given constrains in this project. The lead acid battery in strategy 3 had though a almost constant value of the return at different E_N. The answer to the second question is that in order to maximize the economical return with these strategies and given constrains, a BESS should not be used. But if the battery prices would decrease, E_N of the BESS should be a few kWh.

5.2 Future work

In the development of the simulation model a basic battery model was used. It modelled the battery voltage as a constant value, the losses was seen as an constant efficiency where the losses were only present during charging and the degradation of the SOH was linearly. In order to get more accurate results of the battery, a battery model where the voltage depends on the SOC and the losses is estimated with a resistance could be used. The degradation of SOH could also be investigated more in order to see if it is a valid estimation for Li-ion batteries as it is for lead acid.

Three different strategies where designed where strategy 2 was an development of strategy 1 and strategy 3 had an other approach. Future work with these strategies could be to investigate more when $Buytime$ and $Usetime$ should be defined or what the initial $Limit$ of the month for should be. A mixed strategy of strategy 2 and 3 could also be designed. Such a strategy needs a bigger knowledge about how the different power units in the PV-system will act during the coming hours. A future work could therefore be to define a method to predict the what the energy production will be and how the local load profile will be.

In the project, only one local load profile was used and in order to investigate the economical benefits of the strategies more and different type of local load profiles should be used. Only one electricity trader and grid owner was also used in the project and it could be of interest to see how much these affect the results. For a owner of an EnergyHub the difference between the electricity traders could be of more interest than the different grid owners since the electricity traders can be chosen which is not the case for the grid owners.

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Appendix A

Appendix

The appendices referred to in this master's thesis aims to give a deeper insight of the given material.

A.1 The line diagram of the EnergyHub

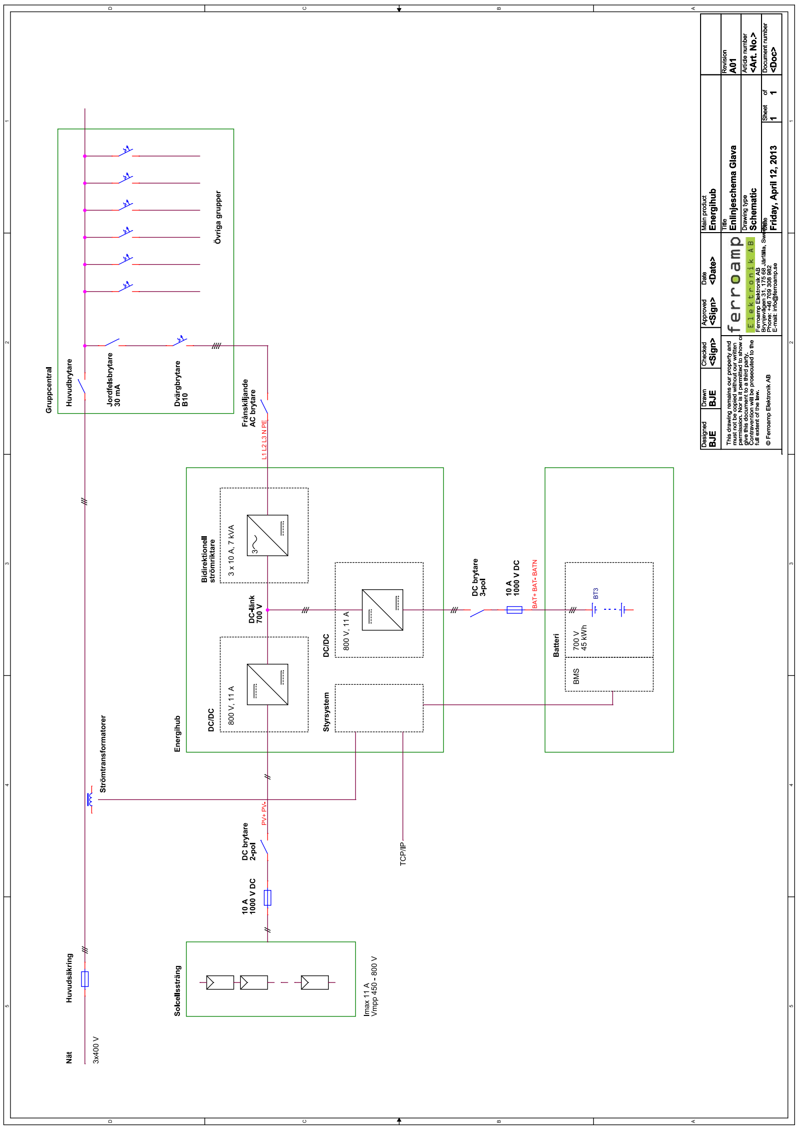
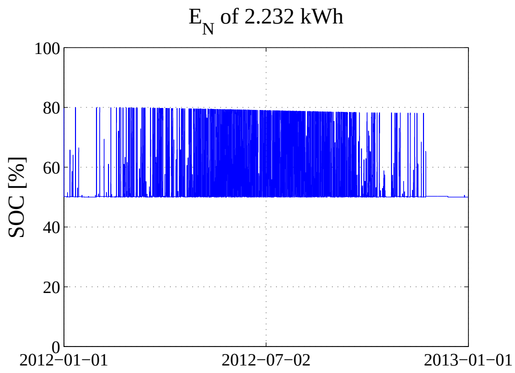
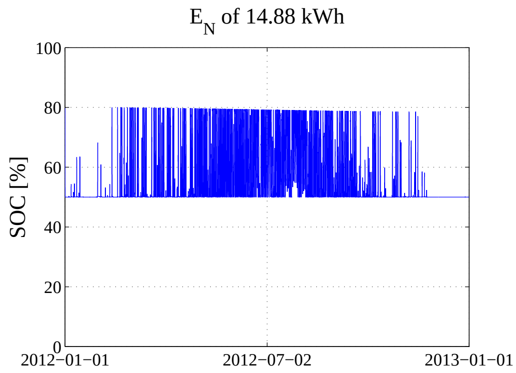


Figure A.1: The line diagram of the EnergyHub from Ferroamp Elektonik AB [3]

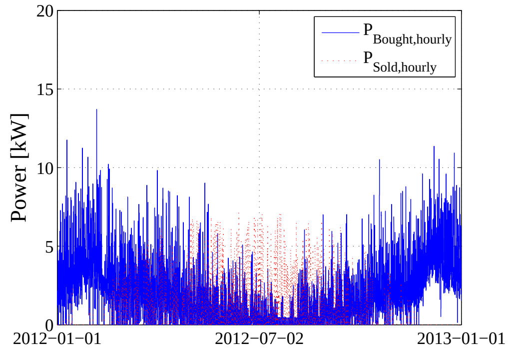
A.2 Behaviour of strategy 1 with the lead acid battery



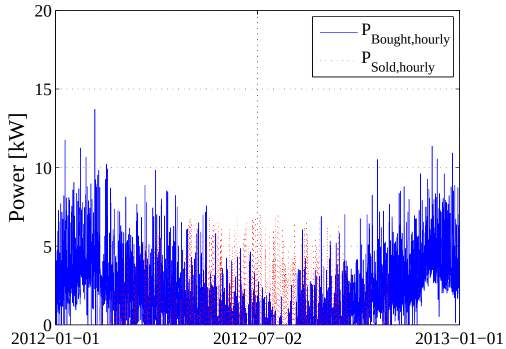
(a)



(b)



(c)



(d)

Figure A.2: SOC, $P_{Bought,hourly}$ and $P_{Sold,hourly}$ of strategy 1 with the lead acid battery over the time period of 2012. In the graphs to the leftE_N is 2,232 kWh and to the right E_N is 14,88 kWh.

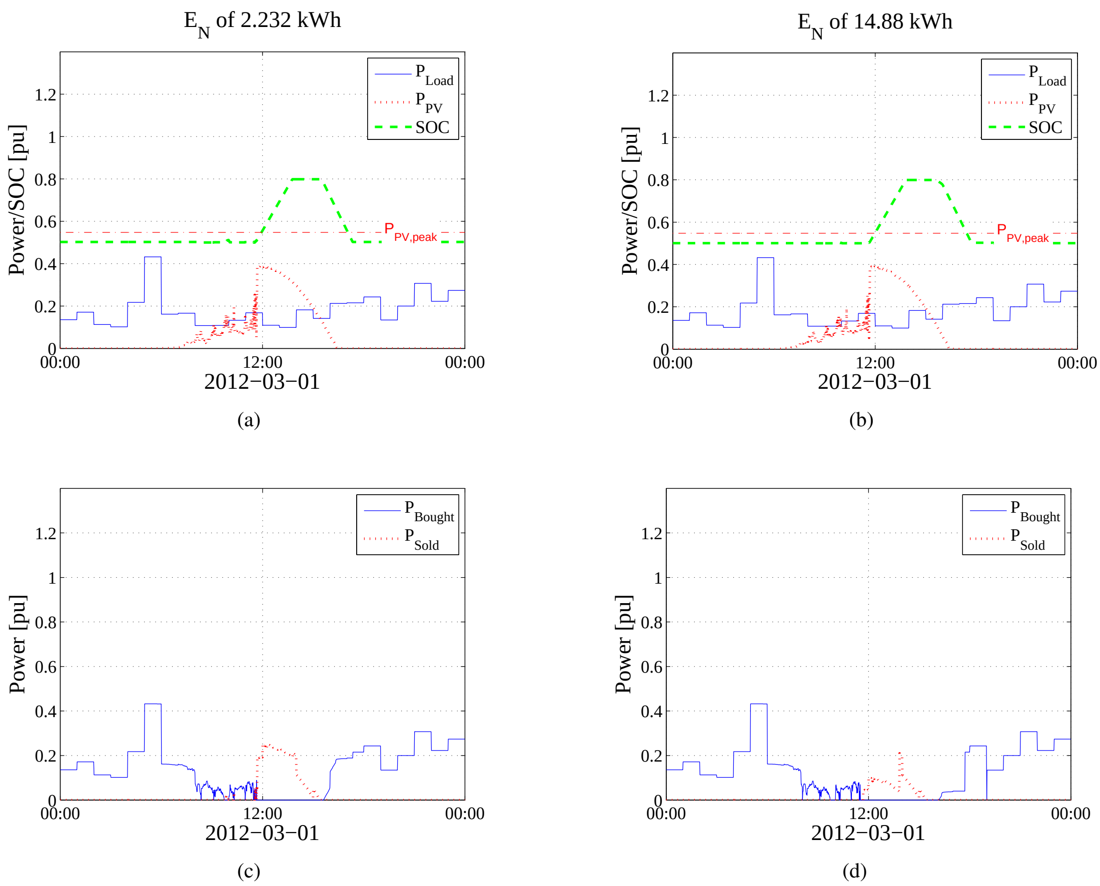
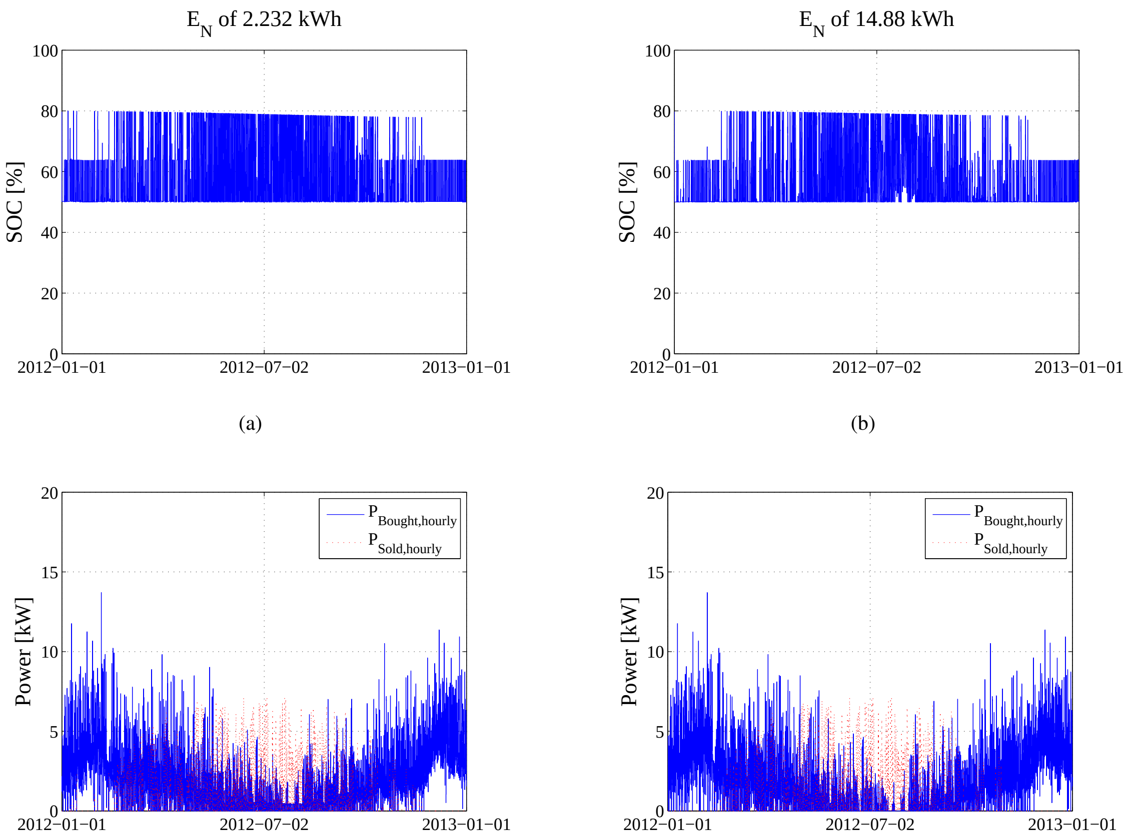


Figure A.3: Behaviour of strategy 1 with the lead acid battery over a day. In the graphs to the left E_N is 2,232 kWh and to the right E_N is 14,88 kWh. 1 pu for the powers corresponds to 13,7 kW and for the SOC to E_N.

A.3 Behaviour of strategy 2 with the lead acid battery



(a) (b) (c) (d)

Figure A.4: SOC, $P_{Bought,hourly}$ and $P_{Sold,hourly}$ of strategy 2 with the lead acid battery and Göteborg Energi as grid owner over the time period of 2012. In the graphs to the left E_N is 2,232 kWh and to the right E_N is 14,88 kWh.

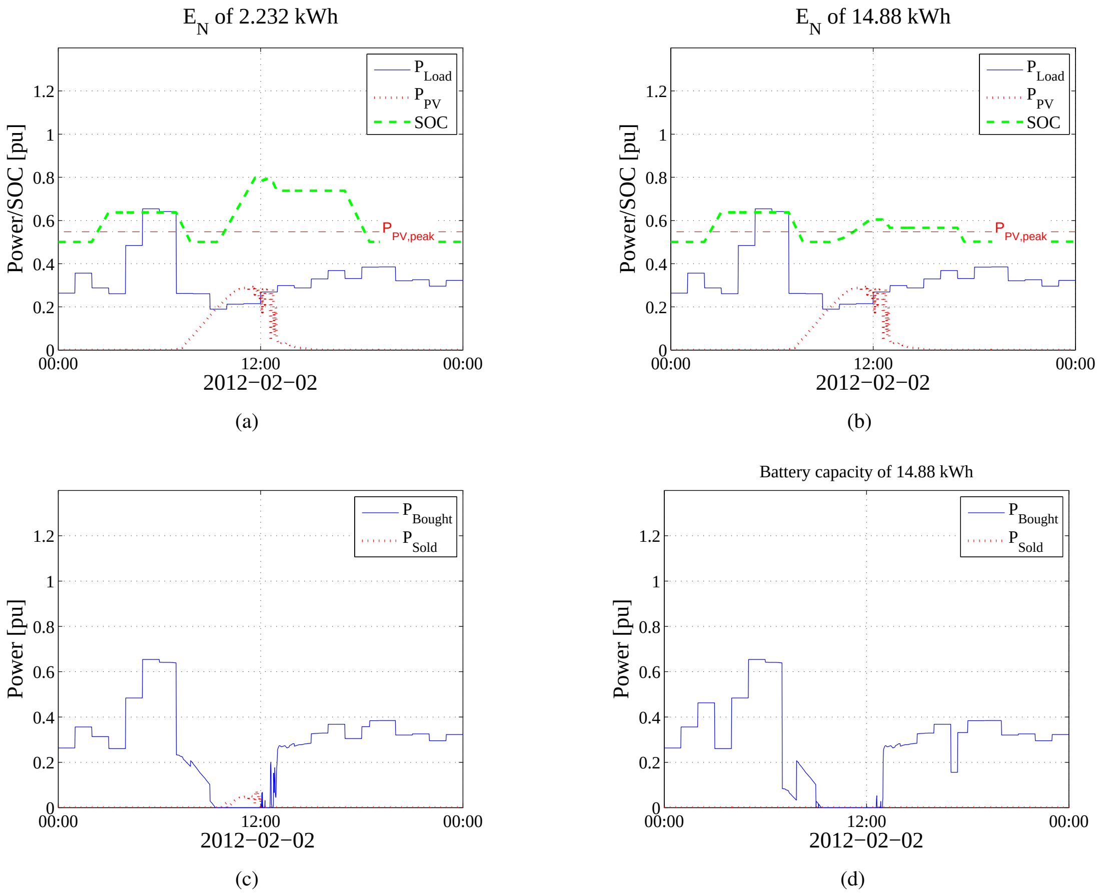


Figure A.5: Behaviour of strategy 2 with the lead acid battery and Göteborg Energi as grid owner over a day. In the graphs to the left is 2,232 kWh and to the right is 14,88 kWh. 1 pu for the powers corresponds to 13,7 kW and for the SOC to E_N.

A.4 Behaviour of strategy 2 over the same days as strategy 1

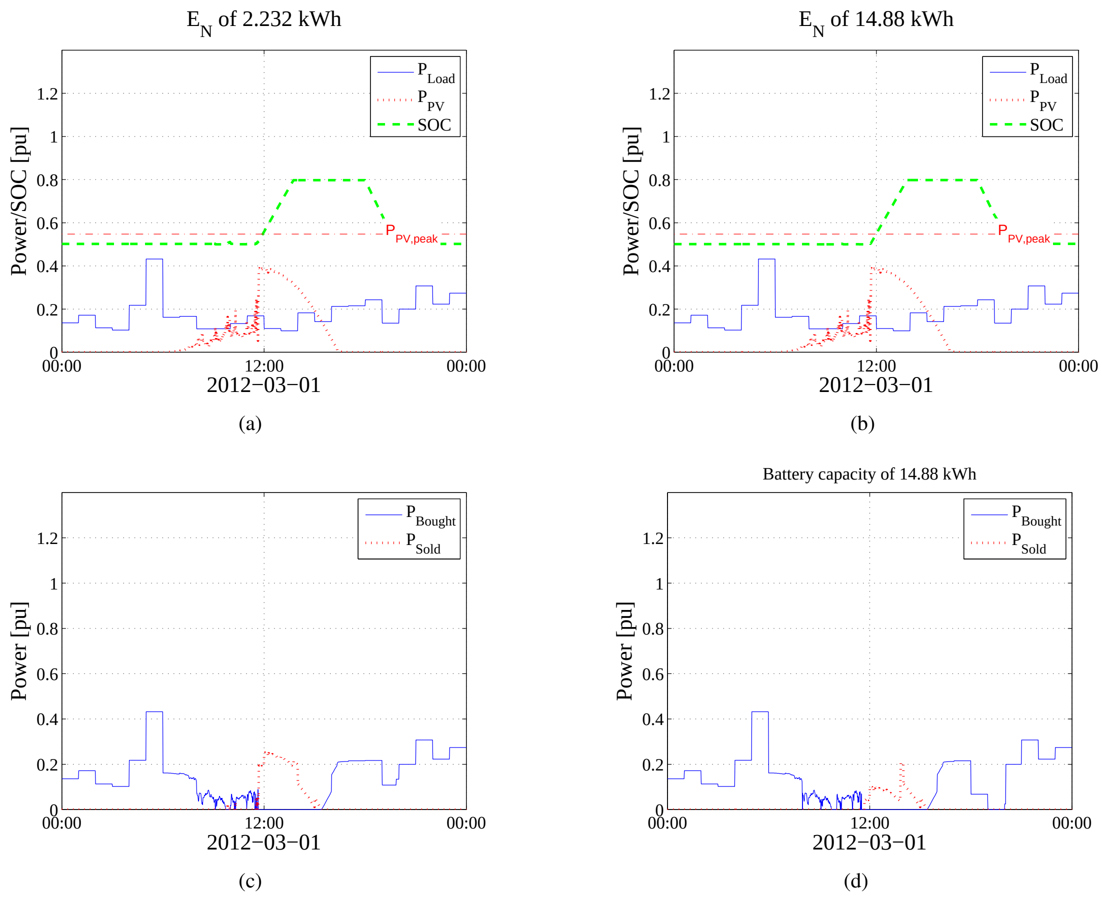


Figure A.6: Behaviour of strategy 2 with the lead acid battery and Göteborg Energi as grid owner over the same day as strategy 1. In the graphs to the left E_N is 2,232 kWh and to the right E_N is 14,88 kWh. 1 pu for the powers corresponds to 13,7 kW and for the SOC to E_N.

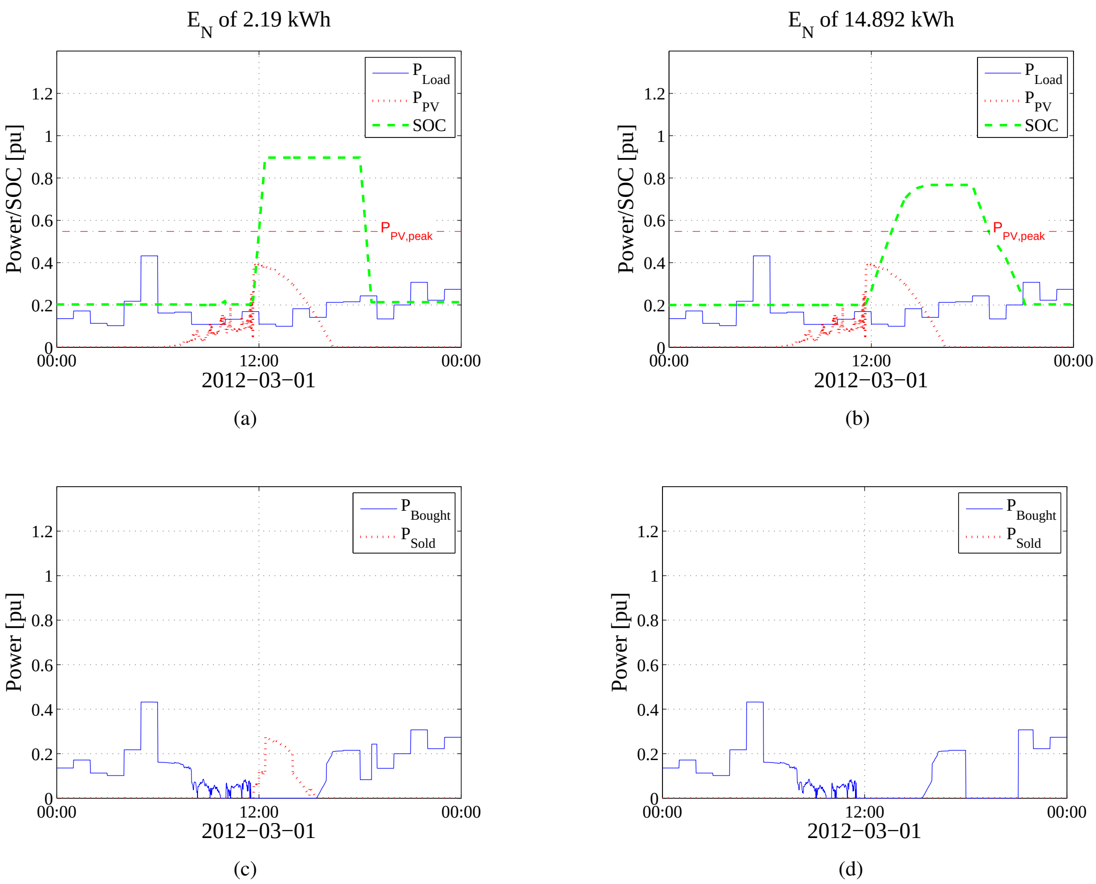
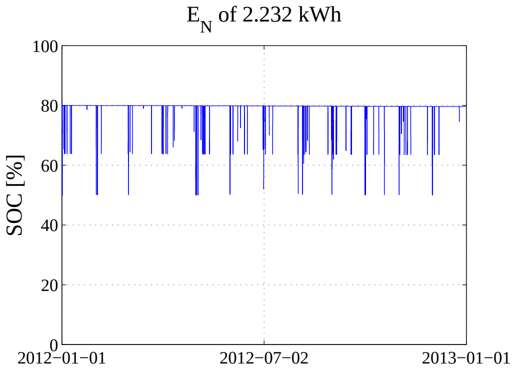
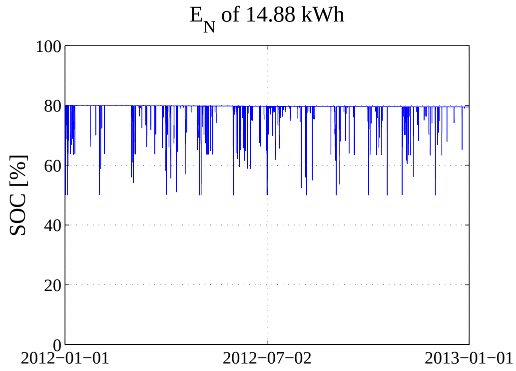


Figure A.7: Behaviour of strategy 2 with the Li-ion battery and Göteborg Energi as grid owner over the same day as strategy 1. In the graphs to the left is 2,232 kWh and to the right is 14,88 kWh. 1 pu for the powers corresponds to 13,7 kW and for the SOC to E_N.

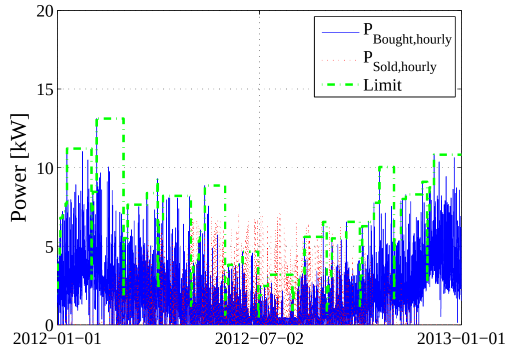
A.5 Behaviour of strategy 3 with the lead acid battery



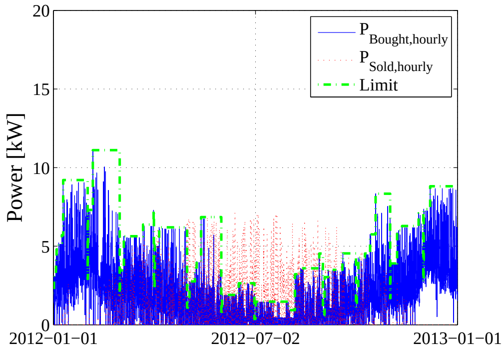
(a)



(b)



(c)



(d)

Figure A.8: SOC, $P_{Bought,hourly}$ and $P_{Sold,hourly}$ of strategy 3 with the lead acid battery and Falbygdens Energi as grid owner over the time period of 2012. In the graphs to the left E_N is 2,232 kWh and to the right E_N is 14,88 kWh.

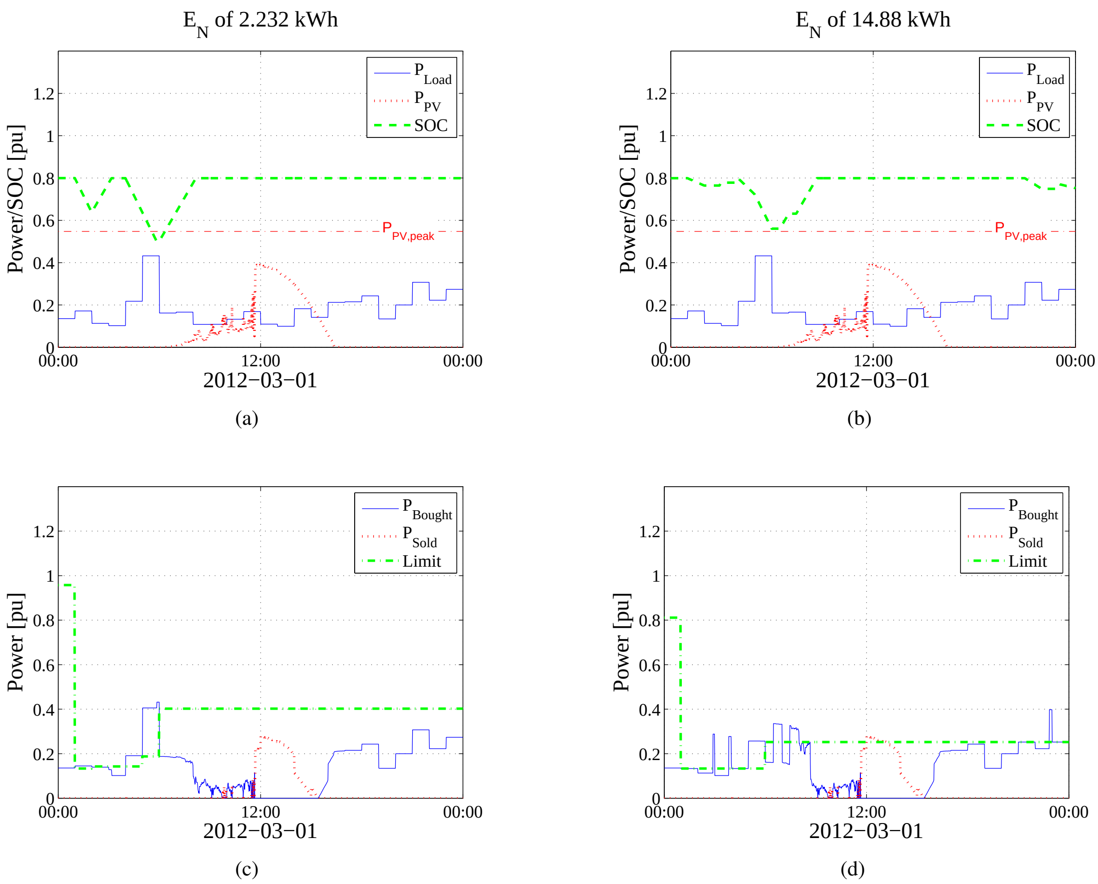
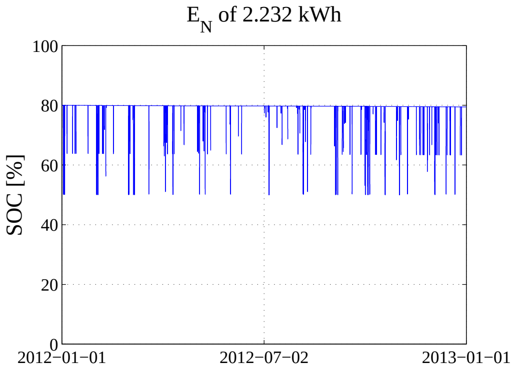
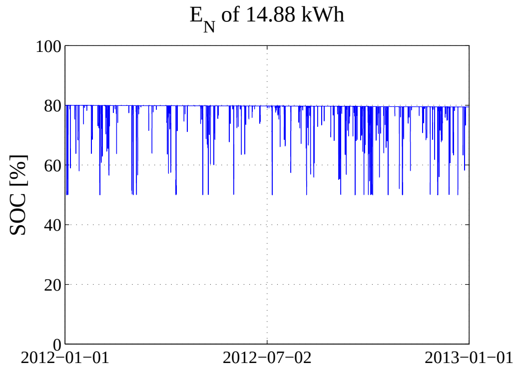


Figure A.9: Behaviour of strategy 3 with the lead acid battery and Falbygdens Energi as grid owner over the same day as strategy 1. In the graphs to the left E_N is 2,232 kWh and to the right E_N is 14,88 kWh. 1 pu for the powers corresponds to 13,7 kW and for the SOC to E_N.

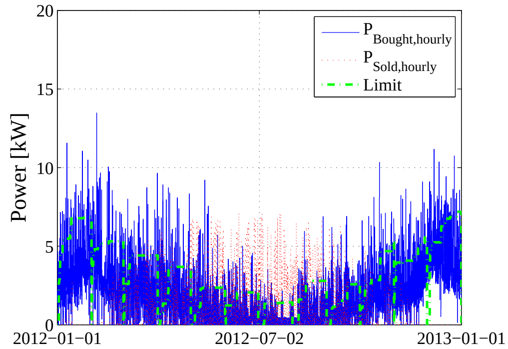
A.6 Behaviour of strategy 3 with Sollentuna Energi as grid owner



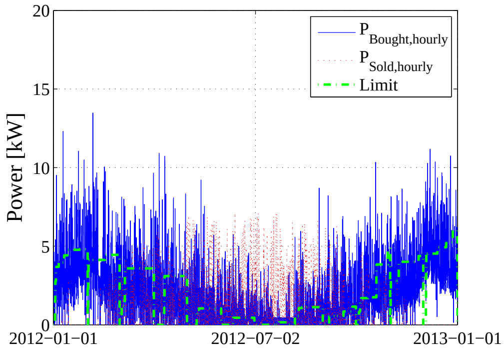
(a)



(b)



(c)



(d)

Figure A.10: SOC, $P_{Bought,hourly}$ and $P_{Sold,hourly}$ of strategy 3 with the lead acid battery and Sollentuna Energi as grid owner over the time period of 2012. In the graphs to the left is 2,232 kWh and to the right E_N is 14,88 kWh.

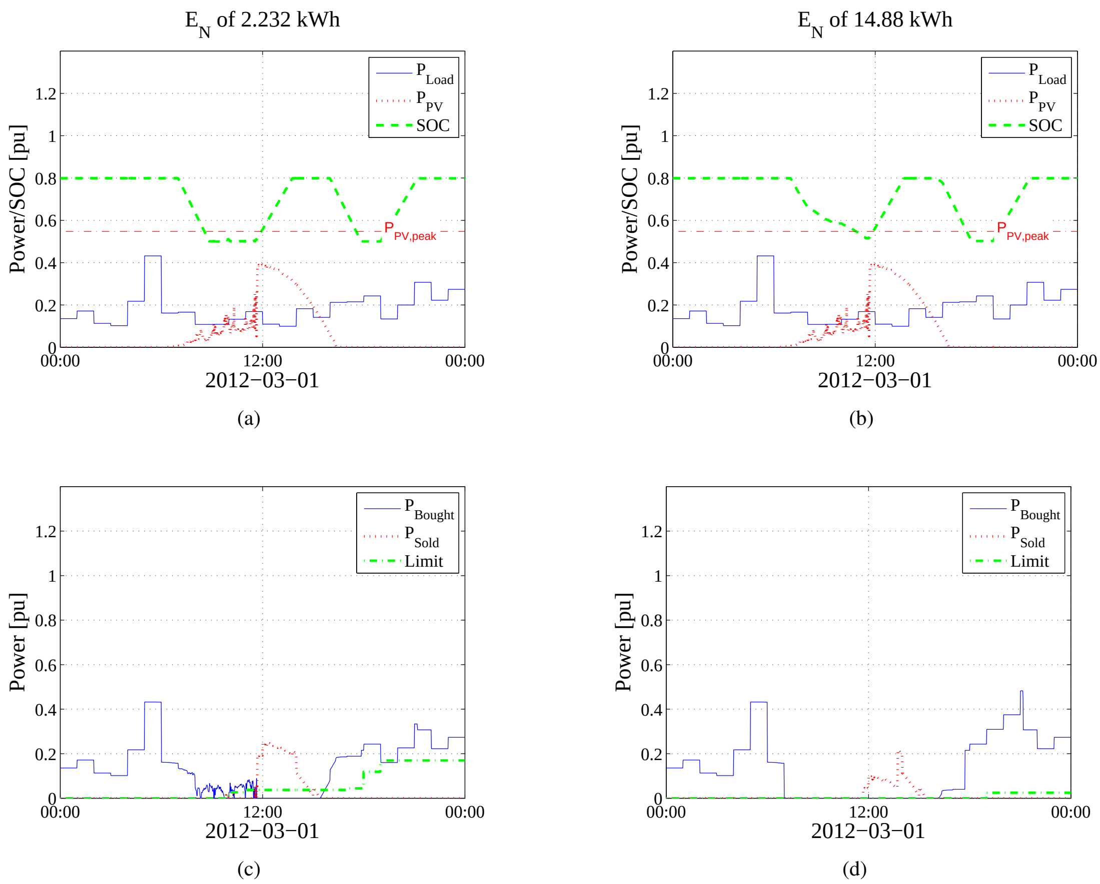


Figure A.11: Behaviour of strategy 3 with the lead acid battery and Sollentuna Energi as grid owner over a day. In the graphs to the left E_N is 2,232 kWh and to the right E_N is 14,88 kWh. 1 pu for the powers corresponds to 13,7 kW and for the SOC to E_N.

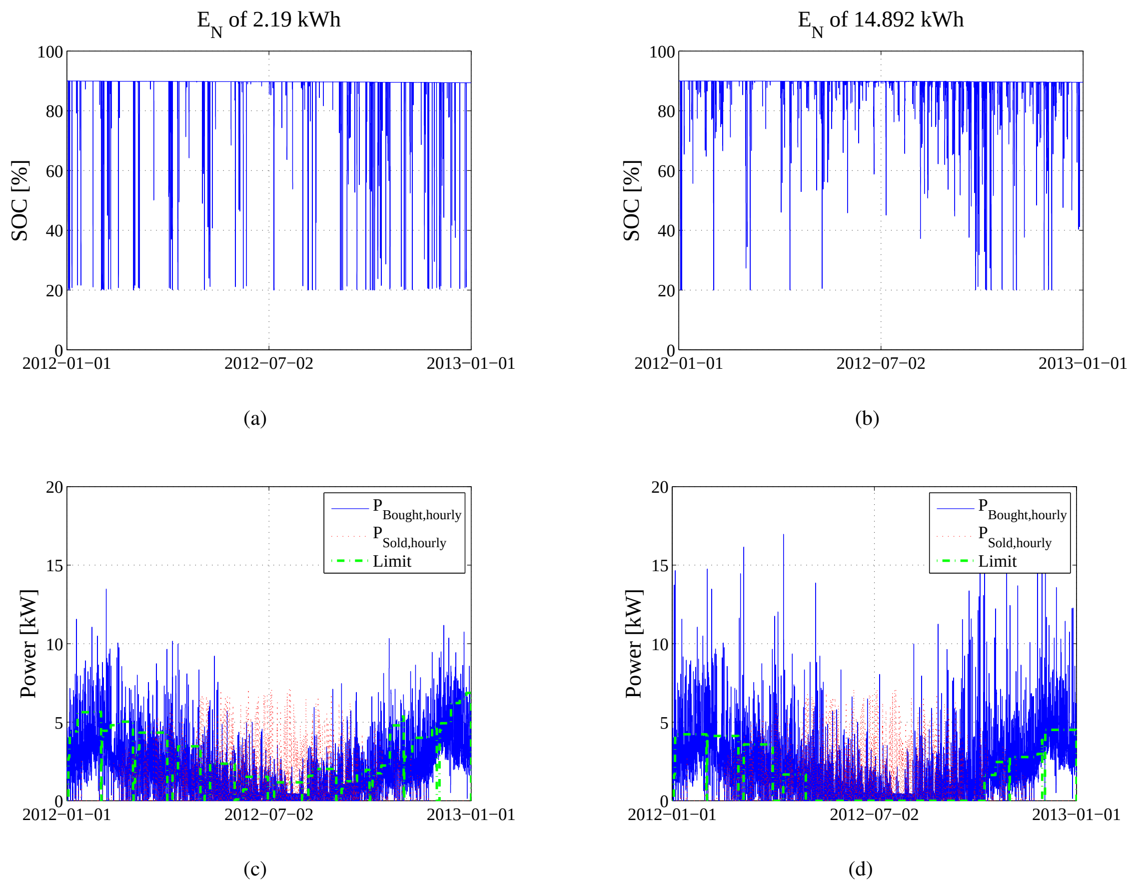


Figure A.12: SOC, $P_{Bought,hourly}$ and $P_{Sold,hourly}$ of strategy 3 with the Li-ion battery and Sollentuna Energi as grid owner over the time period of 2012. In the graphs to the left E_N is 2,112 kWh and to the right E_N is 14,976 kWh.

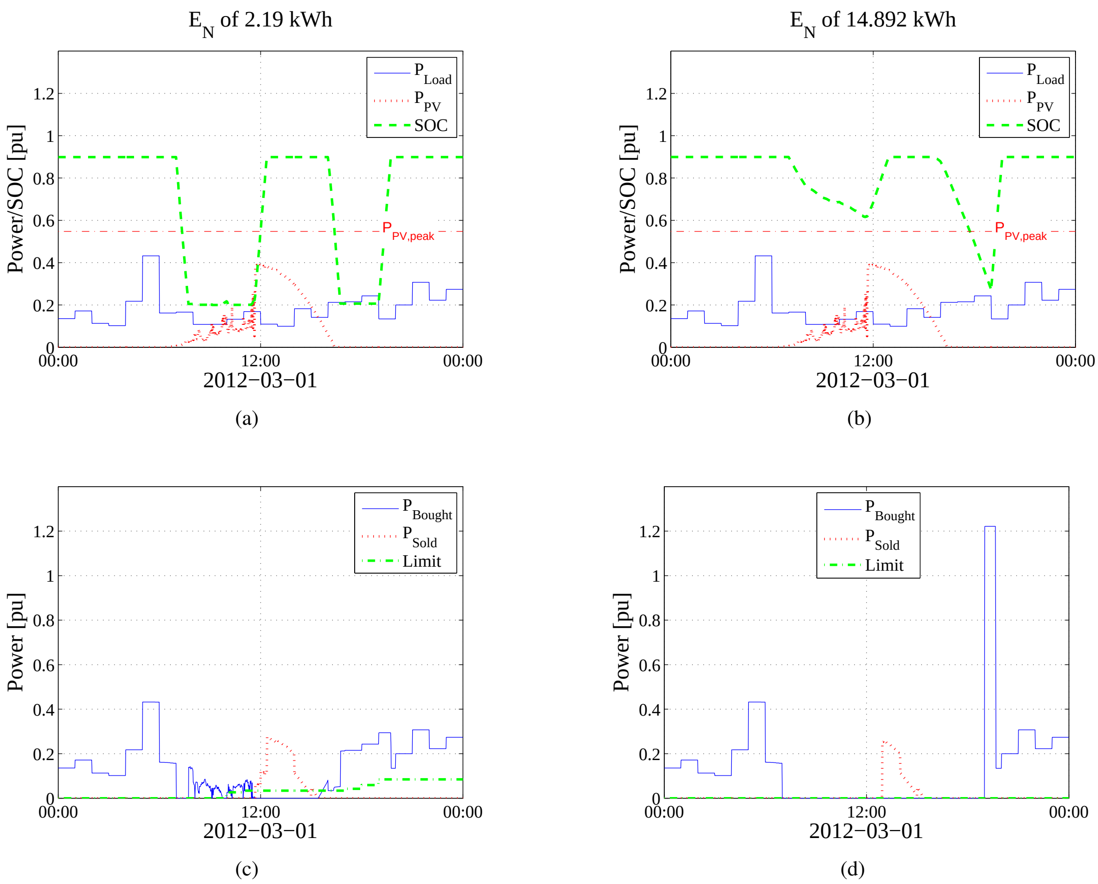


Figure A.13: Behaviour of strategy 3 with the Li-ion battery and Sollentuna Energi as grid owner over a day. In the graphs to the left E_N is 2,112 kWh and to the right E_N is 14,976 kWh. 1 pu for the powers corresponds to 13,7 kW and for the SOC to E_N.

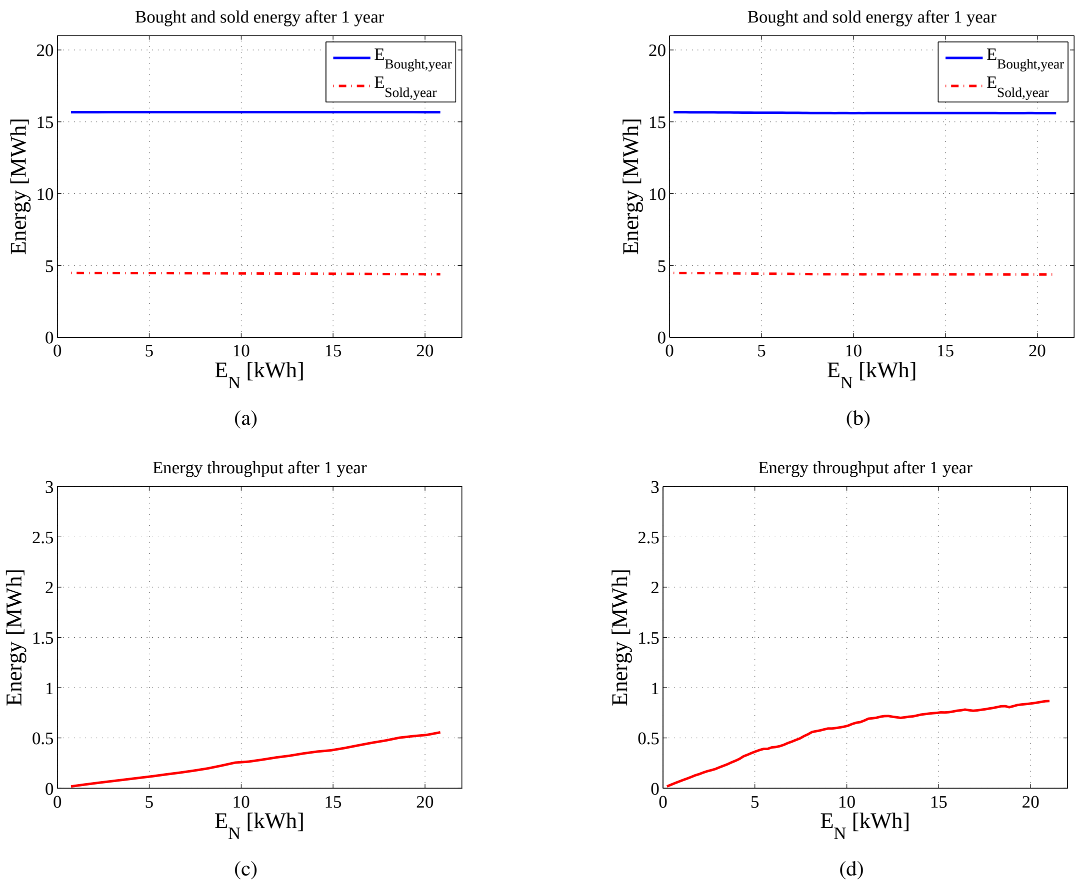


Figure A.14: The bought and the sold energy to the grid and the energy throughput of the battery after 1 year for strategy 3 with Sollentuna Energi as grid owner. The graphs to the left shows the results with the lead acid battery and to the right with the Li-ion battery.