SINTEF Energi AS
SINTEF Energy Research
Address:
Postboks 4761 Torgarden
NO-7465 Trondheim
NORWAY
Switchboard: +47 45456000

energy.research@sintef.no

Enterprise /VAT No:
NO 939 350 675 MVA

Project memo

Techno-economic analysis of Skagerak EnergyLab

Using a battery energy storage system for multiple services

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AUTHOR(S)
Thaddäus Weniger, Kjersti Berg, Matthias Resch

CLIENT(S)	CLIENTS REF.
Skagerak Nett AS	Stig Simonsen

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ABSTRACT
This memo describes a case study performed at Skagerak EnergyLab. The EnergyLab has a battery energy storage system (BESS) of 1.1 MWh installed at Skagerak Arena (football stadium). The arena also has a photovoltaic (PV) power plant of 800 kW nominal power. In this work, it is studied how the BESS can be used for the benefit of the arena, hence corporate benefit, by lowering the monthly peak load and increasing self-consumption of PV electricity. The tool SimSES is used for simulating the degradation of the BESS, considering the Norwegian tariff structure when calculating the costs of electricity. Different cases are studied with different operation strategies for peak shaving, self-consumption maximisation and arbitrage. Finally, a techno-economic analysis has been performed for the different cases. The main outcome of the economic analysis is what the BESS investment cost must be for the different cases to be profitable. The most important outcome of this work is that a multi-purpose case which combines peak-shaving, energy arbitrage, self-consumption and replacement of a diesel backup generator, can be feasible in Norway.

PREPARED BY	SIGNATURE
Kjersti Berg	Kjersti Berg Kjersti Berg (Apr 6, 2020)

APPROVED BY	SIGNATURE
Maren Istad	Maren Istad Maren Istad (Apr 16, 2020)

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1.0	2020-02-24	Final version.

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SYMBOLS

Variable name	Unit	Description
$c_{E,t}$	NOK/kWh	Spot market price in timestep *t*
$CF_{BESS+PV}$	NOK	Cash flows of a system with BESS and PV
$CF_{wo\ BESS+PV}$	NOK	Cash flows of a system without BESS and PV
C_{gen}	NOK	Avoided costs for not using a backup generator
C_{Gf}	NOK	Energy revenues
C_{Gp}	NOK	Energy costs
$C_{Gu,f}$	NOK	Costs for feed-in above feed-in power limit (100 kW)
$c_{Gu,f}$	NOK/kWh	Feed-in tariff when above feed-in power limit (100 kW)
$c_{Gu,p}$	NOK/kWh	Grid usage tariff
c_{PT}	NOK/kW	Peak power tariff
C_{PT}	NOK	Cost for peak power
C_{repl}	NOK	Costs for BESS replacement if necessary
C_{StoDeg}	NOK	Costs of storage degradation
c_{StoDeg}	NOK/kWh	Cost for degradation of battery per energy charged
C_{tot}	NOK	Total costs over analysis period
$E_{bat,t}$	kWh	Amount of energy in battery in timestep *t*
$E_{Bc,t}$	kWh	Energy charged by battery in timestep *t*
$E_{f,t}$	kWh	Feed-in energy to grid in timestep *t*
$E_{Gf,t}$	kWh	Feed-in energy in timestep *t*
$E_{Gf>100,t}$	kWh	Feed-in energy above feed-in power limit in timestep *t*
$E_{p,t}$	kWh	Purchased energy from grid in timestep *t*
h_{Disch}	h	Hours of battery discharge
$OPEX_{BESS+PV}$	NOK	Sum of the operational expenditures of PV system and BESS
$P_{Bc,t}$	kW	Battery charging power in timestep *t*
$P_{Bd,t}$	kW	Battery discharging power in timestep *t*
$P_{G,month}$	kW	Maximum power from grid during month
$P_{Gf,t}$	kW	Grid feed-in power in timestep *t*
$P_{Gf>100,t}$	kW	Feed-in power above feed-in power limit (100 kW) in timestep *t*
$P_{Gp,t}$	kW	Electricity purchased from grid in timestep *t*
$P_{lim,f}$	kW	Feed-in power limit (100 kW in Norway)
$P_{over\ lim}$	kW	Amount of power fed into the grid above the feed-in power limit
$P_{res,t}$	kW	Residual load (load subtracted PV generation) in timestep *t*
Pr_{Batt}	NOK/kWh	Price of the BESS
Pr_{PV}	NOK/kW_p	Price of the PV system
$R_{n,BESS}$	NOK	Rest value of the BESS after the analysis period
$R_{n,PV}$	NOK	Rest value of the PV system after the analysis period

S_{Batt}	kWh	Battery capacity size
S_{PV}	kW_p	PV system size
η_{Bc}	%	Battery charging efficiency
η_{Bd}	%	Battery discharging efficiency
Δt	min	Timestep size
i	%	Real interest rate (calculated from the discount and inflation rate)
n	min	Analysis period
t	min	Timestep

ACRONYMS

BESS	Battery energy storage system
BSS	Battery storage system
FL	Flood lights
OS	Operation strategy
P1	Grid node P1
PV	Photovoltaic
SC	Self-consumption
SOC	State of charge
SOH	State of health

1 Introduction

The work described in this memo has been performed in the IntegER (Integration of energy storage in the distribution grid) project. The objective of the project is to contribute with new knowledge that enables battery energy storage systems (BESS) to be used and integrated in the Norwegian distribution grid.

This work describes a techno-economic analysis based on the actual equipment installed in the Skagerak EnergyLab, which is the name of the living lab at Odd football stadium, including a BESS. One of the reasons for installing the BESS is to replace the backup diesel generators which are required in certain events at the stadium such as football matches to ensure power during the matches ("match load"). The idea is to cover mainly the floodlights as one of the largest loads by either the electricity provided by the photovoltaic (PV) plant or the BESS which was charged earlier using the PV electricity production. To be able to do this, an applicable BESS operation strategy must be developed. In this work, different cases have been studied to illustrate different ways the BESS can be operated, how the BESS then degrades, and finally the costs and revenues associated with the chosen operation strategy.

One of the main purposes of the Skagerak EnergyLab is to study how different actors can have benefit from the BESS, and how the BESS can be used for different purposes to increase the total value. Combining business models may increase the profitability, especially for a stationary BESS, as shown in [1]. In this memo, the focus is on how the BESS would be operated if it was owned by Skagerak Arena, using it to lower the monthly electricity cost by increasing the self-consumption of PV power, performing energy arbitrage[1], peak shaving and/or limiting feed-in from the PV system. Hence, this is an analysis from the corporate profitability perspective, in this case the potential profit of Skagerak Arena. Hence, it is not an analysis from a socio-economic perspective, which would have been the perspective chosen if the DSO should have performed a techno-economic analysis.

The memo is structured in the following way: Chapter 2 gives an overview of costs and revenues in the Norwegian electricity market, Chapter 3 describes the method used for simulations, Chapter 4 introduces the different case studies and input data from the EnergyLab, Chapter 5 shows the technical and economic results from the case studies, Chapter 6 compares the different case studies, and Chapter 7 concludes the memo.

[1] Energy arbitrage is electricity price-dependent shift of feed-in and consumption.

2 Costs and revenues in the Norwegian energy market

2.1 Composition of the electricity price for an end-user

The energy costs and revenues for energy feed-in depend on different elements: the energy price itself and different tariffs which can be added depending on the grid company and type of customer. The main component is the price of the energy decided in the spot market. In addition to this every costumer connected to the grid needs to pay a fixed base grid tariff and a variable grid usage tariff. Some customers also pay another variable tariff, namely the peak power grid tariff, mostly common for industry customers. These different costs will be described more detailed in this section.

Electricity spot market price: The energy price is decided in the spot market. Norway is divided into several price areas having their individual markets, to obtain a price according to the regional power supply situation. For the analysis performed in this memo, the spot market price of Oslo for the year 2018 was chosen. Figure 1 shows the chosen data as a timeseries, which is provided in hourly resolution.

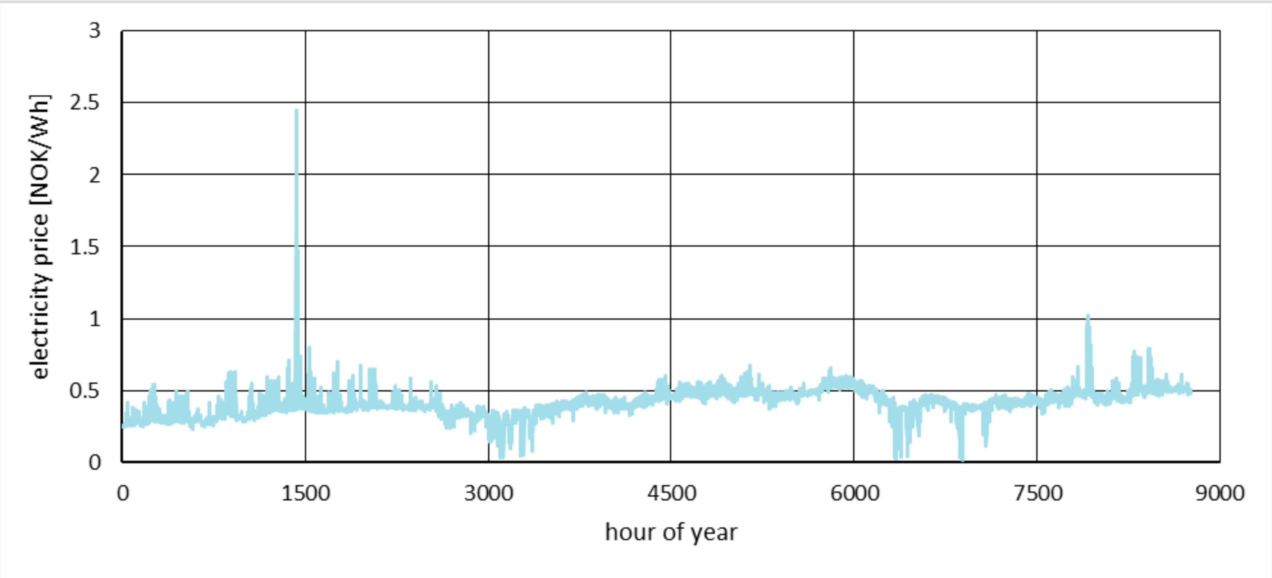

Figure 1: Energy spot market price Oslo for the year 2018 [2].

Figure 2 is a boxplot showing the spread of the electricity prices, and four statistical parameters are shown in Table 1. As shown in the figure, the price varies around 0.5 NOK/Wh throughout the year. The average price was 0.419 NOK/Wh, and the standard deviation was 0.101 NOK/Wh.

Table 1: Statistical parameters of electricity price.

Statistical parameter	Value in NOK/Wh
Average	0.419
Standard deviation	0.101
Maximum	2.454
Minimum	0.018

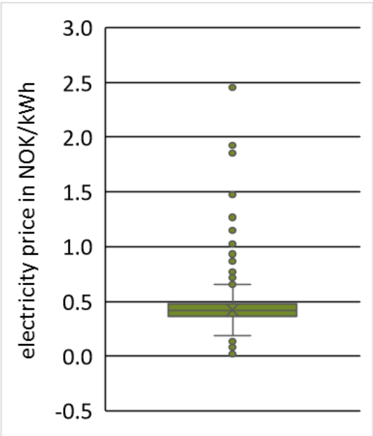

Figure 2: Boxplot showing the spread of the values in electricity price.

Feed-in remuneration: If a customer has installed a distributed generation system, e.g. a PV system, and the generation of electricity exceeds the demand, the customer becomes a prosumer[2]. A prosumer can feed in without paying a fee for the use of the grid only if the power fed in is less than 100 kW. Then the energy is fed into the grid and remunerated with the market price (hence a feed-in profit). If the prosumer feeds in more than 100 kW, a tariff for the usage of the grid of 0.0134 NOK/kWh needs to be paid [3]. Figure 3 shows the resulting feed-in profit depending on the feed-in power. As it can be seen the effect of this grid usage tariff is very low.

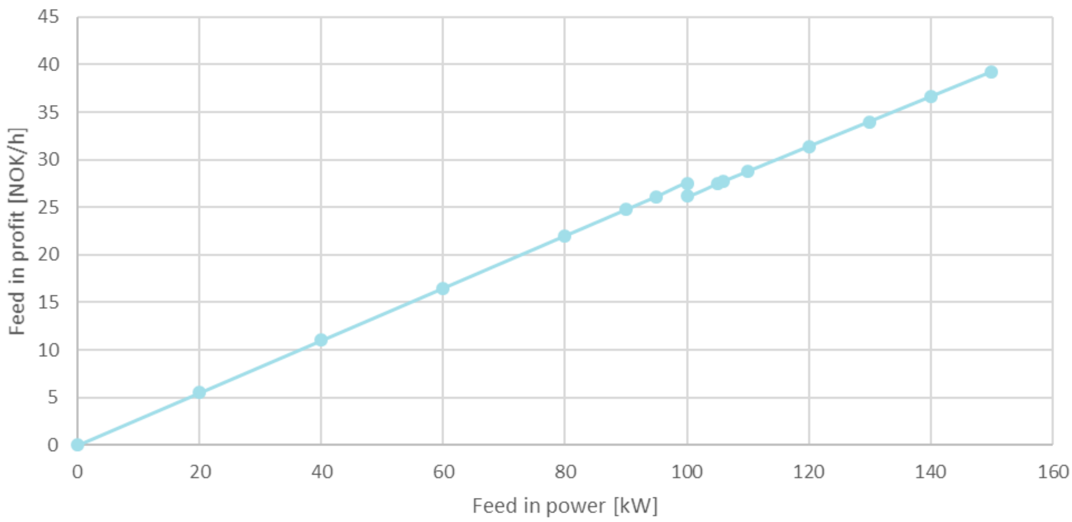

Figure 3: Feed-in profit depending on the feed-in power.

Grid connection costs: A fixed fee must be payed to the grid operator for the service of providing a grid connection. Beside this, there is also a consumption-based fee calculated from consumed energy. As Table 2 shows, these fees depend on the energy consumption in kWh for industrial customers.

Power tariff costs: The power tariff differs for different grid companies, but in this case, it is charged monthly and depends on the peak load power for industrial customers. The aim is to offer an incentive to

[2] A prosumer (no.: plusskunde) is in Norway defined as a consumer which in some hours during the year has surplus power which is fed into the grid (www.nve.no).

avoid high load peaks. There are two different cost multiplicators depending on the power category as shown in Table 2. Some industrial customers also have tariffs for reactive power, but this is not considered in this analysis. The resulting costs depending on the peak power are illustrated in Figure 4.

Table 2: Grid tariff for industrial customer (main fuse above 330 A, voltage level 400-230 V [4].

Season	Fixed tariff [NOK/year]	Consumption-based tariff [øre/kWh]	Power-based tariff [kr/kW per month]	
			0-200 kW	Over 200 kW
Summer (1/4 - 30/9)	22,000	3.6	58.20	51.00
Winter (1/10 - 31/3)		4.2	67.70	57.00

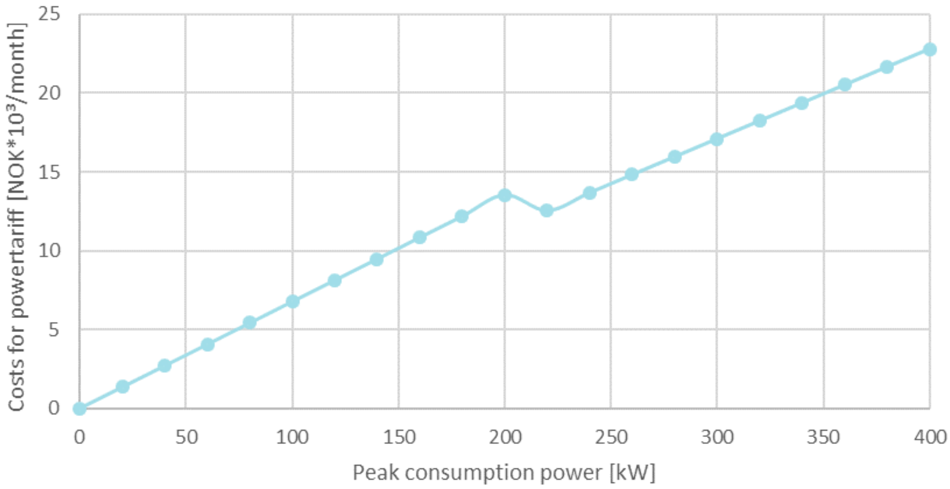

Figure 4: Resulting power tariff costs depending on the maximum peak power, winter.

2.2 Benefits from a battery energy storage system for an end-user

As mentioned in the introduction, a BESS can be used for several purposes with different benefits. This depends on how the BESS is used and how the operation strategy is developed. In this work it is assumed that the BESS is owned and operated by Skagerak Arena, an end-user. The following services provided by the BESS, and therefore also benefits, are considered:

- Self-consumption maximization: Maximising the self-consumption of PV power, hence reducing the amount of purchased energy from the grid.
- Energy arbitrage: Electricity price dependent shift of feed-in and consumption
- Peak shaving: Lowering peaks in consumption, hence reducing the monthly power tariff.
- Feed-in limitation: Limiting the feed-in of PV power to under 100 kW, to avoid paying the grid usage fee.

For the economic analysis of the BESS several costs and revenues are considered, namely:

- Investment and financing costs
- Maintenance costs
- Electricity costs
    - Costs for purchased energy
    - Costs of energy losses
    - Power tariff costs
    - Grid usage costs
    - Grid connection costs
- Revenues
    - Revenues from selling energy to the spot market
    - Reduced electricity costs are also "revenues"
    - Savings from not installing a back-up diesel generator

Some industrial customers also have tariffs for reactive power, this is not considered in this analysis. How the economic evaluation is performed is described in more detail in Section 3.3.

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3 Method

As mentioned earlier, it is assumed that the BESS is owned and operated by Skagerak Arena, an end-user. Skagerak Arena can benefit the BESS in multiple ways, such as lowering their monthly peak load, increasing their own use of PV produced electricity, or avoiding renting a diesel generator for football matches. In this work, a techno-economic analysis has been performed, assuming Skagerak Arena owns the BESS and PV system, and that they are responsible for the whole load at the stadium (flood lights and other loads). The goal of the techno-economic analysis is to study how using the BESS for different purposes will affect the profitability. Figure 5 shows the method for the simulations and assessments.

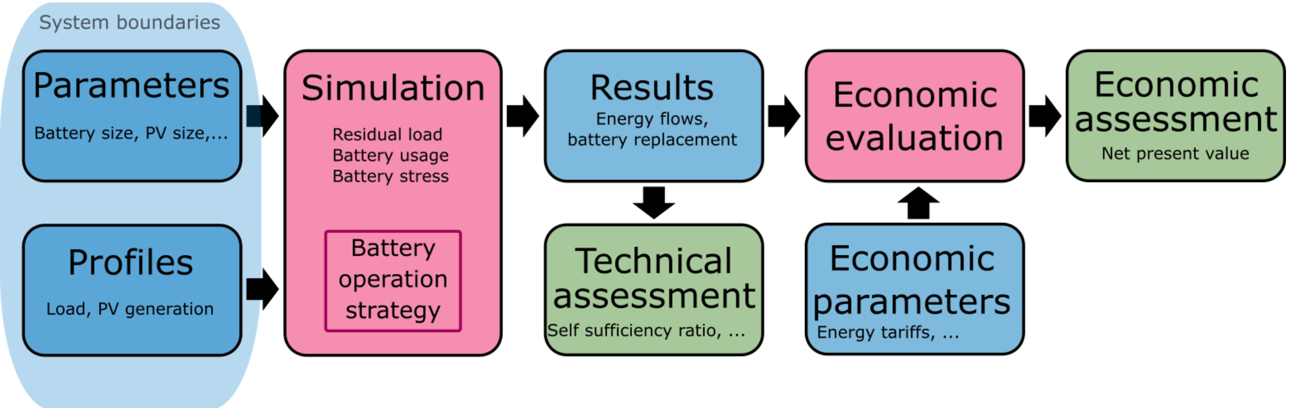

Figure 5: Flowchart showing which data is provided to run the simulation and how the results are used for further assessments.

Input to simulation (parameters and profiles): As input to the simulation, different parameters are given as defined by the system boundaries. I.e., the size of the BESS and PV system are set in an Excel-file (*inputParameters.xlsx*). Profiles for load and PV generation are also given as input in MATLAB, and also depend on the system boundaries. The input parameters and profiles for Skagerak EnergyLab are described in Chapter 4.

Simulation and results: The simulation is carried out in MATLAB and is described in more detailed in Section 3.1. The simulation depends on the selected operation strategy for the BESS and thus calculates the usage and degradation of the BESS. The different operation strategies are described in Section 3.2. The results of the simulation are the energy flows of the system (i.e. how much the BESS is used and how much is needed from the grid for the different strategies).

Technical assessment: From the simulation results, a technical assessment is performed by evaluating some key-performance indicators such as PV self-consumption ratio, self-dependency ratio, and relative usage of BESS. This is covered in Section 3.4.

Economic evaluation and assessment: The economic evaluation is then carried out, based on the simulation results. The input to the economic evaluation is the Norwegian tariff structure and all costs and revenues as described in Section 2.2. Section 3.3 describes the economic evaluation, which is a net present value (NPV) calculation. The result is how much the BESS can cost for NPV to be zero, hence for the project to be profitable.

3.1 Simulation in MATLAB

As mentioned above, the simulations have been carried out in MATLAB, by using an existing open source code called SimSES[3]. The SimSES battery simulation tool is developed by the Technische Universität München. It can simulate an electrical system including different components. The BESS usage is controlled by different operation strategies, which can be adjusted for this application. Figure 6 shows the general structure of this tool. Since the code is open source, it is possible to adapt the input data as well as the operation strategy of the BESS. The usage of the BESS is simulated including multiple ageing characteristics also depending on the chosen battery type. Finally, the data can be analyzed from an economic and technical point of view. More information about this model can be found in [5-7]. For modeling the degradation of the BESS in this work an existing battery model of an NCA lithium-ion battery was used. For more information on how to run the different cases in MATLAB, see Appendix C.

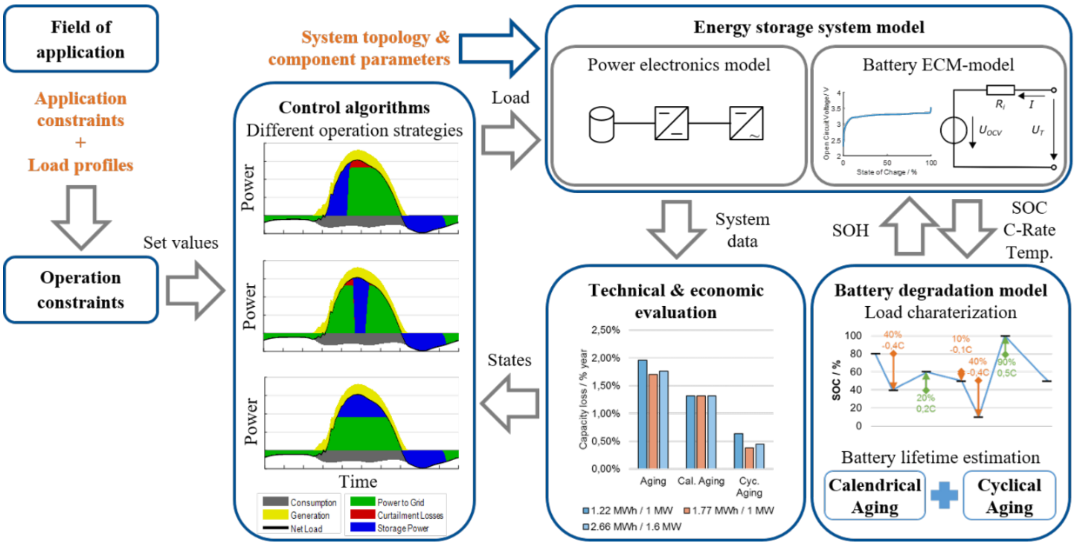

Figure 6: Overview of the SimSES structure [6].

3.2 Operation strategies

A BESS needs an operation strategy to decide how and when to charge/discharge with a certain power. None of the strategies are based on forecasts but assumes that load and PV generation is known. In the following subsections, the different operation strategies used in the case studies in Chapter 4 are described. The different operation strategies described in this section are listed here:

- Self-consumption maximization
- Prioritizing flood lights for football matches
- Energy arbitrage
- Peak shaving, energy arbitrage and feed-in limitation

[3] https://www.ees.ei.tum.de/simses/

3.2.1 Self-consumption maximization

This operation strategy was already made in the SimSES software, called *OSPVHomegreedy*. The strategy follows this sequence:

- Load is primarily covered by PV production
- If there is not enough PV production, the BESS also contributes
- If the BESS is empty, energy is taken from the grid.
- When there is no load, the BESS is charged with maximum possible charging power, from the PV system.

3.2.2 Prioritizing the flood lights

Prioritizing the flood light is used on days where there are scheduled football matches, to ensure that the BESS is reserved and ready to cover the flood lights, so that the flood lights are independent of grid connection during the match. The strategy works like this:

- If it is a match day, the PV power is used to charge the BESS in the morning.
- If there is not enough PV generation, the BESS is charged with power from the grid until it reaches its maximum SOC.
- To avoid the creation of an unnecessary load peak **before** the match, the charging power limit is set to the same value as the assumed flood light power (320 kW).
- During the match, all PV generation is used for the flood light load, and the BESS covers the remaining flood light load if the PV generation is not enough.

3.2.3 Energy arbitrage

This operation strategy uses optimization to perform energy arbitrage, hence taking advantage of the changes in energy price during the day. The optimization approach is based on the one used in [8]. In this strategy, only costs and revenues for energy purchase/feed-in are considered, hence not considering peak load tariff (which is considered in the next strategy). The optimization is described below. More information on how the optimization is performed is provided in Appendices A and B.

The objective function is shown in (1) and minimizes the costs.

$$\min C_{tot} = \sum_{t=1}^{n} C_{Gp}(E_{p,t}) + C_{Gf}(E_{f,t}) + C_{StoDeg}(E_{Bc,t}) \tag{1}$$

Where

C_{Gp} - Energy costs, dependent on $E_{p,t}$, purchased energy in timestep *t*

C_{Gf} - Energy revenues, dependent on $E_{f,t}$, feed-in energy in timestep *t*

C_{StoDeg} - Cost of storage degradation, dependent on $E_{Bc,t}$, charged energy into the battery in timestep *t*

n - Analysis period

The different costs components in equation (1) are described below.

Energy purchase costs C_{Gp}:

$$C_{Gp} = \sum_{t=1}^{n} E_{p,t} \cdot (c_{E,t} + c_{Gu,p}) \tag{2}$$

Where

$E_{p,t}$ - Purchased energy in timestep t

$c_{E,t}$ - Spot market price in timestep t

$c_{Gu,p}$ - Grid usage price for the load, also called consumption-based tariff as shown in Table 2 (øre/kWh).

Feed-in remuneration C_{Gf}:

$$C_{Gf} = -\sum_{t=1}^{n} E_{f,t} \cdot c_{E,t} \tag{3}$$

Where

$E_{f,t}$ - Feed-in energy in timestep t

c_E - Spot market price in timestep t

Storage degradation C_{StoDeg}:

$$C_{StoDeg} = \sum_{t=1}^{n} E_{Bc,t} \cdot c_{StoDeg} \tag{4}$$

Where

c_{StoDeg} - Cost for degradation, in NOK/kWh. The cost for degradation is assumed equal to the cost used in [9]: 0.128 NOK/kWh.

$E_{Bc,t}$ - Charged energy into the battery in timestep t

Constraints in the optimization:

The energy balance in the system is given in (5):

$$P_{Gp,t} + P_{Gf,t} + P_{Bc,t} + P_{Bd,t} = P_{res,t} \qquad , t = 1, \ldots, n \tag{5}$$

Where

$P_{Gp,t}$ - Electricity purchased from grid in timestep t

$P_{Gf,t}$ - Feed-in power in timestep t

$P_{Bc,t}$ - Battery charging power in timestep t

$P_{Bd,t}$ - Battery discharging power in timestep t

$P_{res,t}$ - Resulting load after subtracting PV generation in timestep t

The energy stored in the battery between timesteps should be the same as the difference between the charging and discharging power of the battery (including efficiencies).

$$P_{Bc,t} \cdot \eta_{Bc} + \frac{P_{Bd,t}}{\eta_{Bd}} = -\frac{E_{bat,t} - E_{bat,t-1}}{\Delta t} \qquad , t = 2, \ldots, n \tag{6}$$

Where

η_{Bc} - Efficiency charge

η_{Bd} - Efficiency discharge

$E_{bat,t}$ - Energy in battery in timestep t

3.2.4 Peak shaving, arbitrage and feed-in limitation

This operation strategy also uses optimization, just as for arbitrage, but here peak-load and feed-in costs are also included in the objective function. The objective function is shown in (7) and still minimizes the costs as for the previous operation strategy:

$$\min C_{tot} = \sum_{t=1}^{n} C_{Gp}\left(E_{p,t}\right) + C_{Gf}\left(E_{f,t}\right) + C_{StoDeg}\left(E_{Bc,t}\right) + C_{PT}\left(P_{G,month}\right) + C_{Gu,f}\left(P_{Gf,t}\right) \tag{7}$$

Where

C_{Gp} - Energy costs, dependent on $E_{p,t}$, purchased energy in timestep t

C_{Gf} - Energy revenues, dependent on $E_{f,t}$, feed-in energy in timestep t

C_{StoDeg} - Cost of storage degradation, dependent on $E_{Bc,t}$, charged energy into the battery in timestep t

C_{PT} - Power tariff costs, dependent on $P_{G,month}$, maximum power from grid during a month

$C_{Gu,f}$ - Costs for feed-in above 100 kW, dependent on $P_{Gf,t}$, feed-in power in timestep t

The costs for the purchased energy, the storage degradation and revenues from the fed in energy are calculated as explained for arbitrage. The new cost factors are calculated as follows:

Power tariff costs C_{PT}: The power tariff is charged monthly and depends on the peak load power. To decide what the peak load should be for a given month, an initial limit is set the first day, and adjusted if necessary, on a daily basis. The algorithm is described below, and is only used on days without football matches:

- Day 1: The initial limit for the peak shaving is set to be 75 % of the peak load for that day, i.e. 300 kW, as an initial guess. The peak load is the residual load $P_{res,t}$ (the resulting load after subtracting PV generation).
- Iteration:
    - The total energy needed from the battery to peak shave that day with the given limit (300 kW) is calculated, i.e. 200 kWh.
    - If the total energy needed, i.e. 200 kWh, is more than the energy available in the battery, i.e. 150 kWh, the limit for peak shaving is increased by a certain step (i.e. 10 kW so the peak shave limit is increased to 310 kW). Vice versa if the energy needed is less than the energy in the battery. Since the power tariff cost is included in the optimization, it will try to find the lowest possible peak shave limit. The cost for increasing the peak shave limit, $C_{increase}$, is calculated as in (8).
    - The iteration continues until the total energy needed to peak shave equals the amount of energy in the battery (150 kWh).
- When the total energy needed to peak shave equals the amount of energy the battery, the peak shave limit is updated.
- Day 2: The initial limit of this day equals the updated limit from the day before.
- Perform iteration for day 2 and update to a higher peak shave limit if necessary.
- Continue for all days in one month. The highest peak shave limit of the month is $P_{G,month}$.

The cost for changing the peak shave limit, $C_{increase}$, is calculated as:

$$C_{increase} = P_{over\ lim} \cdot c_{pt} \tag{8}$$

Where

$P_{over\ lim}$	- Increase in peak shave limit, in kW
c_{pt}	- Power tariff cost, in NOK/kW

This cost is a part of calculating the power tariff cost, as shown in (9):

$$C_{PT} = P_{G,month} \cdot c_{pt} = (P_{initial} + P_{over\ lim}) \cdot c_{pt} \tag{9}$$

Where

$P_{G,month}$	- Highest peak shave limit of the month
$P_{initial}$	- Initial peak shave limit (from first day)
$P_{over\ lim}$	- Increase in peak shave limit
c_{pt}	- Power tariff cost, in NOK/kW

Grid usage costs $C_{Gu,f}$: The grid usage costs can be represented by the following regulated function:

$$C_{Gu,f} = \begin{cases} 0 & , \quad P_{Gf,t} \leq P_{lim,f} \\ E_{Gf,t} \cdot c_{Gu} & , \quad P_{Gf,t} > P_{lim,f} \end{cases} \tag{10}$$

Where

$P_{lim,f}$	- Limit for feed-in without paying for grid usage, 100 kW in Norway.
$c_{Gu,f}$	- Feed-in tariff when above 100 kW. Fixed tariff of 0.0134 NOK/kWh (see Section 2.1)
$P_{Gf,t}$	- Feed-in power in timestep *t*
$E_{Gf,t}$	- Feed-in energy in timestep *t*

MATLAB cannot implement regulated functions such as (10), and therefore the equation is formulated by the following two equations:

$$P_{Gf} - P_{Gf>100} \leq P_{lim,Gu,f} \tag{11}$$

Where

P_{Gf}	- Feed-in power in timestep *t*
$P_{Gf>100}$	- Feed-in power above limit (100 kW) in timestep *t*
$P_{lim,Gu,f}$	- Limit for feed-in without paying for grid usage, 100 kW in Norway.

The grid usage cost is only calculated for the energy above this feed-in limitation:

$$C_{Gu,f} = E_{Gf>100} \cdot c_{Gu} \tag{12}$$

Where

$C_{Gu,f}$	- Grid usage costs for feed-in
$E_{Gf>100}$	- Feed-in energy above limit (100 kW)
c_{Gu}	- Grid usage price for feed-in when above 100 kW

The feed-in power above the limit will still be included in the feed-in power $P_{Gf,t}$ because it is only used for the cost calculation and is defined by equation (11). The constraint for the energy balance of the BESS is not influenced by the introduced variables.

3.3 Economic evaluation

In broad terms, there are two ways to gain monetary benefits with existing BESS applications in the Norwegian electricity market for the storage owner/operator: first, revenues received and second, cost reduction or avoidance through for instance not using a back-up generator. In this memo it is assumed that the BESS operator (Skagerak Arena) pursues a cost reduction operation strategy.

To calculate the net present value (NPV) of having a PV system and BESS, four different costs/revenues are considered, as shown in (13). The equation is derived from [10] and adapted to the specific Norwegian case of a PV and BESS system replacing a back-up generator. The different costs/revenues are:

- Investment costs of BESS and PV
- The difference in cash flows between having a PV and BESS and not having them. In the case of not having PV and BESS, all energy is purchased from the grid.
- Costs for replacing the BESS, operation and maintenance (O&M) of PV and BESS, as well as avoided costs since a backup generator is no longer needed
- Rest value of PV and BESS at the end of the analysis period

Figure 7 gives an illustration of the different costs and revenues over the analysis period. The economic evaluation is based on calculating the NPV of each of the cases presented in Chapter 4. The outcome of the evaluation is how much the CAPEX of the BESS can be for the NPV to be zero (hence profitable).

$$NPV = \underbrace{-(S_{BESS} \cdot Pr_{BESS} + S_{PV} \cdot Pr_{PV})}_{\text{Investment costs of BESS and PV}} + \sum_{t=1}^{n} \frac{\underbrace{|CF_{wo\;BESS+PV}| - |CF_{BESS+PV}|}_{\text{Difference in cash flows between a system without BESS and PV and with BESS and PV}} \underbrace{- C_{repl} - OPEX_{BESS+PV} + C_{gen}}_{\text{Costs for replacement, O\&M and avoided costs for not using a backup generator}}}{(1+i)^t} + \underbrace{\frac{R_{n,PV} + R_{n,BESS}}{(1+i)^n}}_{\text{Rest value of PV and BESS}} \tag{13}$$

Where

S_{PV}	- PV system size, in kWp
S_{BESS}	- BESS size/capacity, in kWh -
Pr_{BESS}	- Price of the BESS, in NOK/kWh
Pr_{PV}	- Price of the PV system, in NOK/kW_p
n	- Analysis period, in years
$CF_{wo\;BESS+PV}$	- Cash flows of a system without BESS and PV
$CF_{BESS+PV}$	- Cash flows of a system with BESS and PV
C_{repl}	- Costs for BESS replacement if necessary within n
$OPEX_{BESS+PV}$	- Sum of the operational expenditures of PV system and BESS
C_{gen}	- Avoided costs for not using a backup generator
$R_{n,PV}$	- Rest value of the PV system after the analysis period
$R_{n,BESS}$	- Rest value of the BESS after the analysis period
i	- Real interest rate (calculated from the discount rate and the inflation rate)

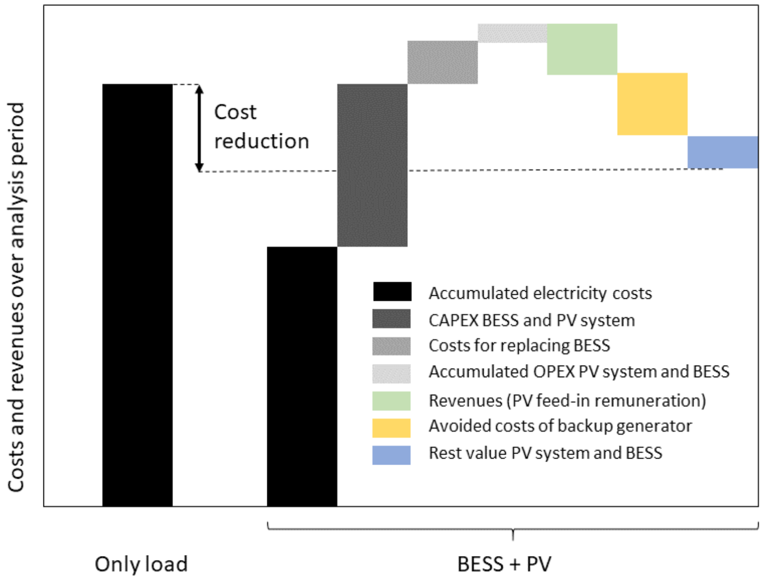

Figure 7: Illustration of how the economic evaluation is performed.

Numeric values applied are given in Table 3.

Table 3: Parameters in the economic evaluation.

Parameter	Assumed value
Interest rate	5 %
Inflation rate	3 %
Real interest rate	1.94 %. Calculated as $\frac{1+interest\ rate}{1+inflation\ rate} - 1$
Analysis period	10 years (assumed lifetime for BESS).
SoH where BESS is replaced	80 %
Rest value of BESS	Calculated according to the SOH at the end of analysis period. E.g. SOH 95 % gives 75 % of rest value.
Saved generator costs	10,000 NOK/football match. This is assuming 18 matches a year, based on data from 2018. These costs include all costs caused by having the back-up generator operational in case of need (CAPEX, OPEX and other costs).
Capital expenditures (CAPEX)/ investment costs of the PV system	1000 NOK/kW_p
Lifetime of PV system	20 years
Rest value of the PV system	50 % of CAPEX after 10 years
CAPEX/investment costs of the BESS	Output of the economic analysis (varies)
Operations and maintenance expenditures (OPEX)	1 % of CAPEX of the PV system, and 1 % of (the varying) CAPEX of the BESS

3.4 Performance indicators for techno-economic assessment

The different cases will be compared and evaluated using key performance indicators. For the technical assessment, the following variables are used:

- Total energy purchased from the grid
- Total energy generated by PV system
- Total energy fed into the grid
- Total energy going in and out of the BESS
- Total energy losses from charging the BESS
- Number of battery replacements during analysis period
- SOH of BESS at end of simulation period

The following relative key performance indicators were chosen:

- PV self-consumption rate: amount of energy produced by the PV system used to cover the load.
- Self-dependency rate: relative amount of consumed power provided directly by the PV system or provided by the PV system after being stored in the BESS.
- Relative battery usage: the number of hours the BESS was used to cover a load divided by the 8760 hours of one year.
- Relative losses: losses divided by feed-in

For the economic evaluation the costs and the revenues of the analysis period and the net present values of the different investments are compared. The different case studies differ in either input parameters or profiles, or in choice of operation strategy. Technical and economic parameters of each case can be compared easily. The cases and their results are described in Chapter 4.

4 Case studies

In order to investigate how different operation strategies affect the techno-economic assessments, the use of the BESS is simulated for different case studies. This chapter gives a description of these, as well as the input data from Skagerak EnergyLab.

Table 4 shows a comparison of all cases, where the main points are:

- All cases include PV generation.
- Cases 2-5 have the whole load of node P1 as input load profile, while case 1 only has the flood light load profile as shown in Figure 10.
- Cases 1-3 use the operation-strategy self-consumption (SC) and do not include energy arbitrage. Case 3 has the BESS reserved (RES) on match days for covering the flood lights.
- Cases 4 and 5 on the other hand use optimized usage (OPT) and hence include energy arbitrage. Case 4 only optimizes based on energy costs (OPT_1), while case 5 also optimizes based on peak power tariff (OPT_2).
- All cases except case 2 have an operation strategy which ensures flood light coverage. Only case 5 includes the peak power tariff in the operation strategy.

Table 4: Comparison of the different cases.

Case	Load	PV	Operation strategy	Reserved for flood lights on match days	Energy arbitrage	Peak power tariff considered
1_SC_FL	FL	✓	SC	✓	✗	✗
2_SC	Node P1	✓	SC	✗	✗	✗
3_SC_FLprio		✓	SC + RES	✓	✗	✗
4_OPT		✓	OPT_1	✓	✓	✗
5_OPT_PS		✓	OPT_2	✗	✓	✓

4.1 Input data from Skagerak EnergyLab

An overview of the energy system at Skagerak Arena is shown on the left side of Figure 8. To run simulations, the following simplifications have been made:

- All consumers are connected to one node (P1)
- BESS and PV system are connected to the same node
- The flood-light power is modeled independently from the other loads

This results in the simplified structure shown on the right side in Figure 8.

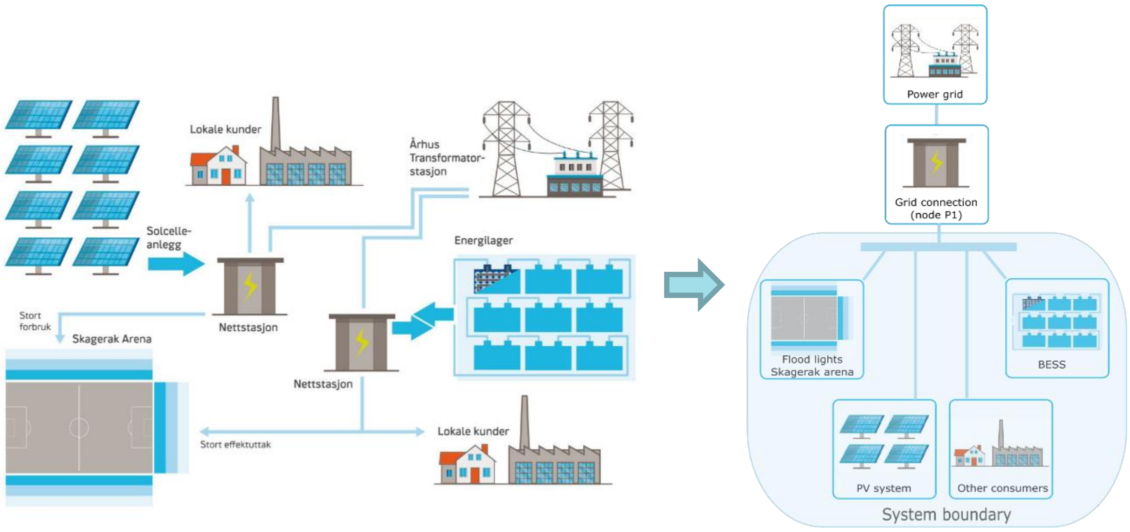

Figure 8: Overview of the real electrical energy system (left) and the simplified structure (right) of Skagerak EnergyLab.

Table 5 shows the specifications of BESS, PV and load at Skagerak EnergyLab. The BESS has a capacity of 1.1 MWh and an inverter with nominal power of 800 kW. The PV system has a peak power of 800 kW, and the generation for 2018 is shown Figure 11. Since the inverter efficiency of the BESS is strongly dependent on the input power, formulas for calculating this variable efficiency is used from [11], and further described in Appendix D.

Table 5: Specifications of BESS, PV and load from Skagerak EnergyLab.

Component	Property	Value
Battery	Nominal capacity	1100 kWh
	Type	Lithium ion
	Nominal voltage	400 V
	Maximum SOC	95%
	Minimum SOC	5 %
	Standby power consumption	0 kW
	End of life SOH	80 %
Power electronics	Inverter efficiency	See Appendix D
PV	Nominal power	800 kW
	Profile type	Measured data (2018)
	PV aging per year	0.5 %
	Resolution	Hourly
Load	Total consumption one year (flood light)	15.9 MWh
	Total consumption one year (node P1)	1752 MWh
	Profile type	Measured data (2018)

The load profile is based on hourly measured data provided by Skagerak Nett and represents the grid node P1 with several connected consumers, including the flood lights (FL). It is shown in Figure 9.

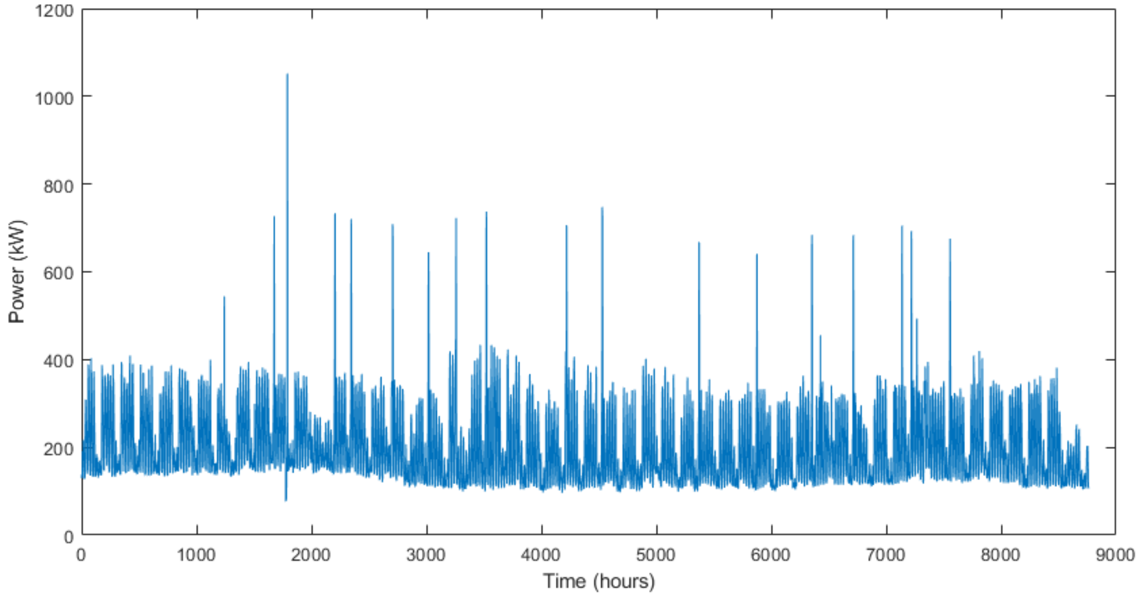

Figure 9: Hourly load profile for the whole consumption at node P1 for 2018 (historical data).

The flood lights have a special role in this study, since the BESS is installed as a backup electricity provider in case of a power outage. This means whenever a match takes place, the BESS should be able to cover the flood light load at any time. The given load data was used to identify the times when a match takes place. As the figure shows there are several peaks around 400 kW, which are assumed to be a peak in normal operation. Some peaks are significantly higher, and these are assumed to be when football matches take place. From these peaks the assumed flood light power is set to 320 kW. The resulting load profile for only flood lights is shown in Figure 10.

To get an overview of when matches take place, the dates when the load exceeds 500 kW are listed in

Table 6, and represent the hours when the flood lights are assumed to be on. Using this load profile, a certain awareness of the inaccuracy is needed, since the load profile for the node consists of hourly values. If the lights were switched on for only a part of a timestep, it might not be represented in the new load profile. Or the other way around, that the listed time is overestimated. Unknown behaviour of other consumers during these time periods also increase the inaccuracy.

Table 6: Indicated activation hours of the flood lights in the arena based on the measured load data.

Date	Duration [h]	Starting time
21.02.2018	1	18
11.03.2018	3	18
16.03.2018	1	14
02.04.2018	3	19
08.04.2018	3	17
23.04.2018	3	18
06.05.2018	4	17
16.05.2018	2	18
27.05.2018	4	17
25.06.2018	4	18
08.07.2018	3	17
12.07.2018	4	19
02.09.2018	2	18
22.09.2018	3	17
07.10.2018	3	17
25.10.2018	2	9
28.10.2018	4	18
10.11.2018	4	18

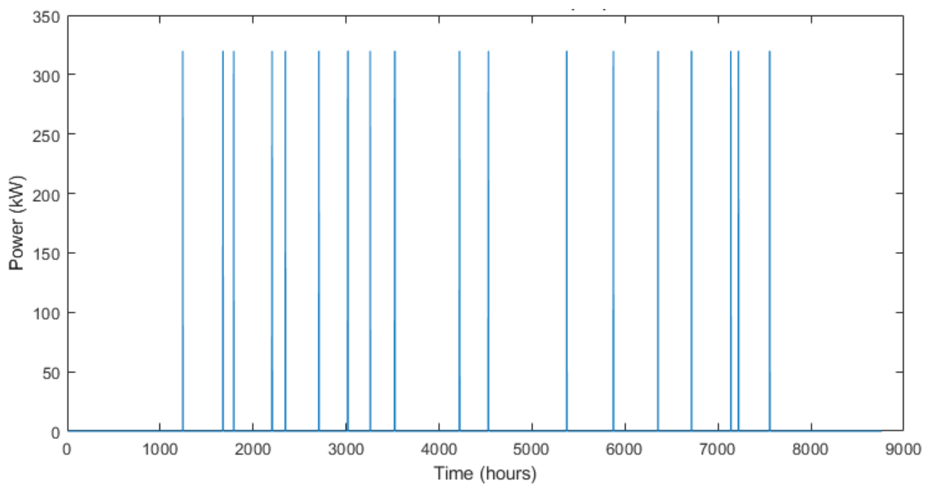

Figure 10: Hourly load profile created for flood lights (for 2018).

There was not any data from the production from the installed PV power plant (nominal power: 800 kW) for 2018 when this work was done, therefore irradiation data is used to create a PV generation profile, shown in Figure 11. In all the cases the electricity provided by the PV is primarily used to cover the load. Since the input profiles for load and generation are given for one year (2018), this data is used for all the ten years in the analysis period.

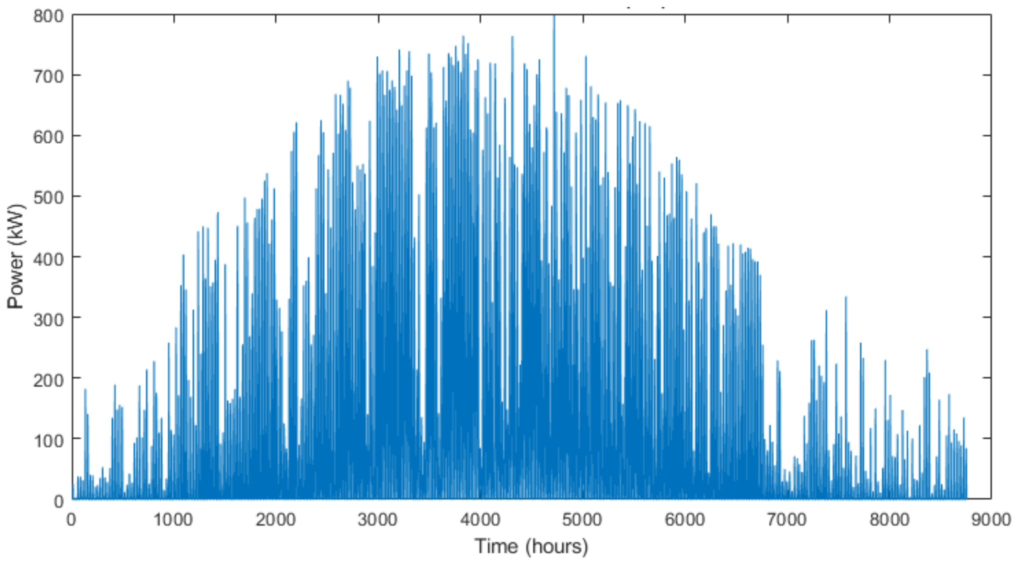

Figure 11: Hourly PV generation for 2018 used in simulations.

4.2 Reference week

For comparison of the different cases a reference week is chosen (Tuesday, 22. May to Monday, 28. May 2018), as shown in Figure 12. The figure shows PV generation and load profile of node P1 of this time period, including the resulting net load, P_{res}, which is the load or generation as seen from the connection point to the grid. This week shows a variety of day types: days with high electricity consumption and low generation, days with high generation and low consumption, and on Sunday (27. May) a match takes place, noticeable by the high peak in the evening hours.

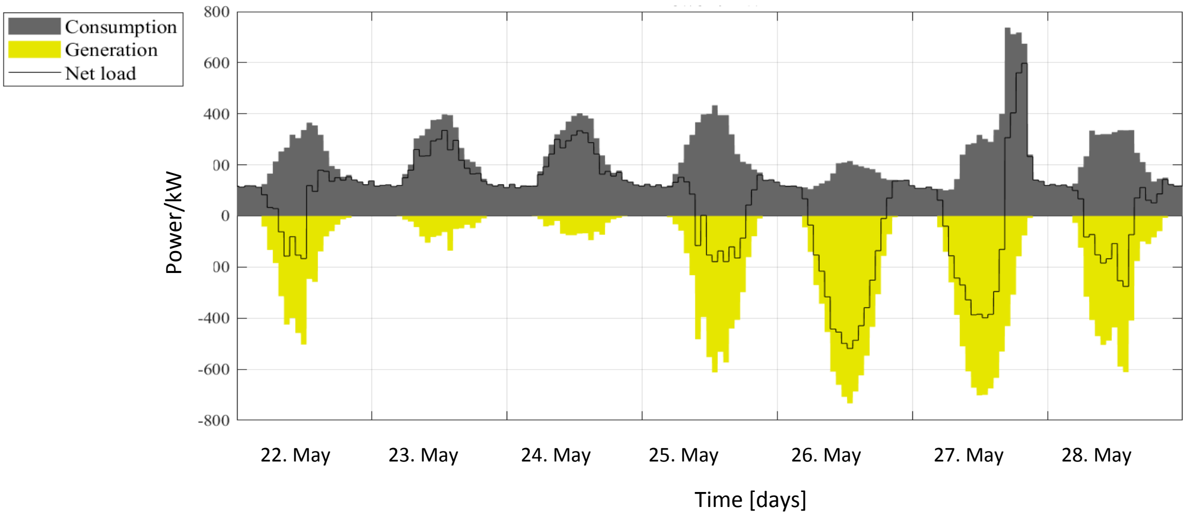

Figure 12: Power consumption (whole node P1), generation and the resulting net load of the reference week.

5 Results from case studies

This chapter shows the results from the case studies. The simulated time horizon is ten years for all cases. In this time the effects of the operation strategy on the battery degradation should be observable, given by the SOH at the end of the analysis period. The results of the simulation will be used for the technical and economic evaluation in Chapter 6.

5.1 Case 1: Self-consumption maximization covering only flood lights

Goal

The first case simulates the usage of the BESS only for the coverage of the flood lights (FL) and no other loads. Since there are only 18 times that the flood lights are used during a year (based on data from 2018), an economic benefit of this usage is not expected. It is therefore more considered as a reference scenario.

Set-up

A constant electricity consumption of 320 kW is assumed during the hours using flood light (

Table 6). The chosen operation strategy is maximizing self-consumption, meaning that the load is first covered by PV production, and secondarily by the BESS. Only if the battery is empty, energy is taken from the grid. The battery is charged as fast as possible using the power provided by the PV modules.

Results – reference week

The result of the case in the reference week are shown in Figure 13. There is only the load during the match, which is mostly covered by the PV generation and partly by the battery. As it can be seen the BESS is rarely used.

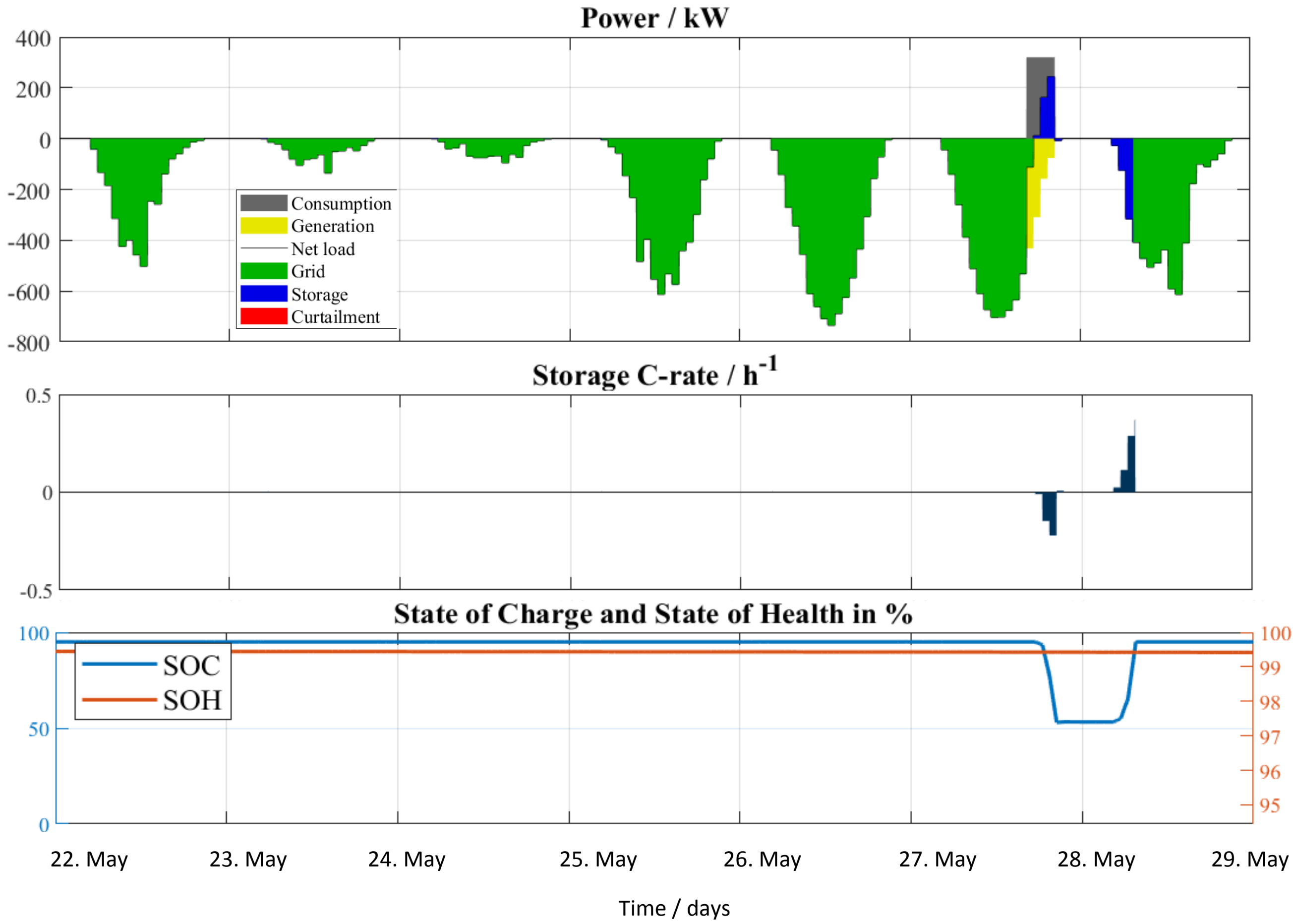

Figure 13: Diagrams showing the power flows in the energy system, the battery charging/discharging power, state of charge (SOC) and state of health (SOH) in case 1.

Technical and economic results

Important technical parameters are shown in Table 7. The comparison with the other cases will be presented in Chapter 6. The period of analysis is 10 years and 2018 data is used as input.

Table 7: Technical parameters of case 1.

Parameters for 10-year simulation	Value	Unit
Total load	61	GWh
Total generation	2989	GWh
Total feed-in	2924	GWh
Total purchased energy	7	GWh
Energy BESS in	51	GWh
Energy BESS out	40	GWh
Energy losses BESS	11	GWh
Relative losses (losses/feed-in)	0.213	-
BESS usage (hours with discharge/total hours)	0.005	-
Number of battery replacements	0	-
SOH end	0.857	-
Self-consumption ratio	0.022	-
Self-dependency ratio	0.890	-
Maximum power drawn from grid	320	kWh/h

Conclusion

The BESS usage is only 0.005 when it is only used to cover the FL, showing that there is a great potential for using the BESS for other purposes. Also it can be noticed that the BESS and the PV system are not able to cover the whole assumed flood light power (E_{Load} = 61 GWh), since there is still energy taken from the grid ($E_{Grid,out}$ = 7 GWh). This might be because the flood lights were used four hours in some matchdays, so the battery was not able to cover the whole load, if there was not enough generation from the PV panels.

5.2 Case 2: Self-consumption maximization

Goal

In this case the BESS is used to cover the load at node P1. This increase of the load should lead to a higher BESS usage and a consequential higher profitability of the battery, as compared to the previous case.

Set-up

The load profile for the node P1 is now used as input, instead of the flood light load profile. The operation strategy is still self-consumption maximization. There is also a constraint on match days where the BESS is charged in the beginning of a match day to ensure it is fully charged when the match begins.

Results – reference week

The result of the case in the reference week is shown in Figure 14. The BESS is used more, but not every day. During the match, the load is covered partly by the PV generation and BESS. The BESS is however emptied during the match, which results in a grid load demand quite close to peak power.

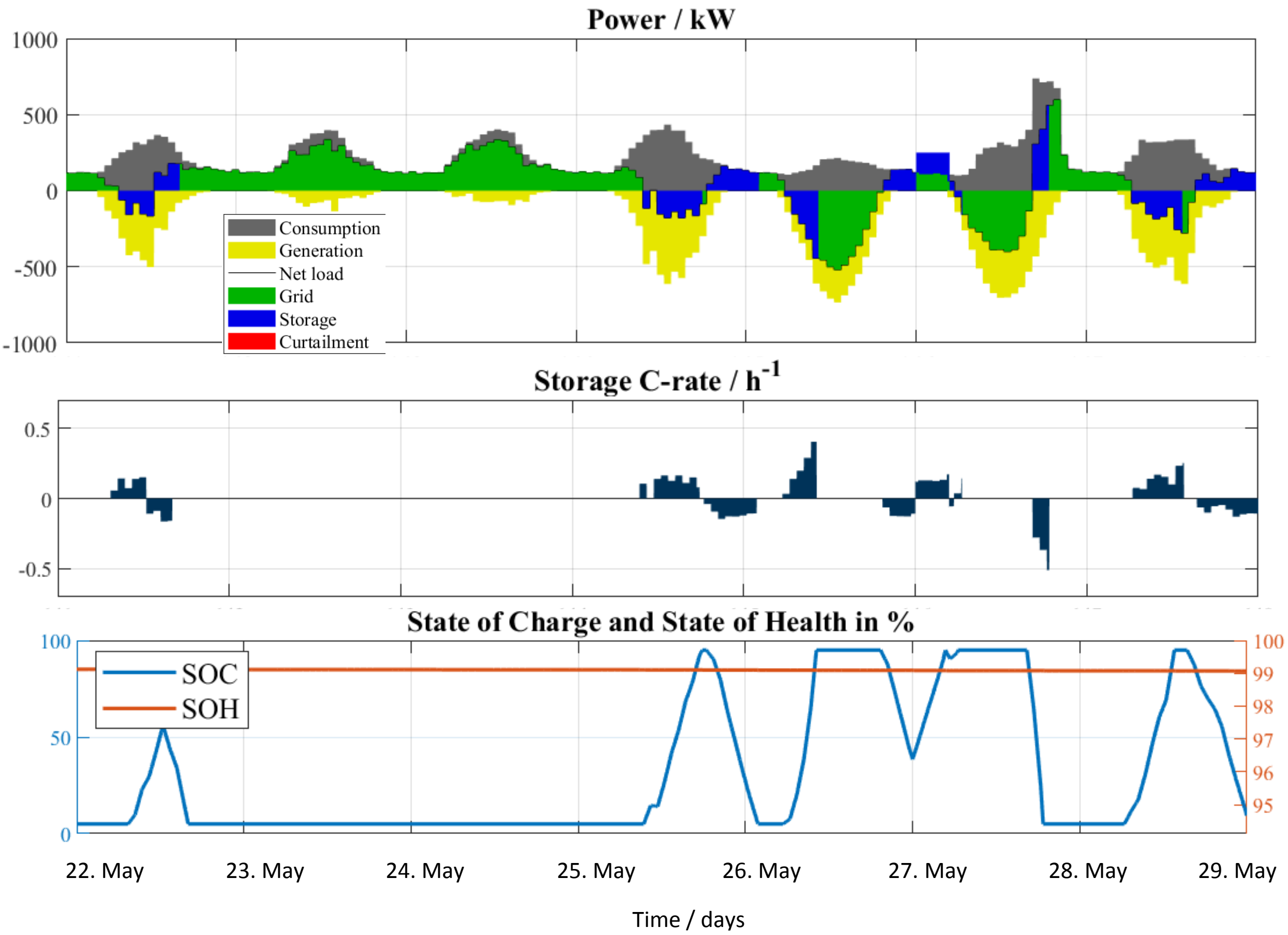

Figure 14: Diagrams showing the power flows in the energy system, the battery charging and discharging power and State of charge (SOC) and state of health (SOH) in case 2.

Technical and economic results

Important technical parameters are shown in Table 8. The comparison with the other cases will be presented in Chapter 6.

Table 8: Technical parameters of case 2.

Parameters for 10-year simulation	Value	Unit
Total load	6307	GWh
Total generation	2989	GWh
Total feed-in	457	GWh
Total purchased energy	3877	GWh
Energy BESS in (charged)	550	GWh
Energy BESS out (discharged)	448	GWh
Energy losses BESS	102	GWh
Relative losses (losses/feed-in)	0.186	-
BESS usage (hours with discharge/total hours)	0.126	-
Number of battery replacements	1	-
SOH end	0.960	-
Self-consumption ratio	0.847	-
Self-dependency ratio	0.385	-
Maximum power drawn from grid	733.6	kWh/h

Conclusion

The increased load leads as expected to a more frequent BESS usage, which naturally increases the self-consumption ratio. It is however shown that the battery is not able to cover the flood light power in all hours of the match, since it is also covering other loads. This is the reason for the introduction of a constraint on the days a match is taking place in the following case 3.

5.3 Case 3: Self-consumption maximization and flood lights prioritized

Goal

The previous case concluded that a constrained operation on the days the flood lights are switched on is required, to make sure the BESS covers the peak when there is a match.

Set-up

The dates when the matches take place are included in the operation strategy, making it possible to operate the BESS differently on these days, and assuring that the BESS is reserved for the flood lights. To ensure that the battery is not empty in the beginning of a match day it is necessary to apply another operation strategy on the day ahead of a match. After the match day the BESS is operated in the self-consumption maximization mode again.

Results - reference week

The results of the case in the reference week is shown in Figure 15. The main difference to the previous case is that the battery is not discharged on the day before a match day and on a match day the BESS is reserved to only cover the flood lights. From the SOC it can be seen that by the end of the match, all energy in the BESS has been used.

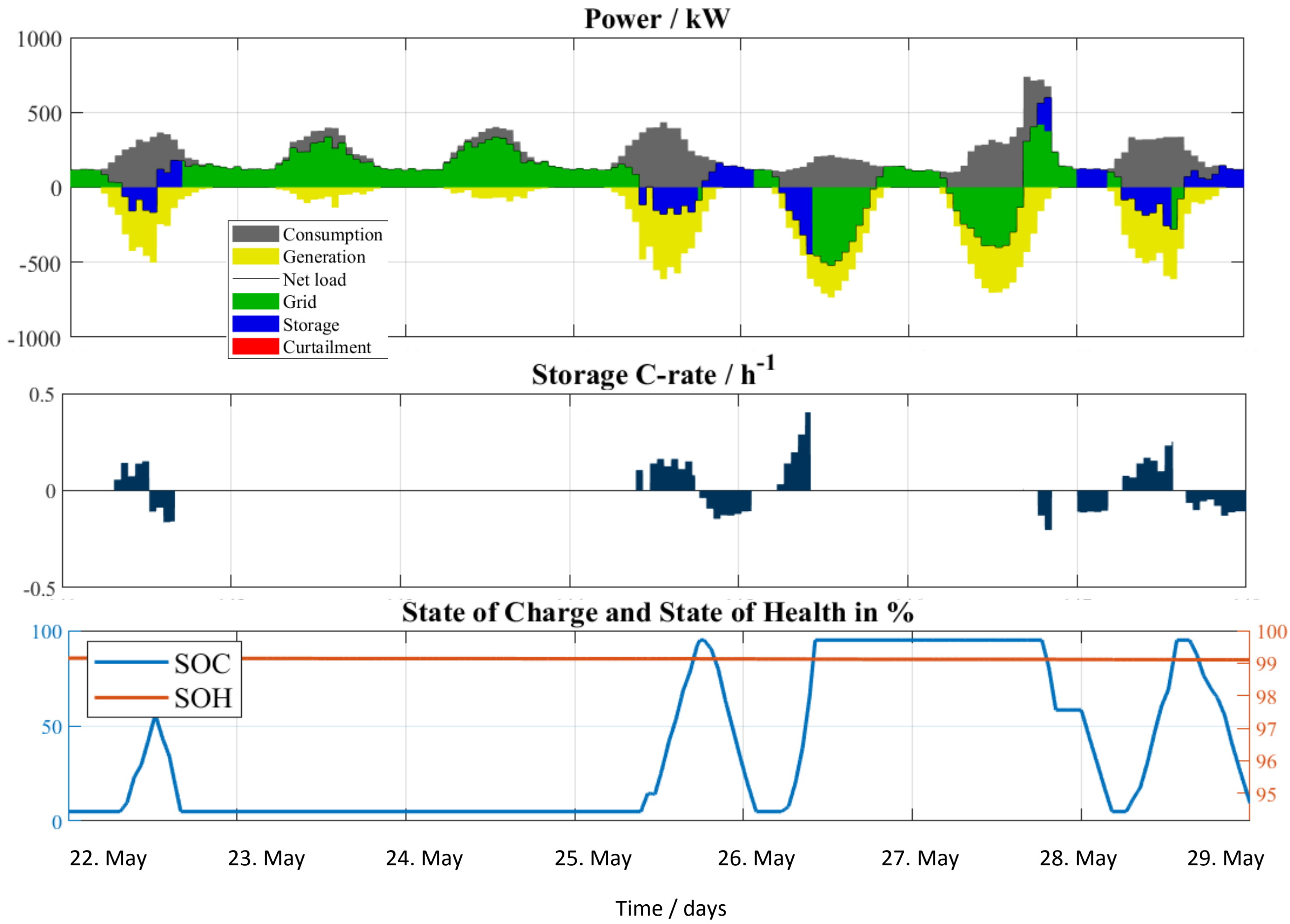

Figure 15: Diagrams showing the power flows in the energy system, the battery charging/discharging power, state of charge (SOC) and state of health (SOH) in case 3.

Technical and economic results

Important technical parameters are shown in Table 9. The comparison with the other cases will be presented in Chapter 6.

Table 9: Technical parameters for case 3.

Parameters for 10-year simulation	Value	Unit
Total load	6307	GWh
Total generation	2989	GWh
Total feed-in	463	GWh
Total purchased energy from grid	3875	GWh
Energy BESS in (charged)	507	GWh
Energy BESS out (discharged)	413	GWh
Energy losses BESS	94	GWh
Relative losses (losses/feed-in)	0.186	-
BESS usage (hours with discharge/total hours)	0.116	-
Number of battery replacements	1	-
SOH end	0.968	-
Self-consumption ratio	0.845	-
Self-dependency ratio	0.386	-
Maximum power drawn from grid	731.6	kWh/h

Conclusion

This case was able to combine the benefits from the self-consumption maximization and covering the flood light load.

5.4 Case 4: Optimized operation to minimize costs – energy arbitrage

Goal

In this case a variable electricity price is introduced. As mentioned already in Chapter 2.1, the price spread on the Norwegian spot market is not big enough to make arbitrage itself profitable, but it can be used in combination with other operation strategies. In difference to the cases above, the costs can be reduced by relaxing the constraint of maximizing self-consumption. To figure out how much the time shift of feed-in or consumption can influence the final costs, an optimization is performed.

Set-up

In this case, the operation strategy is no longer self-consumption maximization. An optimization is performed as described in Section 3.2.3, to minimize the energy costs (considering costs of purchasing energy, revenues from feeding in energy and cost of storage degradation). The peak power tariff is not considered in the optimization in this case. It is assumed that the electricity prices are known. Table 10 shows the boundaries for the variables in the optimization.

Table 10: Boundaries assumed for the optimization.

Variable	Variable explanation	Lower Boundary	Upper boundary
P_{Gp}	Grid power purchased	-∞	0
P_{Gf}	Grid power fed into grid	0	800 kW
P_{Bc}	Battery charging power	0	800 kW
P_{Bd}	Battery discharging power	800 kW	Between 0 and 320 kW depending on load and PV generation of match day
E_{bat}	Energy in battery	Min SOC*1.1 MWh	Max SOC*1.1 MWh

The optimization is carried out in MATLAB, described in detail in Appendix B. The scheduled BESS operation is then given as input to the SimSES simulation. The system operation is then evaluated like in the other cases.

Results - reference week

The result of the case in the reference week is shown in Figure 16. Since energy arbitrage is included, the electricity spot prices in the reference week are shown in Figure 17. The energy stored in the battery is mostly used in times with higher electricity prices, while feed-in is avoided when the prices are low.

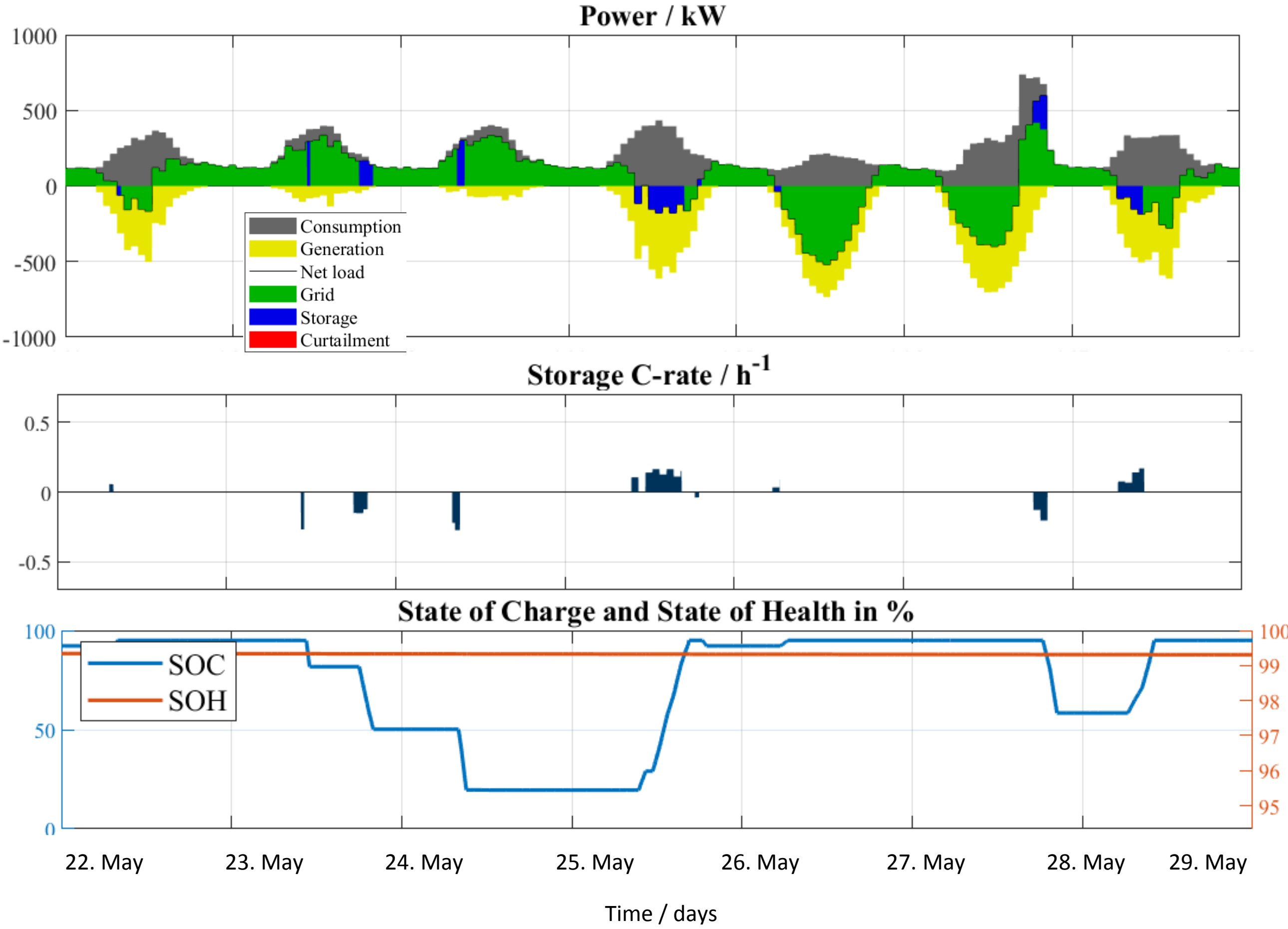

Figure 16: Diagrams showing the power flows in the energy system, the battery charging/discharging power, state of charge (SOC) and state of health (SOH) in case 4.

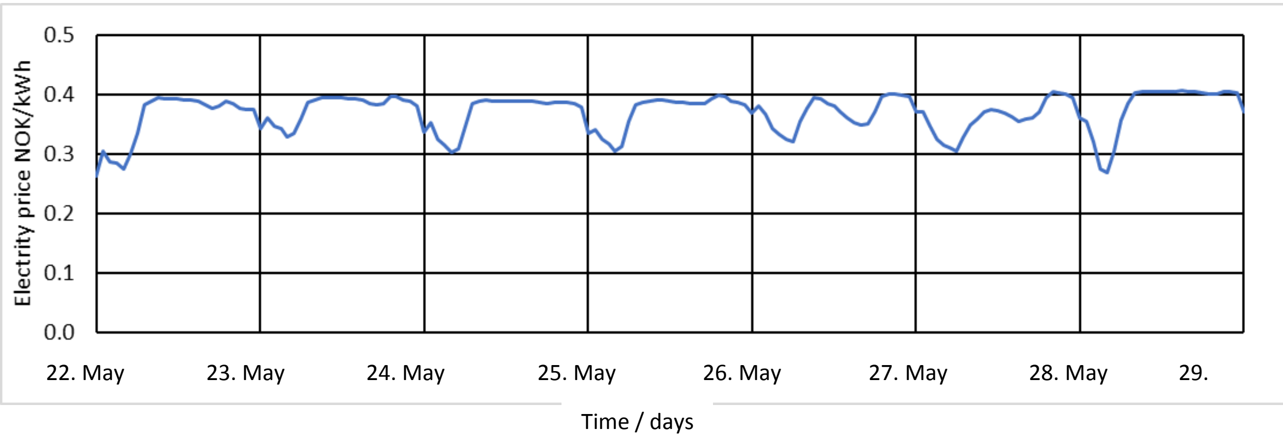

Figure 17: Electricity prices in the reference week.

Technical and economic results

Important technical parameters are shown in Table 11. The comparison with the other cases will be presented in Chapter 6.

Table 11: Technical parameters of case 4.

Parameters for 10-year simulation	Value	Unit
Total load	6307	GWh
Total generation	2989	GWh
Total feed-in	740	GWh
Total purchased energy from grid	4097	GWh
Energy BESS in (charged)	203	GWh
Energy BESS out (discharged)	164	GWh
Energy losses BESS	39	GWh
Relative losses (losses/feed-in)	0.190	-
BESS usage (hours with discharge/total hours)	0.040	-
Number of battery replacements	0	-
SOH end	0.826	-
Self-consumption ratio	0.752	-
Self-dependency ratio	0.350	-
Maximum power drawn from grid	766.7	kWh/h

Conclusion

The optimized operation of the BESS can improve the economic performance of the system. In this case a perfect forecast was assumed. In the application on a system there might be a load, generation and price prediction, but a perfect prediction does not exist and uncertainty will have to be handled in a real situation. Since the electricity costs consist of other components like the power tariff or the power dependent grid usage price as well, they are included in the optimization in the following case. It should also be noticed that the BESS is not replaced in this case.

5.5 Case 5: Optimized operation to minimize costs, including arbitrage, peak shaving and feed-in limitation

Goal

This case is based on the previous case (4), but now the power tariff and grid usage costs are included in the optimization constraints, and the BESS is not explicitly reserved for the flood lights on match days. This means the optimization will decide when to charge the BESS and how much to peak shave. The flood light power is still set as a boundary in the optimization, meaning it should be covered.

Set-up

This case is set up quite similar to case 4, however the optimization is now performed as described in Section 3.2.4. The objective is now to minimize energy costs including the peak power tariff. Table 12 shows the boundaries for the variables in the optimization.

Table 12: Boundaries assumed for the optimization.

Variable	Variable explanation	Lower boundary	Upper boundary
P_{Gp}	Grid power purchased	PT_{lim}	0
$P_{over\ lim}$	Grid power above peak shaving limit	-∞	PT_{lim}
P_{Gf}	Grid power fed into grid	0	800 kW
$P_{Gf>GFlim}$	Grid power when above feed-in limit	$P_{lim,Gu,f}$	∞
P_{Bc}	Battery charging power	0	800 kW
P_{Bd}	Battery discharging power	800 kW	Between 0 or 320 kW depending on load and PV generation of match day
E_{bat}	Energy in battery	Min SOC*1.1 MWh	Max SOC*1.1 MWh

The optimization is carried out in MATLAB, described in detail in Appendix B. The scheduled BESS operation is then given as input to the SimSES simulation. The system operation is then evaluated like in the other cases.

Results - reference week

The results for the reference week are shown in Figure 18. On the match day, the BESS peak shaves so the electricity from the grid is lower than in case 4 (hence, the BESS is covering more load than only the flood lights). It is also obvious that the BESS is charging and discharging at times which are more profitable than others (arbitrage). It should also be noticed that the feed-in from the PV system is exceeding the 100 kW limit on several days. The extra cost for feeding in over 100 kW is in other words not high enough to affect the use of the BESS.

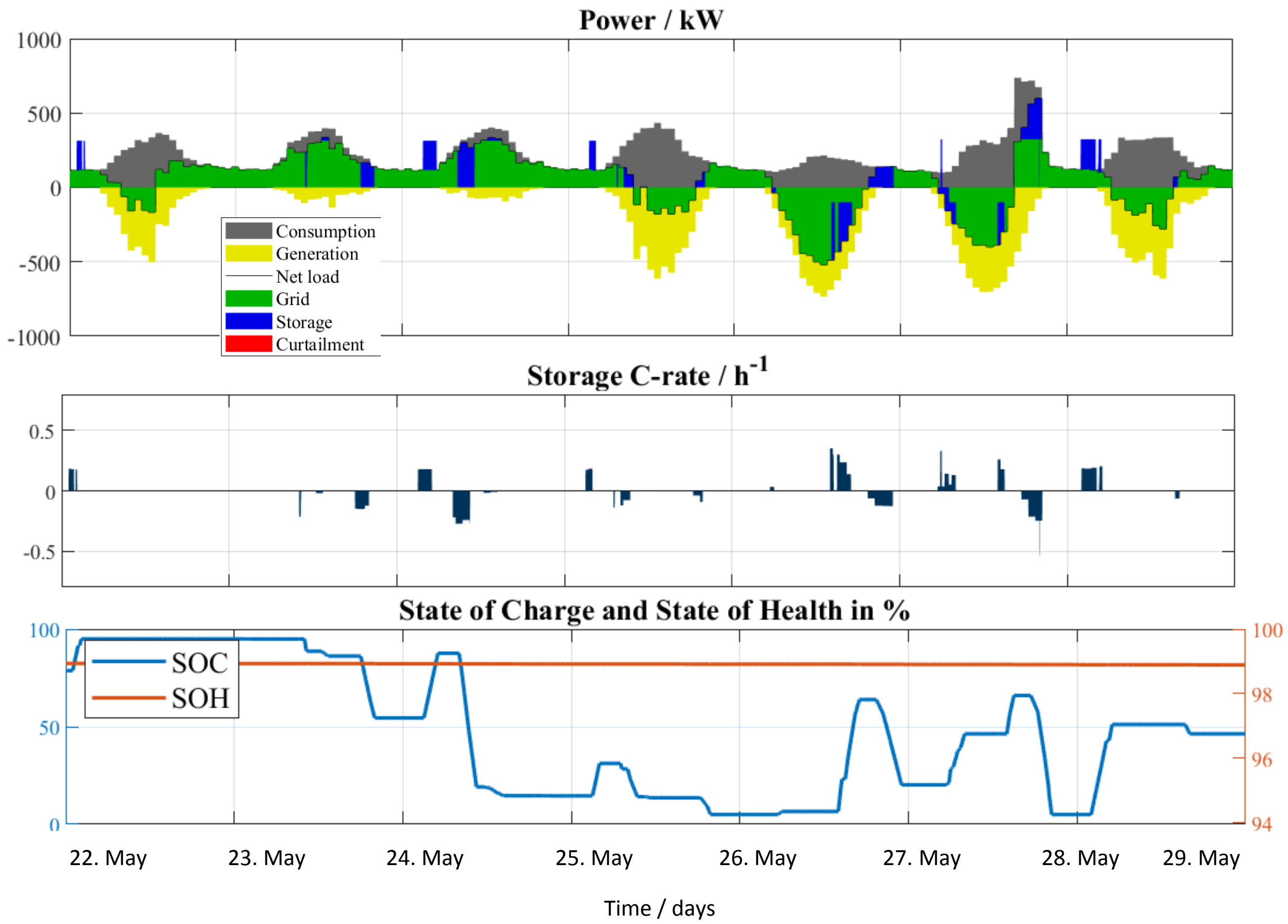

Figure 18: Diagrams showing the power flows in the energy system, the battery charging/discharging power, state of charge (SOC) and state of health (SOH) in case 5.

Technical and economic results

Important technical parameters are shown in Table 13. The comparison with the other cases will be presented in Chapter 6.

Table 13: Technical parameters of case 5.

Parameters for 10-year simulation	Value	Unit
Total load	6307	GWh
Total generation	2989	GWh
Total feed-in	939	GWh
Total purchased energy from grid	4377	GWh
Energy BESS in (charged)	437	GWh
Energy BESS out (discharged)	358	GWh
Energy losses BESS	80	GWh
Relative losses (losses/feed-in)	0.182	-
BESS usage (hours with discharge/total hours)	0.079	-
Number of battery replacements	1	-
SOH end	0.972	-
Self-consumption ratio	0.686	-
Self-dependency ratio	0.312	-
Maximum power drawn from grid	726.8	kWh/h

Conclusion

This case stacks multiple services, using the BESS for arbitrage, peak shaving and self-consumption. The BESS is consequently used more than in case 4, visualized by a relative BESS usage of 0.079 compared to 0.040 for case 4. The BESS must be replaced because of the higher usage, which will increase the costs. This case has the lowest maximum power drawn from grid (when considering the whole load), with 726.8 kWh/h.

6 Techno-economic assessment - comparison of cases

The comparison of the results obtained in Chapter 4 is divided in a technical and an economic assessment.

6.1 Technical assessment

After an analysis of each of the cases in the sections above, the cases are now compared by studying the degradation of the BESS, the energy flows of the system and some relative key-performance indicators.

6.1.1 Degradation of BESS

State of health (SOH) of the BESS over the analysis period is shown in Figure 19, and it clearly depicts how the different operation strategies affect the degradation of the battery. The degradation in case 1 is nearly linear, which is because the load is quite low (only flood lights), meaning the degradation is mainly due to calendar ageing, as opposed to cycle ageing[4]. Cases 2, 3 and 5 are more affected from cycle ageing and reach a SOH of 80 % within the ten years. The BESS is then replaced, clearly visible by the SOH going back up to 100 %. In case 4, the BESS does not degrade as much, thus the BESS is not replaced during the ten years.

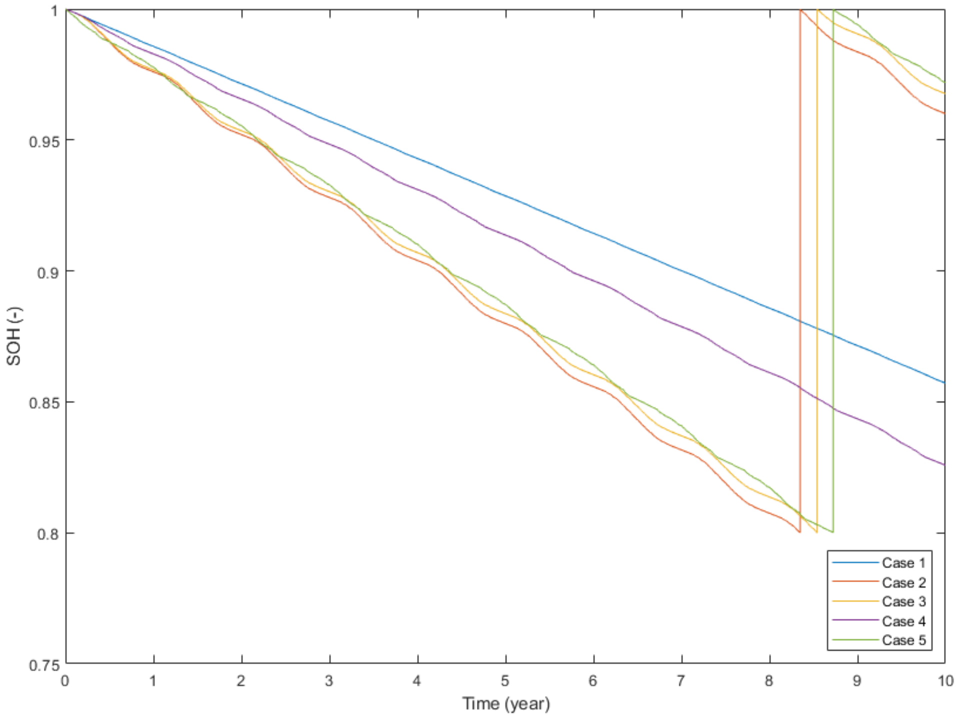

Figure 19: State of health (SOH) over ten-year analysis period for all cases.

Figure 20 shows the state of charge (SOC) of the BESS for one year for all cases. It is clear from the figure that the BESS is used very little in case 1, compared to the other cases. In case 2 and 3 the BESS is used almost equally, which makes sense since the operation strategies are quite similar. In case 4 the BESS is used

[4] Ageing can be divided into two categories: calendar ageing and cyclic ageing. Calendar ageing is ageing occurring when the battery is not being charged or discharged. Cyclic ageing is caused by charging and discharging the battery, and depends on the charge and discharge rate, depth-of-discharge and average state of charge of the battery.

less than the two previous cases. It should also be noticed how the BESS is used very little in the winter season for cases 2, 3 and 4. In case 5, the BESS is used all year, a consequence of the operation strategy taking the peak power tariff into account. It is also used less during summer, which probably is a consequence of high PV production. The battery is therefore not needed as often for peak shaving but is charging energy from the PV panels when the feed-in exceeds 100 kW.

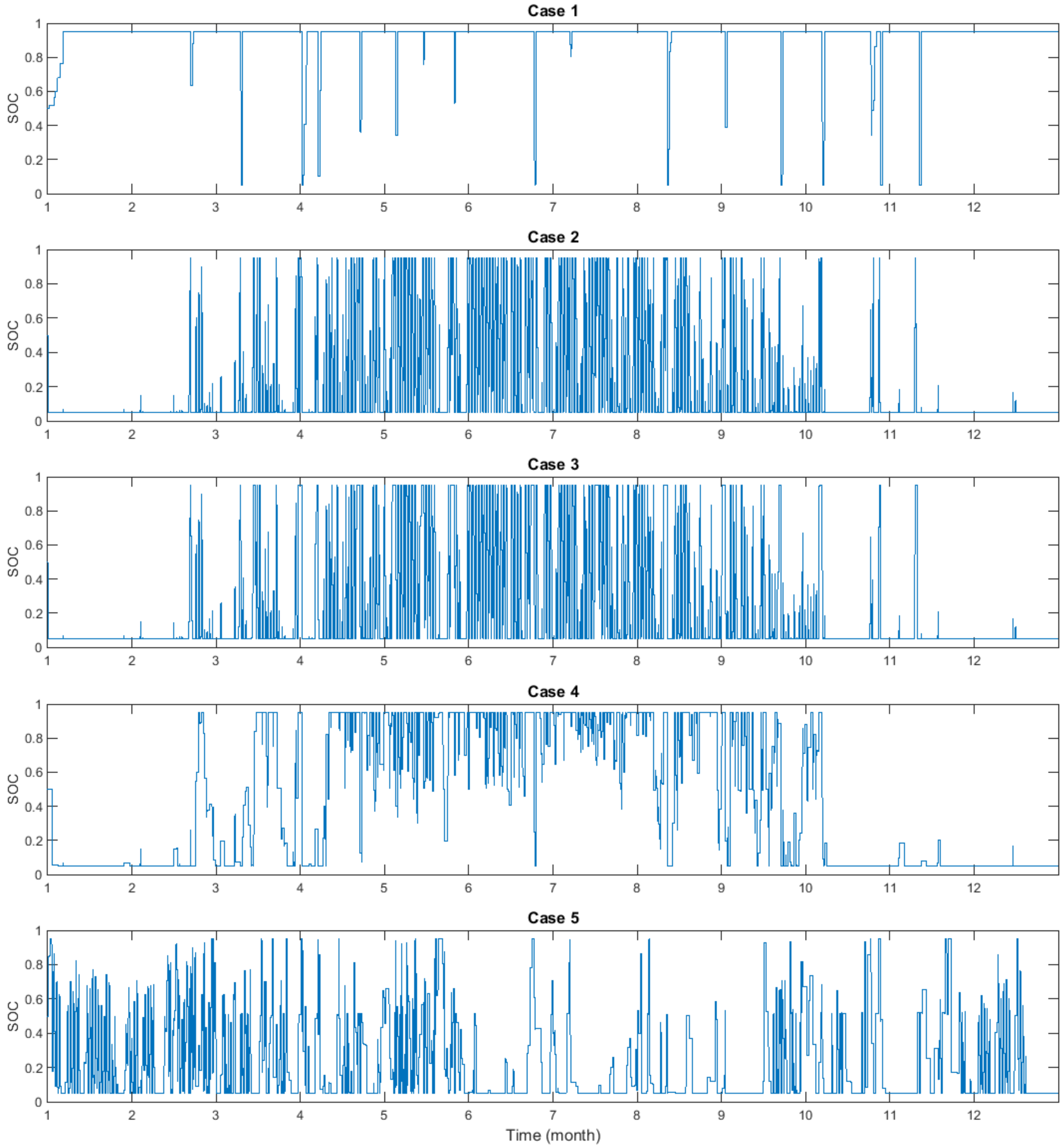

Figure 20: State of charge (SOC) of BESS for one year for all cases.

6.1.2 Energy flow in the system

The left side of Figure 21 shows the total load in energy (E_load), total energy fed into the grid (E_Grid_Feedin) and total energy bought from the grid (E_Grid_out), while the right side shows the total energy going into the BESS (E_Bess_in) and the total losses from charging/discharging the BESS (E_BESS_losses). The values for these parameters are for the whole analysis period of ten years.

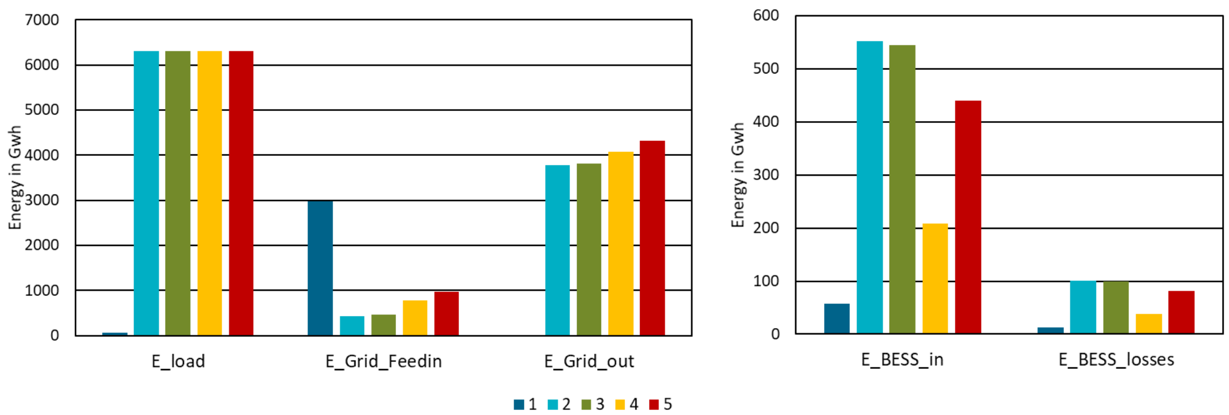

Figure 21: Comparison of the cases based on the energy flows. Note that the scale of y-axis is different for the two figures.

The total load is the same in all cases, expect case 1 where only flood lights were considered. The amount of energy fed into the grid is much higher in case 1, which is natural since the load is much lower in this case. Cases 4 and 5 have a higher amount of energy fed into the grid, which makes sense since arbitrage is a part of the operation strategy. Also cases 1, 2 and 3 maximize self-consumption, hence minimize the amount of PV generation going into the grid. The amount of energy taken from the grid increases for cases 4 and 5, which can also be explained by having arbitrage as a part of the operation strategy. It should also be noted that in case 1 7 GWh are taken from the grid, hence the BESS and PV system are not able to cover all the load.

The energy used to charge the BESS naturally correlates with the losses in the BESS, as shown in the right side of Figure 21. In cases 2 and 3 the BESS is used more than in case 5, probably because of the operation strategy to maximize self-consumption. Case 4 has the second, after case 1, smallest amount of energy going into the BESS. It can be noted that for case 2 and 3, the losses in the BESS for the 10-year simulation amounts to 100 GWh.

6.1.3 Relative key-performance indicators

The following relative key-performance indicators are shown in Figure 22:

- Relative battery usage (BatDischhours): the number of hours the BESS was used to cover a load divided by the 8760 hours of one year.
- Self-consumption rate (r_PVselfcon): amount of energy produced by the PV system used to cover the load.
- Self-dependency rate (r_selfdep): relative amount of consumed power provided directly by the PV system or provided by the PV system after being stored in the BESS.

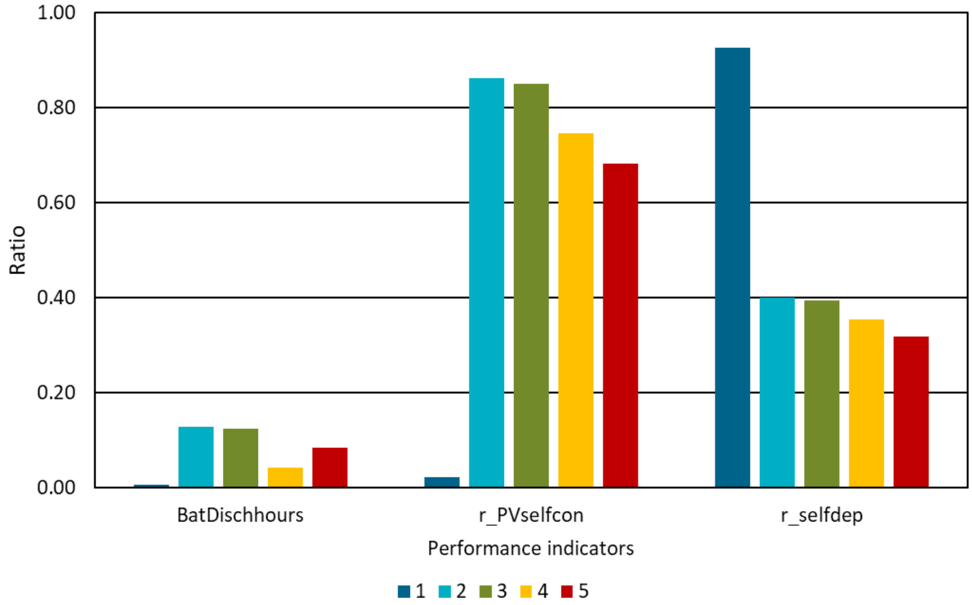

Figure 22: Comparison of the cases based on relative performance indicators.

As already mentioned, the relative battery usage shows that the BESS was rarely used in case 1 and case 4, and most in cases 2 and 3. The self-consumption rate is very low in case 1, due to the load being only the flood lights, and highest in cases 2 and 3 due to their operation strategy of self-consumption maximization. The self-dependency rate is clearly highest in case 1, again natural due to the load difference. For the other cases, again the cases which have operation strategies based on the self-consumption maximization have the highest numbers. It is interesting how case 4 has a low relative battery usage, but a higher self-consumption rate and self-dependency rate, compared to case 5. A higher battery usage in case 5 makes sense since the BESS is used to cover peaks and therefore has a higher need to charge from the grid between peaks, than in case 4. Case 4 has a higher self-consumption and self-dependency rate, since more of the PV power is used for covering the load, and more of the load is covered by the PV power. In case 5, when using the battery to peak shave, one is also more dependent on buying electricity from the grid to recharge. Figure 23 shows peak load drawn from the grid for all cases, where (when disregarding case 1) case 5 has the lowest, tightly followed by case 3. Case 4 has the highest peak load with 982 kW.

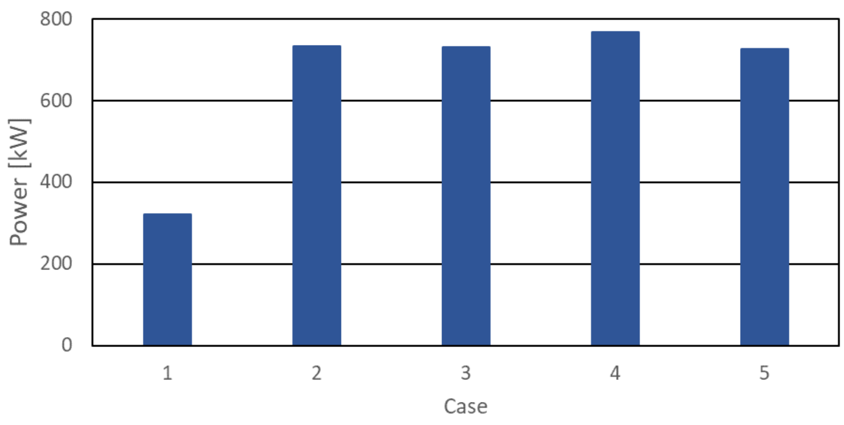

Figure 23: Peak load from grid during analysis period for the cases.

6.2 Economic assessment

The economic assessment is done by a net present value (NPV) calculation for all the five cases. This results in figures for how much the investment cost of the BESS can be for the NPV to equal zero, hence for the case to be financially viable. The NPVs are calculated applying Equation (13) and assumptions as shown in Section 3.3. It is further assumed that the investment cost of the BESS is between 4,000 NOK/kWh and 10,000 NOK/kWh for a 1 MWh/1 MW BESS [12, 13].

In SimSES there are different battery models which can be used for calculating the degradation of the BESS, and this heavily affects the economic assessment. Hence, two different Li-ion battery models are used and compared: A nickel cobalt aluminium oxide (NCA) battery model [14], and a nickel manganese cobalt oxide (NMC[5]) battery model [15]. The NCA Li-ion battery model is used in the results given in Chapter 5. The difference between the two models are that NCA model ages faster (calendric and cyclic aging process), thus resulting in a replacement of the BESS within the ten years analysis period for cases 2, 3 and 5. Figure 24 shows the timeline of replacement of BESS for the cases, as shown in Figure 19. The NMC model on the other hand does not age as fast, and the BESS does not need to be replaced within the ten-year analysis period for any of the six cases.

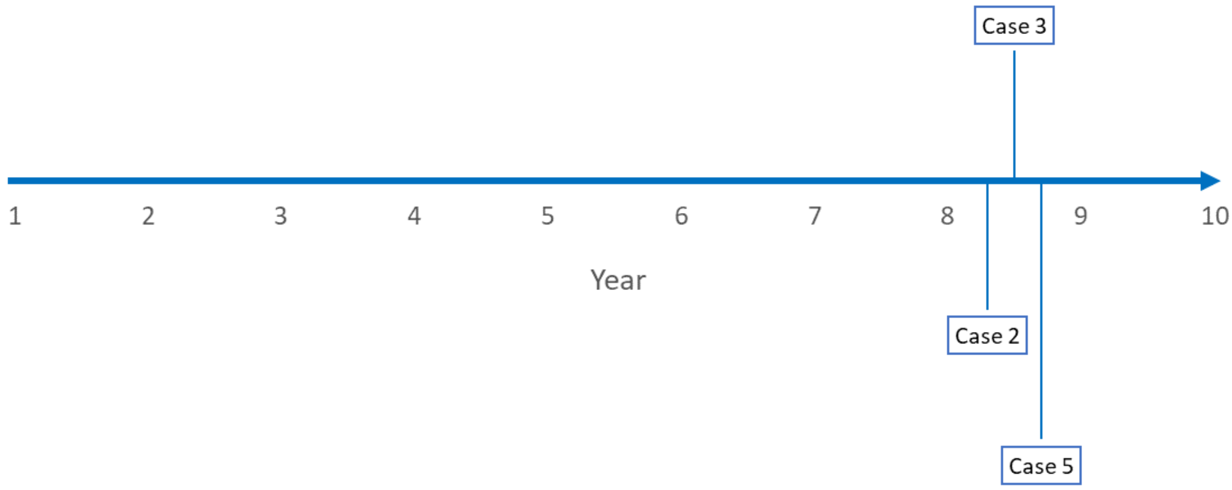

Figure 24: Timeline of replacement of BESS for cases, NCA battery model.

6.2.1 NCA lithium-ion battery model

In this section, the NPV analysis is performed for the NCA Li-ion battery model. Table 14 shows the investment costs (CAPEX) of a BESS necessary to reach an NPV of zero, in other words the maximal investment cost to reach break-even for each case. Further, it also shows the minimal needed cost reduction (if an investment cost of 10,000 NOK/kWh is assumed), and the maximal needed cost reduction (if an investment cost of 4,000 NOK/kWh is assumed).

[5] NMC batteries are used primarily for electric vehicles.

Table 14: NPV results with PV system costs, NCA battery model.

Case number	Case name	CAPEX BESS to reach NPV=0 [NOK/kWh]	Min. needed cost reduction	Max. needed cost reduction
1	SC_FL	170	96 %	98 %
2	SC	590	85 %	94 %
3	SC_FLprio	1 056	74 %	89 %
4	OPT	1 329	67 %	87 %
5	OPT_PS	1 249	69 %	88 %

Main points:

- In the most profitable case (case 4), the investment cost of the BESS has to drop between 67 % and 87 % to break even.
- Replacement of the BESS is necessary within the 10-year analysis period for cases 2, 3 and 5.

6.2.2 NMC lithium-ion battery model

In this section, the NPV analysis is performed for the NMC lithium-ion battery model. Table 15 shows the investment costs (CAPEX) of a BESS necessary to reach an NPV of zero, in other words the maximal investment cost to reach break-even for each case, just as the previous section.

Table 15: NPV results with PV system costs, NMC Li-ion battery.

Case number	Case name	CAPEX BESS to reach NPV=0 [NOK/kWh]	Min. needed cost reduction [%]	Max. needed cost reduction [%]
1	SC_FL	170	96 %	98 %
2	SC	2 177	46 %	78 %
3	SC_FLprio	3 982	0 %	60 %
4	OPT	1 322	67 %	87 %
5	OPT_PS	4 927	-23 %	51 %

Main findings from Table 15:

- Case 5 is the most profitable of all cases, and might already be profitable (if the CAPEX is assumed to be 4000 NOK/kWh). Case 3 breaks even for the minimal needed cost reduction.
- The more profitable results of this battery technology, as compared to the NCA model, are due to the fact that there is no need to replace the BESS within the 10-year analysis period in any of the cases.

6.2.3 Parameter variation of the investment cost for the two battery models

This section shows how the NPV varies with the investment cost of the BESS, for the two different Li-ion battery models.

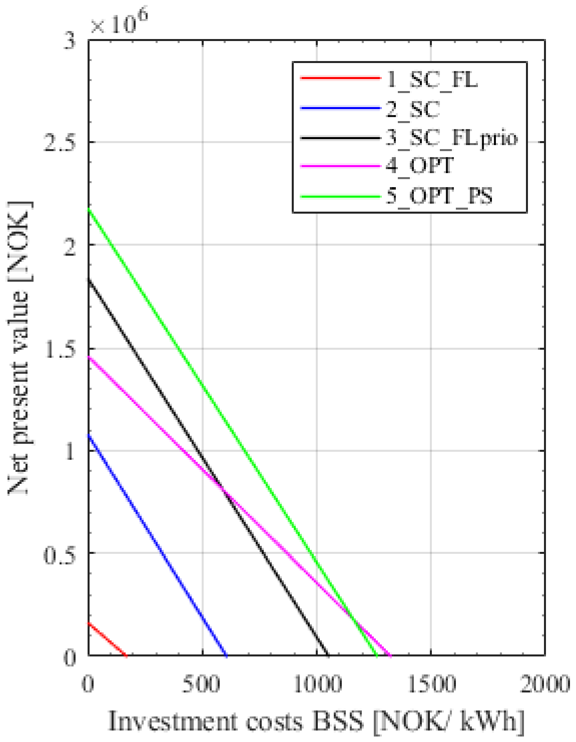

Figure 25: NPV comparison of the cases for an NCA battery model.

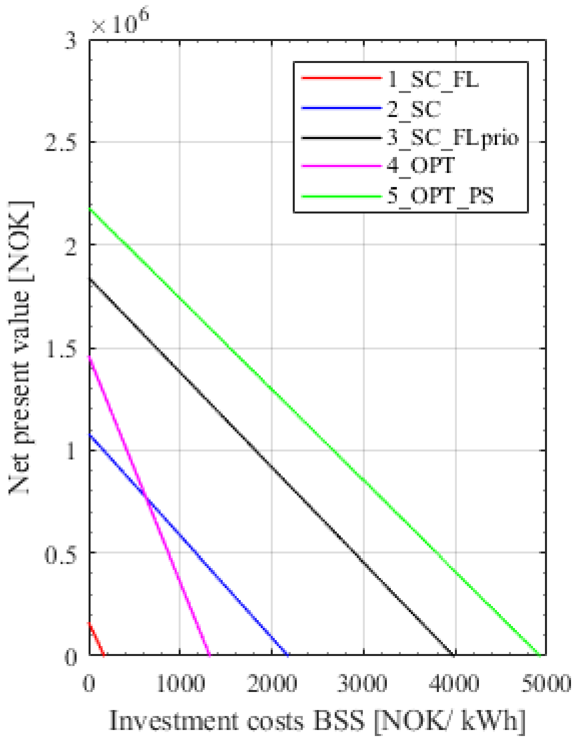

Figure 26: NPV comparison of the cases for an NMC model.

The influence of the type of BESS technology can clearly be seen by comparing Figure 25 and Figure 26. As the BESS for case 2, 3 and 5 with an NMC Li-ion model does not need to be replaced, the possible investment costs for these can be considerably higher than for the NCA model to reach a profitable business case (approx. by a factor of four). If a BESS investment cost of 4000 NOK/kWh is assumed, the cases for the NCA battery model are far from being profitable. Figure 26 shows that with an NMC battery model, case 3 and 5 might already be profitable, as opposed to cases with a fast aging and a subsequently replacement of the BESS within the lifetime.

6.2.4 Sensitivity analysis on PV system costs

In this section, a sensitivity analysis on PV system costs are performed. To study how the PV system costs affect the economic evaluation, PV system costs are here set to zero as opposed to 1000 NOK/kWp which they originally were (therefore the cases are marked with a *). These cases can be seen as the theoretical best case.

Table 16: NPV results with PV system costs set to zero, NCA battery model.

Case number	Case name	CAPEX BESS to reach NPV=0 [NOK/kWh]	Min. needed cost reduction	Max. needed cost reduction
1	SC_FL*	5 855	-46 %	41 %
2	SC*	3 759	6 %	62 %
3	SC_Flprio*	4 301	-8 %	57 %
4	OPT*	6 417	-60 %	36 %
5	OPT_PS*	4 446	-11 %	56 %

Main findings from Table 16:

- Four cases (1, 3, 4 and 5) could be profitable, if a realistic but very low CAPEX of 4,000 NOK [13] is assumed.
- Even with PV system costs set to zero, case 2 is not profitable.

Table 17: NPV results with PV system costs set to zero, NMC battery model.

Case number	Case name	CAPEX BESS to reach NPV=0 [NOK/kWh]	Min. needed cost reduction [%]	Max. needed cost reduction [%]
1	SC_FL*	5 859	-46 %	41 %
2	SC*	13 470	-237 %	-35 %
3	SC_Flprio*	16 070	-302 %	-61 %
4	OPT*	6 396	-60 %	36 %
5	OPT_PS*	17 540	-339 %	-75 %

Main findings from Table 17:

- All cases are profitable for a BESS based on an NMC battery technology for the minimal needed cost reduction.
- Case 5 is definitely most profitable, where the CAPEX of BESS can be over 17 000 NOK/kWh. Since no battery replacement is necessary, case 5 is much more profitable for the NMC model than the NCA battery model.

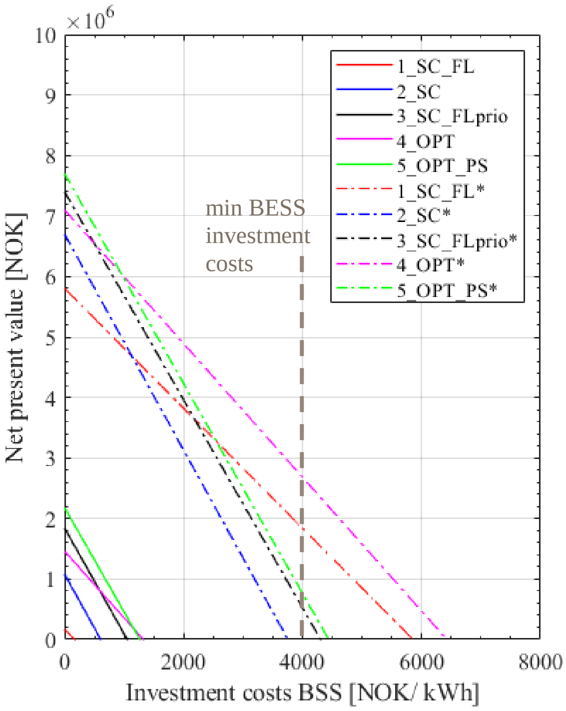

Figure 27: NPV of the cases; NCA battery model.

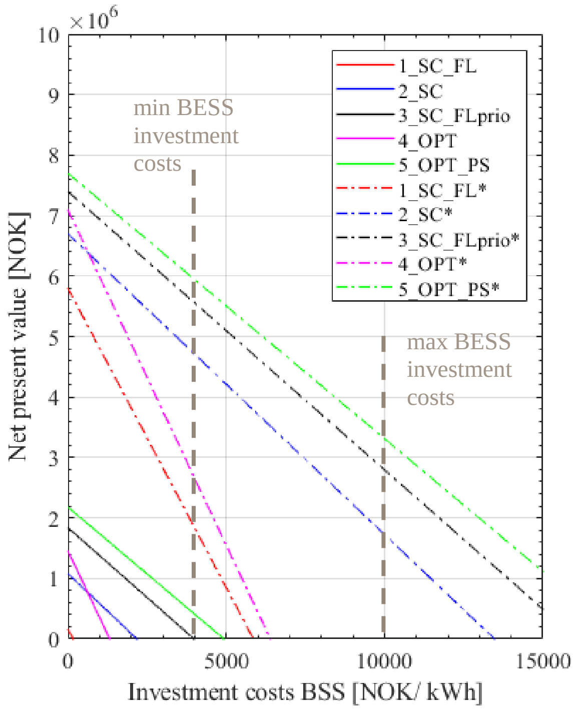

Figure 28: NPV of the cases; NMC model.

Normal line: PV-system costs are included.
Index* and dotted line: PV-system costs set to zero.

Figure 27 and Figure 28 show the influence of the costs of a PV system for both Li-ion battery technologies (realistic costs normal line, dotted line without PV-costs). Assumed minimum and maximum BESS investment costs (4000 and 10000 NOK/kWh, respectively) are also indicated in the figures.

As can be deduced, by comparing the NCA battery model to the NMC battery model, ageing processes have a great impact on the profitability of the case. In other words, ageing/degrading of the BESS and should play an important role when making operation strategies and in evaluating the profitability of cases. This stands in big contrast to vanadium-redox-flow BESS, in which aging does not play an important role [16], and thus the vanadium-redox-flow BESS is more considered in cases where BESS replacement is needed due to aging.

Recent studies show that price drop within the next 5 years for the investment cost of BESS based on lithium-ion (from 2020 to 2025) will continue, but the amount is highly uncertain and is reported to be between 16 % [17] and 33 % [13]. For Li-ion batteries, NMC batteries have the lowest cost, followed by lithium iron phosphate (LFP), and lithium titanate oxide (LTO). Thus, NMC seems to be the best suited technology for stationary BESS, where cost issues have a higher impact than energy density. Furthermore, the car industry heavily opts for NMC battery technology and thus it has the strongest growth rate and economy of scale.

In [18], it is studied how using more detailed ageing models lead to cost-aware battery operation strategies. The authors highlight that using a BESS for multiple services is needed to increase profitability, but their study lack an NPV analysis and they mention that this would be hard because of the ever-changing Li-ion battery prices. In the work described in this memo, it is possible to evaluate the profitability of the BESS for different cases with multiple services, even with the uncertainty of battery costs. In [15], the SimSES tool is used for a German case study which demonstrates that batteries in peak shaving applications are more profitable when used for loads with high peaks, such as the one analysed in this memo.

7 Conclusion

In this memo a techno-economic analysis of the battery energy storage system (BESS) at Skagerak Arena, Skagerak EnergyLab, has been performed. Historical data for PV generation and load have been used as input to simulations carried out in the SimSES software. We have looked at five different case studies, varying operation strategies for the BESS. The simulations resulted in a technical and economic analysis of the different cases. The five different cases were:

- Case 1: Self-consumption maximization covering only flood lights
- Case 2: Self-consumption maximization (for all load)
- Case 3: Self-consumption maximization and flood lights prioritized
- Case 4: Optimized operation to minimize costs – energy arbitrage
- Case 5: Optimized operation to minimize costs, including arbitrage, peak shaving and feed-in limitation

The strategy for self-consumption maximization was already programmed in SimSES, while the other strategies were developed from scratch. None of the strategies are based on forecasts but assumes that load and PV generation is known.

Technical assessment

Since case 1 was considered more a reference case, with only the flood lights as a load, only the remaining four cases are commented here. The technical assessment showed that when using the BESS for self-consumption maximization (case 2), the self-dependency rate is high, there is less energy imported from the grid and the relative battery usage is high. This led to the fastest battery degradation, and a replacement of the battery after eight years. When using the BESS for self-consumption maximization and prioritizing the flood lights (case 3), the technical results are quite similar to case 2, as expected. The exception is that the relative usage of the battery, the self-consumption rate and self-dependency rate are somewhat lower in case 3, and the replacement of the battery occurs some months later.

In case 4, the BESS was used for energy arbitrage, hence considering spot prices but not the peak power tariff. Compared to the two previous cases, the technical assessment showed that there is more feed-in of PV generation and a higher amount of energy imported from the grid. The relative usage of the battery is quite low, as is the self-consumption and self-dependency rate. This case also has the highest peak load of all cases. As shown in Section 2.1, the variation in electricity price is most likely not high enough to benefit from using the BESS for energy arbitrage alone, because of the losses induced by charging and discharging. This coincides with an analysis of the marginal cost of the usage of BESS for energy arbitrage done in [9], which shows that in most markets the costs caused by the energy losses and battery degradation are too high to be covered by the possible revenues. Since the relative battery usage is low, this case has the slowest degradation.

In case 5, the operation of the BESS was aimed to minimize costs, including the peak power tariff. This resulted in the highest amount of feed-in energy, and the highest amount of energy imported from the grid of all cases. The relative usage of the BESS is moderate (lower than case 2 and 3, but higher than case 4), as is the self-consumption and self-dependency rate. The battery degrades faster than in case 4 (but slower than in case 2 and 3), leading to a battery replacement after almost nine years.

Economic assessment

The technical assessment was used as an input to the economic assessment, which is the main outcome of this work. A net present value (NPV) analysis was performed for all cases, resulting in figures for how much the investment cost of the BESS must be for the NPV to equal zero, hence for the case to be financially viable. The analysis was performed for two different lithium-ion battery models: nickel cobalt aluminum oxide (NCA) and nickel manganese cobalt oxide (NMC).

For the NCA Li-ion battery model, none of the cases are profitable when we assume a BESS investment cost between 4000 and 10000 NOK/kWh (Figure 25). The BESS had to be replaced for cases 2, 3 and 5 as shown in Figure 24. Case 4 was the most profitable, but still far from break even with today's battery prices. For the NMC battery model, both case 3 and 5 could be profitable when we assume a BESS investment cost between 4000 and 10000 NOK/kWh. An NPV of zero is reached for BESS investment costs of 3982 and 4927 NOK/kWh, for case 3 and 5, respectively. Profitability is reached at 2177 NOK/kWh for case 2, and 1322 NOK/kWh for case 4 – meaning that case 4 was the least profitable for this battery technology.

This could seem contradicting but emphasizes an important point: for the NCA battery model, case 4 is the most profitable since the operation strategy of energy arbitrage does not require replacing the battery during the period of analysis, as opposed to the other cases. For the NMC battery model, case 4 is the least profitable, since none of the cases require replacing the battery and the other cases are contributing to more revenues. The comparison in Figure 25 and Figure 26 illustrates this. In other words, the profitability highly depends on the operation strategy of the BESS and the battery technology.

Case 5 has the operation strategy combining the most purposes: peak shaving, energy arbitrage and feed-in limitation. For the NCA battery model it is almost as profitable as case 4, even though the battery is replaced. For the NMC model, case 5 is clearly the most profitable case (where none of the cases require battery replacement). This leads to believe that an operation strategy which combines several purposes is more profitable than single-purpose strategies. And, as has been shown, the profitability heavily depends on the operation strategy of the BESS, as well as the battery technology. Hence, the most important outcome of this work is that a multi-purpose case which combines peak shaving, energy arbitrage, self-consumption and replacement of a diesel backup generator, can be feasible in Norway.

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A Adaptations of the original SimSES model

Since the original SimSES Tool was mainly designed for the usage of BESS in the German market, some adaptations for the Norwegian market and also for the application in this case having some special constraints needed to be done.

New Case Skagerak

For using the model according to the needs of the simulation of the BESS installed in the Skagerak arena a new case was created. As basis the "residential PV battery system" case was used and adapted, which means in detail:

- New load profile input
- Load profiles are used directly and are not scaled using the annual load input from the Excel sheet
- Option to have an interpolated minute resolution profile (*ReturnInputfile_Skagerak)*
- New "createTechParamSkagerak.m" script

ReturnInputfile_Skagerak

Interpolation of the data set for gaining minutely resolution for the profiles. Finally, it was decided to not apply this script, since it might change the measured data in a way which was not desired. It was an idea to apply it on the PV generation profile and the load profiles (not the flood lights only load profile), but not on the price profile, since the prices on the market are not set in a minute wise resolution. But since it is good to carry out the simulations using measured unprocessed data the original script *ReturnInputfile* is still used.

Flexible simStart and simEnd

The original code was altered so that analyses could be run for any time period of the year, not only for one year at a time.

Additional result saving for case comparison

In the end of the simulation some figures for the techno-economic comparison are saved in *results_skagerak.txt* in a character separated value (csv) format. The table contains numbers to calculate technical and economic parameters for the different cases.

Matchdays

In this chosen case the battery needs to be operated sometimes different if there is a match on this day. A vector carrying the dates for the matches is now saved in the ees object. It is accessible using this path: *ees.inputSim.matchday*.

Variable energy price vector

Since it is necessary to have a variable electricity price for having a closer look at arbitrage it is read in and saved as well in the ees object (*ees.inputProfiles.Eprice*).

Economic evaluation

It was necessary to set-up a new economic evaluation due to the different composition structure of the energy price in Norway. This will be explained in a more detailed way in the section 3.3.

B Optimization in MATLAB

B.1 General theory

In this section some general information about the chosen optimization approach in MATLAB for this project is provided. In general, an optimization problem is formulated in an objective function like the following cost function, consisting of several variable costs, which shall be minimized:

$$min\ C_{tot} = \sum_{t_1}^{n} C_a(x_{t_i}) + C_b(y_{t_i}) + \dots \tag{14}$$

$$t_i = t_0, \dots, t_n$$

In this case the function is summed over a certain time horizon described by the variable t_i. For the optimization some equations and/or inequations need to be provided representing the dependencies between the variables x, y, …. Assuming k is a set value for t_i it could look like this:

$$x_{t_i} + y_{t_i} = k_{t_i} \tag{15}$$

Or in case the dependency is described by an inequation, like this:

$$x_{t_i} + y_{t_i} \leq k_{t_i} \tag{16}$$

If the equations are linear it is a linear optimization problem. Since the optimization must look at all the different timesteps, it is necessary that the system of equations includes a time dimension. If we include it in equation (15) and formulate it for all timesteps $t_i = t_1, \dots, t_n$ the result looks as follows:

$$\begin{matrix} x_{t_1} & 0 & \dots & 0 & + & y_{t_1} & 0 & \dots & 0 & = & k_{t_1} \\ 0 & x_{t_2} & \ddots & \vdots & + & 0 & y_{t_2} & \ddots & \vdots & = & k_{t_2} \\ \vdots & \ddots & \ddots & 0 & + & \vdots & \ddots & \ddots & 0 & = & \vdots \\ 0 & \dots & 0 & x_{t_n} & + & 0 & \dots & 0 & y_{t_n} & = & k_{t_n} \end{matrix} \tag{17}$$

If the variable x is turned into the vector $\bar{x}$ with the length t_n

$$x \rightarrow \bar{x} = \begin{pmatrix} x_{t_1} \\ x_{t_2} \\ x_{t_3} \\ \vdots \\ x_{t_n} \end{pmatrix} \tag{18}$$

The system of equations (17) can be described using an identity matrix

$$\bar{x} \cdot \begin{bmatrix} 1 & 0 & \dots & 0 \\ 0 & 1 & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \dots & 0 & 1 \end{bmatrix} + \bar{y} \cdot \begin{bmatrix} 1 & 0 & \dots & 0 \\ 0 & 1 & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \dots & 0 & 1 \end{bmatrix} = \bar{k} \tag{19}$$

This way of formulating the constraints is the basis to formulate equations, inequations and other necessary information. For the optimization of the BESS usage in this case the function linprog() provided by MATLAB in the optimization toolbox was chosen. It is a linear programming solver explained in further details in the MATLAB documentation [19]. For solving the linear optimization problem, the linprog function needs to have the cost function and enough equations and inequations provided. Additionally, the upper and lower boundaries for the variables and other options like the algorithm or tolerance can be set. As result the values of the different variables for the optimal solution, the result of the objective function in this case and some more details about the optimization itself is given.

B.2 Optimization for case 4

For the optimization in MATLAB this problem must be described by vectors and matrices as mentioned above. Using the equations (5) and (6) a Matrix A representing this system of equations is created.

$$A \cdot \begin{pmatrix} P_{Gp,t_i} \\ P_{Gf,t_i} \\ P_{Bc,t_i} \\ P_{Bd,t_i} \\ E_{bat,t_i} \\ P_{Gc,t_i} \end{pmatrix} = \begin{bmatrix} P_{res,t_i} \\ 0 \end{bmatrix} \tag{20}$$

$$\begin{bmatrix} 1 & 1 & 1 & 1 & 0 & 1 \\ 0 & 0 & \eta_{Bc} & {}^{1}\!/\eta_{Bd} & 1 & 0 \end{bmatrix} \cdot \begin{pmatrix} P_{Gp,t_i} \\ P_{Gf,t_i} \\ P_{Bc,t_i} \\ P_{Bd,t_i} \\ E_{bat,t_i} \\ P_{Gc,t_i} \end{pmatrix} = \begin{bmatrix} P_{res,t_i} \\ 0 \end{bmatrix} \tag{21}$$

Now it will be shown how all this together is implemented in MATLAB, is shown using equation (5) , which is also the first line of matrix A as an example.

$$P_{Gp,t_i} + P_{Gf,t_i} + P_{Bc,t_i} + P_{Bd,t_i} + P_{Gc,t_i} = P_{res,t_i}$$

$$[1 \quad 1 \quad 1 \quad 1 \quad 0 \quad 1] \cdot \begin{pmatrix} P_{Gp,t_i} \\ P_{Gf,t_i} \\ P_{Bc,t_i} \\ P_{Bd,t_i} \\ E_{bat,t_i} \\ P_{Gc,t_i} \end{pmatrix} = P_{res,t_i} \tag{22}$$

Applied on timesteps $t_i = t_1, \dots, t_n$:

$$\left[\begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 & 0 & \cdots & 0 \\ 0 & 0 & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & 0 \end{bmatrix} \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & 1 \end{bmatrix} \right]$$

$$\cdot \begin{pmatrix} \overline{P_{Gp}} \\ \overline{P_{Gf}} \\ \overline{P_{Bc}} \\ \overline{P_{Bd}} \\ \overline{\Delta E_{bat}} \\ \overline{P_{Gc}} \end{pmatrix} = \overline{P_{res}} \tag{23}$$

Because of equation (6), the BESS energy balance connects the equations for the different timesteps, the energy difference E_{bat,t_i} need to be multiplied by a matrix of the type

$$\begin{bmatrix} 1 & 0 & 0 & \dots & 0 \\ -1 & 1 & 0 & \ddots & \vdots \\ 0 & -1 & 1 & \ddots & 0 \\ \vdots & \ddots & \ddots & \ddots & 0 \\ 0 & \dots & 0 & -1 & 1 \end{bmatrix}$$

Since the charging and discharging efficiencies are included in equation (6), those losses are included in the optimization, but not the losses due to self-discharge. Beside those equations upper and lower boundaries for the different values are set as shown in Table 10.

C How to run the different cases in MATLAB

Make sure to choose the up-to-date inputParameters.xlsx (including the in the technical parameters the operation strategy (OS) for the different cases (e.g. "OSSkagerak_01_02_SC"). Check that in the 02_profile_data the needed profiles are existing. Namely:

- Load_Skagerak_h_floodlights
- Load_Skagerak_h_ConsP1
- PV_Skagerak_h_
- Eprice_Oslo_2018_h

In general, set the desired parameters in the inputParameters file. Make sure the current folder in Matlab is correct (the folder containing the runSimSES_Skagerak.m script). Run the Matlab script runSimSES_Skagerak.m with the following settings for each case:

Case 1

- runSimSES.m: choose load_Skagerak_h_floodlights
- inputParameters OS: OSSkagerak_01_02_SC

Case 2

- runSimSES.m: choose load_Skagerak_h_ConsP1
- inputParameters OS: OSSkagerak_01_02_SC

Case 3

- runSimSES.m: choose load_Skagerak_h_ ConsP1
- inputParameters OS: OSSkagerak_03_SC_FLprio

Case 4

- runSimSES.m: choose load_Skagerak_h_ ConsP1
- inputParameters OS: OSSkagerak_04_OPT

Case 5

- runSimSES.m: choose load_Skagerak_h_ ConsP1
- inputParameters OS: OSSkagerak_06_OPT_aPS

D Calculating efficiency of BESS inverter

The efficiency of BESS inverter is used for calculating the degradation in SimSES. The method for calculating the efficiency is based on [11], where p_{loss} are the total electrical losses, depending on three variables as shown in (24). p_0 and k are constant load-independent variables, found from the efficiencies at 10 % and 100 % of nominal power, η_{10} and η_{100} respectively, as given in (25) and (26). p is a load-dependent variable, defined as the power going through the inverter divided by the rated power of the inverter, as given in (27).

$$p_{loss} = p_0 + kp^2 \tag{24}$$

$$p_0 = \frac{1}{99}\left(\frac{10}{\eta_{10}} - \frac{1}{\eta_{100}} - 9\right) \tag{25}$$

$$k = \left(\frac{1}{\eta_{100}}\right) - p_0 - 1 \tag{26}$$

$$p = \frac{P_{out}}{P_{inv,rated}} \tag{27}$$

The inverter type was chosen to be "Type 2" in [11], with $\eta_{10} = 0.93$, $\eta_{100} = 0.960$, $p_0 = 0.0072$ and k = 0.0345, as this was the type most similar to the efficiency data provided for the inverters of EnergyLab.

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