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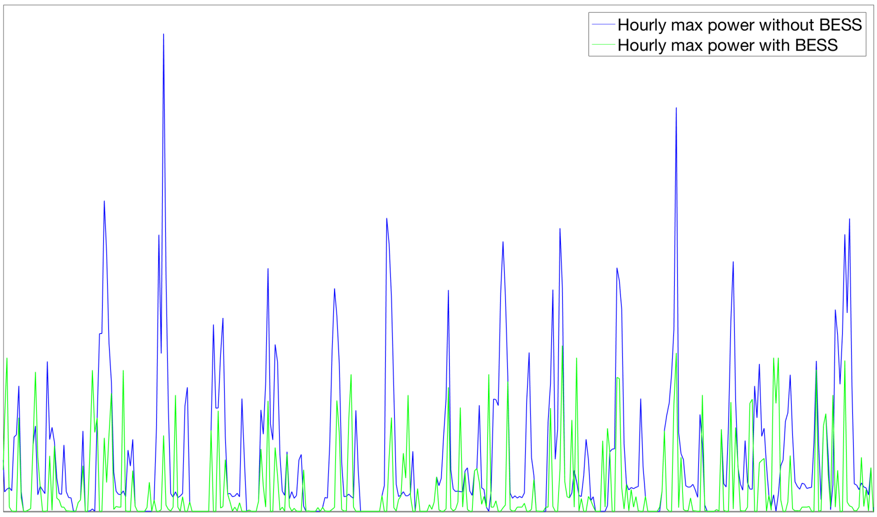

# Simulation and implementation of strategies to control energy flow through a BESS

Master's thesis in Systems, Control and Mechatronics

JOEL STRAND

Department of Energy and Environment
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2016

Master's thesis 2016

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Cover: Plot showing how a BESS could be used to reduce power peaks of a house hold.

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# Abstract

This report discusses different strategies for charging and discharging a battery energy storage system to maximize economic profit. The work is based on the Swedish energy market. Three strategies are evaluated, first the output minimizing strategy attempting to minimize the output energy toward the electric grid, second the peak reduction strategy attempting to minimize the maximum power consumption by discharging the BESS during peak hours and charging at night time when prices are low, and third the floating zero strategy trying to keep the output toward the grid at a certain level based on the local consumption profile.

Simulations show that in an ordinary household the suggested output minimizing strategy saves 2994 kr yearly for a 12 kWh BESS, 3583 kr for a 24 kWh BESS and 3887 kr for a 48 kWh BESS. The peak reduction strategy saves 2447 kr yearly for a 12 kWh BESS, 2853 kr for a 24 kWh BESS and 2960 kr for a 48 kWh BESS. The floating zero strategy saves 2375 kr yearly for a 12 kWh BESS, 3196 kr for a 24 kWh BESS and 3538 kr for a 48 kWh BESS. Numbers are based on current energy cost and consumption for an ordinary household and result in a pay off time of approximately 25 years or greater, depending on system size.

Keywords: BESS, energy storage, energy flow, charging strategy

# Acknowledgements

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I would like to thank all the people at Swedish Box of Energy; Johan, Fredrik, Daniel and Hanz for teaching me everything I need to know about energy storage, the Swedish energy market and solar power. I would also like to thank Consat Engineering AB for providing me with academic support and a very appreciated change of environment once a week. Furthermore, I would like to thank my examiner Torbjörn for providing fast and constructive response regarding the report. And finally all my other friends who I have bugged with questions, general nagging and discussions when I needed an out of the box perspective.

Joel Strand, Gothenburg, May 2016

# Contents

# 1

# Introduction

## 1.1 Problem background

In today's energy grid the amount of green energy production is increasing [1] and as the prices for production units gets lower and many countries offer different subsidies for installation of renewable energy sources, the trend seems to continue [2]. The great increase in renewable energy production, mainly in the form of solar panels, has led to strongly varying power production in the electrical grid, which in some cases have led to an abrupt turn in the commercialization with limits on allowed power infeed to the grid [3]. An easy way to limit the output is to combine the energy production system with a storage unit that could be charged during overproduction rather than outputting the power to the grid.

There are several popular ways to store energy and one rising in popularity is the battery energy storage system (BESS) due to efficiency increase and price drop of batteries. The storage system is easily modified and has good capabilities regarding both size and charge and discharge power.

Swedish Box of Energy makes BESS's of different sizes and different charge and discharge rates to combine with existing energy production mainly for larger power consumers such as apartment buildings and farms. The strategy for the energy flow is written in java code implemented on a Raspberry PI and is currently designed to minimize the energy flow to and from the grid. By changing this strategy to accommodate the price fluctuations on the energy market, the energy costs may be reduced further.

## 1.2 Previous work

In 2013 a master thesis was done at the Department of Energy and Environment at Chalmers University of Technology to design different strategies to minimize energy costs [4]. This thesis was designed for private house holds in Sweden with small storage systems compared to those designed by Swedish box of Energy. The analysis showed that proposed strategies where unprofitable due to high battery wear as well as decreasing profit with size.

Furthermore, [5] optimized size of a BESS and control of energy flow using dynamic programming with focus on minimizing power peaks for larger scale consumers.

However, it does not take any energy production into account thus showing capabilities of controlled energy flow but requiring some more research.

## 1.3 Purpose

The purpose of this thesis is to further investigate different strategies as proposed by [4] and simulate those in a larger scale as well as private households. To implement this, a simulation of the complete system including energy production, consumption and prices is targeted to be done, with focus on the BESS.

# 2

# Collection of known usable theories

## 2.1 Modeling of batteries

As described by [6] there are several ways to model a battery with different complexity and detail where the most simple one consists of a simple circuit built of resistors and capacitors. The aspects gained by these models, however, are usually only relevant in short periods of time and this report will work with a time step in the order of minutes, which will make potential gain from a more detailed model an unnecessary complexity. Instead the batteries are simply considered as energy storage with instant output upon request. With this in mind there will still be a need to simulate the degeneration of the batteries since the simulation will run long enough for this phenomena to impact the result.

### 2.1.1 Battery life estimation

One expenditure regarding BESS is the lifetime of the batteries in the system. Whenever a battery module's capacity is too low it has to be replaced which will introduce a cost based on number of cycles until end of life (EOL) is reached. A battery is considered to have made one cycle when its given capacity have been given as output once, disregarding any charges, meaning that two half discharges equals one cycle. According to [6] the capacity of the battery will degenerate close to linearly which makes an approximation possible without cycling a full life time. Based on the data sheets of the battery it is easy to determine the amount of cycles to use, around 20% should suffice, and then using linear extrapolation to approximate the capacity as function of numbers of cycles performed. In general a battery is considered to have reached its EOL when the capacity of the battery is below 80% of original capacity. This gives us

$$0,8b = ax + b \Rightarrow x = \frac{-0,2b}{a} \tag{2.1}$$

where $x$ is the number of cycles and $a$ and $b$ are constants given by the linear extrapolation. This approach is valid for lithium ion batteries as long as the cycle depth is relatively shallow, which would respond to the case in the BESS.

## 2.2 Energy market

The Swedish energy market consists of two main actors, the grid owner and the electric company. In some cases an electric company might also own the grid. The electric company can be chosen freely by the costumer while the grid owner depends on the location. This gives a clear breakdown of the energy cost in two parts, the grid cost and the electricity cost. The grid cost usually consists of one yearly cost for the connection and one energy transfer cost, depending on amount of bought energy. The yearly cost usually depends on the size of the main fuse to the household, where smaller fuse is cheaper and the cost increases exponentially [7]. Some times a power fee is also added which is payed per kW from the highest hourly average power usage each month. Some companies may use several peaks or only apply this cost during certain hours [8].

The electricity cost usually has different payment plans, most common is the fixed price plan and the flexible price plan, which both will be used in this report. The fixed price is decided when signing up with the electricity company and is a constant cost per kWh during a specified amount of time, usually 1-3 years. In some cases it may be divided into a constant price per quarter instead with some differences between each quarter to reduce energy cost during winter, or similar. Upon this, a monthly fee is added.

The flexible price is a bit more advanced and may vary between every hour, day or month. For implementation purposes the hourly variation is assumed. The biggest variation of this price is decided by Nord Pool, the Nordic energy market [9]. An example of how the price varies over the day is shown in Figure 2.1. On the price given by Nord Pool the electricity company usually add cost for electricity certificate, which will be further described below, volume, gain for the company and taxes. The taxes consists of energy tax, currently 29,20 öre per kWh, and sales tax of 25% of the total cost including the energy tax. [7]. An example including all costs is shown in Table 2.1.

When selling the surplus of produced energy there are several sources of income, some of which have demands on the producer. The most common demand is that the yearly production needs to be lower than the yearly consumption. In the general case this is valid and is therefore assumed in the following description.

When selling electricity a contract is set up with an electricity company to buy the excess energy, usually for the Nord Pool spot price with a fixed reduction corresponding to the margin for the buyer, but could also be a fixed price. From the grid owner the producer receives a compensation for the reduced transmission cost, usually payed per produced kWh. The grid owner may however have a fee for using the grid to sell energy. The sold energy is liable to tax and 25% of the income is to be paid in sales taxes. Above this the producer also needs to pay income tax if the sold energy is over 30000 kr. Furthermore, a producer may also get electricity certificates where one certificate represents 1 MWh of produced energy. The production can

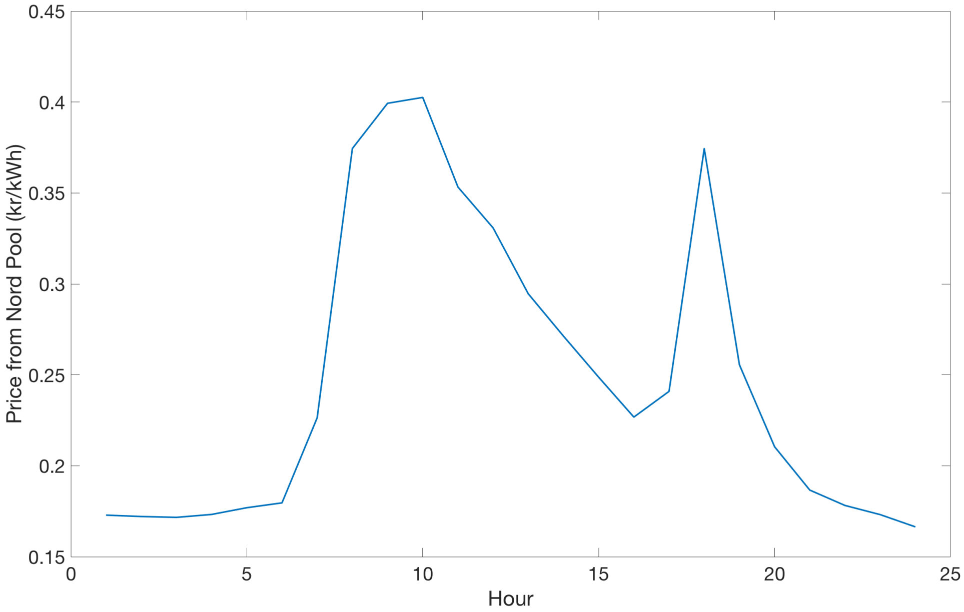

**Figure 2.1:** Example of how the energy price set by Nord Pool may vary over a day.

either be measured directly after the production or by the main fuse resulting in a deduction of own consumption. The latter case is favorable for small producers due to the installation costs of a new energy meter connected to the production unit, but for larger scale production, from approximately 10 kW and above, the first option is more economic. In the case where the produced energy is measured directly after the producing unit a BESS will not affect the amount of certificates. Since this report mainly considers larger producers the certificates will be disregarded, in the case where the production is measured by the main fuse the potential economic gain will be a bit lower than the result of the simulation. Finally, a tax reduction is gained when selling electricity of 60 öre per kWh of sold energy to a maximum of 18000 kr per year.

**Table 2.1:** Example table of costs related to electricity using flexible payment plan [7].

| **Type of cost** | **Cost** |
|---|---|
| Grid costs | |
| *Power peak cost* | 23,85 kr per kW |
| *Transfer cost* | 18 öre per kWh |
| *Connection cost* | 342,50 kr per month |
| Electricity costs | |
| *Spot price* | 21,56 öre per kWh |
| *Electricity certificate* | 3,71 öre per kWh |
| *Vendor fee* | 0,29 öre per kWh |
| *Energy taxes* | 29,20 öre per kWh |
| *Sales taxes* | 13,69 öre per kWh |

# 3

# Case set-up

To develop different strategies a simulation of the subsystems is first generated which will be used by the different strategies. The simulation set-up of the different subsystems is described below while how they work together depends on the strategy and therefore described in Chapter 4. The step size of the simulation is 60 seconds. Data might be acquired with different resolution but is then converted to minute resolution by a method specified for the individual cases.

## 3.1 Simulation set-up of BESS

The BESS simulation is characterized by six properties, currently stored energy, maximum stored energy (size), maximum input power, maximum output power, total energy flow through the system and approximated energy flow during a BESS life time.

When the BESS receives a power request, the corresponding energy is calculated by multiplying it with the time step divided by 3600. If that amount of energy is available and does not violate the input or output constraints the energy of the system is changed according to the request. Negative sign indicates charge request and positive sign indicates discharge. If the energy corresponding to the requested power is larger than the amount of available energy or larger than the constraints of the BESS the output is limited by the tightest constraint. The resulting allowed power is then returned to the caling function. The simulation is represented in the flow chart viewed in Figure 3.1.

In simulations represented in this report the BESS has 12, 24 or 48 usable kWh storage system, defined as size, with maximum input and output power of 3200 or 6400 W and a lifetime energy flow corresponding to 7000 cycles as provided by the battery producer.

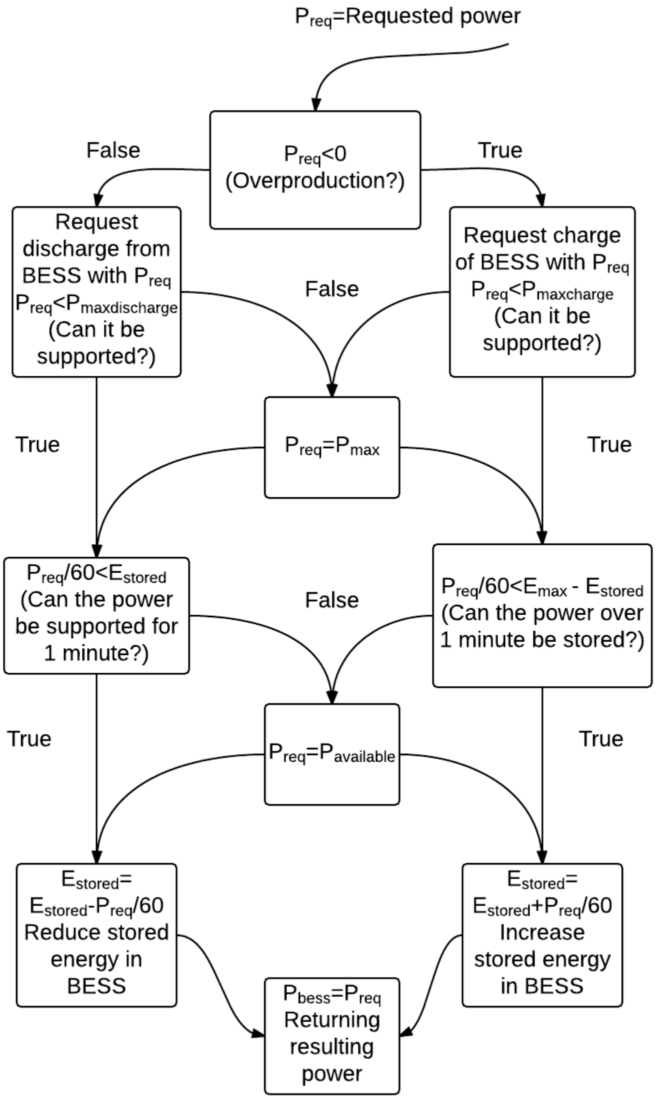

**Figure 3.1:** Flowchart of BESS simulation.

## 3.2 Simulation set-up of energy prices

Since the Swedish energy market has different pricing options, the energy price simulation consists of different modes depending on type of pricing described in Section 2.2. In the case of fixed pricing, the price is set to constants, one for bought energy and one for sold energy. In the case of flexible pricing, a file with the hourly prices set by Nord Pool is loaded and additional costs are added as described in Section 2.2. When the cost is calculated the current hour and weekday is then used to retrieve the current price represented in the Nord Pool matrix.

To take the cost of power peaks into account an average is calculated every hour and the maximum peak is stored. At the end of every month the power peak cost is added to the total cost and the power peak is reset to zero.

In the simulation the electricity certificate granted by the Swedish Energy Agency is disregarded since the certificate won't affect possible economic gain from the BESS, assuming the number of certificates are calculated without consideration of the private consumption.

The energy simulation is called with mode, time and current power as input. The mode decides which type of pricing that is used, the time is used to get current price in the flexible pricing scenario and the power is converted to bought energy based on the current step size of the time vector. The cost is then returned as the product of bought energy and the cost per energy unit.

## 3.3 Simulation set-up of energy production

The simulation of energy production was done by gathering data from different producers and read it into Matlab. The data was mainly from [10], which is 35 MW solar panels located in New York, United States, but some data was gathered from customers of Box of Energy and used as comparison. The data from [10] was scaled down from 35 MW to 7 kW to match the energy consumption of the simulation and re-sampled with zero-order hold to match the sample rate of energy consumption.

## 3.4 Simulation set-up of energy consumption

Energy consumption is simulated for caseloads with different energy profiles similar to the simulation of energy production described above. The gathered data has minute resolution and is given in watts. Data is gathered from [11] which is a small house located outside Paris with a yearly consumption around 10000 kWh. Again, data from customers at Box of Energy is used as comparison. To get a rough simulation of a bigger system the data was scaled up 50 times, to get a rough version of an apartment complex.

## 3.5 Base verification

To verify that the behavior of the simulation is a good approximation of the true system first a step of size 4 kW was used as input for five hours. The sign was then inverted after 30 minutes of zero input. The results are shown in Figure 3.2 where it is clear that the output limit of 3,2 kW limits the output while the State of Charge (SoC) is constantly lowered. When the SoC is zero the output power stops and becomes zero until the sign of the step is changed. The BESS then starts to charge with the limit of 3,2 kW, once again until the SoC is 100% at which point

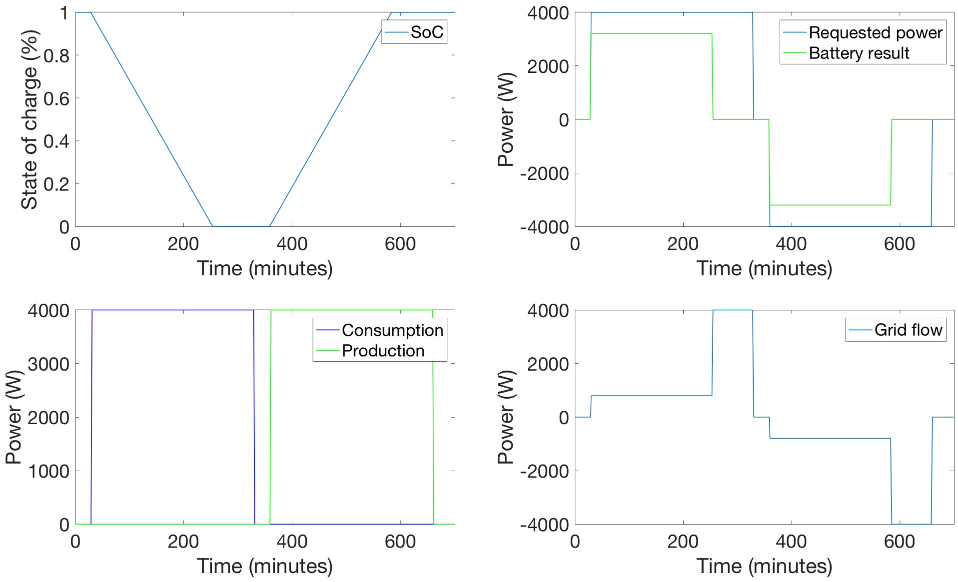

**Figure 3.2:** Verification of the simulation with a step as input and the resulting output. Upper left graph shows the SoC of the BESS. Upper right graph shows the power requested by the strategy and the resulting power from the BESS. Lower left graph shows the production and consumption used as input. Lower right graph shows the energy exchange with the grid where positive sign is bought energy and negative sign is sold energy.

the charging stops. In reality the behavior around fully charged and completely empty will be slightly different since the battery management system will limit the charging and discharging current close to the limits. In the general case this will however not affect the result since the power bought and sold during this time will instead be bought and sold a few minutes later in the model.

To further verify the model, data from a running BESS was used. The system which consisted of a BESS with a size of 10 kWh, maximum input and output of 3,2 kW and the simulated system was defined with the same properties. The grid flow of the two systems are compared in Figure 3.3.

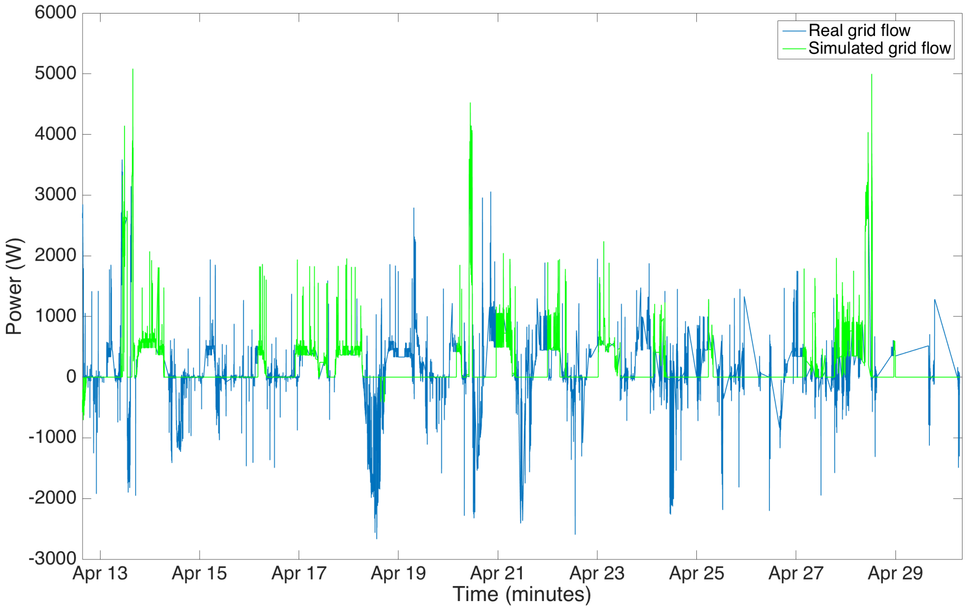

**Figure 3.3:** Comparison of the grid flow in the simulation and in a real system.

As can be noted in Figure 3.3, the grid flow is quite different. The real grid flow is clearly much noisier, which is to be expected. The simulated flow does however capture a lot of the real system, larger peaks in particular, which makes the simulation quite useful, primarily for peak reduction. The differences between the two graphs may very well depend on the simulation rate. The simulation has a step size of 60 seconds, due to limitations in stored data, while the actual installation has a step size of 100 ms. Furthermore, the data stored by the installation is only the instantaneous value, not an average of the last minute. If the recorded data was taken during a partially cloudy day, the solar energy production might have been very fluctuating and an instantaneous data points might vary strongly.

# 4

# Description of energy flow strategies

## 4.1 Exchange minimizing

The first and most intuitive way of saving money is by minimizing the amount of bought and sold energy since the cost to buy electricity is higher than the earnings of selling energy. This strategy simply reads the status of the electricity meter and requests the same power from the BESS, thus trying to control the flow to and from the grid to zero by charging or discharging the BESS instead. If the BESS is fully charged and there currently is an over production, the produced energy will be sold and in the same way. When the BESS is empty and the household needs power, energy will instead be bought from the grid. The same will apply if the over production is higher than the maximum input to the BESS or if consumption is higher than the maximum output of the BESS, the difference will be sold to or bought from the grid. This will be equivalent of putting $P_{req} = P_{res}$ in Figure 3.1, where $P_{res}$ is the difference between consumption and production.

## 4.2 Spot price charging and power peak reduction

The general idea of spot price charging is to use the fact that power is cheaper during night hours when demand is low and charge the BESS with this cheap energy to use during peak hours when price is higher. The idea of the peak reduction is to minimize the hourly power peaks by using battery power during peak hours, which would be useful in the scenario where grid owners apply a power peak fee. Since the highest power peaks in an ordinary household are in the morning and in the evening it is clear that the economic gain could be further increased by combining spot price charging and power peak reduction, as suggested by [4]. By charging the BESS night time and saving the energy until peak hours in the morning, the morning peak could possibly be decreased and by the time of the evening peak the BESS should be fully charged from energy production and thus able to reduce the second power peak. The strategy is represented as a flow chart in Figure 4.1.

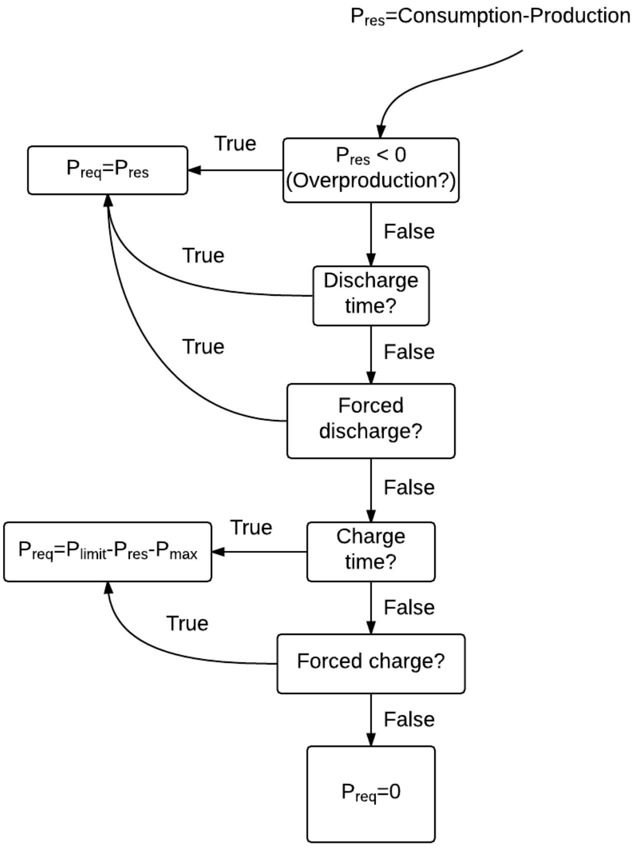

**Figure 4.1:** Flowchart of the spot price charging and power peak reduction strategy. Discharge time is one hour before and two hours after the two biggest peaks from the day before. Forced discharge occurs if $P_{res}$ will cause the current hour's average to go above 90 % of last months peak. Charge time is the cheapest hours during the night, where the number of hours depend on BESS size. Forced charge occurs if the SoC is below 60 % after 13:00, i.e. there has been limited sun during the day. When charging $P_limit$ limits the charging power to ensure that the charging itself do not cause a power peak.

## 4.3 Floating zero

Floating zero strategy is simply a modified version of the exchange minimizing approach. Instead of trying to minimize the exchange, the BESS will try to have a constant exchange during the day. With this strategy, the BESS can be useful in scenarios where the consumption and production differ a lot in size. This method also uses some of the advantages of power peak reduction, but instead of focusing the battery power during peak hours, it uses a lower output for a longer time thus potentially saving power long enough to reduce the peaks but with a lower value than if using full output power just during the peaks. The advantage of this method is the simplicity in implementation. It will also be possible to implement in systems where output to the grid is limited, since the control signal will no longer require a negative sign to start charging. By determining the floating zero value ($C_{fz}$) based on average consumption and production the use of the BESS can be optimized. This will be equivalent of putting $P_{req} = P_{res} - C_{fz}$ in Figure 3.1.

# 5

# Evaluation

Here the different strategies will be analyzed regarding economical profit. The amount of energy bought and sold to the grid will be compared with and without a BESS taking into account the installation cost of the BESS but disregarding installation cost of energy producing unit such as solar panels. Thus assuming they are already installed and only taking the effects of the BESS into account. An approximation of maximum gain during ideal condition is made for each strategy. A summarizing table as well as a comparison between the strategies can be found in Section 5.5.

## 5.1 Evaluation of system

The simulated system is based on data from actual consumption and production, which makes the simulation a close representation of reality. The data, however, is only from one source and one house, limiting the possibility for general statements but is enough to show the concept and draw conclusions regarding strategies' behavior. The BESS itself is an ideal system without errors and delays which appear in the real system. Furthermore, the simulated BESS has a time step of 60 seconds while the real BESS time step is 100 milliseconds. This will cause the gain from a real system to be a bit lower than presented below. The numbers are however a good approximation of maximum potential gain in an operating environment. Finally, it is also good to consider that the gain will also depend on the energy consumption and production where the BESS is implemented and that the BESS is correctly sized.

As reference in the following evaluations, the cost of the BESS will be taken into account. Since BESS are not scaleable, as described by [2], the cost is assumed to be 9500 kr per kWh from 24 kWh and above. For smaller BESS the cost is assumed to be 10545 kr per kWh. The prices are based on the current cost of BESSs from Swedish Box of Energy AB.

## 5.2 Exchange minimizing

Even though exchange minimizing could be considered the most intuitive strategy it is hard to get a good picture of potential savings. An easy approximation would be to assume one full cycle daily, which results in a gain corresponding to the difference between cost to buy and profit by selling multiplied with the size of the BESS. For a 12 kWh BESS this equals 13,13 kr per day if the difference were 1,09 kr per kWh, i.e. 4795 kr per year which would result in a pay off of a little bit above 26 years. For a 24 kWh or bigger BESS the payoff would be barely 24 years. The assumption of a full cycle daily requires enough over production to fully charge the battery every day and enough consumption to completly drain the battery when it is dark. This is highly unlikely but gives a hint of the expected pay off time. It is also clear that the potential savings increases linearly with increasing difference between the buy and sell price, presumably due to increased buy price and unchanged sell price. Another way to lower pay off time would be by reducing the price for the BESS and as described by [2] and [5] the price of lithium ion batteries are decreasing, which is the biggest cost in the construction of BESSs.

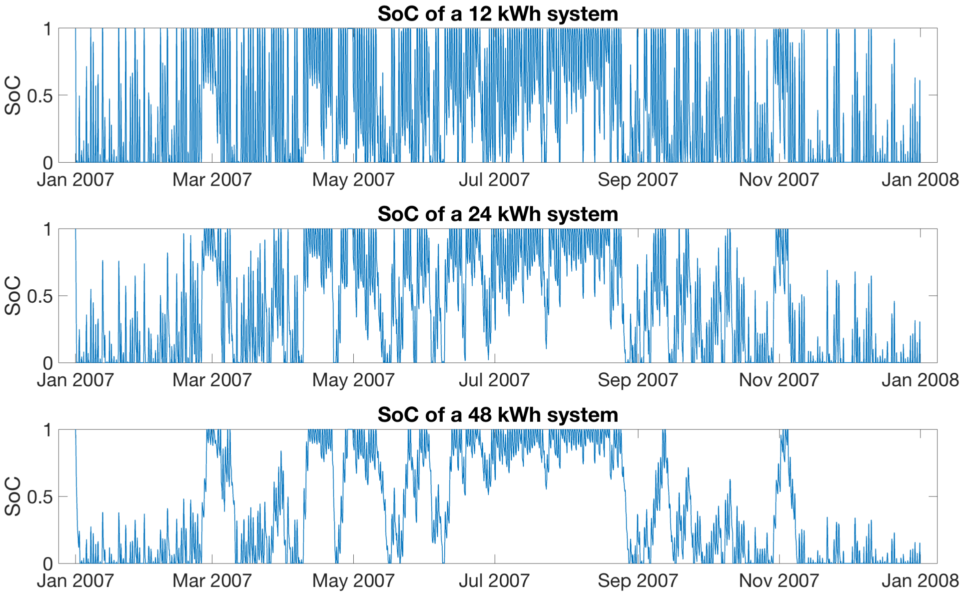

**Figure 5.1:** Simulated State of Charge for different sizes of energy storage using the exchange strategy.

To get a better estimate of potential gain the strategy is run through the simulation described in Chapter 3. The first thing to note is that to maximize the use of the BESS the numbers of cycles per year should be as high as possible while minimizing the amount of sold energy. Figure 5.1 shows how the SoC behaves for a 12, 24 and 48 kWh BESS. It is clear that the 12 kWh BESS have the highest amount of cycles and therefore the largest utilization, in this case 275 cycles per year, while the 24 and 48 kWh only do 141 and 75 cycles respectively. Even though higher utilization result in higher wear on the BESS, it also increase savings and thereby decreases the pay off time, which in general is desired. In addition, batteries have a calendric degeneration which will increase with the life time of the battery [6]. From this it is clear that a 12 kWh BESS would be ideal choice since the larger one will not fully charge during winter due to low production from the solar panels and will not completely discharge during summer due to low consumption compared to the production. With 275 cycles per year the BESS will work for 25 years given the 7000 cycles specified by the manufacturer.

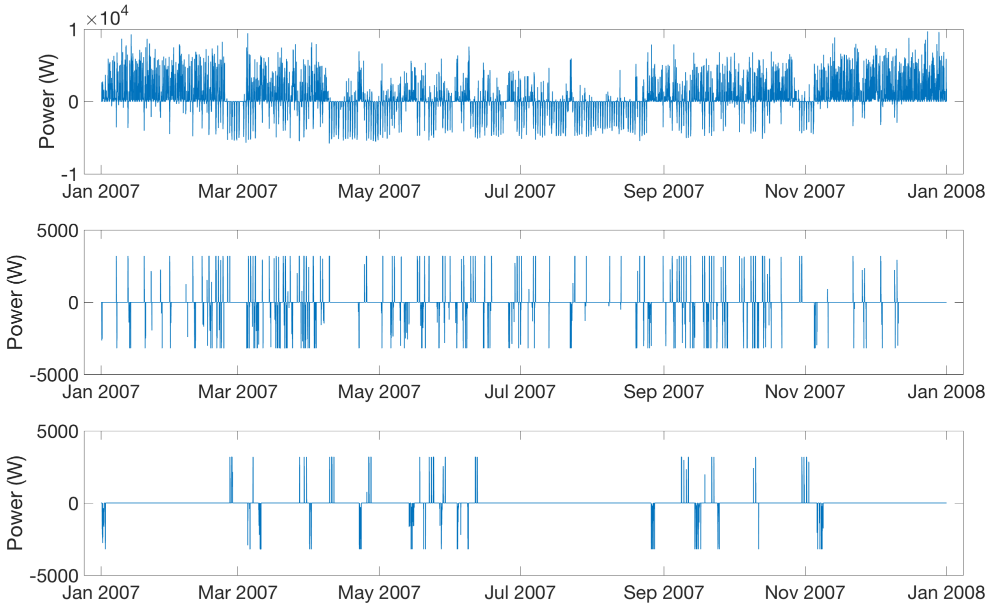

**Figure 5.2:** Differences between sizes of BESS using the exchange minimizing strategy. Upper graph show the grid flow of a 12 kWh BESS with positive values representing bought energy and negative values sold energy. Middle graph shows improvement by upgrading from a 12 kWh BESS to a 24 kWh BESS and bottom graph shows improvement by upgrading from a 24 to a 48 kWh BESS.

To further evaluate the differences between the sizes, Figure 5.2 shows the improvement by increasing size. The upper graph shows the flow to the grid where positive values indicate bought energy and negative values indicate sold energy. Ideally this graph should be zero, meaning no sold or bought energy. The middle graph shows the improvement by upgrading to a 24 kWh BESS, positive values represent a reduction in sold energy and negative values indicate a reduction in bought energy. The bottom graph show the improvement by upgrading from a 24 kWh BESS to a 48 kWh BESS. The bottom graph indicates that an upgrade from 24 to 48 kWh BESS will not generate much improvement since a difference will only be noticed a few times a year, which depends on the size of the solar panels compared to the consumption. With a lot of over production bigger BESSs comes to good use while BESSs with low over production will not generate enough energy to utilize the full size of the BESS. In this case it is clear that a 48 kWh BESS is unnecessarily large while the 24 kWh BESS provides some improvement. By integrating the positive and negative values the improvement can be quantified. By upgrading to a 24 kWh BESS the amount of sold energy will be reduced by another 533 kWh compared to a system with the 12 kWh BESS and the amount of sold energy will be reduced by 545 kWh per year. By upgrading the 24 kWh BESS to a 48 kWh BESS the corresponding numbers are 219 kWh bough energy and 243 kWh sold energy. This confirms that the improvement by upgrading from 24 kWh to a 48 kWh BESS is much smaller than the upgrade from 12 kWh to a 24 kWh BESS.

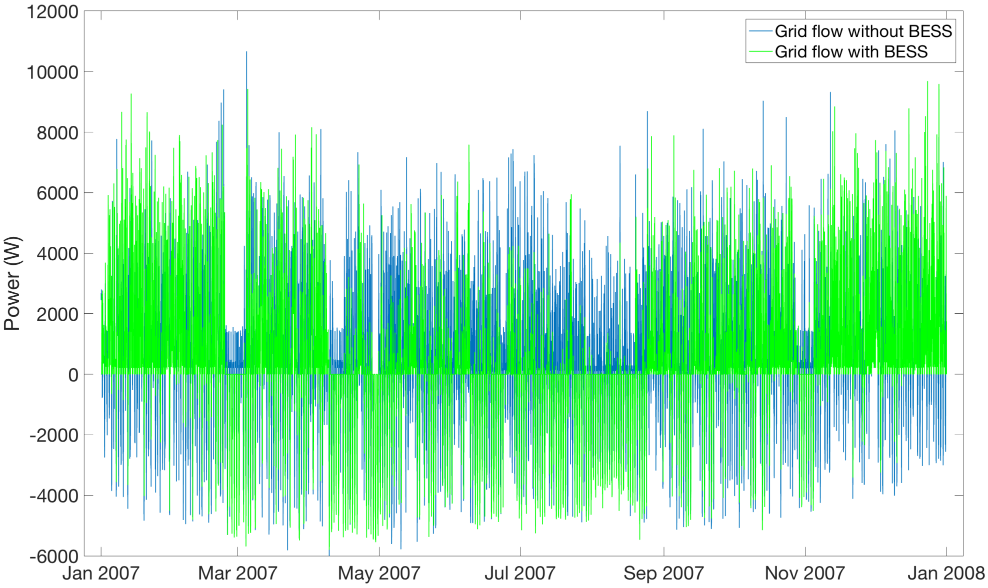

**Figure 5.3:** A comparison of system with and without a BESS. Positive values represent bought energy and negative values represent sold energy. The goal is to minimize those values.

To compare the 12, 24 and 48 kWh BESS the savings from energy cost is calculated for the BESSs and compared to the cost without a BESS. For the 12 kWh BESS the savings in energy cost is 2994 kr per year while the savings for the 24 and 48 kWh BESS is 3583 and 3887 kr per year. This equals a pay off time of 42, 63 and 117 years respectively which is at least two times the expected life time of the BESSs or greater and it would require replacement before pay off time was reached. By again looking at Figure 5.2 it is now clear that the improvements shown in the graphs are not enough to motivate the increase in size due to the increase in cost for a larger BESS. The simulated result is also clearly lower than the theoretical estimation since the estimation did not account for neither sunless days nor power peak costs.

Figure 5.3 visualizes the difference of the grid flow with and without a BESS where the blue areas represent reduction in flow, i.e. the improvement. The purpose is to minimize the flow to and from the grid and thereby the optimal result would be a constant zero but due to the limited size and power of the BESS this is not achieved. It does, however, give a clear improvement compared to a system without a BESS. The amount of bought energy is clearly smaller, especially during the summer months when there is a lot of solar power available, visible from the blue area in the graph, and the amount of sold energy is also lower, especially during winter when the solar power is more limited.

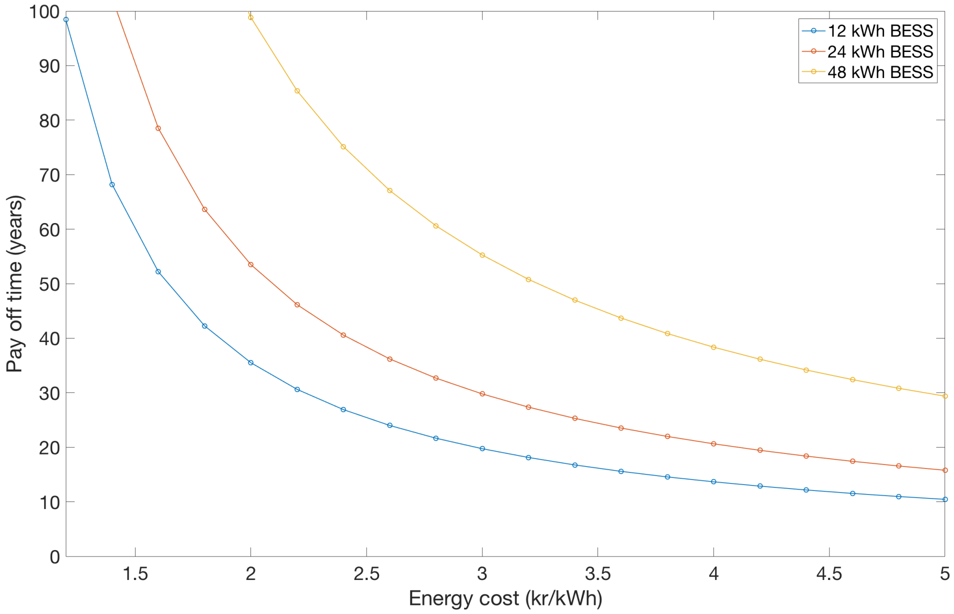

**Figure 5.4:** Pay off time as a function of energy price for 12, 24 and 48 kWh BESSs using the exchange minimizing strategy.

This strategy is of course very sensitive to changes in the energy market. An increase of 1 kr per kWh would reduce the pay off time to 21 years which is a much more reasonable pay off time, in particular for companies leasing apartments. To further investigate how the energy price affects the pay off time Figure 5.4 shows how the pay off time depends on the energy price for the different sized BESSs. From the graph one may note that with a higher energy price the BESS would turn into a profitable investment. However, one can conclude that with today's energy pricing the economic gain alone will not be sufficient to motivate the investment of a BESS using the exchange minimizing strategy in households.

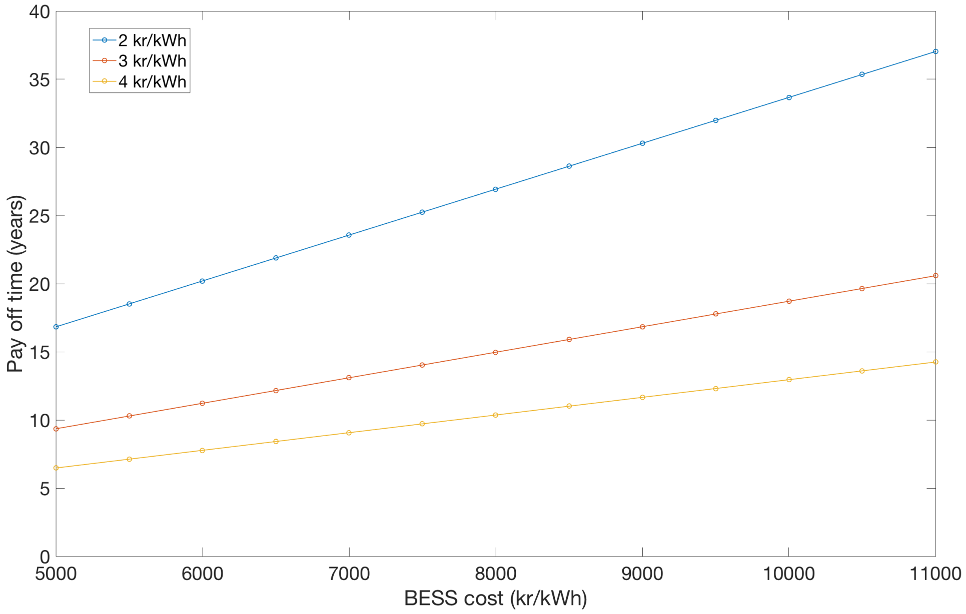

**Figure 5.5:** Pay off time for a 12 kWh BESS as a function of the cost of the BESS using the exchange minimizing strategy with an energy price of 2, 3 and 4 kr per kWh.

Another way to affect the pay off time is to try to reduce the price of the BESS. Figure 5.5 shows pay off time for a 12 kWh BESS as a function of the price per kWh storage with an energy price of 2, 3 and 4 kr per kWh. The figure shows how the energy cost gives a greater impact than the cost of the BESS, but by also reducing the cost of the storage system the pay off time could clearly be further reduced.

By instead looking at an apartment complex the numbers look quite different. In Figure 5.6 the cycles of the different sized BESS can be viewed, corresponding to Figure 5.1 for the household. It is clear that a bigger BESS here has much better utilization than a smaller BESS but the cycling is limited by the input and output power, which is quite notable in the right most graph. To completely fill an empty 48 kWh BESS with 3,2 kW input 15 hours are required and solar panels rarely generates power for that long. This results in a gain of 4773 kr per year, corresponding to a pay off time of 26 years for the 12 kWh BESS, 7874 kr per year and 29 years for the 24 kWh BESS and 8901 kr per year and 51 years for the 48 kWh BESS.

If the input and output power were doubled the gain would increase to 5590, 9451 and 15630 kr per year, corresponding to a pay off time of 22, 24 respectively 29 years, which is a reachable scenario without great increase in production cost of the BESS. From this observation it is clear that the size of the BESS has to be matched to the input and output power to achieve optimal efficiency from the BESS. The behavior of the SoC in this scenario can be seen in Figure 5.7.

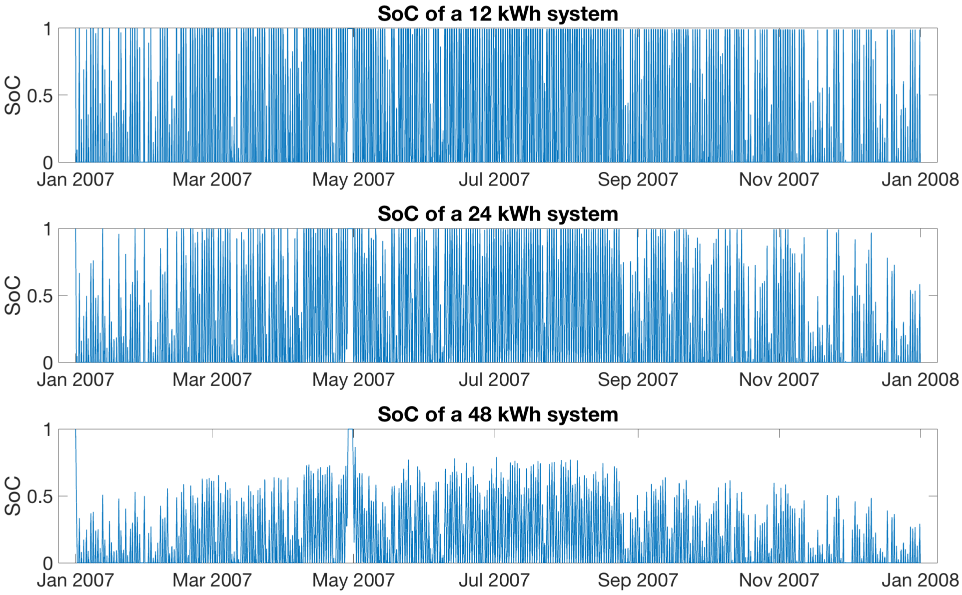

**Figure 5.6:** Simulated state of charge for 12, 24 and 48 kWh BESSs in an apartment complex using the exchange minimizing strategy.

Notably, the pay off time for BESSs in larger systems is still longer than the expected lifetime which for the BESSs with double input and output power is 15, 18 and 23 years respectively. By again comparing the pay off time with an increased energy cost of 1 kr per kWh, the 12 kWh system would have a gain of 11172 kr per year corresponding to a pay off time of 11 years, which is much more reasonable. In the same way the 24 kWh system would have gain of 18474 kr per year and a pay off time of 12 years and the 48 kWh would have a gain of 29848 kr per year and a pay off time of 15 years and would then be a motivated investment since the pay off time is lower than the expected lifetime.

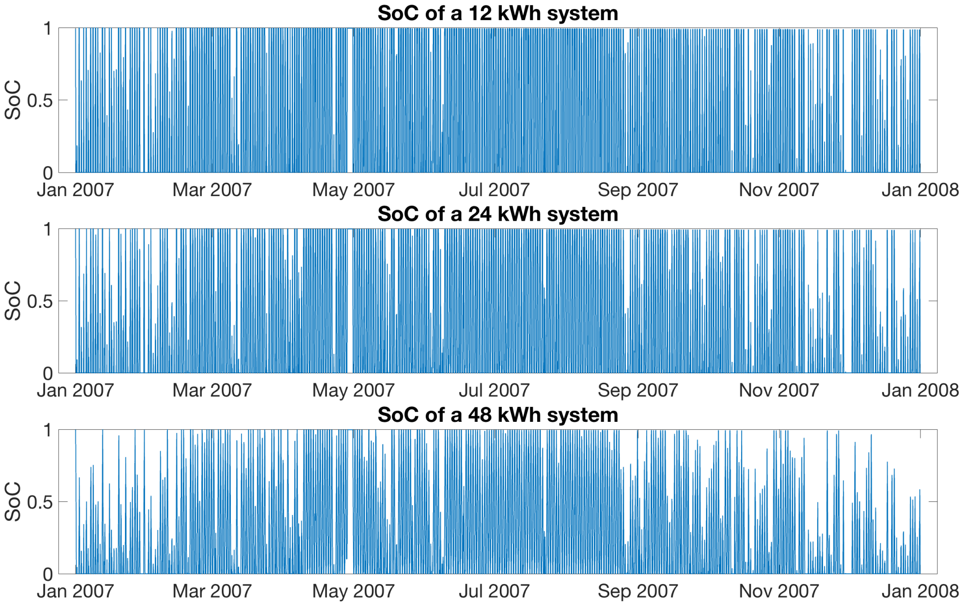

**Figure 5.7:** Simulated state of charge for 12, 24 and 48 kWh BESSs with double input and output power in an apartment complex using the exchange minimizing strategy.

## 5.3 Spot price charging and power peak reduction

To evaluate the spot price charging and peak reduction strategy first an approximation of possible gain is calculated. The theoretical maximum gain from peak reduction would be the peak cost times maximum discharge power of the BESS. In the simulated system with a cost of 23,85 kr per kW every month and a maximum discharge power of 3200 W which equals 76,32 kr per month. This would however require that the BESS is giving full discharge during the full hour in question. Since the BESS is limited, the suggested strategy tries to predict when the peak hours occurs and giving full output these hours. It will always try to keep the highest peak of the day lower than the highest peak of previous month, which will require some run time to reach a good value but thereby an individually calibrated threshold.

Potentially, the peak reduction could also reduce the size of the main fuse with up to 15 A based on a BESS with 3200 W input and output. This reduction could potential save several hundreds of kr per month, as comparison a reduction from a 25 A main fuse to a 16 A main fuse would result in a yearly gain of 2940 kr, but comes with a potential risk. If the size of the main fuse is reduced and the BESS fails it may cause the fuses to melt during high consumption, resulting in blackouts until the BESS is fixed, which might be devastating to a company with high demand on production. This could be avoided by implementing a warning system when consumption is close to the maximum capacity and thereby giving the consumer ability to control power consumption. In this report, the simulated consumers are however unable to benefit from this gain, the household uses a 16 A fuse, which commonly is the smallest, and the apartment complex is in the range where the cost is regulated with a power based cost instead of the size of the main fuse [7], [8]. To indicate possible savings from main fuse reduction, the savings corresponding to reducing the main fuse from 25 A to 16 A is used.

In the same way, the maximum amount of money saved per day by spot price charging could be estimated by multiplying the size of the BESS with the difference between the cheapest and most expensive rates given by the spot price. In our case the price difference is 26 öre per kWh and with 24 kWh storage this gives a maximum gain of 6,24 kr per day which corresponds to 187,20 kr per month. Since the difference during one day rarely is of this size and it takes longer than one hour to fully charge the BESS this gain is of course always lower, but it is clear that this method may very well save as much money as the peak reduction, particularly during days with low production.

Upon this, the save described in Section 5.2 will have some influence in this strategy as well. However, since the BESS only discharges certain hours during the day the influence will be limited by the output power. Assuming that 3200 W output power is used for two hours with solar power only 6,4 of the available 12 kWh will be used makes it reasonable to assume that only half of the capacity will be used. The output from the BESS during the morning is already accounted for with the spot price charging. This, combined with savings from peak reduction and spot price charging, would result in a yearly gain of 4436 kr for a 12 kWh BESS resulting in a pay off time of a 28 and a half year. For a 24 kWh or bigger the pay off time would be almost 29 years. These numbers would be a close representation to attainable values assuming a perfect algorithm for peak detection. By reducing the main fuse, the yearly gain would be 6826 kr, reducing the pay off time to 18 and 21 years respectively.

For a better evaluation of the strategy it is run through the simulation. The effect of the strategy is shown in Figure 5.8. It is clear that the peaks are reduced although, for some cases, the size of the BESS is not sufficient to compensate during the complete duration of the peak. This can be further viewed in Figure 5.9.

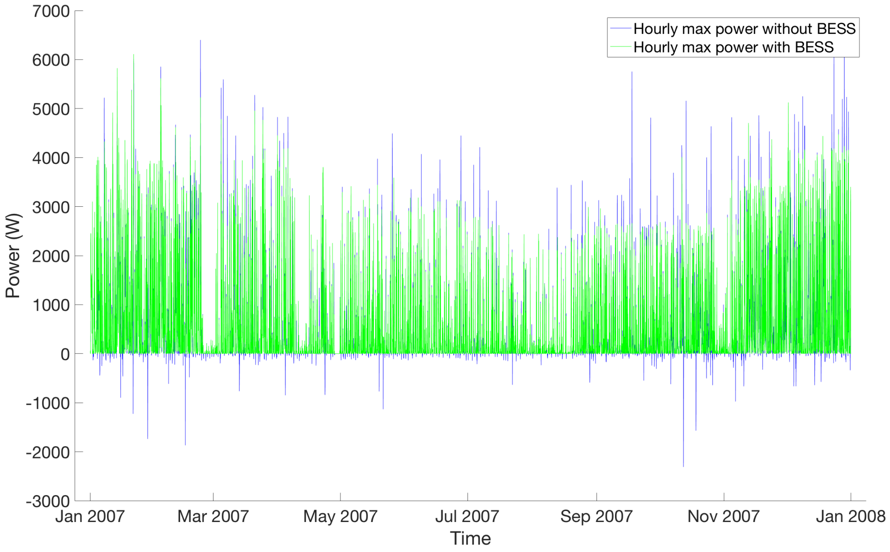

**Figure 5.8:** Improvement of hourly power peaks with a BESS. Blue parts represent the reduction of peaks.

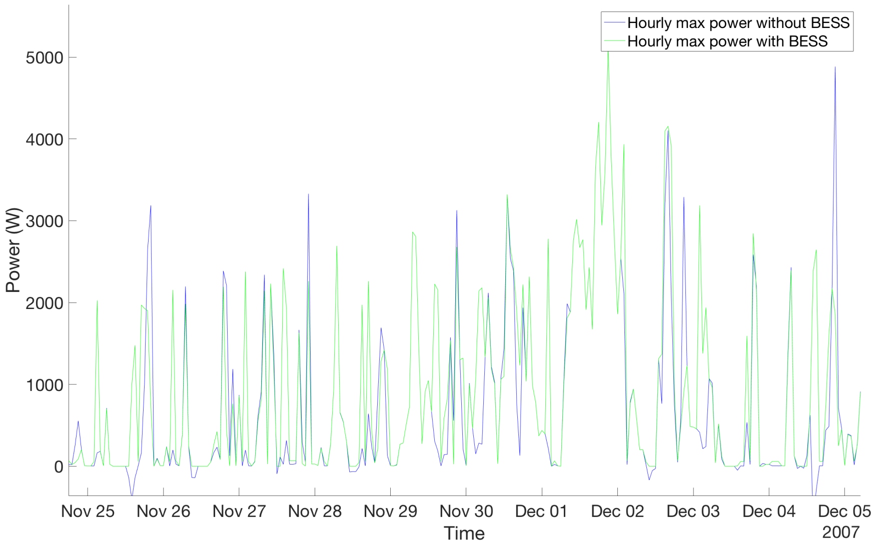

**Figure 5.9:** Closer look of hourly power peaks with a BESS shown in Figure 5.8.

Figure 5.9 shows a closer view of the strategies behavior. During night time the system with a BESS has a slightly higher consumption when it is spot charging as well as during days with low amount of solar power. It is also noticeable how a lot of peaks are reduced but how one in the beginning of December have too long duration and starts too early to be compensated for by the BESS.

As before, the amount of cycles are compared between the different sizes of the BESS, shown in Figure 5.10. The 12 kWh BESS does 264 cycles per year, the 24 kWh BESS do 142 and the 48 kWh BESS does 74. Compared with the exchange minimizing strategy in Figure 5.1 the spot charging and peak reduction strategy do not perform as deep cycles since it charges rather than discharges night time but instead discharges twice a day making the number of cycles similar.

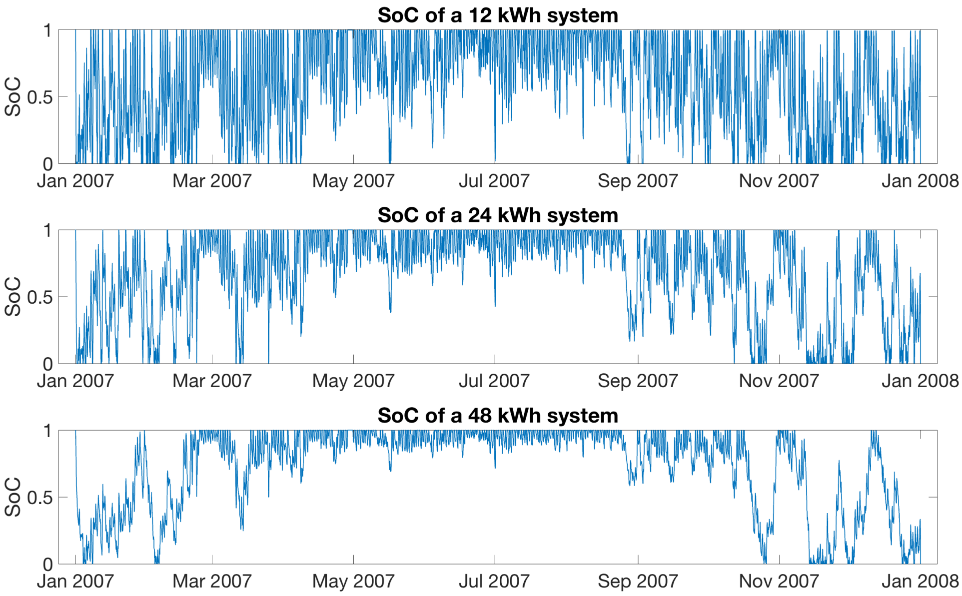

**Figure 5.10:** State of charge for 12, 24 and 48 kWh BESS using peak reduction strategy.

To get a better view of the improvement from the spot price charging and peak reduction strategy the economic gain is calculated. For the 12 kWh BESS the gain is 2447 kr per year and for the 24 and 48 kWh BESS 2853 and 2960 kr per year is saved respectively, showing that the limiting factor is the output power rather than the size of the BESS. The lower economic gain compared to the exchange minimizing strategy is explained by the low cost for power peaks charged by the grid owner combined with the low power output from the BESS which limits the savings and the small difference between spot prices as well as the inability to handle all power peaks as shown in Figure 5.9. The economic gain corresponds to a pay off time of 53 years for the 12 kWh BESS and 80 and 160 years for the 24 respectively 48 kWh BESSs. If main fuse reduction would be used as well, the yearly savings would increase with 2930 kr and the pay off time would be reduced to 23, 29 and 77 years respectively, which reduces the pay off time with over 50%.

By doubling the input and output power of the different BESSs the gain from the 12 kWh BESS is 2668 kr per year which results in 49 years pay off time. The 24 and 48 kWh BESSs saves 3256 respectively 3488 kr per year corresponding to 70 and 131 years pay off time. This shows that even though output power give some impact on the results, the cost for power peaks is simply not enough to focus solely on power peak reduction. It also shows the difficulty to cope with power peaks since if one peak is too large to handle each month it is enough to undermine the purpose of the algorithm, assuming the grid owners only charge for the maximum peak.

As before, the strategy is also simulated for a larger apartment complex. In this scenario the possible peak reduction is relatively small due to the limited output power but the savings from spot price charging is slightly increased because of the greater amount of energy utilized.

Once again the 12, 24 and 48 kWh BESSs are compared assuming double input and output power. Figure 5.11 shows the SoC for the respective BESSs. It is clear that the utilization of the BESSs is much larger with this load, even though the 48 kWh BESS does not use its complete potential. The slight dip of max charge seen on the 12 and 24 kWh BESS are an effect from the degeneration of the battery. The gain in this scenario is 6062 kr per year for the 12 kWh BESS, 8920 kr per year for the 24 kWh BESS and 10050 kr per year for the 48 kWh BESS. This corresponds to a pay off time of 21, 25 and 45 years respectively. Once again showing that output power is a very important resource, since it increases the maximum peak reduction and thereby the maximum economic gain. By once again assuming main fuse reduction is used the pay off times could be reduced even further to 14, 19 and 35 years respectively, which result in pay off times lower than expected life time of both the 12 and 24 kWh BESS.

These results shows that the spot price charging and peak reduction strategy is a more profitable strategy than the simpler exchange minimizing strategy, of course depending on the energy price and power peak price. It is also clear that the output power has larger influence on the savings than the size of the BESS, which is expected when the core in the strategy is to minimize maximum output power rather than amount of bought and sold energy.

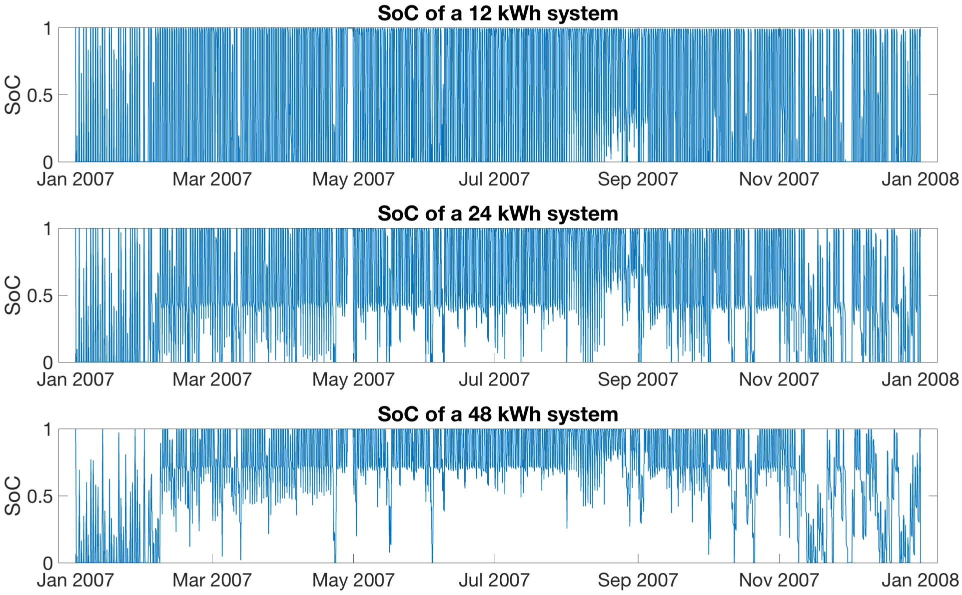

**Figure 5.11:** State of charge for the 12, 24 and 48 kWh BESS using peak reduction strategy in an apartment complex.

## 5.4 Floating zero

The theoretical maximum gain of the floating zero would be equal to the gain from the exchange minimizing strategy, disregarding gain form potential power peak reduction, assuming a good choice of constant for the floating zero value.

In simulations the constant is set daily to the previous day's average flow to the grid. This results in a good value set for the load but is sensitive to weather changes which affects mainly the energy production. The parameter could possibly be further tuned to achieve better performance. In Figure 5.12, the SoC of 12, 24 and 48 kWh BESSs are shown. This is, as expected, very similar to the SoC of the exchange minimizing strategy, seen to utilization, shown in Figure 5.1 due to the similarity of the two strategies. For this strategy the savings of the 12 kWh BESS is 2375 kr per year corresponding to a pay off time of 53 years and for the 24 kWh BESS the saving is 3196 kr per year corresponding to 71 years pay off time. The 48 kWh has a gain of 3538 kr per year and a pay off time of 128 years.

The 12 kWh BESS does 334 cycles per year, shown in Figure 5.12. Corresponding to an expected life time of 21 years which once again is lower than the pay off time. The 24 kWh BESS does 228 cycles per year corresponding to an expected life time

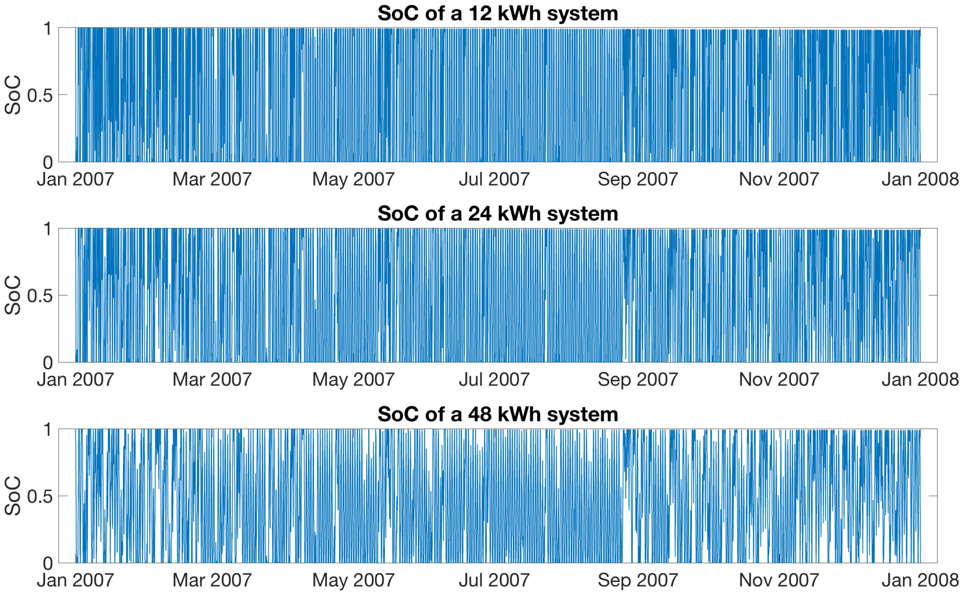

**Figure 5.12:** State of charge for 12, 24 and 48 kWh BESS using floating zero strategy.

of 31 years and the 48 kWh system does 117 cycles per year corresponding to an expected life time of 29 years. Since the expected life time is lower than the pay off time, the BESS using the floating zero strategy to control the energy flow is not profitable for ordinary households with today's energy prices.

With 6400 W input and output power the 12 kWh BESS instead saves 2246 kr yearly, the 24 kWh BESS saves 3164 kr yearly and the 48 kWh saves 3709 kr yearly which is lower than with 3200 W input and output power for both the 12 kWh and 24 kWh BESS. This result is quite counter intuitive but is explained by the increased amount of sold and bought energy when using a non-zero target value which of course is increased with higher input and output. This indicates that the suggested strategy is better used with loads with other requirements than from economic gain, such as loads which are not allowed to feed in electricity to the grid.

If the energy price would increase by 1 kr per kWh, the gain would also be increased and the gains would then be 4475, 5692 and 6387 kr yearly for the 12, 24 and 48 kWh BESSs. This gain would reduce the pay off time to 28, 40 and 71 years respectively, which still is longer than the expected life time thus not making it a profitable investment. Figure 5.13 shows how the pay off time depends on the energy price. From the figure it is clear that the energy price has to increase a lot before the pay off time is reduced below 20 years which is a desirable boundary.

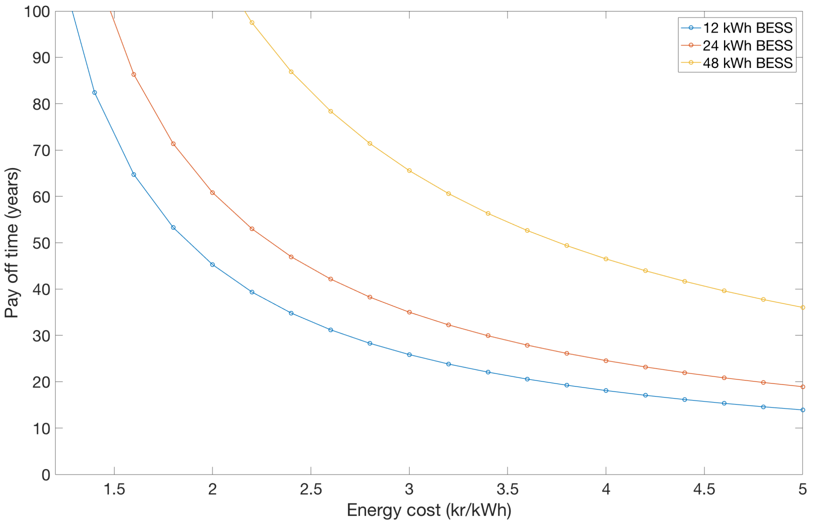

**Figure 5.13:** Pay off time as a function of the energy price for a 12, 24 and 48 kWh BESS using the floating zero strategy.

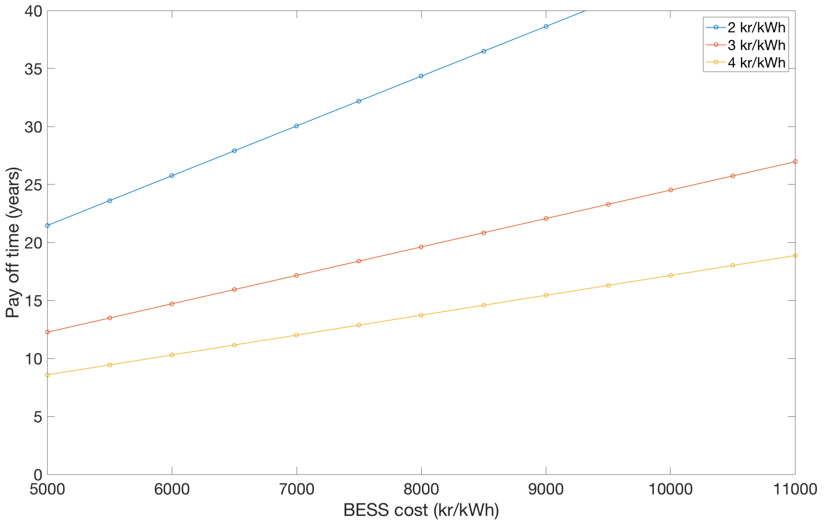

**Figure 5.14:** Pay off time as a function of the cost for a 12 kWh BESS using the floating zero strategy when the energy price is 2, 3 and 4 kr per kWh.

By also reducing the prices of the BESS it is possible to reduce the pay off time further. Figure 5.14 shows how the pay off time would be reduced by a reduction of the cost for the BESS and, as for the exchange minimizing method, the energy cost is a greater influence then the cost of the BESS but by reducing the cost of the BESS the pay off time may be reduced further.

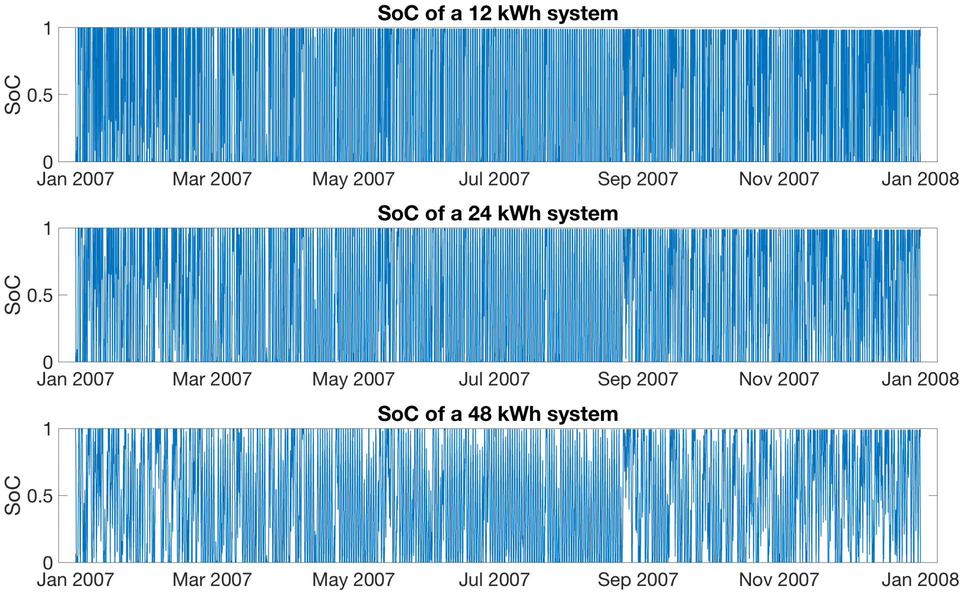

**Figure 5.15:** State of charge for 12, 24 and 48 kWh BESS using exchange strategy in an apartment complex.

When instead running the simulation with a larger load the BESS utilization would be different. The cycles of the different sizes are shown in Figure 5.15. The utilization is much bigger for all BESSs but the cycles gets a bit more sparse for the larger BESSs. In this scenario the savings of the 12 kWh BESS is 3367 kr yearly, the 24 kWh BESS is 6589 kr yearly and 12060 kr per year for the 48 kWh BESS. This results in a pay off time of 37, 34 and 37 years respectively, which is higher than the expected life time and thereby not a profitable investment with current energy prices in this scenario either. As before, other requirements may still make this strategy the natural choice for the system.

## 5.5 Comparison of strategies

The different strategies result in different savings and different behavior of the systems, and the selection might be depending on the customer's preferences. If the customer prefers to maximize their self-supply by using as much of their own energy the exchange minimizing is the way to go but if they prefer to keep their power consumption low, peak reduction is a better choice. To make the comparison between the strategies, sizes and loads easier, Table 5.1 is provided.

**Table 5.1:** The yearly savings and pay off times of BESSs with the three suggested strategies simulated in a household and an apartment complex.

| **Strategy** | **Load** | **Size** | **I/O power** | **Yearly Savings** | **Pay off** |
|---|---|---|---|---|---|
| Exchange minimizing | House | 12 kWh | 3200 W | 2994 kr | 42 years |
| Exchange minimizing | House | 24 kWh | 3200 W | 3583 kr | 63 years |
| Exchange minimizing | House | 48 kWh | 3200 W | 3887 kr | 117 years |
| Exchange minimizing | Complex | 12 kWh | 6400 W | 5590 kr | 22 years |
| Exchange minimizing | Complex | 24 kWh | 6400 W | 9451 kr | 24 years |
| Exchange minimizing | Complex | 48 kWh | 6400 W | 15630 kr | 29 years |
| Peak reduction | House | 12 kWh | 3200 W | 2447 kr | 53 years |
| Peak reduction | House | 24 kWh | 3200 W | 2853 kr | 80 years |
| Peak reduction | House | 48 kWh | 3200 W | 2960 kr | 160 years |
| Peak reduction | House | 12 kWh | 6400 W | 2668 kr | 49 years |
| Peak reduction | House | 24 kWh | 6400 W | 3256 kr | 70 years |
| Peak reduction | House | 48 kWh | 6400 W | 3448 kr | 131 years |
| Peak reduction | Complex | 12 kWh | 6400 W | 6062 kr | 21 years |
| Peak reduction | Complex | 24 kWh | 6400 W | 8920 kr | 25 years |
| Peak reduction | Complex | 48 kWh | 6400 W | 10050 kr | 45 years |
| Floating zero | House | 12 kWh | 3200 W | 2375 kr | 53 years |
| Floating zero | House | 24 kWh | 3200 W | 3196 kr | 71 years |
| Floating zero | House | 48 kWh | 3200 W | 3538 kr | 128 years |
| Floating zero | House | 12 kWh | 6400 W | 2246 kr | 56 years |
| Floating zero | House | 24 kWh | 6400 W | 3164 kr | 72 years |
| Floating zero | House | 48 kWh | 6400 W | 3709 kr | 123 years |
| Floating zero | Complex | 12 kWh | 6400 W | 3367 kr | 37 years |
| Floating zero | Complex | 24 kWh | 6400 W | 6589 kr | 34 years |
| Floating zero | Complex | 48 kWh | 6400 W | 12060 kr | 37 years |

From Table 5.1 it is clear that for smaller loads, such as households, the exchange minimizing strategy is more profitable but have a very long pay off while for larger loads the spot price charging and exchange minimizing is more profitable with today's energy prices. The pay off times regardless are quite long and close to the expected lifetime off the BESS making the BESS close to a break even investment. By looking outside Sweden the energy prices are often higher and a small increase in energy cost would turn the BESS to a more profitable investment.

# 6

# Conclusion

## 6.1 Results

The analysis presented in this report shows that the potential economic gain from installing a BESS varies a lot depending on the pricing from the electricity providers. The Swedish market currently has a relatively low energy price and with the current prices the investment in a BESS will be a loss-making deal. However, if the energy price would increase the economic gain of an installation would increase and even if it is small, the installation could turn profitable.

Currently a 12 kWh BESS in an ordinary household saves between 2000 and 3000 kr yearly, depending on strategy resulting in a payoff time of 40 to 50 years, which is much longer than the expected life time of such a BESS. A 48 kWh BESS installed in an apartment complex would, in the same way, save between 10000 and 15000 kr yearly which corresponds to a pay off time of 30 to 50 years.

For all the analyzed strategies the 12 kWh BESS always came out as the most profitable, mostly due to the low scalability of BESSs. For the exchange minimizing strategy in a household 2994 kr was saved yearly and for an apartment complex the corresponding saving was 5590 kr yearly. For the spot price charging and peak reduction strategy 2668 kr per year was saved in a household and in an apartment complex 6062 kr was saved every year which was the strategy and load with shortest pay off time of 21 years. For the floating zero strategy 2375 kr was saved yearly for a household. With this strategy the 24 kWh BESS proved to be most profitable for the apartment complex with a yearly saving of 6589 kr, corresponding to a pay off of 34 years. The biggest yearly save was achieved with a 48 kWh BESS in an apartment complex using the exchange minimizing strategy. This saved 15630 kr each year, but due to the high cost of the BESS the pay off time was 29 years in this case.

The results are, however, very sensitive to the energy price and much indicates an increase in the future. With an increase of 1 kr per kWh the pay off time of 48 kWh BESS was reduce to 15 years using the exchange minimizing strategy, making it a profitable investment. Furthermore, other differences might appear in the future, such as pricing depending on sun hours or wind, related to the increase in green energy production.

## 6.2 General reflection

Apart from the potential economic gain of implementing a BESS, several other aspects have been regarded as interesting by the caseload which should be taken into account when considering implementing a BESS.

One of these aspects would be the high interest from private energy producers to actually use their own energy rather than selling it. While this has no economic gain it is still a driving force in the Swedish energy storage market. By looking at other countries with more energy producers connected to the smart grid one might also notice that when the produced energy reaches certain limits, the government implemented laws limiting allowed feed in to the grid and with the increased interest for green energy in Sweden this might happen there as well.

One other aspect to consider is that with an energy storage installed the step to a complete uninterrupted power supply (UPS) system might not be that far away which is used to compensate power during blackouts. Even though Sweden has a relatively low down time of the power grid from a global perspective, UPS systems are still requested by costumers. Mainly farmers at the end of the supply line who are highly dependent on a stable energy supply to keep their business going, look for green UPS systems to replace their diesel generators.

## 6.3 Future work

There are several aspects to use for further development of the work presented in this report. To further develop the suggested strategies would in the exchange minimizing case be difficult, but for the spot price charging and peak reduction it would be beneficial to have a good estimate of when future power peaks will appear. This could possibly be solved with neural networks combined with some weather forecasting to try to determine energy production and thereby give better decisions regarding charging during day time.

For the floating zero strategy, the way to decide target value could be further investigated to achieve optimal results. This would of course depend on the requirements from the load and could be hard to get an objective look at.

From an economic perspective it would be beneficial to account for future changes in the energy price, the assumption made in this report of the energy prices staying the same for 20 years is a bit simple. Accounting for this could give further insights to the possible gain in the future. A deeper discussion regarding political impact could also prove to be useful, there are several grants for installing BESSs which of course also affects its cost and therefore the pay off time.

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