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Design of an Optimal Investment Model for a Hybrid Energy Park

An Investigation of the Profitability of a Hybrid Energy Park with Wind Power, Solar PV and Battery Storage

Master's Thesis in Sustainable Energy Systems

Johan Söderbergh

DEPARTMENT OF ELECTRICAL ENGINEERING
DIVISION OF ELECTRIC POWER ENGINEERING
Chalmers University of Technology
Gothenburg, Sweden 2025
www.chalmers.se

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Supervisor: Ludwig Klevtun, SR Energy
Examiner: David Steen, Chalmers University of Technology, Electric Power Engineering

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Department of Electrical Engineering
Division of Electric Power Engineering
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: A visualization of a hybrid energy park with wind power, solar PV and battery storage created by Google Gemini.

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Abstract

This thesis investigates the profitability of building a solar park and battery storage at SR Energy's wind park Örbacken in SE3 and develops an optimal investment model in Excel and Python. Solar park production is calculated in Excel and sent, together with other input, to a Python program that optimizes the electricity flow each hour to maximize yearly revenue. The optimization considers the calendar and cycle aging of the battery. NPV with a discount rate of 5.5% is used to analyze profitability, together with inflation, yearly aging, and reduced revenue from wind. Three sensitivity analyses are carried out on the battery aging cost, revenue, and investment cost.

The results indicate that a solar park is profitable in 2023 but not in 2024, and that battery revenue from energy arbitrage is not sufficient to make battery storage profitable. When the battery cycles were increased by removing the cost of aging, a solar park with larger battery storage was most profitable in 2023, while this was not enough to make any combination profitable in 2024. Doubled battery revenue, representing other revenue streams such as ancillary services, leads to profitability in both 2023 and 2024 for a small battery of size 1-4 MWh. Profitability decreases notably when battery investment cost is doubled, indicating that this has a large impact.

Solar PV is projected to double in SE3 between 2025 and 2029, while Germany has ambitious plans for solar expansion. This is likely to reduce the future profitability of solar power. Battery capacity for energy arbitrage is expected to increase by 50% in the same time period, highlighting the importance of other revenue streams. Reduced costs of solar PV and battery storage in the future and from building next to a wind park could render hybrid parks more profitable. This is not investigated in detail in this thesis, and it is recommended that future work examine this and other financial aspects for a more comprehensive economic evaluation.

Keywords: Hybrid energy park, Wind power, Solar PV, Battery storage, Optimal investment model

Acknowledgments

I would like to thank my examiner David Steen for the help and guidance during this thesis, from which I have gained a lot of knowledge that I bring with me to future work. Thank you also to my supervisor Ludwig Klevtun and Peter Zachrisson at SR Energy for the introduction to the renewable energy industry and the helpful support and guidance along the way.

Johan Söderbergh, Gothenburg, June 2025

Acronyms

AC	Alternating Current
AOI	Angle of Incidence
BESS	Battery Energy Storage System
DC	Direct Current
DHI	Diffuse Horizontal Irradiance
DNI	Direct Normal Irradiance
EOL	End of Life
GHI	Global Horizontal Irradiance
LP	Linear Program
MILP	Mixed-Integer Linear Program
MSEK	Million SEK
NOAA	National Oceanic and Atmospheric Administration
NPV	Net Present Value
POA	Plane of Array
PV	Photovoltaics
PVPMC	PV Performance Modeling Collaborative
SOC	State of Charge
SOE	State of Energy
SvK	Svenska Kraftnät
UN	United Nations

Nomenclature

Indices

t	Index for hour
y	Index for year

Sets

T	Set of hours in one year

Parameters

a_t	Battery age at hour t [days]
A	Active area of the solar panels [m^2]
$\alpha_1, \alpha_2, \beta_1, \beta_2, \gamma_1, \gamma_2$	Calendar aging linearization parameters
albedo	Reflectivity of the ground [unitless]
$C^{\text{bat inv}}$	Initial investment cost of batteries [SEK]
$C^{\text{bat OM}}$	Operational and maintenance cost of batteries per year [SEK]
$C^{\text{PV inv}}$	Initial investment cost of solar park [SEK]
$C^{\text{PV OM}}$	Operational and maintenance cost of solar park per year [SEK]
C^{REP}	Battery replacement cost [SEK]
d	Discount rate [%]
D^{bat}	Annual degradation rate of batteries [%]
D^{PV}	Annual degradation rate of solar park [%]
D^{W}	Annual degradation rate of wind park [%]
DHI_t	Direct horizontal irradiance at hour t [W/m^2]
DNI_t	Direct normal irradiance at hour t [W/m^2]
δ^{PV}	Total solar PV losses [%]
δ_i	Solar PV loss of type i [%]
E_a	Activation energy [J mol^{-1}]
EOL	Retained battery capacity at end-of-life [%]
E^{bat}	Battery capacity [kWh]

E^{PV}	Solar park capacity [kWh]
GHI_t	Global horizontal irradiance at hour t [W/m^2]
G_{max}	Maximum grid export capacity [kWh]
I_t^{b}	Direct irradiance at hour t [W/m^2]
I_t^{d}	Diffuse irradiance at hour t [W/m^2]
I_t^{g}	Reflected irradiance at hour t [W/m^2]
I_t^{POA}	Plane of array irradiance at hour t [W/m^2]
i	Interest rate [%]
$\eta^{\text{AC/DC}}$	AC-to-DC efficiency [%]
η^{bat}	Battery efficiency [%]
$\eta^{\text{DC/AC}}$	DC-to-AC efficiency [%]
η^{PV}	Efficiency of the solar panels [%]
K_t	Battery temperature at hour t [K]
$\mathcal{L}^{\text{bat}}$	Battery lifetime [Years]
M	Big-M constant
$\rho^{\text{g,buy}}$	Grid tariff for buying [SEK/kWh]
$\rho^{\text{g,sell}}$	Grid tariff for selling [SEK/kWh]
ρ_t^{spot}	Electricity pot price at hour t [SEK/kWh]
P_{max}	Maximum charge/discharge power [kW]
π	Annual inflation rate [%]
$r^{\text{DC/AC}}$	DC to AC ratio of solar PV to inverter power
r^{sv}	Ratio of salvage cost to replacement cost
R	Universal gas constant [mol^{-1}]
SOE_{min}	Minimum state of energy [kWh]
SOE_{max}	Maximum state of energy [kWh]
τ	Transmittance of the solar panels [%]
$\theta_{A,t}$	Solar azimuth angle at hour t [°]
$\theta_{A,\text{panels}}$	Azimuth angle of the solar panels [°]
$\theta_{Z,t}$	Solar zenith angle at hour t [°]
θ_T	Tilt angle of the solar panels [°]
W_t	Wind production at hour t [kWh]

Variables

AOI_t	Angle of incidence at hour t [°]
b_t^{buy}	Binary variable for buying electricity at hour t
b_t^{CH}	Binary variable for charging at hour t

b_t^{DS}	Binary variable for discharging at hour t
b_t^{sell}	Binary variable for selling electricity at hour t
C_t^{CAL}	Calendar aging cost at hour t [SEK]
C_t^{CYC}	Cycle aging cost at hour t [SEK]
C_t^{DA}	Grid electricity purchase cost from day-ahead spot market at hour t [SEK]
C_t^{DEG}	Battery degradation cost at hour t [SEK]
$G(\mathrm{SOC}_t)$	Linearized calendar aging function
J_t, K_t, L_t	Binary variables for SOC segments at hour t
K_t^{PV}	Curtailed solar electricity at hour t [kWh]
K_t^{W}	Curtailed wind electricity at hour t [kWh]
$K_t^{\mathrm{W,\ standalone}}$	Curtailed wind electricity of standalone wind park at hour t [kWh]
NPV	Net present value of investment [SEK]
$\mathrm{NPV}^{\mathrm{bat}}$	Net present value of battery [SEK]
P_t^{CH}	Battery charge at hour t [kWh]
P_t^{DS}	Battery discharge to grid at hour t [kWh]
P_t^{G}	Grid electricity bought at hour t [kWh]
P_t^{PV}	Solar electricity sold at hour t [kWh]
P_t^{W}	Wind electricity sold at hour t [kWh]
PV_t	Solar production at hour t [kWh]
R_t^{DA}	Day-ahead spot market revenue at hour t [SEK]
$R_t^{\mathrm{W,\ standalone}}$	Revenue of sold wind electricity of standalone wind park at hour t [SEK]
$\mathrm{R}_y^{\mathrm{bat}}$	Revenues from batteries at year y [SEK]
$\mathrm{R}_y^{\mathrm{PV}}$	Revenues from solar at year y [SEK]
$\mathrm{R}_y^{\mathrm{W,red}}$	Reduced revenue from wind compared to standalone wind park at year y [SEK]
S_t^{PV}	Solar electricity stored at hour t [kWh]
S_t^{W}	Wind electricity stored at hour t [kWh]
SOC_t	State of charge at hour t [%]
SOE_t	State of energy at hour t [kWh]
$\mathcal{U}_t^{\mathrm{CAL}}$	Calendar aging at hour t [%]
$\mathcal{U}_t^{\mathrm{CYC}}$	Cycle aging at hour t [%]
X_t, Y_t, Z_t	Continuous variables for linearizing aging function at hour t

Contents

1. Introduction

Recent years have seen a surge in the popularity of solar power and battery storage. It took nearly 70 years for global solar power capacity to reach the first terawatt, but only two more to reach the second [1]. Solar power is becoming an important part of the green energy transition and is growing rapidly worldwide. In Sweden alone, the capacity have increased tenfold in the last seven years [2]. Battery storage has also seen a significant rise in popularity in Sweden, driven by high prices in ancillary service markets [3]. In 2024, battery storage capacity increase by 400% [4]. This lead to the ancillary service market becoming saturated in 2024, and battery revenue from energy arbitrage is now expected to account for a larger portion of the total revenue [3]. A combination of wind, solar and battery storage in a hybrid energy park may increase the profitability of solar power and battery storage, compared to building stand alone units. Solar power, for example, can benefit from battery storage due to the volatile prices between when the sun is shining during the day and the darker night. A combination of these may also reduce infrastructural costs and provide other benefits to the park owner and electricity system.

1.1 Background

SR Energy is the largest wind power producer in Sweden, with the majority of their wind park capacity located in south of Sweden [5]. The company own and operate around 200 wind power plants and have a yearly electricity production of two terawatt hours. Recently, SR Energy have began planning a solar power park near one of their existing wind parks [6]. At the same time, battery storage became more interesting with the high revenue potentials from the ancillary service markets. But are battery storage still as lucrative with this market becoming saturated? And has the large increase in solar power capacity in Sweden in recent years lead to a solar park being a less viable option? This report will answer these questions with analyses on solar power and battery storage in Sweden, together with modeling of a solar park and battery storage next to SR Energy's wind park Örbacken.

In order to model battery storage, several articles written by my examiner David Steen and his colleagues at the Division of Electric Power Engineering at Chalmers have been used as foundation. [7] explore the optimal charging and discharging scheduling of electric vehicle batteries. The article develops a mixed-integer linear programming (MILP) model and utilizes binary variables to prevent simultaneous charging and discharging. It also considers the state of charge (SOC), the minimum and maximum SOC and the battery degradation to optimize revenue over one year. [8] and [9] expand on the model but focus on a battery energy storage system (BESS). The latter develops the equations on battery degradation and is the main foundation that this work is built upon.

The modeling of solar power is based on the information provided by Sandia National Laboratories and the PV Performance Modeling Collaborative (PVPMC) [10]. This is a collaborative group of solar photovoltaics (PV) professionals with an interest in improving the accuracy and technical depth of PV performance models and analyses. These models can be used to evaluate future value of solar PV projects and influence how these are perceived by the financial community in terms of investment risk [10].

1.2 Aim and Research questions

The aim of this master's thesis is to investigate the profitability of building a hybrid energy park at SR Energy's wind park Örbacken and to design an optimal investment model. To achieve the aim, this thesis tries to answer the following research questions:

- Is building a solar park and/or battery storage at an existing wind park profitable in SE3?
- How has profitability changed in recent years?
- How could the profitability develop in the future?

1.3 Limitations

This project is limited to modeling SR Energy's wind park Örbacken since this work is done in collaboration with SR Energy, and the company is interested in building a solar park and batteries here. The investment in capacity of solar PV and batteries will be in line with SR Energy's possibilities and preferences. The work is limited to Sweden, more specifically price area SE3 as this is where Örbacken is located. SE4 will also be covered due to its relevance for the analysis on solar power, but are not considered in the modeling or economic calculations. In regards to temporal limitations, only 2018-2021 and 2023-2024 will be modeled in this work. The reason for this is time constraints and unusually high electricity prices in 2022.

This thesis will not go into detail on simulation of wind production since SR Energy can provide historical data for the wind production from Örbacken. The focus will mostly be on the simulation of solar power and batteries, on which this work will go into further detail on how to calculate the production from solar PV as well as develop an optimal charging and discharging model for batteries. The wind park is also assumed to be able to operate over the life time of the solar park and batteries.

In regards to the calculations of the electricity output from the solar park, the details on the equations for the irradiance on the solar panels and more advanced calculations on the hourly zenith and azimuth angles of the Sun will not be covered due to this being considered irrelevant for the aim of this thesis and time constraints. The efficiency, transmittance and losses of the solar panels are assumed to be the same for each hour of the year for simplicity.

The battery model in this work only considers revenue from energy arbitrage. Other revenue streams from batteries will be discussed briefly and modeled in a sensitivity analysis, but due to time constraint are not included in the model. Battery aging is modeled, but a reduction in battery capacity each hour as a consequence of the battery degradation is not accounted for in the modeling. This is however considered when evaluating the profitability with the net present value.

Transformer and cable losses are not considered in this work. The reasons being time constraints and that the wind production data from SR Energy is measured after the transformer conversion. This report will also not go into detail on direct current (DC) to alternating current (AC) and AC to DC conversion. Only their efficiencies will be included in the calculations. The investment cost of the power conversion units are assumed to be included in the solar park and battery investment costs. The efficiencies are assumed to be constant throughout their lifetime and their operational costs are assumed to be included in the operational costs of the solar park and battery storage.

Finally, the reduced cost of building a hybrid park compared to building stand alone is not investigated in detail in this work as this data was difficult to find. The economic calculations in this work are simplified by modeling one year and calculating future cash flows based on that year. This was done due to time constraints and limits in the author's knowledge.

2. Theory

This section cover relevant theory regarding Örbacken wind park, solar power, battery storage, hybrid energy parks, optimization modeling and economic evaluation. The reader is presumed to have basic knowledge about the Swedish electricity system, renewable energy, energy systems modeling and economic concepts.

2.1 Wind park Örbacken

The wind park investigated in this work is Örbacken, owned by SR Energy and located south of Mjölby in electricity price area SE3 [11]. The park consist of 11 wind turbines that amounts to a total capacity of 30.25 MW. Figure 2.1 shows the location of Örbacken, while Figure 2.2 shows a picture of the park [11].

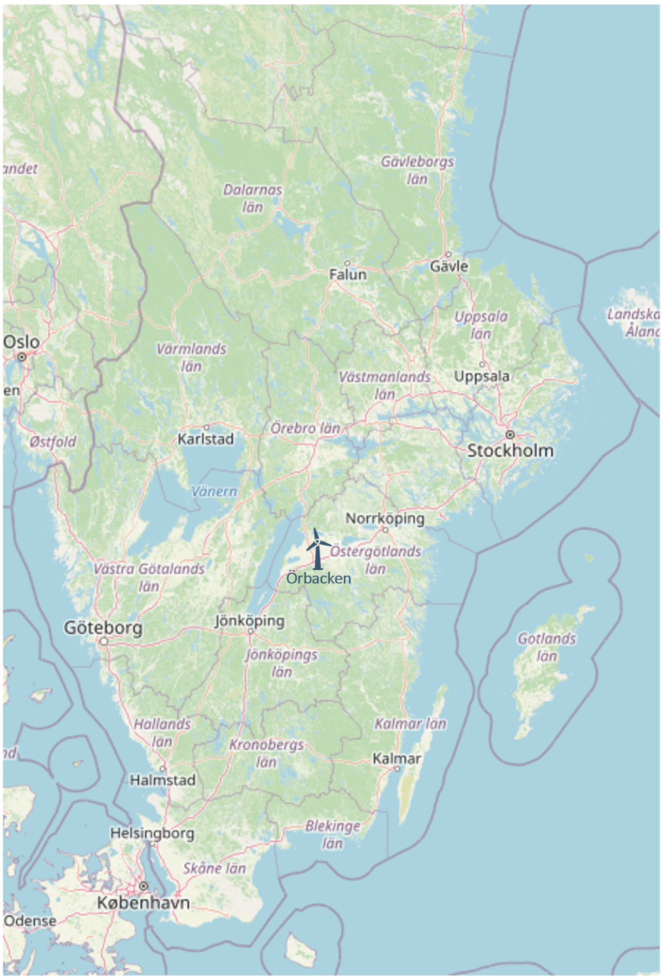


Figure 2.1: The location of SR Energy's wind park Örbacken [11] [12].

Figure 2.2: SR Energy's wind park Örbacken [11].

2.2 Solar power

The solar park that is modeled in this work is assumed to be located in Kolstad, north east of Örbacken wind park [6].

2.2.1 Solar irradiance in southern Sweden

Solar irradiance measures the instantaneous solar power over an area in watts per square meter [10]. There are three types of solar irradiance types that are relevant for calculating the output of solar PVs: direct normal irradiance (DNI), diffuse horizontal irradiance (DHI) and global horizontal irradiance (GHI) [10]. DNI is the uninterrupted irradiance on an area normal to the sun, DHI is the solar irradiance scattered in the atmosphere by e.g. clouds and dust on a horizontal plane, and GHI is the total irradiance on a horizontal surface [10]. DNI, DHI and GHI irradiance determines the electricity output in kWh from the solar park. Maps displaying the DNI and GHI in southern Sweden can be found on the Solargis website at [13]. For simplicity, only the map displaying the potential of solar PV in southern Sweden have been extracted and is shown in Figure 2.3. The figure displays that the solar PV potential at Örbacken is in the mid to high range of the scale. In contrast, Gotland, Öland and the south and southeast of Sweden has the highest potential, approximately 5-10% higher than at Örbacken.

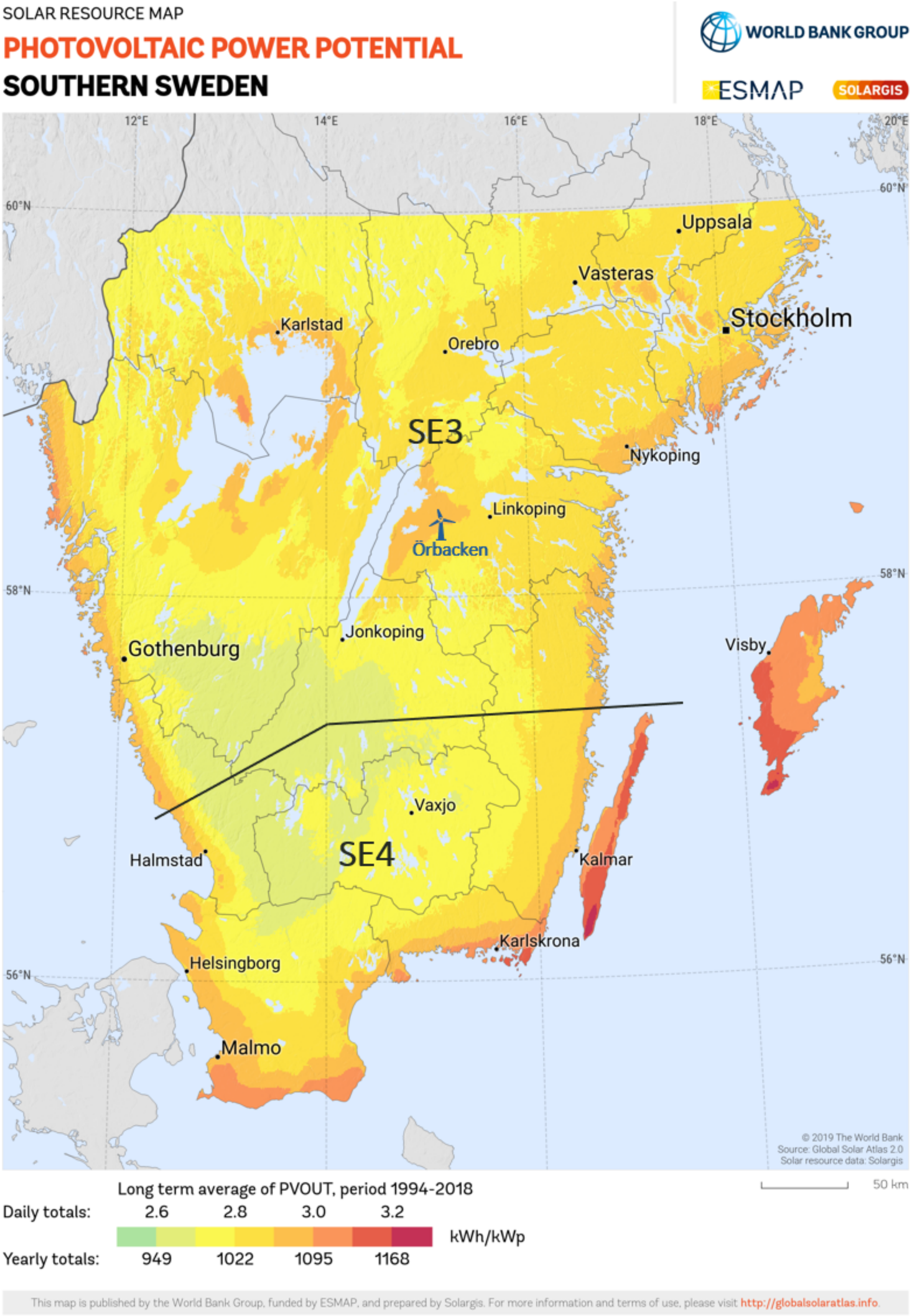


Figure 2.3: The potential of solar PV power production in kWh per kW in southern Sweden, extracted from Solargis website at [13] (Solar resource map © 2021 Solargis). The figure also displays the location of Örbacken wind park [11] and electricity price areas SE3 and SE4 [14].

2.2.2 Historical and future development of solar power

Solar power installations has increased almost exponentially in Sweden over the last years and was almost 5 GW in 2024 [2]. This can be seen in Figure 2.4, which shows the installed solar power capacity from 2018 to 2024.

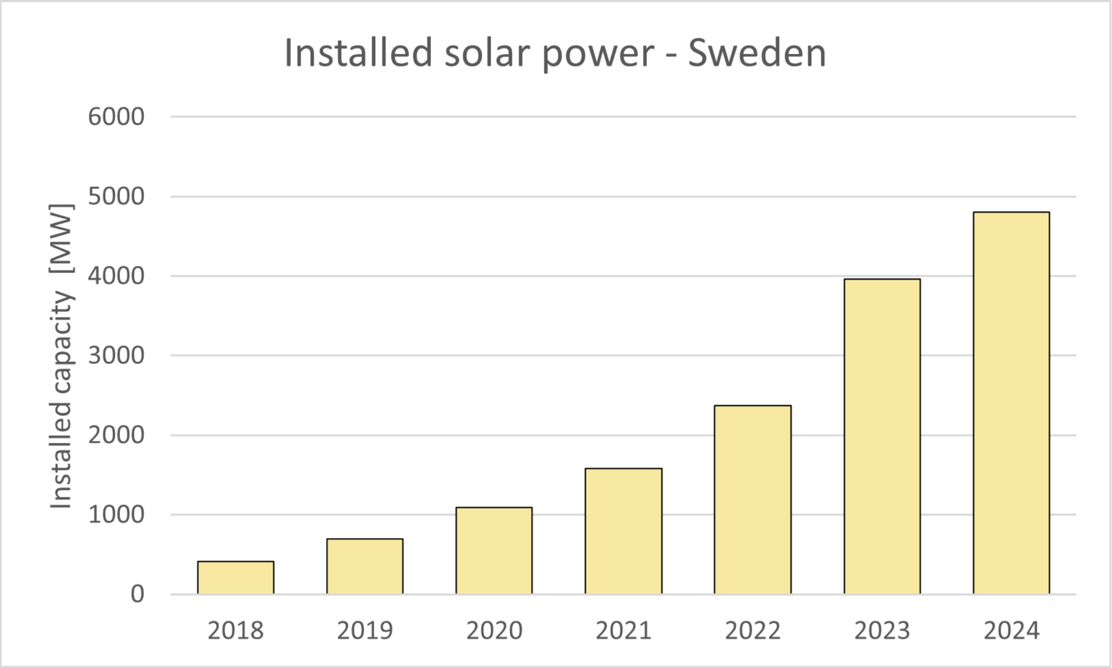


Figure 2.4: Installed solar power capacity in MW in Sweden between 2018 and 2024 [2].

Concerning the future of solar power, Svenska Kraftnät (SvK) has projected an increase by approximately 1500 MW per year from 2025 to 2029, with around 95% estimated to be located in SE3 and SE4 [15]. The projections of installed solar power capacities for SE3 can be seen in Figure 2.5, which shows that the solar power capacity is projected to almost double from 2025 to 2029.

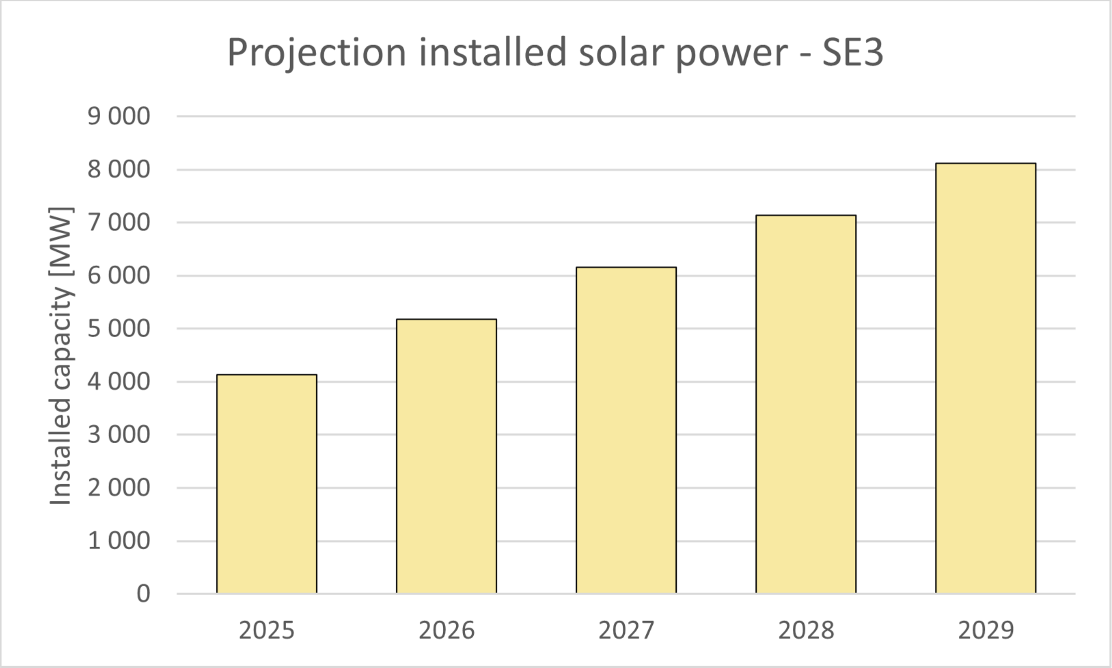


Figure 2.5: Projection of installed solar power capacity in MW in SE3 between 2025 and 2029 [15].

2.3 Battery storage

The batteries modeled in this work is assumed to be located next to Örbacken and the modeled solar park. The model include battery aging (calendar and cycle aging) and energy arbitrary (the shifting of load from hours with lower electricity prices to hours with higher). The modeling is based upon the work by my examiner David Steen and his colleagues at the Division of Electric Power Engineering at Chalmers, specifically on their articles [7], [8] and [9].

2.3.1 Calendar and cycle aging

The aging of the battery is modeled in this work, specifically the calendar and cycle aging. These are two common metrics of battery aging. Calendar aging occurs continuously throughout the battery's lifetime and depends on the energy content, temperature and age of the battery [7]. Cycle aging instead only occurs when the battery is being charged or discharged. For more details regarding calendar and cycle aging see Chapter 4.3.5.

2.3.2 Revenue streams

Battery storage have several different revenue streams, with the highest share in recent years coming from participation in ancillary services [16]. Batteries have almost exclusively been used for this in the last few years, but as more batteries have been introduced and the market for ancillary services has reached saturation this revenue has decreased [3]. Thus, other revenue streams such as energy arbitrage become more important [16]. However, actors in the market does not deem the revenues from energy arbitrage enough to cover the investment and mention that the uncertainty regarding future revenues makes investing decisions more difficult. At the same time, it is not simple to evaluate the revenue from a battery and the complexity in the modeling also means that the expected returns are often undervalued [17].

The battery market for ancillary services in the UK started to become saturated in 2022 [16]. At that time the energy arbitrage only made up around 9% of the revenue share, while in 2024 this share had increased to approximately 32%. This could give an indication to how the revenue share from energy arbitrary could develop in Sweden, as the country's ancillary service market became saturated in 2024 [3]. Another article states that the energy arbitrage typically make up 20-50% of the revenue and that this is expected to increase to around 60% by 2030 [17].

2.3.3 Future development of batteries

Svenska Kraftnät projects battery storage available for energy arbitrage in Sweden to increase over the next years [15]. Approximately 93% of this capacity is expected to be located in SE3 and SE4. Figure 2.6 shows SvK's forecast of available battery capacity for energy arbitrary in SE3 from 2025 to 2029, displaying an increase by around 50%.

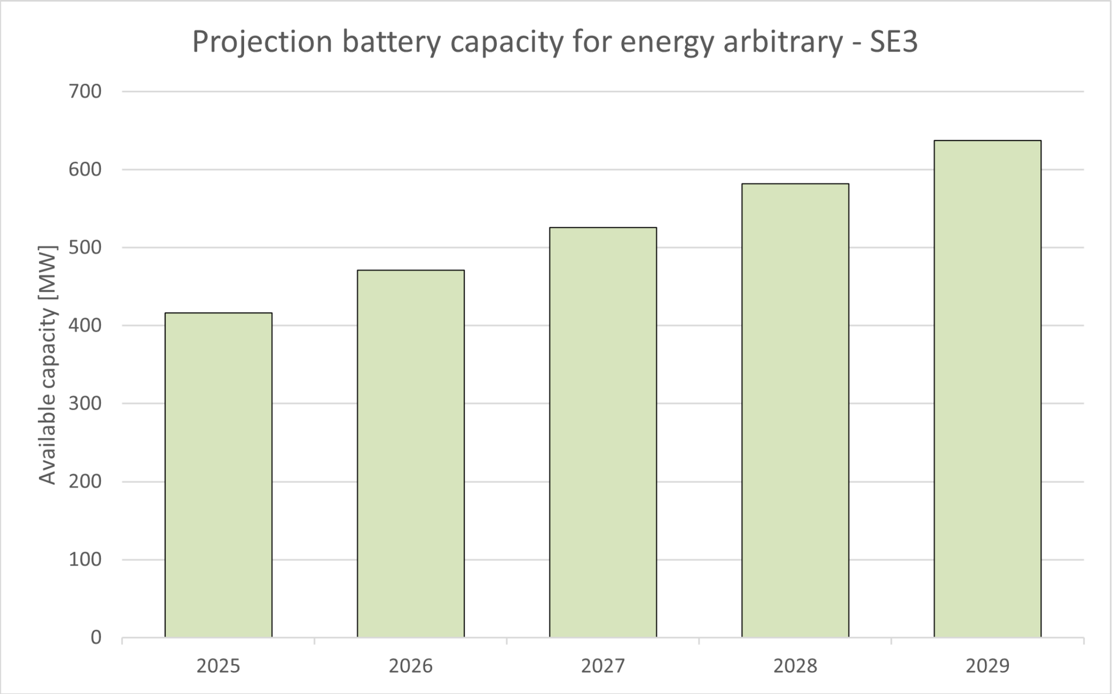


Figure 2.6: Projection of available battery capacity for energy arbitrary in SE3 between 2025 and 2029 [15].

2.4 Hybrid energy park

The hybrid energy park modeled in this work consist of Örbacken wind park together with the modeled solar park and battery storage.

2.4.1 Wind and solar power complement each other well

Wind and solar electricity production complement each other well since solar power produce more during warm and sunny periods, while wind power is more productive in colder times when the winds are stronger [18]. This is also the case throughout the year, with solar PV producing more during the summer time and wind power having a higher production in the colder winter months with more wind. The combination of the two renewable energy sources, compared to only using for instance wind, means that the electricity production output will be higher and more balanced [19].

2.4.2 Infrastructural savings

Infrastructural savings can be achieved by combining solar and wind power in one area. Estimates from SR Energy gives an approximate cost of building a solar park next to Örbacken to around 5100 SEK/kW for 20 MW and 5300 SEK/kW for 40 MW in 2021 [20].

A study from 2024 investigated co-location of a solar park with and without batteries to an existing wind farm [21]. The article’s implied percentage savings on the investment costs are presented in Table 2.1.

Table 2.1: Savings on investment costs from co-locating solar PV and battery storage to an existing wind park compared to building standalone units [21].

Technology	Investment cost savings [%]
Solar PV	9.1%
Battery storage	20.05%
Solar PV and battery storage	6.30%

2.5 Electricity price

The electricity price Sweden have seen a reduction over the last years. This is shown in Figure 2.7, which shows the monthly average spot price of electricity in SE3 between 2018 and 2024 [22]. The figure displays a more smooth price curve from 2018-2021, significantly higher prices in 2022 and lower but more volatile prices in 2023 and 2024. August 2024 had particularly low prices with a monthly average of 85 SEK/MWh.

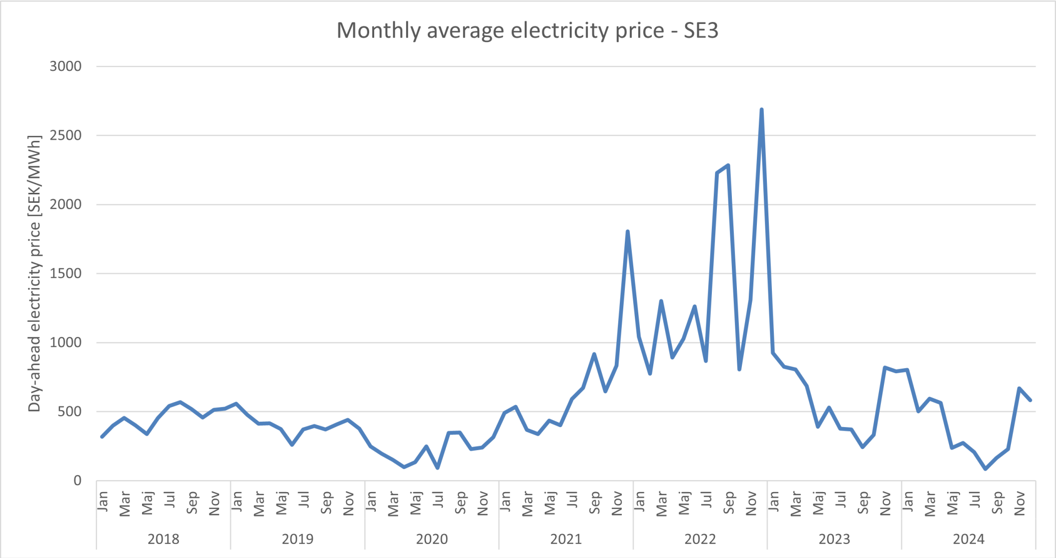


Figure 2.7: Monthly average day-ahead spot price of electricity in SE3 between 2018 and 2024 [22].

In regards to the future, Energimyndigheten predicts the average electricity price in Sweden will increase. Figure 2.8 displays the average electricity price from four forecast scenarios investigated by Energimyndigheten and shows an increase from approximately 330 to 550 SEK/MWh between 2025 and 2060 [23]. Energimyndigheten state that this increase is due to a rise in electricity consumption and that the price needs to be high enough to incentivize new investments. The rise in consumption leads to an increased need for electricity production with higher marginal cost, which leads to higher electricity prices [23].

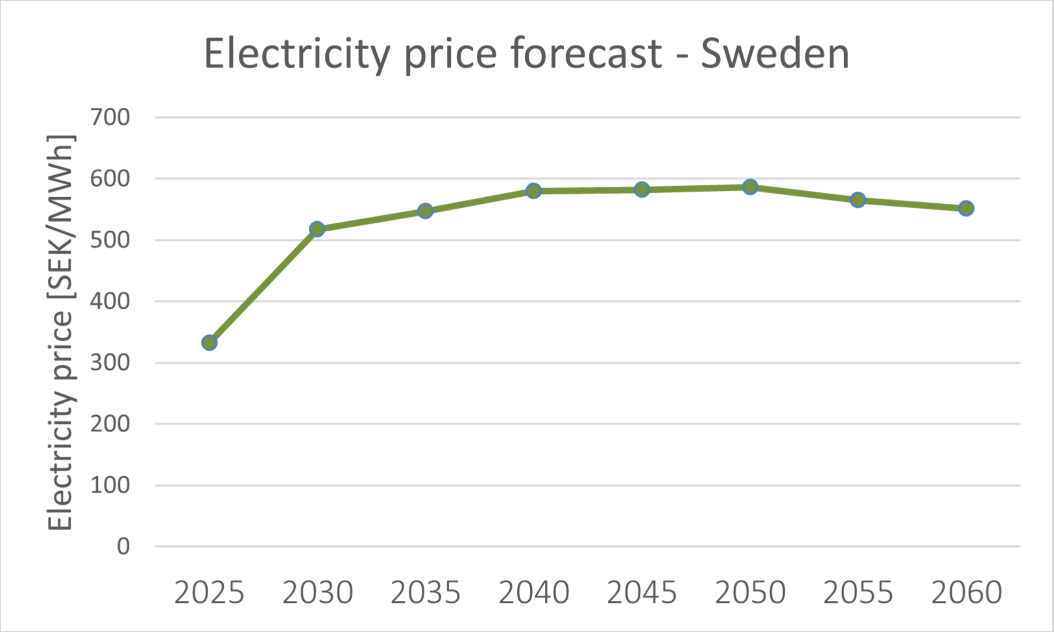


Figure 2.8: Forecast of electricity price in Sweden using the average electricity price from four different scenarios presented in Energimyndigheten's report [23]. The figure shows the projected average spot price in the whole of Sweden from 2025 to 2060.

Another aspect to mention is the ambitious plans of solar expansion in Germany, which is expected to result in an export of electricity from Germany and reduced electricity prices during summer days [23]. This correlates with SvK's forecast, which predicts the yearly average electricity price in SE4 to decrease from around 630 to 485 SEK/MWh [15] [24]. The average price in SE3 is projected to increase slightly from 420 to 460 SEK/MWh in the same time period, while the price in SE1 and SE2 is predicted to almost double.

SvK also simulated the average weekly electricity price in the four price areas in 2025, 2026 and 2029. The results indicate that the summer price levels in SE3 in 2029 are expected to be slightly higher compared to those in 2024 [15], with an estimated average of approximately 220 SEK/MWh.

2.6 Electric power conversion

Electric power conversion is the transfer of electricity from one form to another [25]. These forms include AC and DC. For this thesis there are two types of power conversions that are relevant: AC to DC and DC to AC conversion.

Wind turbines generate AC electricity which goes through AC/AC conversion in a transformers before being sold to the grid [25]. Solar PV instead generate DC electricity that needs to be converted to AC before being sold to the grid. When combining solar with batteries there are two main system options: AC or DC coupling [26]. AC coupling means that the electricity generated from solar PV is converted to AC before either being sold to the grid or converted to DC again for storage. DC coupling is when solar electricity directly charges the battery without conversion to AC first [26]. AC coupling has historically been the most common for solar parks and has the advantage of being able to charge from both solar PV and the grid simultaneously. The disadvantage of AC coupling is that the stored solar electricity is converted three times, reducing overall efficiency [26].

2.7 Optimization model

The optimization model solved in this work is a mixed-integer linear program (MILP), which is a linear program (LP) that also uses integer variables [27]. The use of binary variables in the optimization model makes this a MILP instead of a LP problem.

Python, the library `linopy` [28] and the solver Gurobi [29] are used to solve the optimization model. `linopy` is an open-source Python package that solves optimization problems with a speedup of times 4-6 and a memory reduction of 50% compared to the commonly used Pyomo package [28]. Gurobi is a solver for optimization problems [29]. For an open-source alternative to Gurobi, the package HiGHS [30] can be used.

3. System design

An overall schematic of the hybrid park is shown in Figure 3.1. The figure displays the wind and solar park, battery storage, power converting units, power station, electricity grid and the flow of DC and AC electricity (represented by the red and blue arrows respectively). The figure shows that electricity from wind is either curtailed or sent to the power station where it is sold or stored in the battery. Electricity generated from the solar park is also either curtailed or converted from DC to AC before being sold or stored. The figure also shows the battery and the bidirectional inverter that both converts stored wind and solar electricity to DC, and discharged electricity from the battery to AC [31].

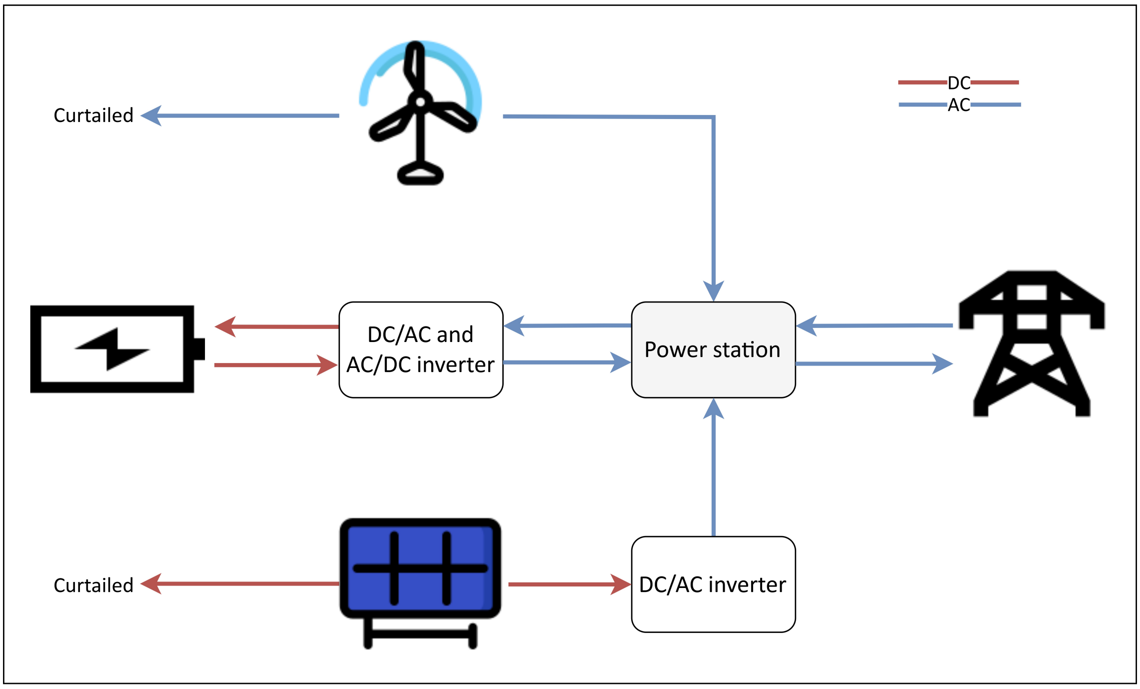


Figure 3.1: A simple overview of the hybrid park, which includes the wind and solar park, the battery and the power conversions from DC to AC and AC to DC. The red and blue arrows represent the flow of DC and AC electricity.

The system is AC coupled since this has the advantage of being able to charge from wind, solar and the grid. This is useful during times when wind and solar are not generating electricity and the electricity price is low or negative.

4. Method

This chapter covers the methodology of this work as well as the calculations. A simple model with existing wind and solar data was first created in Excel, which was thereafter expanded with more advanced solar park calculations. To include batteries in the model, a MILP optimization program was created in Python. Wind and calculated solar production was extracted from Excel to Python were the program maximized the revenue over one year. Finally, calculations on the net present value (NPV) were made to asses the profitability of different solar and battery capacities.

4.1 Wind park calculations

Calculations on the hourly revenue from the standalone wind park Örbacken without solar and batteries were done in Excel. These calculations were necessary for future profitability evaluation with NPV. The price obtained per kWh of sold electricity were the spot price subtracted by the grid tariff for selling. If the wind power production was larger than the grid limit, or the price of selling was negative, wind electricity were curtailed according to Equation 2. The data for the hourly wind power production and the grid tariff of selling from Örbacken were given by SR Energy and the hourly spot price was extracted from Entsoe [32].

$$R_t^{\text{W, standalone}} = \left(\rho_t^{\text{spot}} - \rho^{\text{g,sell}}\right) \cdot W_t - K_t^{\text{W,standalone}} \tag{1}$$

$$K_t^{\text{W, standalone}} = \begin{cases} \max\left(0, W_t - G_{\max}\right), & \rho_t^{\text{spot}} - \rho^{\text{g,sell}} \geq 0, \\ W_t, & \text{otherwise} \end{cases} \tag{2}$$

where:

t = Index for hour

$R_t^{\text{W, standalone}}$ = Revenue of sold wind electricity of standalone wind park at hour t [SEK]

ρ_t^{spot} = Spot price at hour t [SEK/kWh]

$\rho^{\text{g,sell}}$ = Grid tariff for selling [SEK/kWh]

W_t = Wind production at hour t [kWh]

$K_t^{\text{W, standalone}}$ = Curtailed wind electricity of standalone wind park at hour t [kWh]

$G_{\max}$ = Maximum grid export capacity [kWh]

4.2 Solar park calculations

The calculations for the solar park were made in Excel and the resulting solar output was sent to the optimization program in Python.

4.2.1 Solar electricity production

The DC electricity production from the solar park was calculated for every hour in Excel. The total plane of array (POA) irradiance was multiplied with the total active area (the area that can produce electricity [10]), efficiency, transmittance and losses of the solar panels. The transmittance is the fraction of solar radiation that passes through the panels and is converted into electricity [33].

$$P_t^{\mathrm{PV}} = \frac{I_t^{\mathrm{POA}} \cdot A \cdot \eta^{\mathrm{PV}} \cdot \tau \cdot (1 - \delta^{\mathrm{PV}})}{1000}, \quad \forall t \tag{3}$$

$$P_t^{\mathrm{PV}} = I_t^{\mathrm{POA}} \cdot A \cdot \eta^{\mathrm{PV}} \cdot \tau \cdot (1 - \delta^{\mathrm{PV}}) \quad \forall t \tag{4}$$

where:

P_t^{PV} = DC electricity production from the solar park [kWh]
I_t^{POA} = Plane of array irradiance [W/m^2]
A = Active area of the solar panels [m^2]
η^{PV} = Efficiency of the solar panels [%]
τ = Transmittance of the solar panels [%]
δ^{PV} = Total solar PV losses [%]

Table 4.1: Solar PV parameters.

Parameter	Value
η^{PV}	21.5% [34]
τ	90% [33]

4.2.2 Plane of array irradiance

Plane of array irradiance is the total amount of DNI, DHI and GHI irradiance on the surface of a solar panel [10]. Data for DNI, DHI and GHI was extracted from STRÅNG, a model for solar radiation by SMHI [35]. The values for albedo was set to 0.2 for all hours of the year [36]. The angle of incidence (AOI) is the angle between the Sun's rays and the solar panel, and was used to calculate the POA direct normal irradiation [10]. The tilt angle of the solar panels was set to 42° and azimuth angle to 180° [37]. For more details on these calculations the reader is referred to Sandia National Laboratories [10].

$$I_t^{\mathrm{POA}} = I_t^{\mathrm{b}} + I_t^{\mathrm{d}} + I_t^{\mathrm{g}} \tag{5}$$

$$I_t^{\mathrm{b}} = \mathrm{DNI}_t \cdot \cos(\mathrm{AOI}_t) \tag{6}$$

$$I_t^{\mathrm{d}} = \mathrm{DHI}_t \cdot \frac{1 - \cos(\theta_T)}{2} + \mathrm{GHI}_t \cdot \frac{(0.012 \cdot \theta_{Z,t} - 0.04) \cdot (1 - \cos(\theta_T))}{2} \tag{7}$$

$$I_t^{\mathrm{g}} = \mathrm{GHI}_t \cdot \mathrm{albedo} \cdot \frac{1 - \cos(\theta_T)}{2} \tag{8}$$

$$\mathrm{AOI}_t = \cos^{-1}\left[\cos(\theta_{Z,t})\cos(\theta_T) + \sin(\theta_{Z,t})\sin(\sin(\theta_T))\cos(\theta_{A,t} - \theta_{A,\mathrm{panels}})\right] \tag{9}$$

where:

albedo = Reflectivity of the ground [unitless]
I_t^{b} = Direct irradiance [W/m^2]
I_t^{d} = Diffuse irradiance [W/m^2]
I_t^{g} = Reflected irradiance [W/m^2]
DNI_t = Direct normal irradiance [W/m^2]
DHI_t = Direct horizontal irradiance [W/m^2]
GHI_t = Global horizontal irradiance [W/m^2]
$\theta_{Z,t}$ = Solar zenith angle [°]
$\theta_{A,t}$ = Solar azimuth angle [°]
θ_T = Tilt angle of the solar panels [°]
$\theta_{A,\mathrm{panels}}$ = Azimuth angle of the solar panels [°]

The solar zenith and azimuth angles used in Equation 9 were calculated using an Excel spreadsheet from NOAA [38], where the coordinates for Örbacken wind park and the year simulated were entered, and the solar zenith and azimuth angles were given for each hour. The specifics of these calculations are outside of this report's scope and the reader is referred to the Excel sheet at NOAA for more details.

4.2.3 Solar PV losses

To calculate the total solar PV losses Equation 10 and the losses in Table 4.2 was used [36]. Default values for the losses was selected and was assumed to be the same for each hour of the year.

$$\delta^{\mathrm{PV}} = 100 \cdot \left[1 - \prod_i \left(1 - \frac{\delta_i}{100}\right)\right] \tag{10}$$

where:

δ_i = Loss of type i [%]

Table 4.2: Losses from solar PV.

Type of loss (δ_i)	Default value [36]
Soiling	2%
Shading	3%
Snow	0%
Mismatch	2%
Wiring	2%
Connections	0.5%
Light-induced degradation	1.5%
Nameplate rating	1%
Age	0%
Availability	3%
Total losses	14.08%

4.3 Optimization model

An optimization model was made in Python, using the package `linopy` [28] and the solver Gurobi [29]. The model was a mixed-integer linear program and maximized revenue from day-ahead spot market over one year from the hybrid park, while also taking into account the aging cost of the battery and the cost of buying electricity for storing.

4.3.1 Objective function

The model maximizes net revenue over one year [9]:

$$\max \sum_{t \in T} \left(R_t^{\mathrm{DA}} - C_t^{\mathrm{DA}} - C_t^{\mathrm{DEG}} \right) \tag{11}$$

where:

T = Set of hours in one year
R_t^{DA} = Day-ahead spot market revenue at hour t [SEK]
C_t^{DA} = Grid electricity purchase cost from day-ahead spot market at hour t [SEK]
C_t^{DEG} = Battery degradation cost at hour t [SEK]

The day-ahead spot market revenue is the revenue from sold wind and solar electricity and discharged AC electricity from the battery. The cost of the day-ahead market comes from the bought electricity from the grid that is stored in the battery, while the cost of battery degradation is the sum of the calendar and cycle aging cost of the battery [9]. The grid tariff for buying electricity was given by SR Energy [39].

$$R_t^{\mathrm{DA}} = \left(\rho_t^{\mathrm{spot}} - \rho^{\mathrm{g,sell}} \right) \cdot \left(P_t^{\mathrm{W}} + P_t^{\mathrm{PV}} + P_t^{\mathrm{DS}} \cdot \eta^{\mathrm{bat}} \cdot \eta^{\mathrm{DC/AC}} \right) \tag{12}$$

$$C_t^{\mathrm{DA}} = \left(\rho_t^{\mathrm{spot}} + \rho^{\mathrm{g,buy}} \right) \cdot P_t^{\mathrm{G}} \tag{13}$$

$$C_t^{\mathrm{DEG}} = C_t^{\mathrm{CAL}} + C_t^{\mathrm{CYC}} \tag{14}$$

where:

$\rho^{\mathrm{g,buy}}$ = Grid tariff for buying [SEK/kWh]
η^{bat} = Battery efficiency [%]
$\eta^{\mathrm{DC/AC}}$ = DC-to-AC efficiency [%]
P_t^{W} = Wind electricity sold at hour t [kWh]
P_t^{PV} = Solar electricity sold at hour t [kWh]
P_t^{DS} = Battery discharge to grid at hour t [kWh]
P_t^{G} = Grid electricity bought at hour t [kWh]
C_t^{CAL} = Calendar aging cost at hour t [SEK]
C_t^{CYC} = Cycle aging cost at hour t [SEK]

Table 4.3: Battery and power conversion efficiencies.

Parameters	Values
η^{bat}	95% [40]
$\eta^{\text{DC/AC}}$	97 % [41]
$\eta^{\text{AC/DC}}$	97% [42]

4.3.2 Hybrid park constraints

Wind and solar production was allocated to sold, stored, and curtailed electricity. Solar production was converted into AC since solar electricity is converted from DC to AC before either being sold or stored. Curtailed solar electricity thereby represent the amount that could have been sold, not the actual amount of DC electricity that is curtailed. The sold and stored solar electricity was limited by the capacity of the DC/AC inverter. The difference between the solar park capacity and DC/AC inverter capacity is also known as the DC to AC ratio, which was set to 1.2 [43]. Solar PV seldom produce at full capacity, which means that a smaller inverter capacity compared to solar park capacity is preferred as the inverter then can run at higher efficiencies while also having a lower investment cost [44].

$$W_t = P_t^{\text{W}} + S_t^{\text{W}} + K_t^{\text{W}}, \quad \forall t \tag{15}$$

$$\text{PV}_t \cdot \eta^{\text{DC/AC}} = P_t^{\text{PV}} + S_t^{\text{PV}} + K_t^{\text{PV}}, \quad \forall t \tag{16}$$

$$P_t^{\text{PV}} + S_t^{\text{PV}} \leq \frac{E^{\text{PV}}}{r^{\text{DC/AC}}} \tag{17}$$

where:

PV_t = Solar production at hour t [kWh]
S_t^{W} = Wind electricity stored at hour t [kWh]
S_t^{PV} = Solar electricity stored at hour t [kWh]
K_t^{W} = Curtailed wind electricity at hour t [kWh]
K_t^{PV} = Curtailed solar electricity at hour t [kWh]
E^{PV} = Solar park capacity [kWh]
$r^{\text{DC/AC}}$ = DC to AC ratio of solar PV to inverter capacity

4.3.3 Grid constraints

The amount of electricity that can be sold to the grid each hour was limited to the grid limit of Örbacken. This electricity includes the sold wind and solar electricity and the discharged AC electricity from the battery. The model also included the possibility for the hybrid park to buy electricity from the grid to the battery. This amount was limited by the maximum charging capacity of the battery divided by the AC to DC efficiency. To ensure that electricity cannot be sold and bought simultaneously, binary variables for selling to and buying from the grid were included.

$$P_t^{\text{W}} + P_t^{\text{PV}} + P_t^{\text{DS}} \cdot \eta^{\text{bat}} \cdot \eta^{\text{DC/AC}} \leq G_{\text{max}} \cdot b_t^{\text{sell}}, \quad \forall t \tag{18}$$

$$P_t^{\mathrm{G}} \leq \frac{P_{\max}}{\eta^{\mathrm{AC/DC}}} \cdot b_t^{\mathrm{buy}}, \quad \forall t \tag{19}$$

$$b_t^{\mathrm{sell}} + b_t^{\mathrm{buy}} \leq 1, \quad \forall t \tag{20}$$

where:

$P_{\max}$ = Maximum charge/discharge power [kW]
b_t^{sell} = Binary variable for selling electricity at hour t
b_t^{buy} = Binary variable for buying electricity at hour t
$\eta^{\mathrm{AC/DC}}$ = AC-to-DC efficiency [%]

4.3.4 Battery constraints

The battery charging is the sum of the stored electricity from wind, solar and the grid times the AC to DC efficiency. The battery efficiency is not accounted for here, as it is included in the state of energy (SOE) constraints [8]. The SOE measures the amount of energy in the battery at each hour, and was initially set to 50% of the battery capacity for simplicity. For all other times the current SOE was measured as the SOE in the previous time step plus the actual amount of charged minus discharged electricity. Since a battery should not fully charge or discharge, the SOE was constrained within the $\mathrm{SOC}_{\min}$ and $\mathrm{SOC}_{\max}$ range, which was set to 10% and 90%. The SOC measures the percentage of stored energy relative to the battery capacity and was required for calculations on battery aging cost. The battery was assumed to have a C rating of 0.5, meaning that it could discharge half its capacity in one hour. Finally, binary variables were used to ensure that charging and discharging cannot occur simultaneously.

$$P_t^{\mathrm{CH}} = \left(S_t^{\mathrm{W}} + S_t^{\mathrm{PV}} + P_t^{\mathrm{G}}\right) \cdot \eta^{\mathrm{AC/DC}}, \quad \forall t \tag{21}$$

$$\mathrm{SOE}_{t=1} = 0.5 \cdot E^{\mathrm{bat}} + \left(P_{t=1}^{\mathrm{CH}} \cdot \eta^{\mathrm{bat}} - \frac{P_{t=1}^{\mathrm{DS}}}{\eta^{\mathrm{bat}}}\right), \quad t = 1 \tag{22}$$

$$\mathrm{SOE}_t = \mathrm{SOE}_{t-1} + \left(P_t^{\mathrm{CH}} \cdot \eta^{\mathrm{bat}} - \frac{P_t^{\mathrm{DS}}}{\eta^{\mathrm{bat}}}\right), \quad \forall t > 1 \tag{23}$$

$$\mathrm{SOE}_{\min} \leq \mathrm{SOE}_t \leq \mathrm{SOE}_{\max}, \quad \forall t \tag{24}$$

$$\mathrm{SOC}_t = \frac{\mathrm{SOE}_t}{E^{\mathrm{bat}}}, \quad \forall t \tag{25}$$

$$P_t^{\mathrm{CH}} \leq P_{\max} \cdot b_t^{\mathrm{CH}}, \quad \forall t \tag{26}$$

$$P_t^{\mathrm{DS}} \leq P_{\max} \cdot b_t^{\mathrm{DS}}, \quad \forall t \tag{27}$$

$$b_t^{\mathrm{CH}} + b_t^{\mathrm{DS}} \leq 1, \quad \forall t \tag{28}$$

where:

P_t^{CH} = Battery charging at hour t [kWh]
$\eta^{\mathrm{AC/DC}}$ = AC-to-DC efficiency [%]
SOE_t = State of energy at hour t [kWh]
SOC_t = State of charge at hour t [%]
$\mathrm{SOC}_{\mathrm{min}}$ = Minimum state of charge [%]
$\mathrm{SOC}_{\mathrm{max}}$ = Maximum state of charge [%]
E^{bat} = Battery capacity [kWh]
b_t^{CH} = Binary variable for charging at hour t
b_t^{DS} = Binary variable for discharging at hour t

4.3.5 Battery degradation

Battery degradation includes calendar and cycle aging. The specifics of aging, aging costs and the derivations of its equations are outside of this report's scope and the reader is referred to [9] for more details.

4.3.5.1 Aging cost

The calendar and cycle aging costs were calculated using the hourly aging values, the battery NPV and the end of life (EOL) percentage of retained capacity [7].

$$\mathrm{NPV}^{\mathrm{bat}} = (1 - r^{\mathrm{sv}})\, C^{\mathrm{REP}} \frac{1}{(1+i)^{\mathcal{L}^{\mathrm{bat}}}} + C^{\mathrm{bat\ OM}} \frac{(1+i)^{\mathcal{L}^{\mathrm{bat}}} - 1}{i(1+i)^{\mathcal{L}^{\mathrm{bat}}}} \tag{29}$$

$$C_t^{\mathrm{CAL}} = \mathrm{NPV}^{\mathrm{bat}} \cdot \frac{\mathcal{U}_t^{\mathrm{CAL}}}{1 - \mathrm{EOL}}, \quad \forall t \tag{30}$$

$$C_t^{\mathrm{CYC}} = \mathrm{NPV}^{\mathrm{bat}} \cdot \frac{\mathcal{U}_t^{\mathrm{CYC}}}{1 - \mathrm{EOL}}, \quad \forall t \tag{31}$$

where:

$\mathrm{NPV}^{\mathrm{bat}}$ = Battery net present value [SEK]
r^{sv} = Ratio of salvage cost to replacement cost
C^{REP} = Battery replacement cost [SEK]
$C^{\mathrm{bat\ OM}}$ = Operation and maintenance cost per year [SEK]
i = Interest rate [%]
$\mathcal{L}^{\mathrm{bat}}$ = Battery lifetime [Years]
EOL = Battery retained capacity at end-of-life [%]
C_t^{CAL} = Cost of cycle aging at hour t [SEK]
C_t^{CYC} = Cost of calendar aging at hour t [SEK]
$\mathcal{U}_t^{\mathrm{CAL}}$ = Calendar aging at hour t [%]
$\mathcal{U}_t^{\mathrm{CYC}}$ = Cycle aging at hour t [%]

Table 4.4: Battery NPV parameters [9].

Parameters	Values	Parameters	Values
r^{sv}	0.5	$\mathcal{L}^{\text{bat}}$	15 years
C^{REP}	1500 SEK/kWh	i	5%
$C^{\text{bat OM}}$	30 SEK/kWh	EOL	80%

Note: C^{REP} and $C^{\text{bat OM}}$ was converted from €/kWh to SEK/kWh. The conversion rate was set to 11 SEK/€, which is close to the conversion rate in March 2025 [24].

4.3.5.2 Calendar aging

Calendar aging depends on SOC, temperature and battery age in days [7]. The temperature in this model was assumed to be constant at 20 °C (293.15 K) for simplicity. $G(\text{SOC}_t)$ is a pre-exponential function that was linearized using piece-wise linearization in Python (see A.1). This function differs within the SOC segments 0-50%, 50-70% and 70-100% [7]. To include this function, binary and continuous variables were used over the three SOC spans [9]. The battery was assumed to be 90 days old at hour 1 to mitigate the elevated calendar aging that occurs at the initial stages of battery usage. The equation for battery aging was retrieved from the code of [7] and differs from the equations in the previous articles on the subject [7] [9] [8]. This is because the calendar aging is calculated for each hour instead of each day (see Appendix A.2 for more details).

$$\mathcal{U}_t^{\text{CAL}} = G(\text{SOC}_t) \cdot e^{\frac{-E_a}{R \cdot K_t}} \cdot 0.5 \cdot 0.042 \cdot \frac{1}{(a_t + 90)^{0.5}}, \quad \forall t \tag{32}$$

$$G(\text{SOC}_t) = \alpha_1 X_t + \alpha_2 J_t + \beta_1 Y_t + \beta_2 K_t + \gamma_1 Z_t + \gamma_2 L_t, \quad \forall t \tag{33}$$

$$0.5K_t - M \cdot J_t + 0.7L_t \leq \text{SOC}_t \leq 0.5J_t + 0.7K_t + M \cdot L_t, \quad \forall t \tag{34}$$

$$0 \leq X_t \leq M \cdot J_t, \quad \forall t \tag{35}$$

$$\text{SOC}_t - M \cdot (1 - J_t) \leq X_t \leq \text{SOC}_t, \quad \forall t \tag{36}$$

$$0 \leq Y_t \leq M \cdot K_t, \quad \forall t \tag{37}$$

$$\text{SOC}_t - M \cdot (1 - K_t) \leq Y_t \leq \text{SOC}_t, \quad \forall t \tag{38}$$

$$0 \leq Z_t \leq M \cdot L_t, \quad \forall t \tag{39}$$

$$\text{SOC}_t - M \cdot (1 - L_t) \leq Z_t \leq \text{SOC}_t, \quad \forall t \tag{40}$$

$$J_t + K_t + L_t = 1, \quad \forall t \tag{41}$$

where:

$G(\text{SOC}_t)$ = Linearized aging function
K_t = Battery temperature at hour t [K]
a_t = Battery age at hour t [days]
$\alpha_1, \alpha_2, \beta_1, \beta_2, \gamma_1, \gamma_2$ = Calendar aging linearization parameters
J_t, K_t, L_t = Binary variables for SOC segments at hour t
X_t, Y_t, Z_t = Continuous variables for linearizing aging function at hour t
M = Big-M constant

Table 4.5: Calendar aging parameters [9].

Parameter	Values	Parameter	Values
E_a	24 500 J mol^{-1}	R	8.314 mol^{-1}
K_t	293.15 K	M	10^6
α_1	34.7	α_2	1224.6
β_1	155.27	β_2	-4803.9
γ_1	34	γ_2	3685

Note: $G(\text{SOC}_t)$ was linearized using piecewise linearization in Python. It was found that the linearized coefficients α_1, β_1, β_2, γ_1 and γ_2 were different from [7] (see Appendix A.1).

4.3.5.3 Cycle aging

Cycle aging depends on the energy charged and discharged. Equation 42 is a linearized version of the original cycle aging equation (see [9] for more details). Charging and discharging was converted from kW to MW to comply with the units in [9].

$$\mathcal{U}_t^{\text{CYC}} = 2.216 \cdot \left(P_t^{\text{CH}} \cdot \eta^{\text{bat}} + \frac{P_t^{\text{DS}}}{\eta^{\text{bat}}} \right) \cdot 10^{-3}, \quad \forall t \tag{42}$$

4.4 Economic calculations

Profitability calculations for the hybrid park are provided here. Since the wind park was already built, these calculations only cover the revenues and costs of the new solar and battery investments. However, since the introduction of solar and batteries may reduce the revenue from the sold wind electricity due to storage or increased curtailment, the calculations were adjusted to account for this. Also, the cost of battery aging was not be included in the economic calculations since this cost was solely used to decide when to charge and discharge in the optimization model.

4.4.1 Revenue

The revenue from solar and batteries were calculated separately. The cost of aging was not included in the battery revenue. The reduced wind revenue was calculated by subtracting the revenue from the standalone wind park with the revenue from sold wind electricity in the hybrid park.

$$\mathrm{R}_y^{\mathrm{PV}} = \sum_{t \in T} \left(\rho_t^{\mathrm{spot}} - \rho^{\mathrm{g,sell}}\right) \cdot P_t^{\mathrm{PV}} \tag{43}$$

$$\mathrm{R}_y^{\mathrm{bat}} = \sum_{t \in T} \left(\rho_t^{\mathrm{spot}} - \rho^{\mathrm{g,sell}}\right) \cdot P_t^{\mathrm{DS}} \cdot \eta^{\mathrm{bat}} \cdot \eta^{\mathrm{DC/AC}} - C_t^{\mathrm{DA}} \tag{44}$$

$$\mathrm{R}_y^{\mathrm{W,red}} = R_t^{\mathrm{W,\ standalone}} - \sum_{t \in T} \left(\rho_t^{\mathrm{spot}} - \rho^{\mathrm{g,sell}}\right) \cdot P_t^{\mathrm{W}} \tag{45}$$

where:

$\mathrm{R}_y^{\mathrm{PV}}$ = Revenues from solar at year y [SEK]
$\mathrm{R}_y^{\mathrm{bat}}$ = Revenues from batteries at year y [SEK]
$\mathrm{R}_y^{\mathrm{W,red}}$ = Reduced revenue from wind compared to standalone wind park at year y [SEK]

4.4.2 Future cash flows

The future cash flows was estimated by adjusting the solar, battery and reduced wind revenue of the modeled year with the degradation rates of wind, solar and batteries over the project lifetime of 30 years [45]. The revenues and operational costs were also adjusted for inflation. Battery degradation was reset to 0% after 15 years since the batteries are replaced. Thus, cash flows for the first 15 years were calculated differently (Equation 46) from the subsequent 15 years (Equation 47).

$$\begin{aligned}\mathrm{CF}_y = &\Big(\Big(\mathrm{R}_y^{\mathrm{PV}} \cdot (1 - \mathrm{D}^{\mathrm{PV}})^{y-Y_0} + \mathrm{R}_y^{\mathrm{bat}} \cdot (1 - \mathrm{D}^{\mathrm{bat}})^{y-Y_0} - \mathrm{R}_y^{\mathrm{W,\ red}} \cdot (1 - \mathrm{D}^{\mathrm{W}})^{y-Y_0}\Big) \\ &- \mathrm{C}_y^{\mathrm{PV\ OM}} + \mathrm{C}_y^{\mathrm{bat\ OM}}\Big) \cdot (1 + \mathrm{i})^{y-Y_0}, \quad \forall y \in [Y_0, Y_0 + 15]\end{aligned} \tag{46}$$

$$\begin{aligned}\mathrm{CF}_y =&\Big(\Big(\mathrm{R}_y^{\mathrm{PV}} \cdot (1-\mathrm{D}^{\mathrm{PV}})^{y-Y_0} + \mathrm{R}_y^{\mathrm{bat}} \cdot (1-\mathrm{D}^{\mathrm{bat}})^{y-(Y_0+15)} - \mathrm{R}_y^{\mathrm{W,\,red}} \cdot (1-\mathrm{D}^{\mathrm{W}})^{y-Y_0}\Big) \\ &- \mathrm{C}_y^{\mathrm{PV\ OM}} + \mathrm{C}_y^{\mathrm{bat\ OM}}\Big) \cdot (1+\mathrm{i})^{y-Y_0}, \quad \forall y \in [Y_0+15, Y_0+30]\end{aligned} \tag{47}$$

where:

CF_y = Future cash flow from solar and batteries at year y [SEK]
Y_0 = Year simulated
D^{PV} = Annual degradation rate of solar park [%]
$\mathrm{D}^{\mathrm{bat}}$ = Annual degradation rate of batteries [%]
D^{W} = Annual degradation rate of wind park [%]
π = Annual inflation rate [%]

Table 4.6: Future cash flow parameters

Parameter	Value
D^{PV}	0.5% [46]
$\mathrm{D}^{\mathrm{bat}}$	1.55% [47]
D^{W}	0.64% [48]
π	1.6% [49]

4.4.3 Net present value

The net present value was calculated by discounting future cash flows to their present value with a discount rate and subtracting the initial investments of solar PV and batteries. Since the battery lifetime is 15 years and the solar park around 30, the initial cost for batteries was assumed to be the investment cost of two batteries. This was done under the assumption that the price increase due to inflation and the reduced future investment cost would somewhat match. It was also assumed that there were no more investment costs other than $\mathrm{C}^{\mathrm{PV\ inv}}$ and $\mathrm{C}^{\mathrm{bat\ inv}}$, such as a new solar inverter after 15 years [45]. The cost of solar PV was extracted from SR Energy's calculations [20], which was quite similar to other sources [21]. The discount rate was assumed to be 5.5% [39]. Note that this NPV is not correlated with the battery NPV in Equation 29, which was only used to calculate the cost of battery aging.

$$\mathrm{NPV} = \sum_{y=Y_0}^{Y_0+30} \frac{\mathrm{CF}_y}{(1+d)^{y-Y_0}} - \left(\mathrm{C}^{\mathrm{PV\ inv}} + \mathrm{C}^{\mathrm{bat\ inv}}\right) \tag{48}$$

where:

NPV = Net present value [SEK]
d = Discount rate [%]
$\mathrm{C}^{\mathrm{PV\ inv}}$ = Solar PV investment cost [SEK]
$\mathrm{C}^{\mathrm{bat\ inv}}$ = Battery investment cost [SEK]

Table 4.7: Solar PV and battery investment costs

Parameter	**Value**
$C^{PV\ inv}$	5200 SEK/kW [39]
$C^{bat\ inv}$	1150 SEK/kWh [50]

4.5 Sensitivity analyses

Three sensitivity analyses was carried out on batteries since batteries were more complex to model than solar PV and less data was available. The first sensitivity analysis set the battery aging cost to 0 in order to investigate the effects of the battery aging cost and asses the impact this has on the profitability. The second doubled the battery revenue to try to represent other revenue streams such as frequency regulation [17]. Finally, a third sensitivity analysis doubled the investment cost of 1150 SEK/kWh [50] to investigate the effects of a more expensive battery, which may be more in line with current Swedish prices.

5. Results

The modeling results are presented in this chapter. The results of only building a solar park next to Örbacken are displayed first, followed by only batteries and lastly solar and batteries combined. The results of building only a solar park or only batteries are shown for 2018-2024, with 2022 not included due to unusually high prices compared to the other years. The results for solar and batteries combined only cover 2023 and 2024 since these years are considered the most relevant.

5.1 Solar park

The NPV values of only building a solar park of different capacities for 2018-2024 (2022 excluded) are shown in Figure 5.1. The figure indicates that a solar park is profitable for years similar to 2018, 2019, 2021 and 2023, with 2019 only resulting in slight profits. The optimal solar park capacity is at around 30-40 MW on average for these years, while for 2020 and 2024 a solar park of any capacity was not profitable.

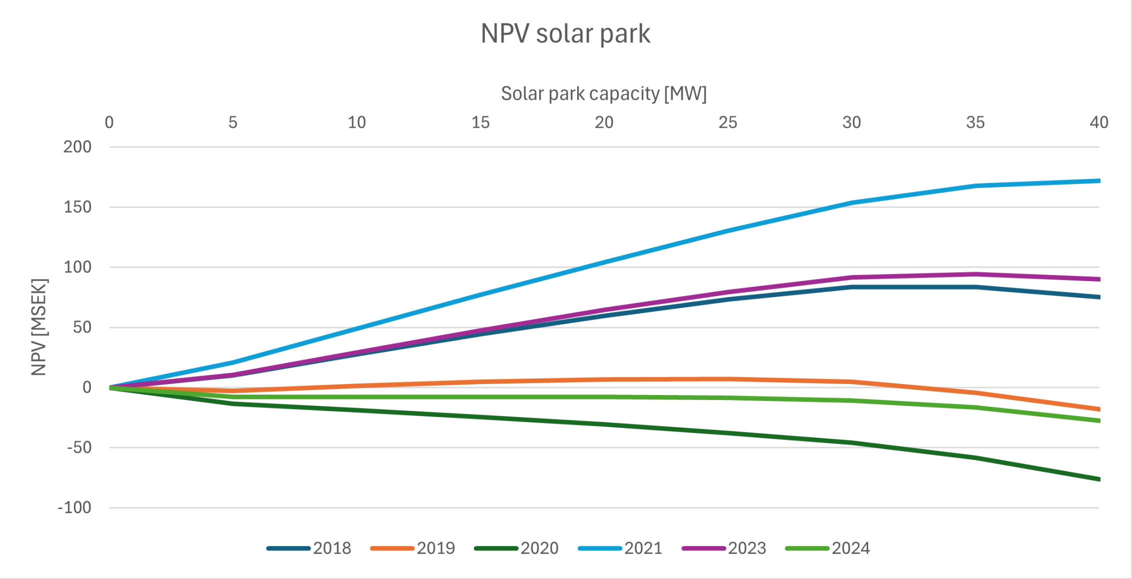


Figure 5.1: Net present value of building different solar park capacities at Örbacken wind park for years 2018-2021 and 2023-2024.

5.2 Battery storage

The NPV values of only building battery storage of different capacities for the same years as above are shown in Figure 5.2. The figure indicates that it is not profitable to build batteries of any capacity at Örbacken when the revenue is only from energy arbitrage.

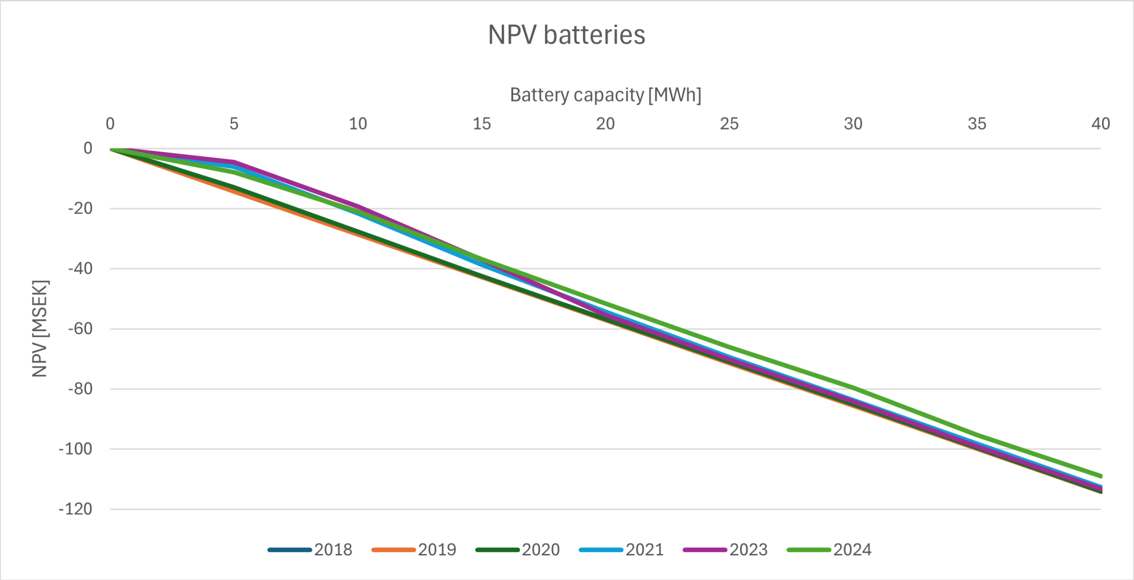
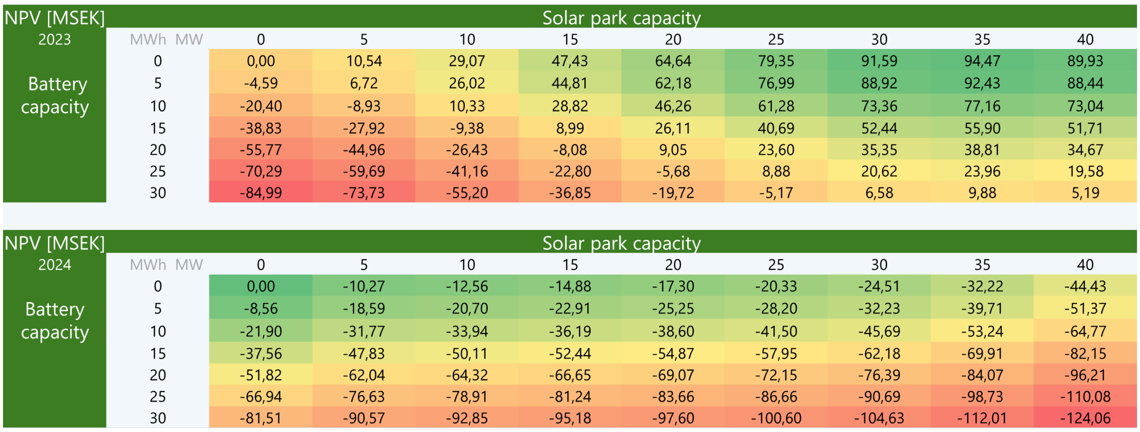


Figure 5.2: Net present value of building different battery capacities at Örbacken wind park for years 2018-2021 and 2023-2024. The revenue is only from energy arbitrage.

5.3 Solar park and battery storage

The NPV values in 2023 and 2024 for solar park capacities between 0-40 MW and battery capacities between 0-30 MWh are shown in Figure 5.3. The figure illustrates only negatives NPV values in 2024 and indicates that none of the combinations are profitable, while in 2023 it was most profitable to build a large solar park with no battery. It appears that a smaller battery between 0-10 MWh is overall more profitable compared to a larger one. Therefore, the results will focus on these smaller capacities moving forward.



NPV [MSEK]		Solar park capacity								
2023	MWh MW	0	5	10	15	20	25	30	35	40
Battery capacity	0	0,00	10,54	29,07	47,43	64,64	79,35	91,59	94,47	89,93
	5	-4,59	6,72	26,02	44,81	62,18	76,99	88,92	92,43	88,44
	10	-20,40	-8,93	10,33	28,82	46,26	61,28	73,36	77,16	73,04
	15	-38,83	-27,92	-9,38	8,99	26,11	40,69	52,44	55,90	51,71
	20	-55,77	-44,96	-26,43	-8,08	9,05	23,60	35,35	38,81	34,67
	25	-70,29	-59,69	-41,16	-22,80	-5,68	8,88	20,62	23,96	19,58
	30	-84,99	-73,73	-55,20	-36,85	-19,72	-5,17	6,58	9,88	5,19

NPV [MSEK]		Solar park capacity								
2024	MWh MW	0	5	10	15	20	25	30	35	40
Battery capacity	0	0,00	-10,27	-12,56	-14,88	-17,30	-20,33	-24,51	-32,22	-44,43
	5	-8,56	-18,59	-20,70	-22,91	-25,25	-28,20	-32,23	-39,71	-51,37
	10	-21,90	-31,77	-33,94	-36,19	-38,60	-41,50	-45,69	-53,24	-64,77
	15	-37,56	-47,83	-50,11	-52,44	-54,87	-57,95	-62,18	-69,91	-82,15
	20	-51,82	-62,04	-64,32	-66,65	-69,07	-72,15	-76,39	-84,07	-96,21
	25	-66,94	-76,63	-78,91	-81,24	-83,66	-86,66	-90,69	-98,73	-110,08
	30	-81,51	-90,57	-92,85	-95,18	-97,60	-100,60	-104,63	-112,01	-124,06

Figure 5.3: Net present values for different combinations of solar park capacities between 0-40 MW and battery storage capacities between 0-30 MWh. Green indicates higher NPV, while red indicates lower.

Figure 5.4 shows the NPV values for solar park capacities between 0-40 MW and the smaller battery capacities between 0-10 MWh in 2023 and 2024. The figure illustrates that a 2 MWh battery with a solar park of 35 MW was most profitable in 2023, while in 2024 none of the combinations were profitable.

NPV [MSEK]		Solar park capacity								
2023	MWh MW	0	5	10	15	20	25	30	35	40
Battery capacity	0	0,00	10,54	29,07	47,43	64,64	79,35	91,59	94,47	89,93
	1	-0,18	11,04	29,64	48,02	65,19	79,87	91,82	94,70	90,24
	2	-0,77	10,93	29,68	48,13	65,30	80,08	91,67	96,37	92,68
	3	-1,74	10,09	29,07	47,62	64,81	79,61	91,44	94,55	90,41
	4	-3,33	8,67	27,80	46,50	63,74	78,41	90,24	95,05	91,75
	5	-5,27	6,72	26,02	44,81	62,18	76,99	88,92	92,43	88,44
	6	-7,85	4,05	23,27	42,13	59,54	74,33	86,18	91,13	87,95
	7	-10,73	1,05	20,33	39,17	56,65	71,58	83,65	87,36	83,31
	8	-13,64	-1,87	17,45	36,20	53,81	68,69	80,88	84,63	80,84
	9	-16,81	-5,30	14,02	32,63	50,15	65,21	77,34	82,26	79,25
	10	-20,40	-8,93	10,33	28,82	46,26	61,28	73,36	77,16	73,04

NPV [MSEK]		Solar park capacity								
2024	MWh MW	0	5	10	15	20	25	30	35	40
Battery capacity	0	0,00	-10,27	-12,56	-14,88	-17,30	-20,33	-24,51	-32,22	-44,43
	1	-0,72	-10,77	-13,02	-15,34	-17,77	-20,78	-24,96	-32,69	-44,84
	2	-1,98	-11,88	-14,06	-16,36	-18,78	-21,80	-25,98	-33,20	-45,12
	3	-3,81	-13,76	-15,91	-18,18	-20,59	-23,58	-27,65	-35,19	-47,14
	4	-6,15	-16,15	-18,34	-20,60	-22,95	-25,91	-30,04	-37,16	-48,79
	5	-8,56	-18,59	-20,70	-22,91	-25,25	-28,20	-32,23	-39,71	-51,37
	6	-10,86	-20,90	-22,98	-25,20	-27,59	-30,48	-34,57	-41,71	-53,27
	7	-13,49	-23,40	-25,45	-27,70	-30,22	-32,77	-37,10	-44,30	-55,99
	8	-16,25	-26,28	-28,33	-30,55	-32,93	-35,85	-39,84	-47,30	-58,78
	9	-19,06	-29,06	-31,16	-33,58	-35,93	-38,81	-42,97	-50,18	-61,44
	10	-21,90	-31,77	-33,94	-36,19	-38,60	-41,50	-45,69	-53,24	-64,77

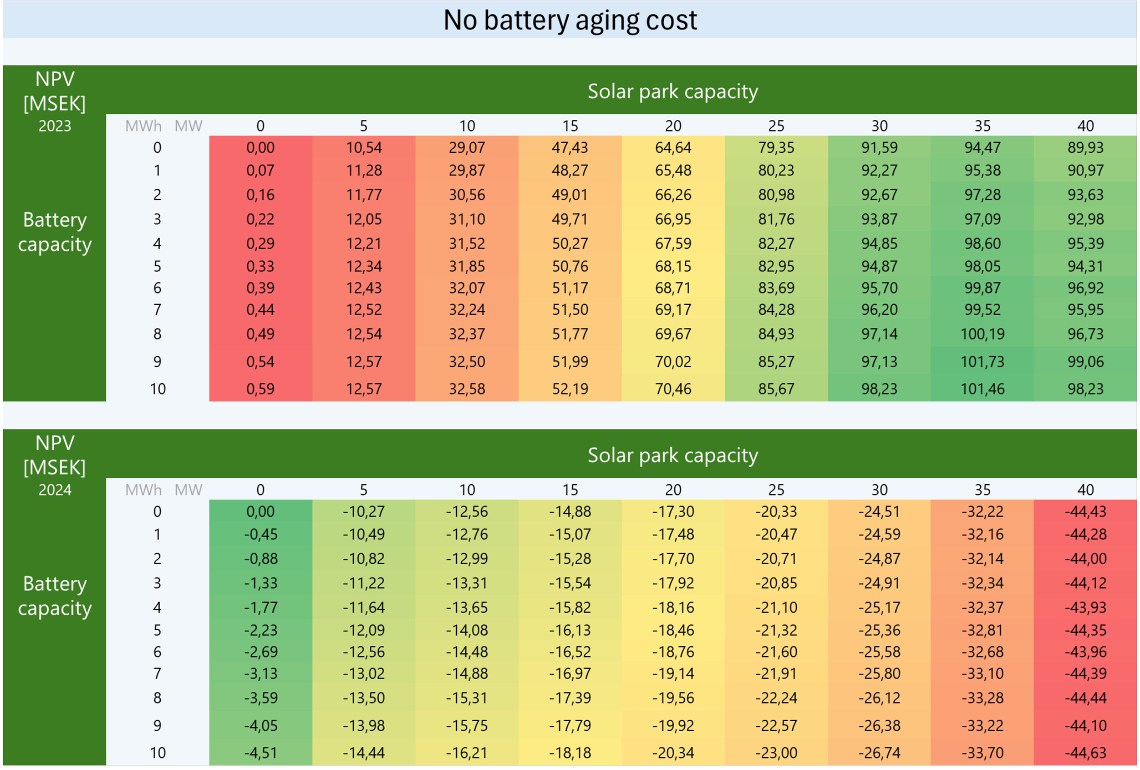
Figure 5.4: Net present values for solar park capacities between 0-40 MW and battery storage capacities between 0-10 MWh.

5.4 Sensitivity analysis

This section presents the results from the three sensitivity analysis. The first analysis sets the battery aging cost to 0, while the second doubles the battery revenue to attempt to represent the actual revenue where frequency regulation and other revenue streams are included. The third and final analysis investigates the effects of doubling the battery investment cost.

5.4.1 No battery aging cost

Figure 5.5 shows the NPV values in 2023 and 2024 when the battery aging cost was not included in the modeling. The figure shows an increase in NPV for larger batteries in 2023 for each of the solar park capacities. A larger battery increased the NPV more when built together with a large solar park compared to on its own or a smaller solar park. In 2024 none of the combinations were profitable even without aging, but the decrease in NPV with larger battery sizes was not as steep compared to when aging was included.



No battery aging cost

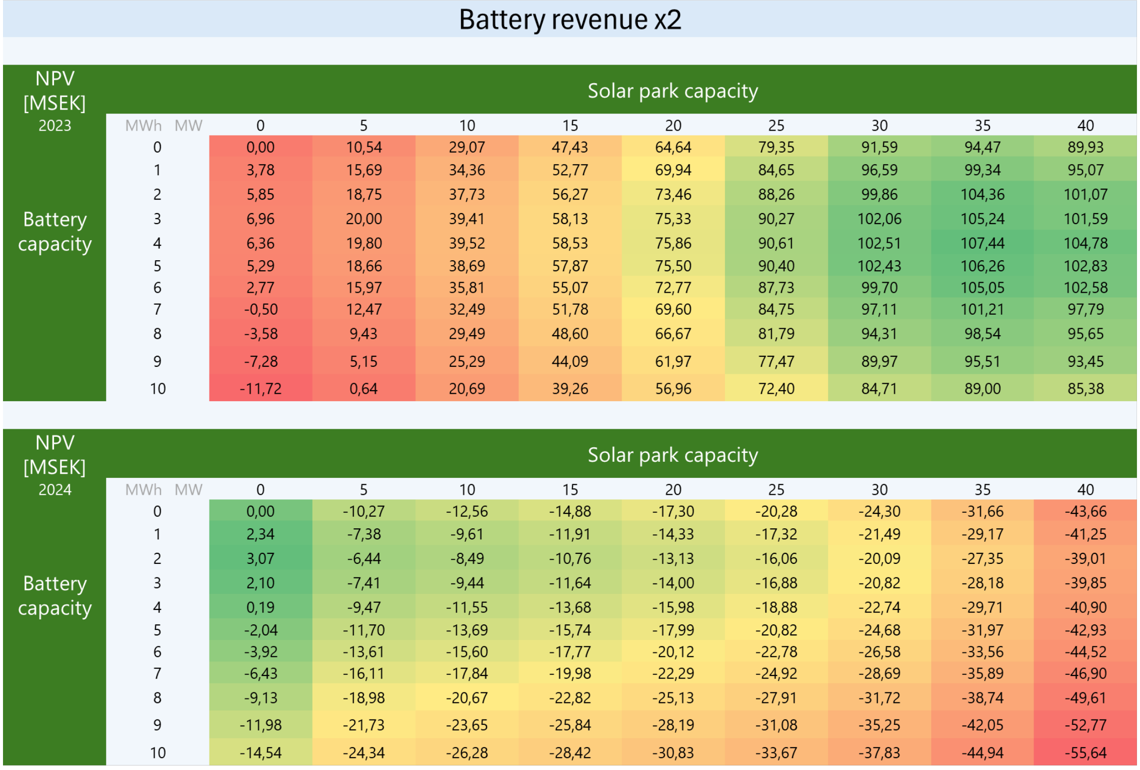
NPV [MSEK] 2023	Solar park capacity								
Battery capacity MWh \ MW	0	5	10	15	20	25	30	35	40
0	0,00	10,54	29,07	47,43	64,64	79,35	91,59	94,47	89,93
1	0,07	11,28	29,87	48,27	65,48	80,23	92,27	95,38	90,97
2	0,16	11,77	30,56	49,01	66,26	80,98	92,67	97,28	93,63
3	0,22	12,05	31,10	49,71	66,95	81,76	93,87	97,09	92,98
4	0,29	12,21	31,52	50,27	67,59	82,27	94,85	98,60	95,39
5	0,33	12,34	31,85	50,76	68,15	82,95	94,87	98,05	94,31
6	0,39	12,43	32,07	51,17	68,71	83,69	95,70	99,87	96,92
7	0,44	12,52	32,24	51,50	69,17	84,28	96,20	99,52	95,95
8	0,49	12,54	32,37	51,77	69,67	84,93	97,14	100,19	96,73
9	0,54	12,57	32,50	51,99	70,02	85,27	97,13	101,73	99,06
10	0,59	12,57	32,58	52,19	70,46	85,67	98,23	101,46	98,23

NPV [MSEK] 2024	Solar park capacity								
Battery capacity MWh \ MW	0	5	10	15	20	25	30	35	40
0	0,00	-10,27	-12,56	-14,88	-17,30	-20,33	-24,51	-32,22	-44,43
1	-0,45	-10,49	-12,76	-15,07	-17,48	-20,47	-24,59	-32,16	-44,28
2	-0,88	-10,82	-12,99	-15,28	-17,70	-20,71	-24,87	-32,14	-44,00
3	-1,33	-11,22	-13,31	-15,54	-17,92	-20,85	-24,91	-32,34	-44,12
4	-1,77	-11,64	-13,65	-15,82	-18,16	-21,10	-25,17	-32,37	-43,93
5	-2,23	-12,09	-14,08	-16,13	-18,46	-21,32	-25,36	-32,81	-44,35
6	-2,69	-12,56	-14,48	-16,52	-18,76	-21,60	-25,58	-32,68	-43,96
7	-3,13	-13,02	-14,88	-16,97	-19,14	-21,91	-25,80	-33,10	-44,39
8	-3,59	-13,50	-15,31	-17,39	-19,56	-22,24	-26,12	-33,28	-44,44
9	-4,05	-13,98	-15,75	-17,79	-19,92	-22,57	-26,38	-33,22	-44,10
10	-4,51	-14,44	-16,21	-18,18	-20,34	-23,00	-26,74	-33,70	-44,63

Figure 5.5: NPV for different combinations of solar park capacities between 0-40 MW and battery storage capacities between 0-10 MWh next to the wind park without cost of battery aging.

5.4.2 Doubled battery revenue

Figure 5.6 presents the NPV values when the battery revenue was doubled in an attempt to represent other revenue streams. The figure illustrates that it was more profitable to build a solar park with a small battery of around 2-6 MWh in 2023, while in 2024 a battery size of 1-3 MWh resulted in the highest NPV. The figure gives an indication that a smaller battery could be slightly profitable at years with lower electricity prices, such as 2024, when other revenue streams are included. For 2023, a small battery of 4 MWh increased the revenue from the solar park the most, an increase by around 14% at most.



Battery revenue x2

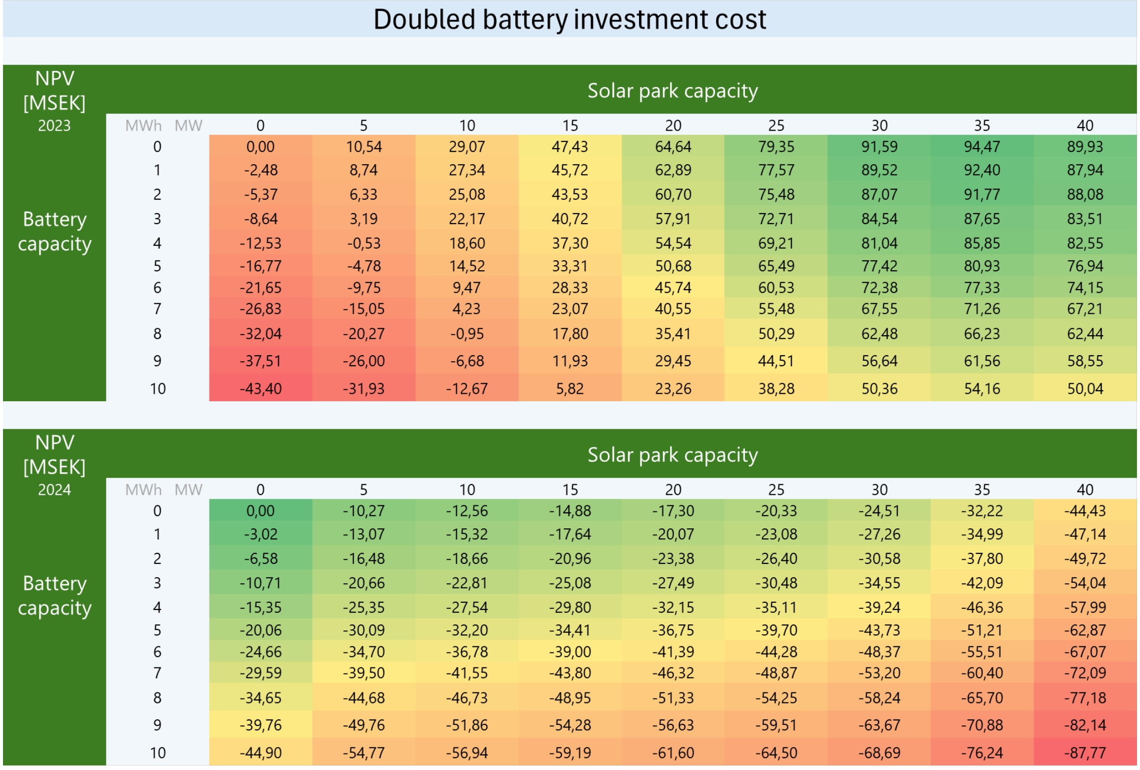
NPV [MSEK] 2023	Solar park capacity								
Battery capacity MWh \ MW	0	5	10	15	20	25	30	35	40
0	0,00	10,54	29,07	47,43	64,64	79,35	91,59	94,47	89,93
1	3,78	15,69	34,36	52,77	69,94	84,65	96,59	99,34	95,07
2	5,85	18,75	37,73	56,27	73,46	88,26	99,86	104,36	101,07
3	6,96	20,00	39,41	58,13	75,33	90,27	102,06	105,24	101,59
4	6,36	19,80	39,52	58,53	75,86	90,61	102,51	107,44	104,78
5	5,29	18,66	38,69	57,87	75,50	90,40	102,43	106,26	102,83
6	2,77	15,97	35,81	55,07	72,77	87,73	99,70	105,05	102,58
7	-0,50	12,47	32,49	51,78	69,60	84,75	97,11	101,21	97,79
8	-3,58	9,43	29,49	48,60	66,67	81,79	94,31	98,54	95,65
9	-7,28	5,15	25,29	44,09	61,97	77,47	89,97	95,51	93,45
10	-11,72	0,64	20,69	39,26	56,96	72,40	84,71	89,00	85,38

NPV [MSEK] 2024	Solar park capacity								
Battery capacity MWh \ MW	0	5	10	15	20	25	30	35	40
0	0,00	-10,27	-12,56	-14,88	-17,30	-20,28	-24,30	-31,66	-43,66
1	2,34	-7,38	-9,61	-11,91	-14,33	-17,32	-21,49	-29,17	-41,25
2	3,07	-6,44	-8,49	-10,76	-13,13	-16,06	-20,09	-27,35	-39,01
3	2,10	-7,41	-9,44	-11,64	-14,00	-16,88	-20,82	-28,18	-39,85
4	0,19	-9,47	-11,55	-13,68	-15,98	-18,88	-22,74	-29,71	-40,90
5	-2,04	-11,70	-13,69	-15,74	-17,99	-20,82	-24,68	-31,97	-42,93
6	-3,92	-13,61	-15,60	-17,77	-20,12	-22,78	-26,58	-33,56	-44,52
7	-6,43	-16,11	-17,84	-19,98	-22,29	-24,92	-28,69	-35,89	-46,90
8	-9,13	-18,98	-20,67	-22,82	-25,13	-27,91	-31,72	-38,74	-49,61
9	-11,98	-21,73	-23,65	-25,84	-28,19	-31,08	-35,25	-42,05	-52,77
10	-14,54	-24,34	-26,28	-28,42	-30,83	-33,67	-37,83	-44,94	-55,64

Figure 5.6: Sensitivity analysis on the battery revenue. The figure shows NPV values for different combinations of solar park capacities between 0-40 MW and battery capacities between 0-10 MWh in 2023 and 2024. The battery revenue was doubled to try to represent other battery revenue streams, such as frequency regulation.

5.4.3 Doubled battery investment cost

Figure 5.7 shows the NPV values when the battery investment cost was doubled to 2300 SEK/kWh for each of the two batteries. The figure illustrates that for a 10 MWh battery, the NPV is around 23 MSEK lower when the battery investment cost is doubled. This correlates with the increase in investment cost of batteries, and showcases that the investment cost can have a significant impact on the profitability of battery storage.



Doubled battery investment cost

NPV [MSEK] 2023	Solar park capacity								
Battery capacity MWh \ MW	0	5	10	15	20	25	30	35	40
0	0,00	10,54	29,07	47,43	64,64	79,35	91,59	94,47	89,93
1	-2,48	8,74	27,34	45,72	62,89	77,57	89,52	92,40	87,94
2	-5,37	6,33	25,08	43,53	60,70	75,48	87,07	91,77	88,08
3	-8,64	3,19	22,17	40,72	57,91	72,71	84,54	87,65	83,51
4	-12,53	-0,53	18,60	37,30	54,54	69,21	81,04	85,85	82,55
5	-16,77	-4,78	14,52	33,31	50,68	65,49	77,42	80,93	76,94
6	-21,65	-9,75	9,47	28,33	45,74	60,53	72,38	77,33	74,15
7	-26,83	-15,05	4,23	23,07	40,55	55,48	67,55	71,26	67,21
8	-32,04	-20,27	-0,95	17,80	35,41	50,29	62,48	66,23	62,44
9	-37,51	-26,00	-6,68	11,93	29,45	44,51	56,64	61,56	58,55
10	-43,40	-31,93	-12,67	5,82	23,26	38,28	50,36	54,16	50,04

NPV [MSEK] 2024	Solar park capacity								
Battery capacity MWh \ MW	0	5	10	15	20	25	30	35	40
0	0,00	-10,27	-12,56	-14,88	-17,30	-20,33	-24,51	-32,22	-44,43
1	-3,02	-13,07	-15,32	-17,64	-20,07	-23,08	-27,26	-34,99	-47,14
2	-6,58	-16,48	-18,66	-20,96	-23,38	-26,40	-30,58	-37,80	-49,72
3	-10,71	-20,66	-22,81	-25,08	-27,49	-30,48	-34,55	-42,09	-54,04
4	-15,35	-25,35	-27,54	-29,80	-32,15	-35,11	-39,24	-46,36	-57,99
5	-20,06	-30,09	-32,20	-34,41	-36,75	-39,70	-43,73	-51,21	-62,87
6	-24,66	-34,70	-36,78	-39,00	-41,39	-44,28	-48,37	-55,51	-67,07
7	-29,59	-39,50	-41,55	-43,80	-46,32	-48,87	-53,20	-60,40	-72,09
8	-34,65	-44,68	-46,73	-48,95	-51,33	-54,25	-58,24	-65,70	-77,18
9	-39,76	-49,76	-51,86	-54,28	-56,63	-59,51	-63,67	-70,88	-82,14
10	-44,90	-54,77	-56,94	-59,19	-61,60	-64,50	-68,69	-76,24	-87,77

Figure 5.7: Sensitivity analysis on the battery investment cost. The figure shows the NPV values in 2023 and 2024 for different combinations of solar park capacities between 0-40 MW and battery capacities between 0-10 MWh. The battery investment cost is doubled to two times 2300 kSEK/kWh, representing the investment cost of two batteries over the solar park lifetime.

6. Discussion

This chapter presents discussion and analysis on the results. First, the profitability of solar PV and battery storage is discussed, followed by how the profitability could develop in the future and improvements for future work.

6.1 Profitability of solar power

The results indicate that it is profitable to build a solar park next to Örbacken with price levels similar to 2023, but not for the price levels of 2024. One reason for this is likely the increased amount of solar power capacity installed in Sweden in the last years, with Figure 2.4 showing that the capacity increased from around 1000 to 5000 MW between 2020 and 2024. This increase is likely one reason for the large decline in electricity prices in the summer in 2023 and 2024, seen in Figure 2.7, compared to 2018-2021. The capacity is also projected to increase in the coming years, as Figure 2.5 shows, which could lower the electricity prices even further at hours with high solar irradiance.

Another potentially small factor why solar PV is not profitable at Örbacken is that the PV power potential, seen in Figure 2.3, is in the middle of the range. Other locations, such as parts of southern Sweden, Öland and Gotland, have around 5-10% higher potential. With this in consideration and the higher electricity prices, SE4 can be seen as more suitable for solar power. The ambitious solar power development in Germany should be taken into consideration though, which could reduce the future profitability as this will likely lead to even lower electricity prices at hours with a lot of solar irradiation. By 2030, for example, the electricity price in SE4 is projected to decrease by approximately 40%, possibly as a consequence of the higher share of solar power in Sweden, Germany and the rest of Europe. The average electricity price in SE3 is instead projected to increase slightly, but considering the projected doubling of solar capacity it would be surprising if this applied to the summer price levels.

6.2 Profitability of battery storage

The results indicate that revenue from energy arbitrage is not enough to make battery storage profitable at Örbacken. A very slight increase in profitability was seen in 2023 for battery sizes of 1-2 MWh in combination with a solar park, as seen in Figure 5.4. This suggest that a smaller battery could be profitable but that the increase is only slight and perhaps not enough to warrant an investment. Figure 2.6 also shows that the projected battery capacity available for energy arbitrage is expected to increase in SE3, which could lead to a more saturated market and further reducing incentives for investment.

One aspect that could make battery storage more attractive is the increased volatile electricity prices as a consequence of the higher share of renewables. The summer price levels could be very volatile with a high share of solar power in Sweden and Germany in the day and no solar at night. The profitability would be dependent on how much battery storage are available, since a high share could flatten out the prices and reduce profitability. However, the battery capacity for energy arbitrage is expected to increase by 50% from 2025 to 2029, as seen in Figure 2.6. This will likely lead to a smoother electricity price and decreased volatility, further reducing the profitability of batteries. This is hard to predict though, as other factors such as wet and dry hydrological years may also impact the price and volatility. These aspects have not been analyzed in this report but likely can have a large impact on the year to year profitability.

Another aspect to consider is the other revenue streams, such as frequency regulation. These revenue streams are predicted to make up around 40% by 2030, however this is likely very hard to predict. The market for ancillary services has become saturated in Sweden, and with the battery capacity projected to increase this suggests even higher competition for these revenues. The sensitivity analysis that doubled the battery revenue, as shown in Figure 5.6, does show an increase in NPV by 12 MSEK at best in 2023 for a 35 MW solar park with a 4 MWh battery. This indicates that other revenue streams can have significant impacts on the profitability of the battery. However, considering that analysts find it challenging to model and predict these markets, it is difficult to draw conclusions.

The sensitivity analysis on battery aging shows that this can have a quite significant effect on the profitability. Perhaps the model underestimates the charging cycles of the battery, and other scenarios where the battery aging cost is lower and the charging cycles higher are more realistic. One aspect to consider is that the battery NPV used to calculate the aging cost is not correlated with the battery investment cost. Calculating the battery NPV with parameters correlated to the investment cost could likely make the model more accurate.

Finally, the sensitivity analysis that doubled the battery investment cost showed that this had a quite significant impact on profitability. The battery prices are likely only going to decrease in the coming years, perhaps making battery storage a more attractive investment in the future. Also, as seen in Table 2.1, co-locating an existing wind park with battery storage could reduce the investment cost by 20%. This is likely to have a significant impact on the profitability, and together with decreased future prices could further incentivize investment.

6.3 How could the profitability develop in the future?

The projection is that solar PV and battery storage capacities will continue to increase, maturing the markets and reducing the profitability. Energimyndigheten do predict the electricity price in Sweden to increase slightly in SE3 [23]. However, with the projected solar and battery capacity growth, this outlook may be overly optimistic from a company perspective, which typically adopts a more conservative stance. Germany's ambitious plans on solar PV is also likely to reduce the profitability even further in the future. The high share of solar PV could create more negative pricing, which could mean that building a solar park without battery storage will become more unusual. The increased negative electricity prices is perhaps a growing revenue potential for BESS in the future, as the batteries could charge at negative prices for increased revenue. However, this market may become saturated as the battery capacity grows.

The profitability in the future could also increase as a consequence of the lowered costs of solar PV and battery storage. The global solar PV capacity increased as much in two years as it did in the previous 70 [1], likely as an effect of lowered prices. A continued decrease in price could incentivize an investment. However, it should be considered that the electricity prices likely will be very low or negative when solar power is at peak production, meaning that a combination with battery storage may be necessary to ensure the revenue is high enough.

Other solar PV tilt angles could also be considered. A higher tilt angle can produce more in the winter when the electricity price usually is higher, compared to a lower tilt angle which is optimal for summer production. This may increase profitability since the solar PV penetration is likely lower in the winter. Perhaps having the possibility to change the tilt angle once or twice a year could be a worthwhile investment. Solar tracking panels could instead track the sun automatically, increasing electricity production. This is likely an expensive investment today, but could possibly be more lucrative in the future if the costs were to decrease.

6.4 Improvements

Some improvements to this work include extracting cost sheets from companies selling BESS and solar panels, to make the cost estimations of initial investment and operational and maintenance costs more accurate. Also the projected future cost of solar PV and battery storage could be investigated to better evaluate the profitability at a future year when the solar park and batteries could be built.

Another improvement is to include ancillary services and other revenue streams from BESS in the model. This is difficult to do, as discussed previously, but could provide more accurate results on the profitability of BESS and BESS in combination with wind and solar power. It would then perhaps be interesting to analyze a battery with a separate grid connection to that of the wind and solar park, as this would allow it to participate in down-regulating services directly from the grid but probably also increase the investment costs.

Future work could also benefit from more advanced economic analysis on profitability, investment costs and the decreased costs from building a hybrid park next to an existing wind park. This was not investigated in detail in this work due to time constraints, but could provide more tangible and valuable information on hybrid energy parks. Another aspect that could be investigated is the increased negative prices and their effects on solar PV and battery revenue.

7. Conclusion

This thesis aimed to investigate the profitability of building a hybrid energy park with solar PV and battery storage at SR Energy's wind park Örbacken, and to develop an optimal investment model. The solar output was calculated and the calendar and cycle aging of the battery was considered to decide when to charge and discharge each hour. NPV with a discount rate of 5.5% was used to evaluate profitability.

The main findings in this work are as follows:

1. A solar park was profitable at 2023 electricity price levels, but not at 2024 levels.
2. There is a risk that the profitability of solar power will decline in the future considering a projected doubling of capacity in SE3 between 2025 and 2029 and Germany's ambitious plans.
3. Revenue from energy arbitrage is not enough to make battery storage profitable.
4. Other battery revenue streams, such as from ancillary services, can make a smaller battery profitable if this is equally as large as the revenue from energy arbitrage.
5. Battery aging cost and investment cost can have significant impacts on profitability.
6. A combination of solar PV and battery storage is seemingly not more profitable compared to only building a solar park.
    - However, a battery aging cost of 0 and thus more charging cycles resulted in a combination of solar PV and BESS being the most profitable.
7. Reduced investment costs in solar PV and battery storage in the future, along with building next to a wind park, could make hybrid parks more lucrative.
    - This was not investigated in detail in this report, and future work could benefit from diving deeper into this.

This work can provide valuable insights into the future of hybrid energy parks and methods to investigate the profitability of combining wind, solar and BESS. The technical aspects of a solar park and battery storage have been modeled, providing a foundation for more detailed economic evaluations in the future. For example, more research around the actual costs of building a solar park and battery storage in Sweden, along with the reduced costs of building next to a wind park, could improve the investment model and economic evaluation. This, along with investigating different battery aging costs, perhaps looking further into replacement and operational costs of batteries from company brochures, could give a more realistic charging and discharging schedule of the battery. Additionally, the NPV calculations can be improved by, for example, considering that a new battery is bought at year 15 at a possibly significantly lower cost compared to today. Internal rate of return calculations can also be beneficial for a more comprehensive economic evaluation.

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A. Appendix

A.1 Linearizing calendar aging

The linearized aging function is, where the calendar aging coefficients was derived from the ordinary, nonlinear equation in [8] and linearized in Python:

$$G(\mathrm{SOC}_t) = \begin{cases} 34.7 \cdot \mathrm{SOC}_t + 1224.6, & 0 \leq \mathrm{SOC}_t \leq 0.5 \\ 155.27 \cdot \mathrm{SOC}_t - 4803.9, & 0.5 < \mathrm{SOC}_t \leq 0.7 \\ 34 \cdot \mathrm{SOC}_t + 3685, & 0.7 < \mathrm{SOC}_t \leq 1 \end{cases} \tag{1}$$

The nonlinear and linearized $G(\mathrm{SOC}_t)$ using the coefficient from [9] can be seen in Figure A.1.

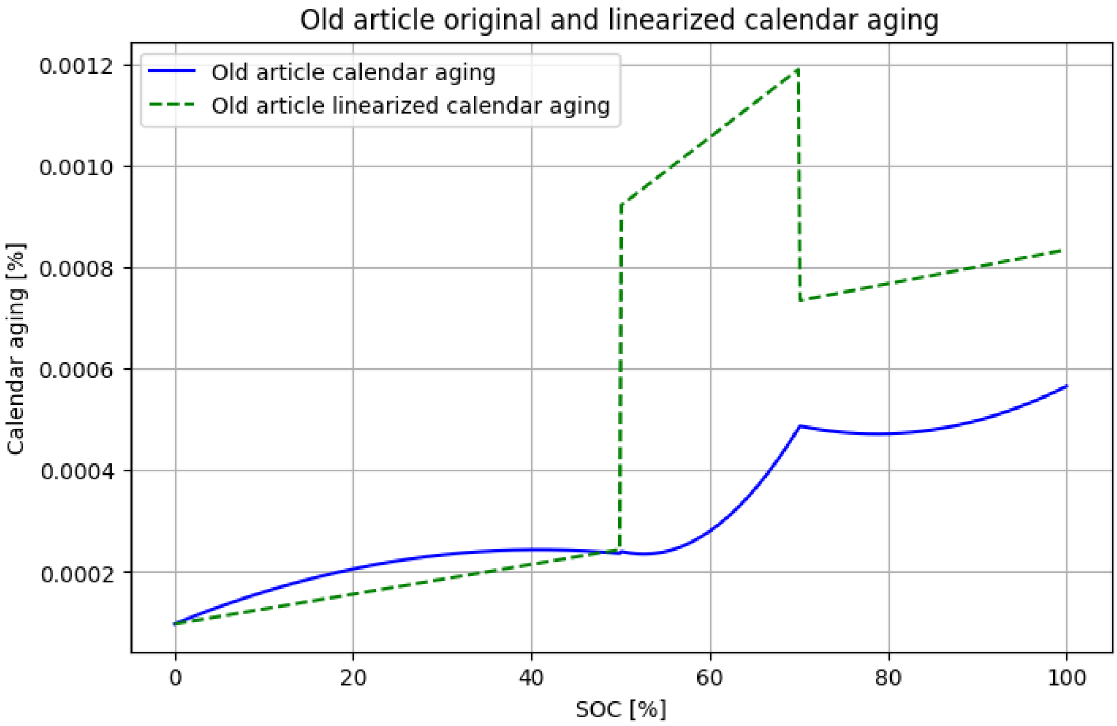


Figure A.1: The linearized $G(SOC_t)$ using the linearized calendar aging coefficients in [9]. The blue line represents the nonlinear and the dotted green line represents the linearized function.

The linearization does not seem correct. To correct this, a new linearization was made in Python between the three intervals of SOC of 0-50%, 50-70% and 70-100%. The resulting linearized function can be seen in Figure A.2.

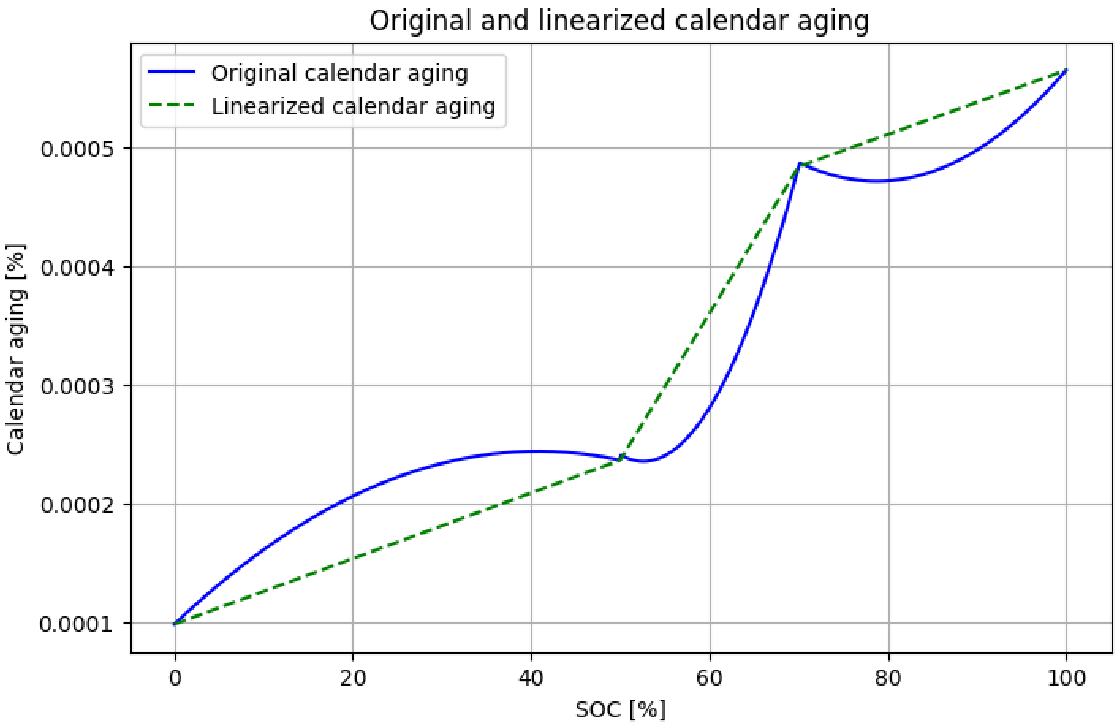
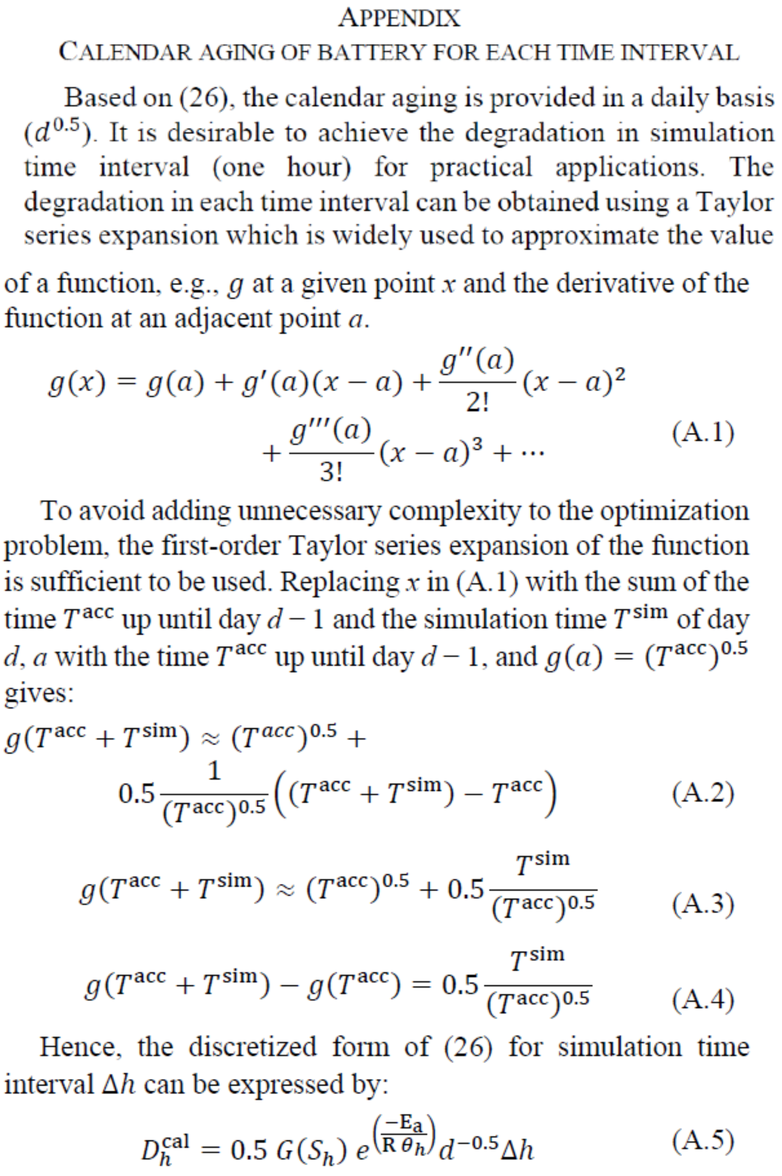


Figure A.2: The linearized $G(SOC_t)$ using the linearized calendar aging coefficients that were found from linearization in Python. The blue line represents the nonlinear function and the dotted green line represents the linearized function.

A.2 Equation for hourly calendar aging

The equation for calendar aging is different in this thesis compared to [7], [8] and [9]. The reason is that the calendar aging equation in the articles is on a daily basis, while this work calculates the aging each hour. Figure A.3 explains the derivation of this equation in further detail.



APPENDIX

CALENDAR AGING OF BATTERY FOR EACH TIME INTERVAL

Based on (26), the calendar aging is provided in a daily basis ($d^{0.5}$). It is desirable to achieve the degradation in simulation time interval (one hour) for practical applications. The degradation in each time interval can be obtained using a Taylor series expansion which is widely used to approximate the value of a function, e.g., g at a given point x and the derivative of the function at an adjacent point a.

$$g(x) = g(a) + g'(a)(x-a) + \frac{g''(a)}{2!}(x-a)^2 + \frac{g'''(a)}{3!}(x-a)^3 + \cdots \qquad \text{(A.1)}$$

To avoid adding unnecessary complexity to the optimization problem, the first-order Taylor series expansion of the function is sufficient to be used. Replacing x in (A.1) with the sum of the time T^{acc} up until day $d-1$ and the simulation time T^{sim} of day d, a with the time T^{acc} up until day $d-1$, and $g(a) = (T^{\text{acc}})^{0.5}$ gives:

$$g(T^{\text{acc}} + T^{\text{sim}}) \approx (T^{acc})^{0.5} + 0.5\frac{1}{(T^{\text{acc}})^{0.5}}\left((T^{\text{acc}} + T^{\text{sim}}) - T^{\text{acc}}\right) \qquad \text{(A.2)}$$

$$g(T^{\text{acc}} + T^{\text{sim}}) \approx (T^{\text{acc}})^{0.5} + 0.5\frac{T^{\text{sim}}}{(T^{\text{acc}})^{0.5}} \qquad \text{(A.3)}$$

$$g(T^{\text{acc}} + T^{\text{sim}}) - g(T^{\text{acc}}) = 0.5\frac{T^{\text{sim}}}{(T^{\text{acc}})^{0.5}} \qquad \text{(A.4)}$$

Hence, the discretized form of (26) for simulation time interval Δh can be expressed by:

$$D_h^{\text{cal}} = 0.5\, G(S_h)\, e^{\left(\frac{-\mathrm{E_a}}{\mathrm{R}\,\theta_h}\right)} d^{-0.5} \Delta h \qquad \text{(A.5)}$$

Figure A.3: Unpublished part of an appendix provided by my examiner David Steen that explains the difference between Equation 32 for calendar aging in this thesis and the equations provided in [7], [8] and [9].

A.3 Solar production

Figure A.4 shows the hourly DC electricity output in 2024 from a 30 MW solar park next to Örbacken wind park with a 42° tilt angle and 180° azimuth angle.

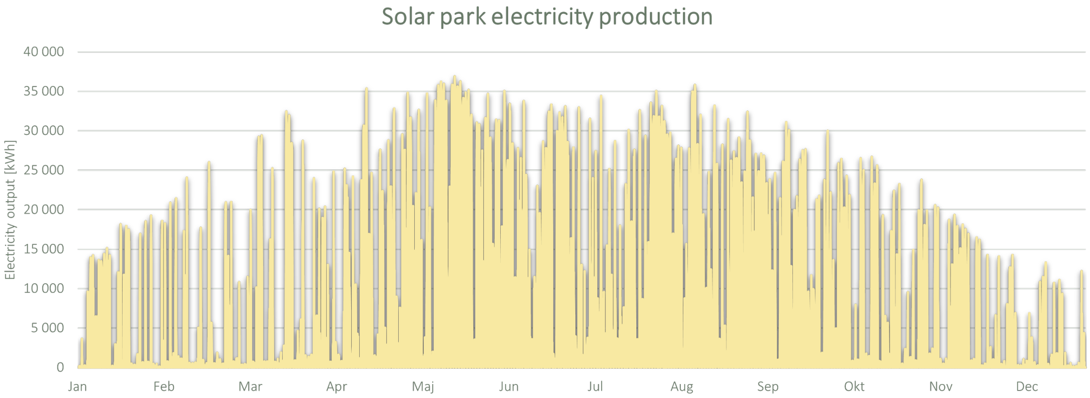


Figure A.4: DC electricity production in 2024 from the solar park with a capacity of 30 MW, a 42° tilt and 180° azimuth angle.

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