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Industrial Electrical Engineering and Automation

The Synergy of Natural Resources in Renewable Power Generation

Optimising Operation and Dimension of Grid-connected Wind and Solar Power Plant with Pumped Hydro Energy Storage

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This master's thesis, for the degree of Master of Science in Engineering - Engineering Physics, has primarily been conducted at the Division of Industrial Electrical Engineering and Automation, Faculty of Engineering, Lund University.

Supervisor from Lund University was Jörgen Svensson from the Division of Industrial Electrical Engineering and Automation.

Examiner from Lund University was Olof Samuelsson from the Division of Industrial Electrical Engineering and Automation.

The thesis was conducted in collaboration with Eolus Vind. Supervisor from Eolus Vind was Julia Lundkvist from the Project Development team.

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Abstract

Renewable energy projects are essential for a sustainable energy transition. In addition to the fundamental benefits of renewable power generation, such as climate change mitigation and clean air, renewable power projects with energy storage solutions can provide economic benefits for electricity producers and add value to the operation of the national grid. This thesis investigates the innovative operation of a grid-connected wind and solar power plant coupled with pumped hydro energy storage system based on operability and techno-economic feasibility.

A comprehensive model for optimising the hourly management of a grid-connected hybrid power plant coupled with pumped hydro energy storage system was introduced and applied to a case study in Sweden. The energy management model was formulated as a mixed-integer optimisation problem in MatLab with the objective of maximising operating profit. To assess the functionality of the proposed model, another electrical system model in the OpenModelica software was utilised. This thesis analyses generation curtailment of a stand-alone hybrid power plant in relation to generation curtailment of a hybrid power plant coupled with pumped hydro energy storage. The dimension of the pumped hydro energy storage plant was techno-economically optimised through an iterative process of testing different energy storage sizes in the two models and analysing the financial results in investment appraisals.

Results revealed that pumped hydro energy storage decreases the lost revenue due to generation curtailment, increases the system operating profit from electricity arbitrage trading on the day-ahead market and opens up the possibility for participation in frequency regulation markets. This thesis concludes that coupling both a solar power plant and a pumped hydro energy storage to a wind power plant can be more financially profitable than coupling only the solar power plant to the wind power plant. The prospect is that this type of co-integrated renewable energy project will contribute to bringing the future Swedish power grid into balance.

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Abbreviations

AC	Alternating current
BESS	Battery energy storage system
BRP	Balance responsible party
BSP	Balance service provider
CF	Capacity factor
DC	Direct current
DSO	Distribution system operator
EBITA	Earnings before interest, taxes, depreciation and amortisation
EI	The Swedish energy markets inspectorate
ENTSO-E	European network of transmission system operators for electricity
ESS	Energy storage system
FCFE	Free cash flow to equity
GCP	Grid connection point
HPP	=SPP+WPP, Hybrid power plant
IRENA	International renewable energy agency
IRR	Internal rate of return
LCOE	Levelised cost of electricity
MPPT	Maximum power point tracker
NPV	Net present value
OM	Operation and maintenance
PHES	Pumped hydro energy storage
PPA	Power purchase agreement
PV	Photovoltaic
SOC	State of charge
SP	Simple payback
SPP	Solar power plant
SvK	Svenska kraftnät
TSO	Transmission system operator
VRES	Variable renewable energy sources
WPP	Wind power plant

Nomenclature

η_p	Performance of pump per hour
η_t	Performance of turbine per hour
ρ^h	Spotprice per hour (EUR/MWh)
C^h_{pt}	Cost of change from pump to turbine mode per hour (EUR)
C^h_{start}	Cost of start-up pump/turbine per hour (EUR)
C^h_{tp}	Cost of change from turbine to pump mode per hour(EUR)
E^h_{curt}	Electricity curtailed per hour (MWh)
E^h_{exp}	Electricity exported to grid-connection per hour (MWh)
E^h_{imp}	Electricity imported from grid-connection per hour (MWh)
E^h_p	Electricity received by pump per hour (MWh)
E^h_{SPP}	Electricity from solar power plant per hour (MWh)
E^h_t	Electricity delivered by turbine per hour (MWh)
E^h_{WPP}	Electricity from wind power plant per hour (MWh)
E_{init}	Initial state of charge in energy storage (MWh)
E_{PHES}	Energy storage size (MWh)
E_{Smax}	Maximum state of charge in energy storage (MWh)
E_{Smin}	Minimum state of charge in energy storage (MWh)
E_{SOC}	State of charge in energy storage at the end of an hour (MW)
f_p	Operating cost of pump (EUR/MWh)
f_t	Operating cost of turbine (EUR/MWh)
h	Index for number of a specific hour within a time window (-)
I^h_{curt}	Binary indicator for hourly energy curtailment (on[1]/off[0])
I^h_{exp}	Binary indicator for hourly energy transfer to grid (on[1]/off[0])
I^h_{imp}	Binary indicator for hourly energy transfer from grid (on[1]/off[0])
I^h_{pt}	Binary indicator for hourly change from pump to turbine (on[1]/off[0])
I^h_p	Binary indicator for hourly operation of pump (on[1]/off[0])
I^h_{start}	Binary indicator for hourly start-up of pump or turbine (on[1]/off[0])
I^h_{tp}	Binary indicator for hourly change from turbine to pump (on[1]/off[0])
I^h_t	Binary indicator for hourly operation of turbine (on[1]/off[0])
k_{pt}	Cost of change from pump to turbine mode (EUR)

k_{start}	Cost of start-up pump or turbine (EUR)
k_{tp}	Cost of change from turbine to pump mode (EUR)
N_H	Number of hours per time window (-)
P_p^h	Operating power of pump per hour (MW)
P_t^h	Operating power of turbine per hour (MW)
P_{curt}	Maximum power capacity of generation curtailment (MW)
P_{GCP}	Maximum power capacity of grid-connection (MW)
P_{PHES}	Maximum power capacity of energy storage (MW)
P_{pmax}	Maximum operating power capacity of pump (MW)
P_{pmin}	Minimum operating power capacity of pump (MW)
P_{tmax}	Maximum operating power capacity of turbine (MW)
P_{tmin}	Minimum operating power capacity of turbine (MW)

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1 Introduction

1.1 Background

To reduce greenhouse gas emissions and fight climate change, a global energy transition to renewable energy sources is taking place. In the report Renewables 2023 published by International Renewable Energy Agency (IRENA), a doubling of installed renewable energy capacity globally is forecasted by 2028, corresponding to an additional 532 GW. At the leading edge is the predicted growth in solar power with 70%, dominated by more solar PV installations in distributed systems, and the growth in wind power with 26%, dominated by new onshore projects. The European Green Deal sets the EU on a path to decouple resource use from economic growth and to reach no net greenhouse gas emission by 2050 [1]. As part of the contribution to the EU energy cooperation, a Swedish energy target is to reach 100% fossil-free electricity production by 2040 [2].

In Sweden, it is evident that the share of wind and solar power has increased in recent years, and this trend is expected to continue [3]. With great probability there will be an increased need for electricity in the future Swedish energy system due to electrification of the industry and transport sector, for instance. A challenge with these renewable energy sources is that they are intermittent, leading to greater power variations that the power grid has to manage. The difference in availability of natural wind and solar resources makes wind power plants and solar power plants a good combination. By installing solar modules and wind turbines closely and connecting them to a common grid connection point, the hybrid power plant can increase power balance in the electricity grid. Moreover, solar power plants can be installed at locations where wind power plants already exists, and thus increase the utilisation of an already existing grid connection point. Much onshore wind power is in operation in Sweden, and therefore the possibilities for more hybrid power plants are great.

In order to further increase the balancing possibilities and the availability of power, various energy storage technologies can be utilised. Energy storage systems can be used both in the short and long-term to even out hourly, weekly and seasonal variations in produced electricity and can provide grid services. A hybrid power plant coupled with energy storage has the potential to increase the annual electricity production from the power sources due to that surplus energy can be stored. In the case of an existing grid-connected wind power plant, an energy storage solution can increase the profitability of installing higher solar power plant capacity compared to wind power plant capacity.

There are several types of energy storage technologies such as pumped hydro energy storage, lithium ion batteries, lead-acid batteries, compressed air and hydrogen [4]. Pumped hydro energy storage is a simple form of energy storage that utilises differences in gravitational energy between water reservoirs at different elevation levels to store energy [5]. By pumping water from a lower reservoir to a higher reservoir during periods of low electricity prices and during periods of high electricity prices allow water to flow through turbines to generate electricity, a pumped hydro energy storage plant can act as a ”mechanical battery” [5].

As of today, there are only a few pumped hydro energy storage plants in Sweden and by some people the technology has been considered outdated due to the lack of high mountain areas within the country [6]. Nonetheless, in recent years discussions about the possible benefits of pumped hydro energy storage in the Swedish power system have flared up and modern technology has enabled construction of pumped hydro energy storage plants in closed mines. By utilising underground mines, the visual impacts of energy storage plants are minimised and decommissioned mining areas are repurposed [6].

1.2 Collaboration

This thesis is conducted in collaboration with Eolus Vind. Eolus Vind was founded in 1990 and is one of the largest developers of renewable energy projects in northern Europe. The company has offices in Sweden, Finland, Latvia, Poland and the United States and manages solar power, wind power and energy storage projects from origination to construction and delivery. By the end of March 2024, their project portfolio comprised a total installed capacity of 28 100 MW; divided between 8200 MW onshore wind power, 11 000 MW offshore wind power, 6100 MW solar power and 2800 MW battery energy storage.

1.3 Objectives

The thesis purpose is to examine a grid-connected wind and solar power plant coupled with pumped hydro energy storage system considering system operability, functionality and financial profitability. The aim of the investigation is to find a technically and economically viable system configuration that can be applied to a case study in Sweden. Briefly, the scientific contributions of this thesis can be scaled down to the research areas that are listed below.

- Evaluation of a grid-connected wind and solar power plant coupled with pumped hydro energy storage system on the basis of generation curtailment.
- Optimal operation of grid-connected wind and solar power plant coupled with pumped hydro energy storage system to maximise operating profits from electricity arbitrage on the day-ahead market.
- Investigation of a grid-connected wind and solar power plant coupled with pumped hydro energy storage electrical system functionality.
- Optimal dimension of a grid-connected wind and solar power plant coupled with pumped hydro energy storage system to maximise lifetime profitability of the system.
- Execution of initial data analysis and techno-economic feasibility analysis on a case study in Sweden and application of an energy management model and electrical system model to the case study.

1.4 System overview

The system as a whole consists of four main components: solar power plant (SPP), wind power plant (WPP), grid connection point (GCP) and pumped hydro energy storage (PHES). All of these components are connected to a point of common connection (PCC) within the system. The wind and solar power plants create a hybrid power plant (HPP). An overview of the grid-connected wind and solar power plant coupled with pumped hydro energy storage system, hereinafter also referred to as only hybrid power plant with pumped hydro storage system, can be viewed in Figure 1.1.

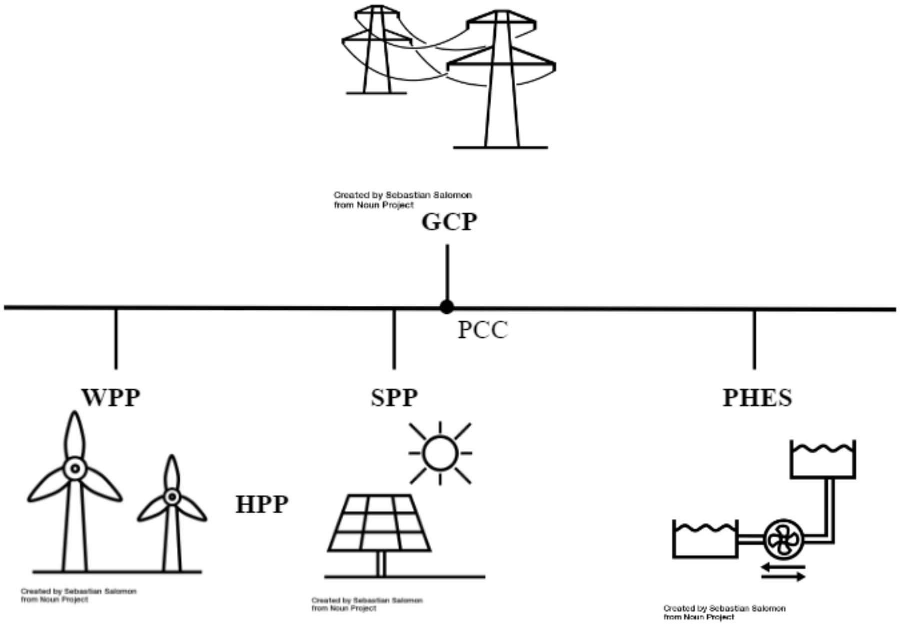


Figure 1.1: Overview of hybrid power plant with pumped hydro storage system. Icons are sourced from [7].

1.5 Case study

A case study is conducted on a project called Project Garpenberg, which is under initial development by Eolus Vind. The location of the project is east of Garpenberg and covers land area in both Hedemora Municipality and Avesta Municipality, Dalarna County, Sweden. The project area is located in the Swedish electricity area SE3 and the plan is to construct a grid-connected wind power plant, Garpenberg WPP. The wind power project plan comprises 21 wind turbines within the wind power project area that is circumscribed in Figure 1.2. The suggested total installed capacity of Garpenberg WPP is about 140 MW. In terms of solar power, there is no project plan established yet but there are possibilities for a solar power plant close to wind power project area. Garpenberg WPP and SPP are connected to the same grid connection point, Garpenberg GCP, that has an available capacity of 140 MW. Herewith, Garpenberg WPP and SPP create the grid-connected hybrid power plant Garpenberg HPP. The energy storage studied in this case study is based on a fictitious case with pumped hydro storage in a disused mine nearby Garpenberg HPP. Naturally, the project plan for Garpenberg PHES is assumed to not be established, but as part of Project Garpenberg it is assumed that the pumped hydro storage plant can be connected to the same grid connection point as the hybrid power plant.

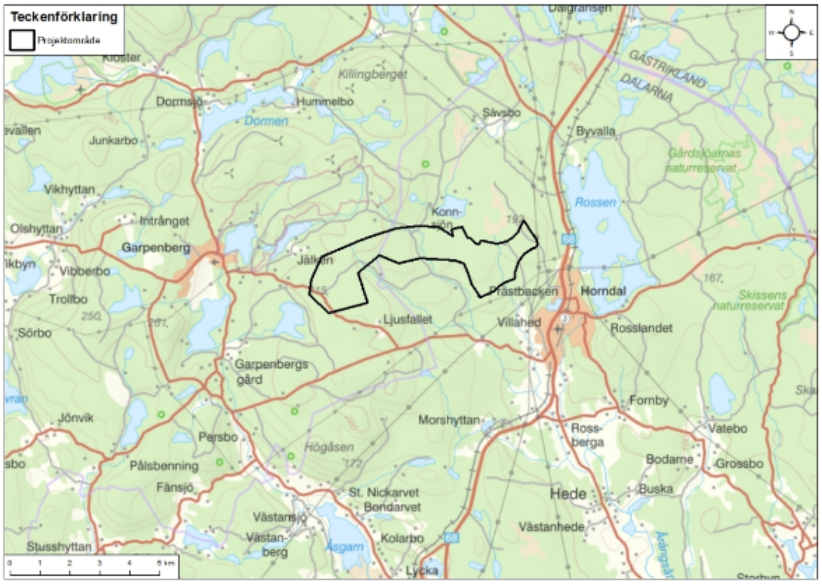


Figure 1.2: Garpenberg wind power project area.

1.6 Report structure

The thesis outline includes introduction, theoretical background, main method, results, discussion and conclusion. The main method of this thesis is described in the methodological framework and is further divided into four parts: initial data analysis, energy management modelling, electrical system simulation and techno-economic analysis. Each of these parts intends to investigate a specific aspect of a grid-connected hybrid power plant with pumped hydro storage system. A brief description of the different sections of this thesis is given below.

- **Introduction**: Introductory presentation of the thesis followed by the research objectives. Information on thesis collaborations and the case study.
- **Theoretical background**: Background information on renewable energy technologies: solar power, wind power and pumped hydro storage, and information on the electricity system and markets in Sweden. The aim of the theoretical background is to lay the foundation for upcoming sections of the thesis.
- **Methodological framework**: The research design is presented and explained. In this study, multiple methods are used to analyse a hybrid power plant with pumped hydro storage system and this section of the report aims to provide guidance on the methods adopted and how the methods are linked together.
- **Initial data analysis method**: Initial data on wind and solar power generation from the hybrid power plant in the case study is analysed to determine the patterns of electricity production and generation curtailment at different sizes of the solar power plant. Based on electricity production and price data, the specific need for energy storage coupled with the hybrid power plant and what size of energy storage that is reasonable is briefly studied.

- **Energy management modelling method**: A mathematical model on energy management of a grid-connected hybrid power plant with pumped hydro storage system is proposed and applied to the case study. The model focuses on optimising the operating profit with respect to electricity flows within the system, prices on the Swedish electricity market, technical constraints on components and costs associated with deterioration of the pumped hydro storage plant.
- **Electrical system simulation method**: Important aspects of the electrical system of a grid-connected hybrid power plant and pumped hydro storage project is considered in this part of the thesis. An electrical system configuration is presented and simulations are conducted to study the functionality and operation of the system upon the outcome of the energy management simulations.
- **Techno-economic analysis method** A techno-economic feasibility study is conducted to analyse revenues and costs associated with a grid-connected hybrid power project without and with a pumped hydro storage plant during its lifetime. To achieve an attractive and profitable project, the pumped hydro storage plant is dimensioned to achieve as high IRR and low LCOE as possible.
- **Results**: Presentation and explanation of the results divided according to the methods adopted.
- **Discussion**: The results are further analysed and discussed from today's and future perspective. The discussion ends with suggestions on future research topics.
- **Conclusion**: A compilation of findings and conclusions that can be drawn from the results.

2 Theoretical background

2.1 Variable renewable energy

Variable renewable energy sources (VRES), also called intermittent renewable energy sources, are sources of energy that are dependent upon non-dispatchable natural resources. Common VRES are solar, wind, ocean and partially hydro. The electricity production from these energy sources is characterised by natural fluctuations and there are direct limitations to the possible electricity production from power plants that utilise VRES. Capacity factor (CF) is an important measure to determine the ratio between actual electricity production over a given time period and theoretical maximum electricity production over the same time period, as defined in Equation 1.

$$CF = \frac{E_t}{P \cdot t} \tag{1}$$

E_t: Energy produced during time period t (MWh)
t: Time period (h)
P: Installed power capacity (MW)

2.1.1 Wind power

Wind is an abundant source of energy on Earth. As long as the sun heats the Earth differently depending on location, it will give rise to air pressure differences, and thereby winds. A wind turbine is a machine that takes advantage of the wind energy and converts it into electrical energy. By rotating the blades of a wind turbine, the kinetic wind energy is transformed into kinetic mechanical energy of the blades, and then transferred through a shaft to the generator where it is finally converted into electricity. The available energy in the air depends on the wind speed cubed, which in turn depends on the ground terrain and at what elevation the wind speed is measured [8]. A wind turbine power curve is a graph of the power generation from a turbine over different wind speeds whence the cut-in, rated and cut-out wind speeds can be deduced [8]. A collection of wind turbines; connected in arrays via internal cables and further connected to the power grid via external cables, creates a wind power plant.

The largest electricity loss in a wind power plant is derived from the wake effect, which can be explained as the cylinder of air left by each wind turbine where the wind speed is reduced. For a large wind power plant, wake effect typically decrease electricity production from the wind power plant with about 10% annually. More short-term, the wake effect can range from a few percentage to as high as 20% depending on wind direction and wind power plant design. Other smaller energy losses in wind power plants are icing losses, friction losses due to dirt on blades, and losses in internal cables, for instance.

In general, Sweden has a good wind resource and the mean wind power density at an elevation of 100 m can be viewed in Figure 2.1. The purple dot in the figure marks the location of Garpenberg. The CF of new Swedish onshore wind power plants are commonly smaller than the CF of new offshore wind power plants. Typically, the CF of new onshore wind power plants ranges from 35 to 45% and the CF of new offshore wind power plants ranges from 45 to 55%. The wind resource changes on an hourly, daily and seasonal basis. In Sweden, it is most common that the wind speeds are highest at nighttime and during the winter months.

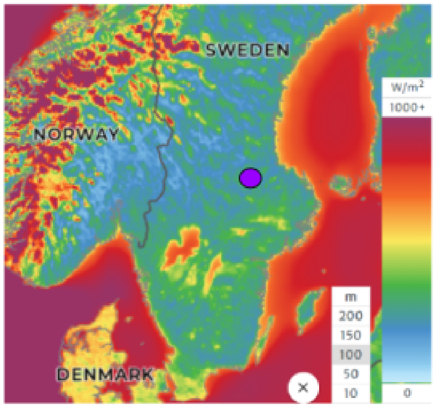


Figure 2.1: Map over average wind power density in southern and central Sweden. Image generated using Global Wind Atlas [9].

2.1.2 Solar power

The sun is an eternal source of energy on Earth. The sun emits electromagnetic radiation and the surface power density of the radiation is called solar irradiance. In solar cells, the energy in the sunlight is converted into electrical energy by the photovoltaic (PV) effect. A solar panel is a collection of several solar cells, which are wired together and assembled into a module [10]. There are various types of solar panels and the types differ in terms of efficiency, material usage and manufacturing costs. The most commonly used solar panels are monocrystalline and polycrystalline panels. Solar panels produce direct current and a maximum power point tracker (MPPT) is an electronic DC to DC converter that optimises the electricity production from a solar system. Inverters are widely used in solar systems to convert DC to AC before connection to the national grid. Solar systems can be implemented both on a small-scale for residential applications and large-scale for utility production of electricity. In an utility-scale solar power plant, a large collection of solar panels are connected in solar arrays internally before the plant is connected to the grid network [10].

Electricity losses in a solar power plant typically accounts for 10% of the direct electricity production from a solar array and can be derived from irradiance level, mismatched modules and inverter operation, for instance. Commonly, the installed solar power plant capacity is oversized in comparison to total inverter capacity by 30% to increase the number of hours the plant runs at peak power. The main reason for cutting the electricity production by the inverters is that inverters are generally more expensive than solar panels, and therefore it is desirable for the utilisation of inverter capacity to be high.

Sweden is located at high northern latitudes, and thus the solar irradiation within the country is low compared to countries closer to the Equator. The solar irradiation in central and southern Sweden can be viewed in Figure 2.2. The purple dot in the figure marks the location of Garpenberg. In general, a Swedish solar power plant has a CF of about 10%, provided that the solar power plant capacity is not overdimensioned in comparison to the inverter capacity. Solar power plants are characterised by electricity production only at daytime and most electricity production during the summer months.

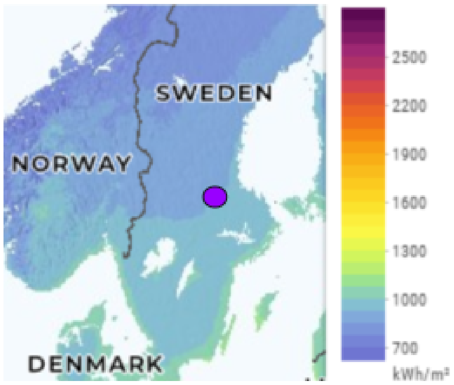


Figure 2.2: Map over average global horizontal irradiation in southern and central Sweden. Image generated using Global Solar Atlas [11].

2.1.3 Hybrid power

As previously stated, solar power is characterised by highest electricity production during the summer months and the opposite applies to wind power. Another difference between wind and solar power generation is the resource availability during a 24-hour period; solar power can only be generated at daytime and generate most electricity during cloudless days, while wind power can be generated all hours of the day but usually generate slightly less electricity in the middle of the day. The power generation by a wind power plant and a solar power plant is decently complementary and by coupling the power plants to a common grid-connection the drawbacks existing in each individual power solution can be benefited from. A hybrid power plant can contribute to better utilisation of a grid connection point and improve power balance in the national grid network [12]. It is noteworthy that the wind power plant and the solar power plant do not need to be constructed simultaneously for a hybrid power plant to be created, but a solar power plant can be installed close to an already existing grid-connected wind power plant, and thus increase the utilisation of an already existing grid connection point.

2.2 Energy storage

The power grid has to constantly be in balance, meaning that electricity must be produced and consumed simultaneously. An energy storage system (ESS) is a system that is capable of storing energy for the purpose of being able to supply energy at a later time. Energy storage can be used both on short and long-term to balance second-by-second, hourly, weekly and seasonal variations. The technological diversification of existing energy storage solutions is limited and mainly pumped hydro storage and batteries are implemented on a large-scale globally [4]. Nonetheless, there are other energy storage technologies that are currently being tested, such as compressed air and hydrogen storage, but the future of these technologies is still uncertain [6].

A conventional ESS is a stand-alone system that is directly connected to the national grid network. This form of ESS can help mitigate grid imbalances caused by intermittent electricity production [5]. Another configuration of an energy storage solution, is a system coupled with a power plant onsite [13][5]. In order to change the power generation to be obtained from VRES entirely, integration of storage systems are necessary. Energy storage systems can store excess electricity that is produced in times of beneficial weather conditions for renewable power generation and supply electricity to the national grid at times of unavailability of natural resources [14][13]. Energy storage in combination with a solar and/or wind power plant can both decrease the imbalances in the national grid network and prevent more volatile electricity production to be transferred to the grid. In addition, an ESS coupled with a hybrid power plant onsite can absorb excess electricity production from VRES, and thereby decrease generation curtailment [5].

Generation curtailment is the concept of reducing the electricity production below the level of electricity that is possible to produce at a specific time. The reason behind generation curtailment of wind and solar power in a hybrid power plant, is problems associated with weather forecasting, balancing supply and demand in the grid network and installing a smaller grid-connection capacity in comparison to wind and solar power plant capacity [15].

2.2.1 Pumped hydro energy storage

Pumped hydro technology is an old and globally established energy technology, and in 2018 the total installed pumped hydro storage capacity was 161 GW [5]. Nevertheless, IRENA calls for an increase in installed hydropower capacity on Earth to speed up the energy transition, and as part of this target, the institute predicts a duplication of the installed pumped hydro storage capacity by 2030 compared to 2018 [5]. In Sweden, five pumped hydro storage plants have existed, but today only three of these plants are still operated as pumped hydro storage plants and the other two have been converted into general hydroelectric power plants [6]. The total installed pumped hydro storage capacity of the currently existing plants: Letten power plant (36 MW), Kymmen power plant (55 MW) and Eggensjön power plant (less than 1 MW), is about 91 MW [6]. Eggensjön power plant is currently not often operated as a pumped hydro storage plant, but the possibility of reversible operation still exists.

The principle of pumped hydro storage is simple; utilise two water reservoirs at different elevations to store gravitational energy and connect the reservoirs through water conductors, pump and turbine units [5]. The energy storage is “charged” by using electricity to pump water from the lower reservoir to the upper reservoir and the energy storage is “discharged” by releasing water from the upper reservoir and passing it through turbines to generate electricity on its way to the lower reservoir. The energy stored (E) in the upper reservoir is determined by the formula in Equation 2.

$$E = V \cdot \rho \cdot g \cdot z \tag{2}$$

V: Volume of water storage (m^3)
ρ: Density of water (kg/m^3))
g: Gravitational constant ($m^3/(kg \cdot s^2)$)
z: Head = Elevation difference between upper and lower water reservoir (m)

The electricity is transferred in both directions between the pumped hydro storage power house and the grid connection point. A simple illustration of a pumped hydro storage scheme can be viewed in Figure 2.3.

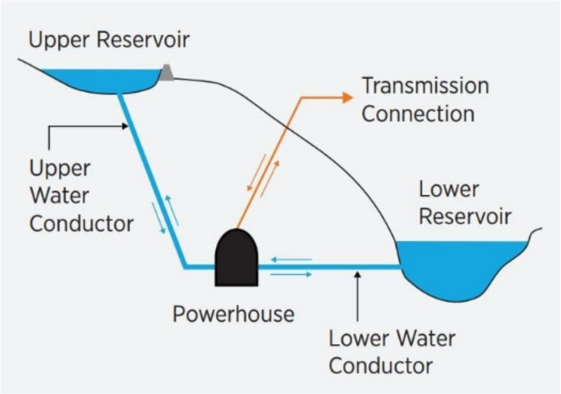


Figure 2.3: Overview of pumped hydro storage scheme. Sourced from [16]

In general, pumped hydro storage systems are divided into two types: closed and open-cycle systems. In a closed-cycle configuration, the two water reservoirs are isolated from each other and any natural water flow, whereas in an open-cycle configuration the two water reservoirs are in some manner connected to a natural water flow [5].

The fundamental components of a pumped hydro storage plant are the turbines, pumps, generators, switchgears, motors, control equipment and protection equipment [17]. These components can predominantly be found in the power house. There are three main configurations of motor, generator, pump and turbine: quaternary set, ternary set and binary set, which are illustrated in Figure 2.4. The most suitable configuration is determined by several factors such as head, infrastructure and desired relationship between efficiency and installation cost [18].

In a quaternary set, the pump and turbine is totally decoupled; a turbine-driven generator is connected to one penstock and a motor-driven pump is connected to another penstock [18]. This set has a high efficiency due to the individually optimised components, but the set is also associated with a high equipment and infrastructure cost [17]. A ternary set consists of a main shaft to which the pump, turbine, motor and generator are coupled [18]. The shaft can only rotate in one direction and when the turbine spins the generator - the pump is decoupled from the shaft. Likewise, when the motor drives the pump - the turbine spins in air. The ternary set can be advantageous to simplify the synchronisation to the national grid network and to increase the speed of the transition from pump to turbine mode and vice versa [17]. The most commonly used set nowadays is the binary set, where the motor and generator units are connected via a shaft to a reversible pump and turbine [17]. The shaft rotates in two directions depending on the operating mode: pump or turbine mode. When the pump is activated from standstill, the motor-driven pump is synchronised with the national grid network and the turbine runner is dewatered and spinning-in-air [17]. The binary set is characterised by the lowest infrastructure and equipment cost but has a lower efficiency than the quaternary and ternary set [17].

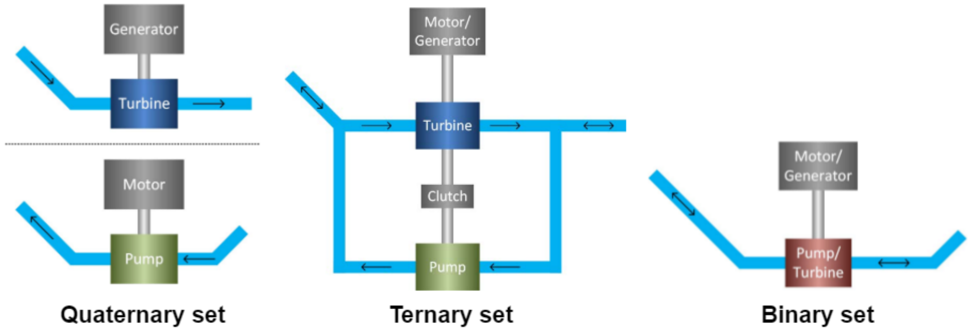


Figure 2.4: Different pumped hydro storage configurations. The three images are sourced from [17].

On the subject of electromechanical equipment, pumped hydro storage plants can be divided into two categories: fixed speed and variable speed plants [17] [18]. The variable speed option is more expensive than the fixed speed option but enables optimisation of operation in both pump and turbine mode over a larger range of heads and water flow rates [17]. In a fixed speed pumped hydro storage plant, the rotational speed of the motors and generators is fixed and synchronous machines are utilised to ensure that the rotation is synchronous with the national grid frequency [18]. In a variable speed pumped hydro storage plant, the motors and generators operate at various rotational speeds. The machines can be either singly-fed synchronous or doubly-fed asynchronous machines [17] [18]. Singly-fed machines are decoupled from the grid network with back-to-back converters and can therefore operate at various speeds independent upon grid frequency. The converters operate using DC electricity within the system and must be rated for full motor and generator power [17]. Doubly-fed asynchronous machines, on the other hand, are coupled to the grid network with static frequency converters. These converters operate at low-frequency AC, utilise variable AC electricity that is synchronous with the grid frequency and must not be rated for full motor and generator power [17] [18].

The turbine options in pumped hydro storage plants include Pelton, Francis and Kaplan turbines. The most suitable turbine option for a pumped hydro storage plant is mainly determined by the head and water flow rate [17]. The most popular turbine in modern pumped hydro storage plants is the reversible Francis pump and turbine that can be used for heads up to 700 m [17]. In a Francis turbine, guide vanes control the water flow and direct the water radially into the runner where pressure energy can be extracted due to the drop in pressure when water flows through the runner. The rotational kinetic energy of the turbine is transferred via a shaft to the generator where it is converted into electrical energy.

The average round trip efficiency of a pumped hydro storage plant is about 80% [17][19]. The round trip efficiency is obtained from multiplication of the plant efficiency in the two modes: pump and turbine mode. In pump mode, losses can be derived from operation of transformers, pumps and motors [17]. In turbine mode, losses can be derived from operation of transformers, turbines and generators [17]. Also, there are friction losses in the pipelines.

Pumped hydro storage in underground mines

The majority of the currently existing pumped hydro storage reservoirs are located above ground in mountain areas. In spite of that, modern hydropower technology has allowed for pumped hydro storage plants to be constructed in old mines. The concept of pumped hydro storage in abandoned underground mines is built upon a closed-cycle system where the lower reservoir is a former mining pit and the upper reservoir commonly is an artificial lake [20]. The upper reservoir could also be a former mining pit located at a higher elevation than the lower water reservoir. There is no shortage of abandoned mines in the world; currently there are more than 1 million disused mines without real purpose [21]. In Sweden, there is no existing mine storage as of today but two companies; Mine Storage and SENS, have performed extensive mine screening of Swedish mining areas and manages several pumped hydro storage projects under initial development [6]. When repurposing old mines, functioning infrastructure; including ventilation systems, mine corridors and grid connections, can be utilised to reduce construction costs and environmental impacts [21].

The power capacity, storage duration and efficiency of pumped hydro storage plants in old mines depends on several factors such as mine depth, water volume of reservoirs and pipeline diameter [17]. In general, it is estimated that a mine storage has an installed capacity of 15 to 200 MW, corresponding to 30 to 2400 MWh, and a storage duration of 2 to 12 h [21]. With modern equipment and just smaller equipment refits, the project lifetime of a mine storage is estimated as 40 to 80 years [21].

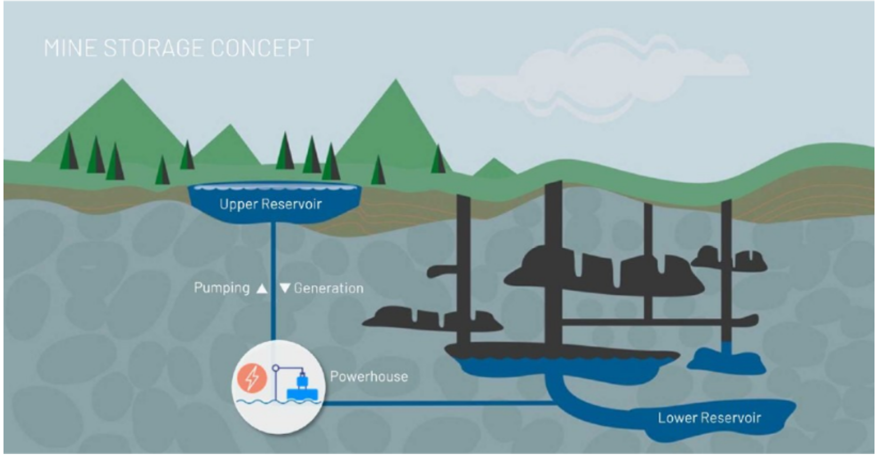


Figure 2.5: Concept of pumped hydro storage in underground mines. Sourced from [21].

2.3 The Swedish electricity system

In 2022, the total electricity production in Sweden was about 173 TWh [22]. The production was predominantly fossil-free and renewables accounted for 67% of the power generation [22]. The installed capacity of wind power was about 12,5 GW in 2021 and has increased steadily in recent years [3]. The installed capacity of grid-connected solar power increased 46% from 2020 to 2021 and was about 1,6 GW in 2021 [3]. The historical development of electricity production by source in Sweden between 2000 and 2022 is presented in Figure 2.6. The total electricity production has been fairly stable, but the share of electricity production by source has changed significantly.

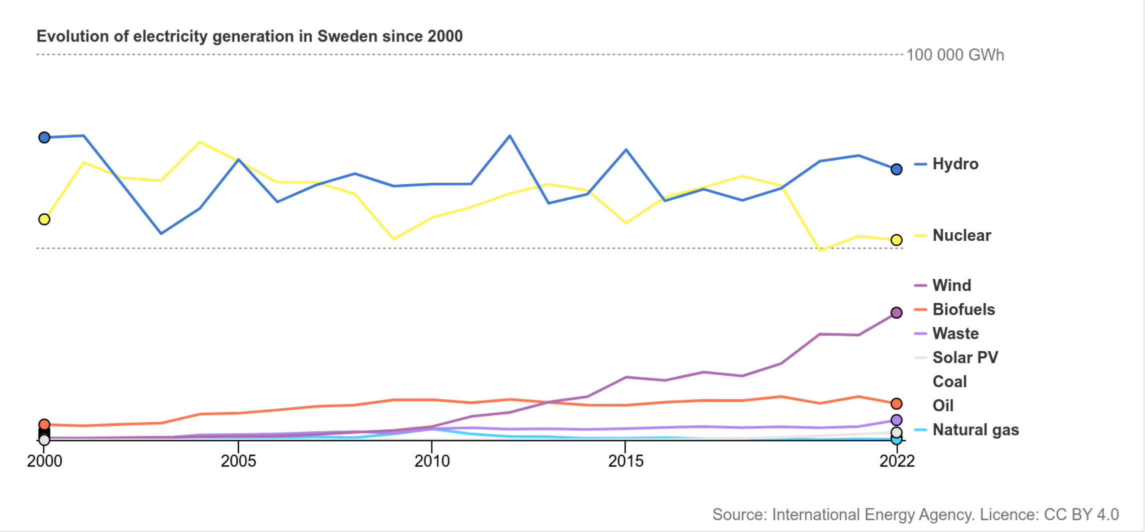


Figure 2.6: Historical development of electricity production by source in Sweden. Sourced from [22]

The Swedish electricity grid network can be divided into distribution networks, transmission networks and interconnection lines [23]. The transmission lines are administered and maintained by the transmission system operator (TSO), which in Sweden is Svenska Kraftnät (SvK) [23]. The transmission lines reach from northern to southern Sweden and create connections between large electricity suppliers, large electricity consumers and neighbouring countries' electricity grid network. The distribution networks transport electricity from the transmission lines to the remaining majority of electricity suppliers and consumers. The distribution networks can be divided into the regional and local networks and are owned by multiple power network companies [23].

The Swedish grid network is operated at 50 Hz and the Swedish TSO is responsible for frequency regulation of the power grid [24] [25]. Electricity can not be stored within the grid, and thus the addition and withdrawal of electricity must equal at all times to keep the frequency stable and power grid in balance. Balance responsible parties (BRPs) are companies that handle the economic responsibility to keep equilibrium between electricity production and consumption within the power grid. This responsibility is divided by electricity areas in Sweden [26]. Previously, the BRPs also have been market participants in the frequency regulation markets, and thus provided ancillary services, but from 1 June 2024 the provision of reserves are instead managed by the newly acquired balance service providers (BSPs) [26]. Frequency regulation markets will be explained in The Nordic electricity market section.

2.3.1 Electricity areas

Sweden is divided into four electricity areas: SE1, SE2, SE3 and SE4, which are numbered from northern to southern Sweden, as illustrated in Figure 2.7. The reason why electricity areas in Sweden were introduced in 2011 was physical limitations of the national grid network [27]. Grid congestion results in bottlenecks in the grid network, which affect the electricity market by giving each area its own electricity price when the transfer capacity will not suffice to deliver electricity between the areas. Another term for electricity area is ”bidding area” [27].

By observing the location of the electricity production and consumption in Sweden, it can be noticed that most electricity is produced in the northern parts of Sweden by mainly hydropower, but the majority of the population lives in the southern parts of Sweden [3][28]. In particular, various energy-intensive industries are located in SE3, as evident in Table 2.1. The electricity areas SE1 and SE2 are net-exporters of electricity and the electricity areas SE3 and SE4 are net-importers of electricity on a yearly basis [28]. Sweden, as a unitary country, is a net-exporter of electricity on a yearly basis, but is dependent upon electricity from neighbouring countries in times of peak electricity demand, bad wind resources and failures of large power plants [28] [29].

Figure 2.7: Map over electricity areas in Sweden. Sourced from [29].

Table 2.1: Electricity consumption in TWh by sector and electricity area in Sweden in 2021 [28].

Sector	**SE1**	**SE2**	**SE3**	**SE4**	**Total**
Households	1,7	3,6	25,0	7,6	37,9
Mineral extraction & manufacturing	6,3	6,9	26,3	6,8	46,3
Trade & Other	1,1	1,0	9,2	2,4	13,7
Contruction & property	0,5	0,9	9,8	2,6	13,8
Agriculture & forestry	0,1	0,3	1,6	1,0	3,0
Supply & Transport	0,5	0,9	6,0	1,4	8,8
Public services	0,4	0,8	4,8	1,3	7,4
Total (excl. grid losses)	10,6	14,4	82,7	23,2	130,9

2.4 Grid services

Grid services support the operation and management of the grid network and are essential for a well-functioning: stable, reliable and efficient, national grid. Various grid services can be provided by different energy technologies. A pumped hydro storage plant can provide several grid services such as inertial response, frequency control, voltage support, black-start capability, load shifting, fast ramping and generating capacity [5] [19]. When pumped hydro storage is co-integrated with renewable power plants, the total system can provide curtailment reduction and capacity firming [5] [18] [30]. Furthermore, the system can provide black start capability, which means that a pumped hydro storage plant can restart itself without the support from external power supply [31]. Black-start capability is valuable for the grid network in the event of blackout or outage. A subset of grid services, which are not part of the original process of electricity production and delivery, are called ancillary services.

In the following three sections, the grid services: inertial response, voltage control and flexibility reserve, are further explained. Curtailment reduction was previously discussed in the Energy storage section, black-start capability is explained in the text above and frequency control services are introduced with respect to frequency regulation markets in the Frequency regulation market section.

2.4.1 Inertial response

Rotational kinetic energy is stored when large generators spin, causing the generators to remain rotating. Rotational inertia is referred to as the rate of frequency change when generators spin [32]. Machines with high mechanical inertia can resist drops in frequency and limit the impact of the drops. Frequency drops are usually an effect of failures in transmission networks or power plants and temporary response to the drops, provided by mechanical inertia, can limit the size of the drops [32]. The power plants that currently supply mechanical inertia to the Swedish grid network are thermal, nuclear and hydropower plants, for instance. Common to these power plants is that they use grid-connected synchronous generators and often have large turbines [33]. Wind power plants and solar power plants are grid-connected through power electronics and can for this reason not contribute with mechanical inertia.

Considering the energy transition to more wind and solar power, the Swedish Energy Market Inspectorate (EI) contemplates the loss in system inertia within the Swedish grid network a problem. In this regard, grid integration of pumped hydro storage plants can bring significant value to the functionality of the power grid since a pumped hydro storage plant consists of turbines and generators that can supply mechanical inertia [5]. It is also noteworthy that energy storage in the form of batteries can not supply mechanical inertia, but remuneration for inertial response is provided for participation on the FFR market, which has a similar function as inertial response, and it is mainly batteries that participate on this market.

2.4.2 Voltage control

Reactive power affects the voltage level in the transmission grid network. Renewable power plants, such as wind power plants and solar power plants, are technically capable to provide reactive power just like plants with synchronous generators. A pumped hydro storage generator has an excitation system that can control the conductors and field windings of the electromagnets, and thereby change the reactive power [17]. The Swedish grid network operates at a voltage around 1 pu and proper voltage regulation is important to maintain the voltage level and ensure high quality operation of the national grid. In the Swedish electricity markets, there are currently no compensation provided for grid voltage control services but the technical value of this is being investigated by the Swedish TSO.

2.4.3 Flexibility reserve

Flexibility in the context of power systems refers to the ability of consumption or generation to adapt to system needs, possibly reflected by price signals [6]. A flexible system is necessary to increase the integration of grid-connected wind power plants and solar power plants and to efficiently operate the power grid [6][33]. Pumped hydro storage plants can improve the grid operator's potential to regulate the grid network by serving as a flexibility reserve [5][6]. Large-scale pumped hydro storage can provide both long-term and short-term flexibility, whereas small-scale pumped hydro storage mainly provides short-term flexibility. Revenue streams for flexibility reserves are currently not generally provided in Sweden, anyhow the concept of local flexibility markets are at present successfully being tested in six provinces of Sweden [6].

2.5 The Nordic electricity market

The Nordic countries have a multinational market for electricity trading. The market consists of multiple marketplaces; each marketplace corresponding to a specific time window prior to the physical trading of electricity, also known as the operating hour [28]. An overview of the markets is presented in Figure 2.8.

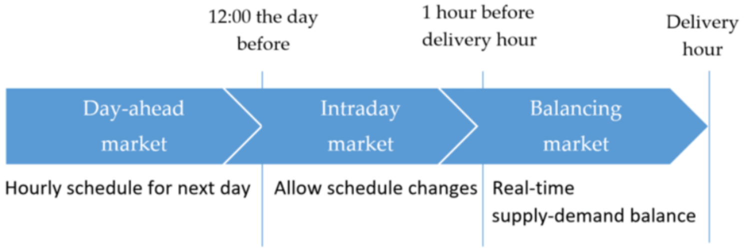


Figure 2.8: Overview of Nordic electricity markets from a time perspective. Sourced from [34].

The largest marketplace for electricity trading in Sweden is the power market Nord Pool [28]. Nord Pool offers multinational power exchange within Europe on both the day-ahead market and intraday market [28][35]. The balancing markets, also known as frequency regulation markets, provide market-based compensation to providers of reserves to be on standby in case of frequency disturbances. These markets are offered by the TSO in Sweden [36].

2.5.1 Financial settlement

Derivative contracts are utilised for financial risk management and to guarantee prices. They can be traded long before the operating hour and this financial market is provided by NASDAQ OMX Commodities Europe [28].

2.5.2 Day-ahead market

The day-ahead market, also known as the spotmarket, allows participants to submit bids for selling and buying electricity each of the 24 hours of the following day [37]. The participants on the day-ahead market are electricity producers, electricity retailers and large electricity consumers. A bid must pertain to a specific bidding area in Sweden and include the operating hour, the quantity of electricity and the lowest price at which an electricity producer is willing to sell electricity or the highest price at which an electricity consumer is willing to buy electricity [37]. The electricity auction takes place at 12:00 p.m. the day before the operating day and is conducted such that electricity supply matches electricity demand, establishing a marginal price. Due to the fact that the bids are submitted for each hour and each bidding area, also the electricity price can fluctuate on an hourly basis and differ between bidding areas if bottlenecks occur [37]. In Sweden, most electricity is traded on the day-ahead market [28]. The average electricity price on the day-ahead market in Sweden between 2012 and 2022 is presented in Figure 2.9. Between 2012 and 2019 the average spotprice increased, but it did not vary greatly between electricity areas. However, from 2020 onwards the spotprice in electricity area SE3 and SE4 was significantly higher than the spotprice in electricity area SE1 and SE2.

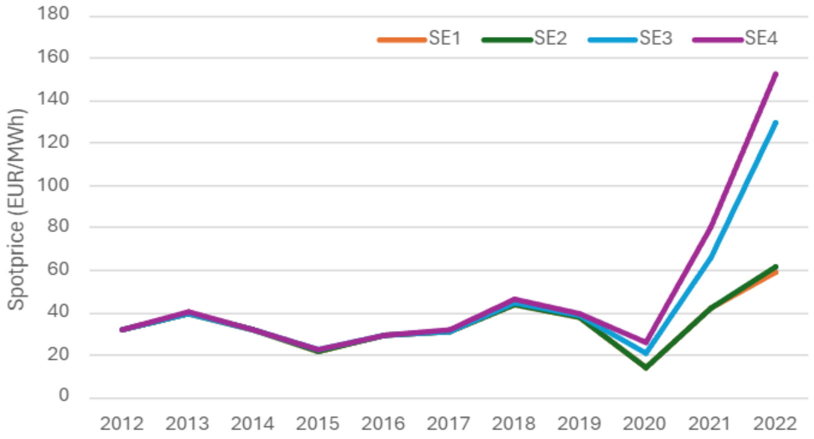


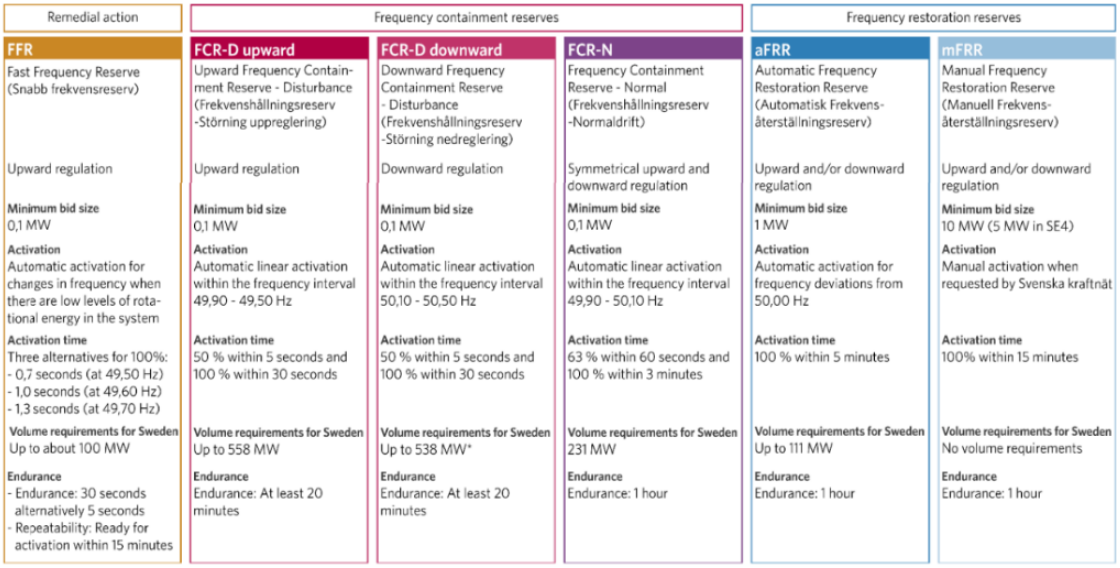
Figure 2.9: Historical development of spotprice by electricity area in Sweden. Data is sourced from [28].

2.5.3 Intraday market

The intraday market has the task of adjusting the electricity trading on the day-ahead market closer to the physical trading of electricity. The electricity trading on the intraday market opens three hours after the closure of the day-ahead market and closes one hour before the operating hour [38]. Sell and buy bids are continuously matched when the intraday market is open, and thus the pricing method applied is pay-as-bid pricing [28]. If there is grid capacity available, electricity can also be traded between bidding areas on this market [38]. Chiefly, the participants on the intraday market are BRPs wanting to ensure that they are in electricity balance at the start of an operating hour. A well-functioning intraday market is necessary to minimise the financial risks associated with investments in wind and solar power generation.

2.6 Frequency regulation markets

The power balance within the national grid network must be preserved at every second, and in order to ensure that the electricity supply in Sweden is reliable, the Swedish TSO purchases reserves [39]. The reserves are provided by BSPs and can consist of different units: energy storage units, production units and units that can adapt to electricity consumption [24]. To increase competition in the purchase of reserves and enhance diversification of reserve units, the Swedish TSO has established markets for reserves. The reserves are divided into four types of reserves: FFR, FCR, aFRR and mFRR, on the basis of various factors such as response time and endurance [24] [39]. This division of reserves sets the framework for the existing frequency regulation markets in Sweden, as established in Figure 2.10.



Remedial action	Frequency containment reserves			Frequency restoration reserves	
FFR	**FCR-D upward**	**FCR-D downward**	**FCR-N**	**aFRR**	**mFRR**
Fast Frequency Reserve (Snabb frekvensreserv)	Upward Frequency Containment Reserve - Disturbance (Frekvenshållningsreserv -Störning uppreglering)	Downward Frequency Containment Reserve - Disturbance (Frekvenshållningsreserv -Störning nedreglering)	Frequency Containment Reserve - Normal (Frekvenshållningsreserv -Normaldrift)	Automatic Frequency Restoration Reserve (Automatisk Frekvens-återställningsreserv)	Manual Frequency Restoration Reserve (Manuell Frekvens-återställningsreserv)
Upward regulation	Upward regulation	Downward regulation	Symmetrical upward and downward regulation	Upward and/or downward regulation	Upward and/or downward regulation
Minimum bid size 0,1 MW	**Minimum bid size** 0,1 MW	**Minimum bid size** 0,1 MW	**Minimum bid size** 0,1 MW	**Minimum bid size** 1 MW	**Minimum bid size** 10 MW (5 MW in SE4)
Activation Automatic activation for changes in frequency when there are low levels of rotational energy in the system	**Activation** Automatic linear activation within the frequency interval 49,90 - 49,50 Hz	**Activation** Automatic linear activation within the frequency interval 50,10 - 50,50 Hz	**Activation** Automatic linear activation within the frequency interval 49,90 - 50,10 Hz	**Activation** Automatic activation for frequency deviations from 50,00 Hz	**Activation** Manual activation when requested by Svenska kraftnät
Activation time Three alternatives for 100%: - 0,7 seconds (at 49,50 Hz) - 1,0 seconds (at 49,60 Hz) - 1,3 seconds (at 49,70 Hz)	**Activation time** 50 % within 5 seconds and 100 % within 30 seconds	**Activation time** 50 % within 5 seconds and 100 % within 30 seconds	**Activation time** 63 % within 60 seconds and 100 % within 3 minutes	**Activation time** 100 % within 5 minutes	**Activation time** 100% within 15 minutes
Volume requirements for Sweden Up to about 100 MW	**Volume requirements for Sweden** Up to 558 MW	**Volume requirements for Sweden** Up to 538 MW*	**Volume requirements for Sweden** 231 MW	**Volume requirements for Sweden** Up to 111 MW	**Volume requirements for Sweden** No volume requirements
Endurance - Endurance: 30 seconds alternatively 5 seconds - Repeatability: Ready for activation within 15 minutes	**Endurance** Endurance: At least 20 minutes	**Endurance** Endurance: At least 20 minutes	**Endurance** Endurance: 1 hour	**Endurance** Endurance: 1 hour	**Endurance** Endurance: 1 hour

Figure 2.10: Overview of reserve types and requirements on reserves in Sweden. Sourced from [39].

The historical development of the Swedish TSO's annual remuneration cost for different reserve types and forecasts of future development can be seen in Figure 2.11.

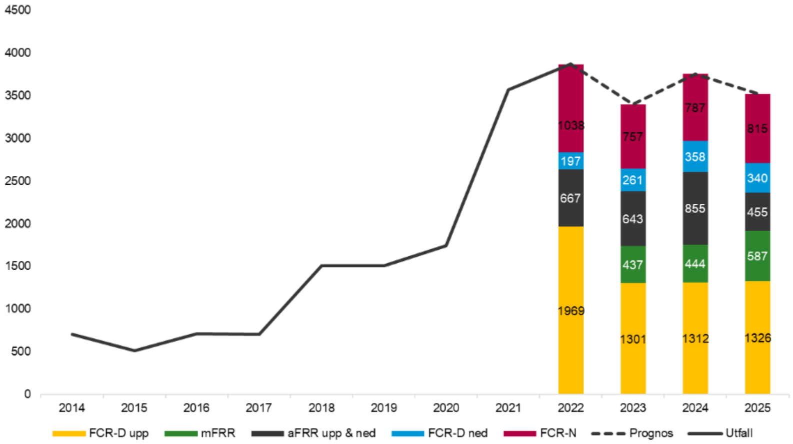


Figure 2.11: The Swedish TSO´s annual expenditure in MSEK on ancillary services. Sourced from [40]

2.6.1 Fast frequency reserve

The fast frequency reserve, abbreviated as FFR, is activated if low levels of inertia occur in the Nordic power grid. This reserve handles rapid and transient frequency deviations and is activated within 1,3 seconds at 49,70 Hz, 1,0 seconds at 49,60 Hz and 0,7 seconds at 49,50 Hz [24].

2.6.2 Frequency containment reserve

The frequency containment reserve, abbreviated as FCR, is essential to ensure grid balance in event of any deviation from the standard frequency. This reserve is activated automatically when the frequency deviates from the frequency interval it is intended to support. FCR is further divided into three FCR-products: FCR-N, FCR-D upward and FCR-D downward [24]. FCR-N is activated during normal operation of the power grid with small frequency changes ranging from 49,90 Hz to 51,10 Hz [24]. FCR-D is activated during disturbances; the upward reserve when the frequency is below 49,90 Hz and the downward reserve when the frequency is above 50,10 Hz [24].

2.6.3 Automatic frequency restoration reserve

The automatic frequency restoration reserve, abbreviated as aFRR, has the purpose of automatically restoring the frequency to 50 Hz after a larger deviation [24].

2.6.4 Manual frequency restoration reserve

The manual frequency restoration reserve, abbreviated as mFRR, is manually regulated by the TSO when control signals indicate that the frequency has deviated from 50,0 Hz [24]. The objective of the manual regulation of frequency is to offload the automatically activated reserves.

2.6.5 Providers of reserves

To qualify as a provider of a reserve, the provider must meet technical requirements in accordance with the European Network of Transmission System Operators for Electricity (ENTSO-E) [24]. The Swedish TSO collaborates with ENTSO-E to strengthen the Swedish interconnection with the European Union and promote an open electricity market [41]. The technical requirements differ between reserve types and for a reserve unit to qualify as a provider of a specific reserve type it must demonstrate that the requirements are fulfilled. Reassessment of reserves occurs if requirements change or at 5-year intervals [24]. A company must cooperate with or be a BSP to participate in frequency regulation markets, excluding the FFR market. An application of interest can be submitted to the TSO if a potential reserve provider is doubtful which reserves an unit can provide [24].

2.6.6 Procurement of reserves

Procurement of reserves occurs on different time horizons depending on reserve type, as illustrated in Figure 2.12. Procurement of FFR takes place on an annual basis. FCR-products are procured one day ahead of the physical electricity trading during two interdependent auctions. The largest volume of FCR-products is procured in the first auction [24]. Before 1 February 2024, FCR-products applied pay-as-bid pricing but this was adjusted, and currently FCR-products apply pay-as-cleared pricing, also known as marginal pricing [42]. Similar to FCR-products, procurement of aFRR takes place one day ahead of the physical electricity trading. mFRR is procured in two markets: mFRR capacity and energy market. In the capacity market, procurement takes place one day ahead of the physical electricity trading and in the energy market, procurement takes place from the closure of the day-ahead market to 45 min before the operating hour. Both aFRR and mFRR apply pay-as-cleared pricing [24].

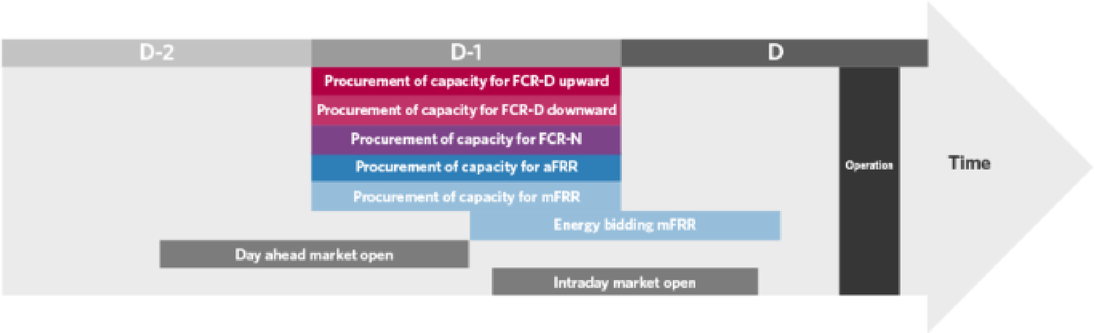


Figure 2.12: Time horizon on procurement of reserves in Sweden. Sourced from [24]

The TSO determines whether to accept or reject bids. If a bid is accepted, remuneration is provided to the reserve provider but it is not until the TSO calls for provision of the intended service that the service should be provided. Remuneration is always provided for a reserve to be prepared to provide a service since reserve availability is important for the TSO in event of unexpected imbalances. Conditional upon reserve type, additional remuneration is also provided for activation of reserves.

2.6.7 Imbalance settlement

Up to two weeks after the operating hour, a BRP can be eligible to pay imbalance fees if disproportion in supply and consumption occurred during the operating hour [39].

2.7 Participation in electricity markets

The largest volume of electricity in Sweden is traded on the day-ahead market [37]. All power plants are allowed to participate in this market as long as they meet certain criteria in terms of environmental regulations, market rules and reliability standards. The intraday market is the second largest electricity market in Sweden, but the current trading volume on this market is significantly smaller than the trading volume on the day-ahead market [43]. As of today, wind and solar power plants can participate in frequency regulation markets such as the FCR-D and mFRR, but the participation of variable renewable power plants in these markets are still not very common.

It is important to mention that there is a strong upward trend in terms of trading volume on the intraday market in Sweden due to the increased share of wind power in the Swedish electricity mix [43]. The inability to dispatch wind and solar power and imposition of high imbalance fees incentivise BRPs to adjust electricity bids closer to the operating hour. Germany and the Netherlands are two countries in Europe with prominent high shares of VRES in their electricity mixes. In these countries, the trading volume on the intraday market is currently almost half of the trading volume on the day-ahead market. In 2022, a 90% growth on the previous years total intraday market trading was observed on the Nord Pool marketplace in central and western Europe. This can be compared to a growth of 50% on the total intraday market trading in the whole of Europe [44]. Starting in 2023, the intraday market in the Nordic countries will gradually transition to intraday trading with a temporal resolution of 15 minutes instead of one hour, which is already common in central Europe [43].

The participation of energy storage in electricity markets is highly dependent upon storage technology and the functionality of the specific technology. The authors of [18] explain that pumped hydro storage plants can participate in both day-ahead, intraday and frequency regulation markets. This is confirmed by the authors of [45] that investigate the desirability of energy storage in the Nordic electricity markets. A special focus in the report [45] is placed on the possibility of energy storage units to provide ancillary services.

In view of the flexible nature of energy storage technologies, energy storage units are well-suited as reserves as long as technical requirements are met. Which frequency regulation markets that a specific energy storage unit can participate in, is contingent upon plant performance; response times and ability to shift between different operating modes on command by the TSO. In terms of pumped hydro storage, the plant performance is mainly dependent upon the plant configuration; which set and turbine type is used, but also head and energy storage size affect the functionality and operation of the plant. In view of that pumped hydro storage plants have not yet provided reserves in Sweden, there are uncertainties surrounding pumped hydro storage participation in Swedish frequency regulation markets [45].

2.8 Power purchase agreements

Power purchase agreements, abbreviated as PPAs, are contractual agreements between electricity producers and electricity consumers and these agreements play a crucial role in the renewable energy sector [46]. Commonly, the electricity producers are responsible for large power plants and the electricity consumers are responsible for large energy-intensive industries. PPAs should benefit both parties by ensuring a steady revenue stream and a trustworthy electricity supply during a specific time period, as stipulated in the agreements. In addition to the number of years the agreements are valid, PPAs must pertain rules regarding electricity production; how much electricity that should be sold and purchased and to what electricity price [46]. Overall, PPAs are divided into two types: pay-as-produced PPAs and baseload PPAs, which are further explained in the following sections.

2.8.1 Pay-as-produced PPA

What characterises a pay-as-produced PPA is that the electricity producer receives a fixed price for every unit of energy delivered to the electricity consumer [46]. This PPA is often preferable for trading with electricity from VRES since renewable power generation is difficult to predict on a daily basis. Also, the possible electricity delivery from wind and solar power varies on a yearly basis and with a pay-as-produced PPA, the electricity producer is not penalised for the natural weather variations [46].

2.8.2 Baseload PPA

Baseload PPAs provide a fixed amount of electricity delivered to electricity consumers, and thus both the electricity production and payment is constant during a year [46]. The structure of baseload PPAs is advantageous for conventional power plants, which uses dispatchable sources of energy such as oil, coal or natural gas, since these plants can guarantee a somewhat consistent electricity supply. For electricity trading with renewable power generation, fixed-shape baseload PPAs can be costly for the electricity producers if underproduction forces the producers to buy expensive electricity from the day-ahead market to meet the terms in the agreements. In order to better adapt baseload PPAs to VRES, fixed-shape baseload PPAs for renewables have recently been developed [46]. These PPAs take into account electricity production forecasts but still limit the minimum level of electricity delivery.

3 Methodological framework

3.1 System overview

The system investigated in this thesis is a grid-connected wind and solar power plant coupled with pumped hydro storage system. As previously stated, the system as a whole consists of four main components: WPP, SPP, GCP and PHES, and all of these components are connected to the PCC, as shown in Figure 3.1. The study on this system is built upon the case study of Project Garpenberg. In the study, the WPP component was assigned a fixed value on installed power capacity of 140 MW and also the GCP component was assigned a fixed value on power capacity of 140 MW. The starting point for the SPP component was a value on installed inverter power capacity of 105 MW but this value was not considered fixed, and thus the value was varied in the analysis. From the beginning, the PHES system component was neither assigned a fixed value on installed power capacity nor installed storage size, but instead different energy storage dimensions were tested in the methods.

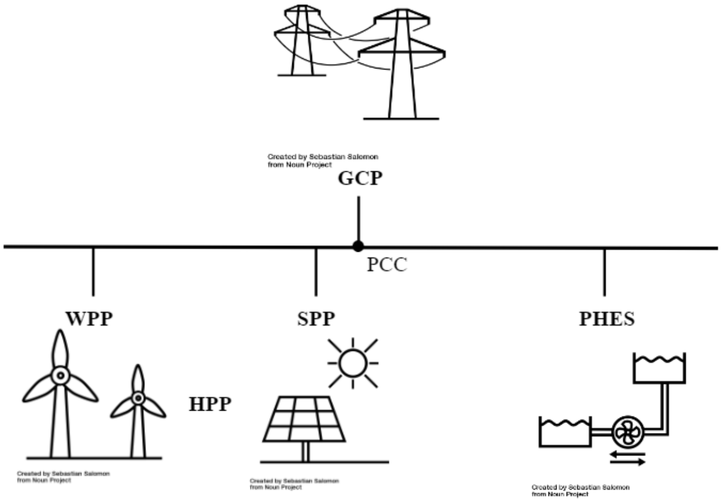


Figure 3.1: Overview of hybrid power plant with pumped hydro storage system. Icons are sourced from [7].

3.2 Data collection

Information on hourly electricity production from wind and solar power in Garpenberg and spotprice in SE3 was kindly provided by Eolus Vind. Data from last year: 2023, was chosen since it is the latest entire year with data available. In the last few years, much has changed with regards to the Swedish power system and electricity markets, and therefore it was of great importance to use as up-to-date data as possible. The data collection information is compiled in Table 3.1. The electricity production data is assumed to correspond to the electricity that is expected to reach the PCC within the system.

The study on the pumped hydro storage system component consider pumped hydro storage plants in general. Thus, a specific plant configuration is not considered in this thesis and no clear distinctions are made between pumped hydro storage plants in underground mines and plants above ground. Nevertheless, due to the fact that there is a lack of mountain areas but plenty of old mining areas in southern and central Sweden, pumped hydro storage in underground mines possesses the best potential considering the case study of Project Garpenberg.

Table 3.1: System data collection information.

Data	Resolution	No. of data points	Unit	Year	Source
Wind power generation	1-hour	8760	MWh	2023	Eolus Vind
Solar power generation	1-hour	8760	MWh	2023	Eolus Vind
Spotprice SE3	1-hour	8760	EUR/MWh	2023	Eolus Vind

3.3 Method design

The structure of the main method is rooted in the first stages of a general renewable energy project development model used by Eolus Vind, for instance. Their project development model encompasses initial business case evaluation, market analysis, pre-design and feasibility studies in the initial stage.

This thesis employ four different methodological approaches. Two of these methods are data analysis methods and the other two are modelling and simulation methods. The four methods proceed in sequential order: initial data analysis, energy management modelling, electrical system simulation and techno-economic analysis. An overview of the method design is presented in Figure 3.2 and the overview is further explained in the following text.

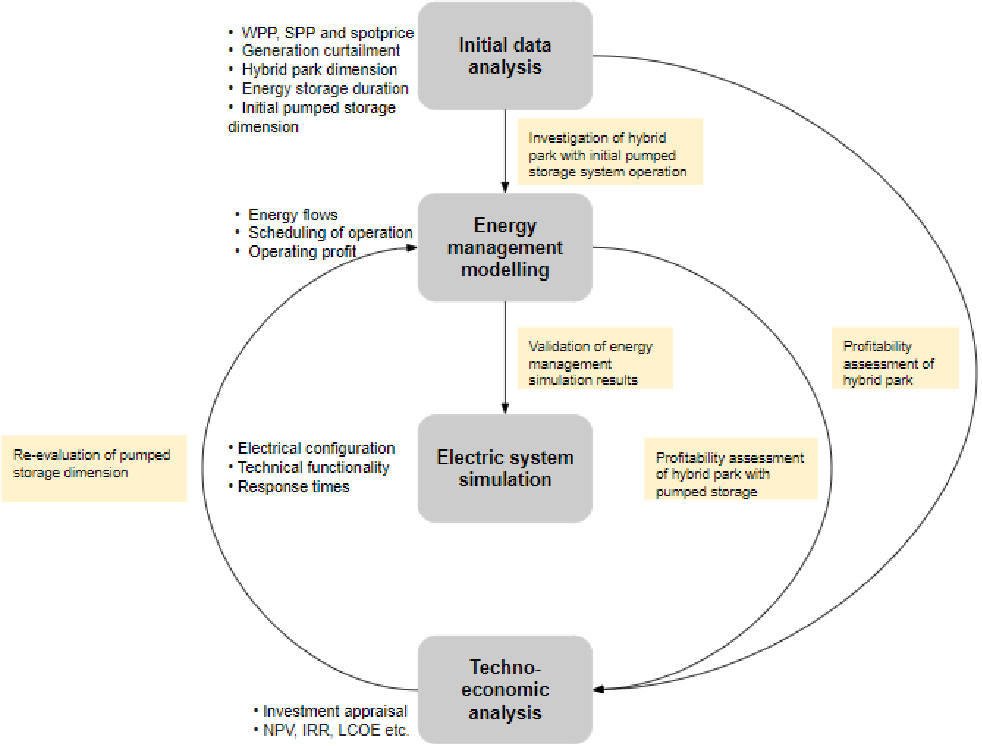


Figure 3.2: Overview of the method design employed in this thesis.

In the initial data analysis, the data on wind and solar power generation from the hybrid power plant in the case study of Project Garpenberg was analysed. The main purpose of the analysis was to investigate the patterns of electricity production and generation curtailment at different sizes of the solar power plant. Based on generation curtailment data and possibility of real-world appliance, the SPP system component was assigned a fixed value on installed power capacity that also was employed in the forthcoming methods. Furthermore, the specific need for energy storage coupled with the hybrid power plant was examined and a reasonable storage duration of the PHES system component was determined. With respect to the chosen storage duration, an initial size of pumped hydro storage plant in terms of installed power capacity and storage size was decided.

The initial data analysis method is followed by the energy management modelling method. A mathematical model on energy management of a combined hybrid power plant and pumped hydro storage system was programmed with MatLab and applied to the case study. The model focuses on optimising the operating profit with respect to electricity flows within the system, technical constraints of components and costs associated with deterioration of the pumped hydro storage plant. By simulating the model, it was possible to obtain information on optimal system operation; the electricity flows within the system, the variations in energy storage level and the expected revenue from electricity sales to the grid. The only input data that was varied between different simulations was the pumped hydro storage power capacity and storage size.

In the electrical system simulation method, a combined hybrid power plant and pumped hydro storage electrical system configuration was chosen and modelled with OpenModelica. Focus in the model was system functionality; that no technical limitations on maximum power capacities are exceeded and that the system can respond fast enough to changes in electricity production from wind and solar power. In this thesis, the electrical system model is used to test the results of simulations of the energy management model, and thus investigate if the proposed system operation and configuration has possible real-world application.

Finally, the techno-economic analysis method is designed to examine the techno-economic feasibility of the grid-connected hybrid power plant with pumped hydro storage project during its lifetime. Potential returns and risks associated with investments in renewable energy projects was evaluated in an investment appraisal where IRR and LCOE were calculated. An investment appraisal of a stand-alone grid-connected hybrid power plant system, called scenario 1, was performed based on results of the initial data analysis. Investment appraisals of the grid-connected hybrid power plant with pumped hydro storage system, called scenario 2, were also performed and by comparing the results of scenario 1 and 2 it was possible to evaluate the economic benefits of pumped hydro storage connected to the hybrid power plant.

For scenario 2, multiple investment appraisals were conducted based on results of energy management simulations with different sizes of energy storage. The starting point for the techno-economic dimensioning was the size of energy storage suggested in the initial data analysis and based on the techno-economic results of that energy storage size other dimensioning attempts were made. It was an iterative process between testing pumped hydro storage dimensions in the energy management model, validating the simulation results using the electrical system model, inserting the energy management simulation results in financial calculations, analysing the techno-economic results with the aim of finding another energy storage size that could be even more profitable and, subsequently, repeat the process for the new dimension in another attempt. The process ended after a few attempts and a final energy storage dimension was chosen for the combined hybrid power plant and pumped hydro storage system.

4 Initial data analysis method

4.1 Initial data presentation

The initial data consists of electricity production from Garpenberg WPP (140 MW), Garpenberg SPP (105/160/210 MW), the total electricity production from Garpenberg HPP (245/300/350 MW) and spotprice in SE3 in 2023.

4.1.1 Wind and solar power generation

The CF of Garpenberg WPP (140 MW) and SPP (105 MW) in 2023 was 45% and 15% respectively. The CF of Garpenberg SPP is high considering that the solar power plant is located in Sweden, but the high CF depends on the fact that the solar power plant is overdimensioned with 30% in relation to the inverter capacity. Hence, Garpenberg SPP (105 MW) has an installed inverter power capacity of 105 MW, while the PV modules have a total installed peak power capacity of about 140 MW. The average hourly electricity production from Garpenberg WPP (140 MW) and SPP (105 MW) per month can be viewed in Figure 4.1. The hourly distribution of electricity production from the wind power plant and solar power plant is illustrated in Figure 4.2. The wake losses and other electricity losses; such as friction losses in cabels and availability, are included in the hourly wind power generation data. Also, the electricity losses within Garpenberg SPP are included in the solar power generation data.

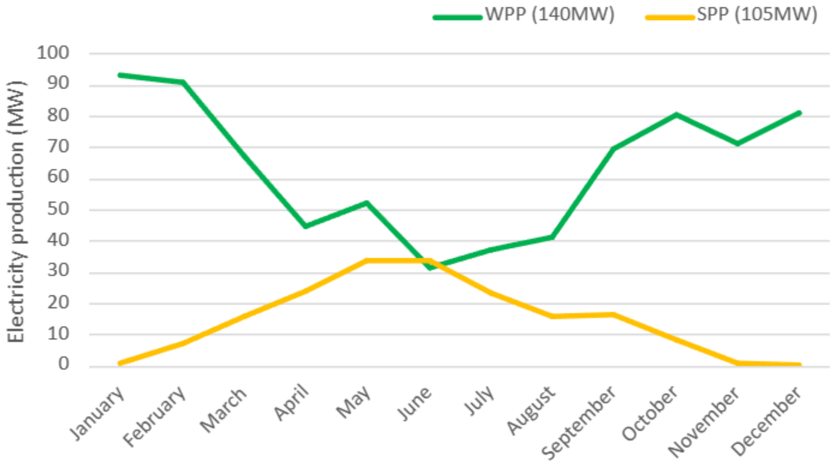


Figure 4.1: Monthly averages of hourly electricity production from the wind power plant and the solar power plant per month.

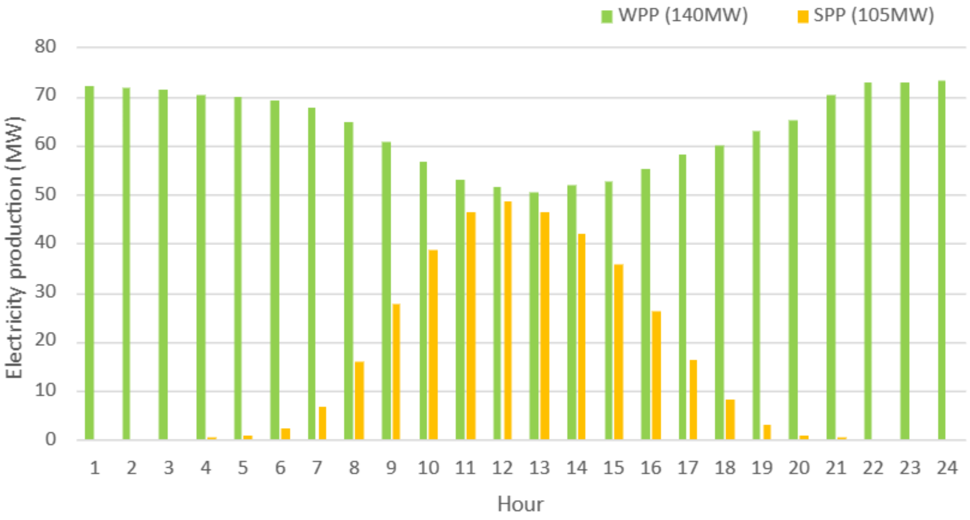


Figure 4.2: Average hourly electricity production from the wind power plant and the solar power plant each hour of a day.

4.1.2 Electricity prices

The CF of Garpenberg HPP (245 MW) in 2023 was 27 % and the average hourly electricity production from the hybrid power plant is illustrated in Figure 4.3. In the same figure, the hourly spotprice can be viewed. The average hourly distribution of electricity production from Garpenberg HPP (245 MW) and spotprice is illustrated in Figure 4.4.

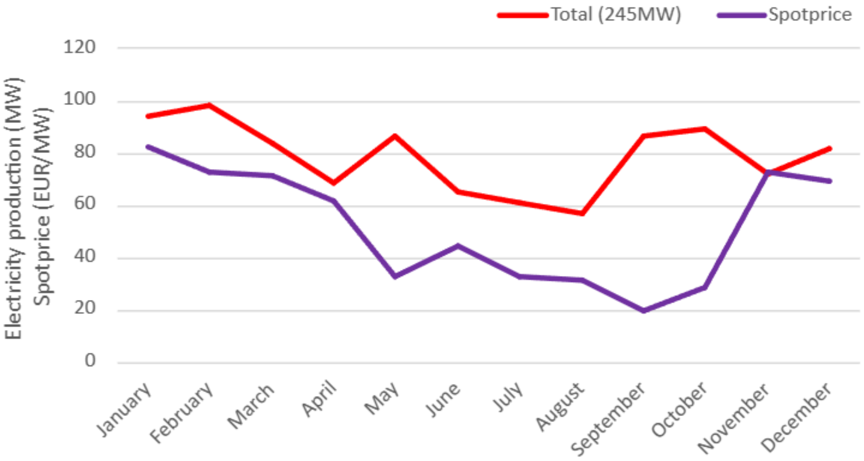


Figure 4.3: Monthly averages of hourly electricity production from the hybrid power plant and spotprice.

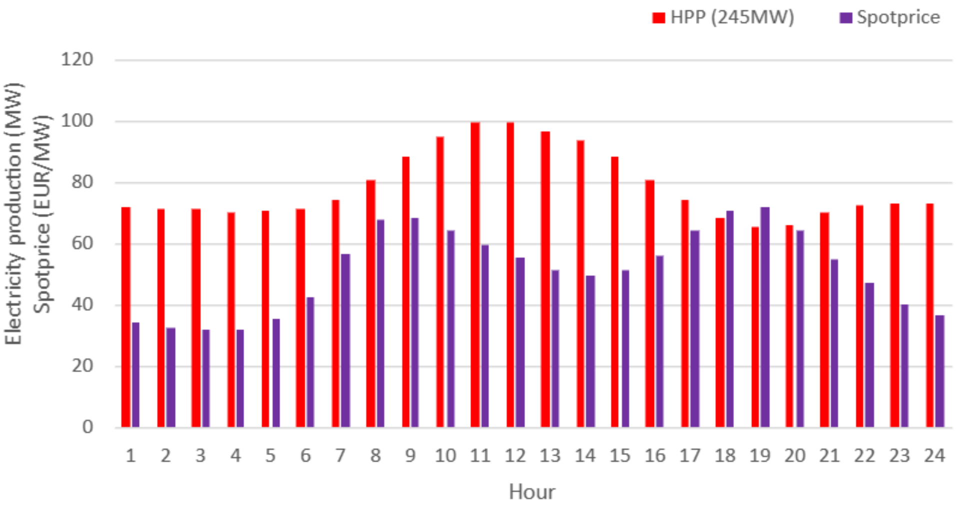


Figure 4.4: Average hourly electricity production from the hybrid power plant and spotprice each hour of a day.

4.2 Data analysis technique

The initial data was analysed using Excel. Data calculations were performed and the results are presented in tables and figures. The data analysis consider both technological and economic aspects of combined hybrid power plant and pumped hydro storage projects, and especially generation curtailment, price cannibalisation and electricity arbitrage trading was studied in the analysis. These three subjects of focus are briefly explained later in this section. Based on the initial data analysis, a general understanding of desired energy storage operation and an indication on a reasonable size of energy storage to couple with the hybrid power plant was expected. The reasonableness of the data analysis was investigated by comparing the analysis results with what was expected from the theoretical background and previous research studies.

4.2.1 Generation curtailment

As aforementioned, generation curtailment is the concept of reduction in electricity production below the level of electricity that is possible to produce at a specific time [15]. The reason behind curtailment of wind and solar power generation in a hybrid power plant is problems associated with weather forecasting, balancing supply and demand in the national grid and having a smaller grid-connection capacity in comparison to the total installed hybrid power plant capacity. Generation curtailment can be divided into power and energy curtailment. Power curtailment is the immediate power of the surplus electricity production that the system needs to quickly regulate in order to not damage electrical components, whereas energy curtailment is the amount of energy that is curtailed on every occasion that the electricity production exceeds the grid-connection capacity.

4.2.2 Price cannibalisation

Generation curtailment of wind and solar power occurs hours with good natural wind and solar resources and electricity from these renewable sources accounts for a significant part of the Swedish electricity mix. Consequently, the electricity supply is commonly high in Sweden when much renewable electricity can be produced, leading to lower electricity prices on the market. The connection between high variable renewable electricity production and low electricity prices is called price cannibalisation and can be problematic if electricity prices drop below the levelised costs [47]. More installed grid-connected renewable energy capacity can undermine its own value by lowering the feasibility of new renewable energy projects and preventing the construction of additional wind power plants and solar power plants. Price cannibalisation is of great interest in the analysis of revenue losses from generation curtailment and possible revenues from shifting production in time using pumped hydro storage.

4.2.3 Electricity arbitrage trading

Electricity arbitrage trading is the concept of generating profit by selling electricity when electricity prices are high and buying electricity when electricity prices are low [48]. Energy arbitrage trading commonly refers to trading on the day-ahead market, but the concept is also applicable to trading on other markets as the intraday market, for instance.

5 Energy management modelling method

5.1 Energy system overview

An illustration of the grid-connected hybrid power plant with pumped hydro storage system is presented in Figure 5.1. The possible flows of electricity within the system is highlighted and generation curtailment is included in the figure to demonstrate that part of the electricity that reach the PCC is curtailed. Generation curtailment is illustrated using a bin that symbolises discarded energy.

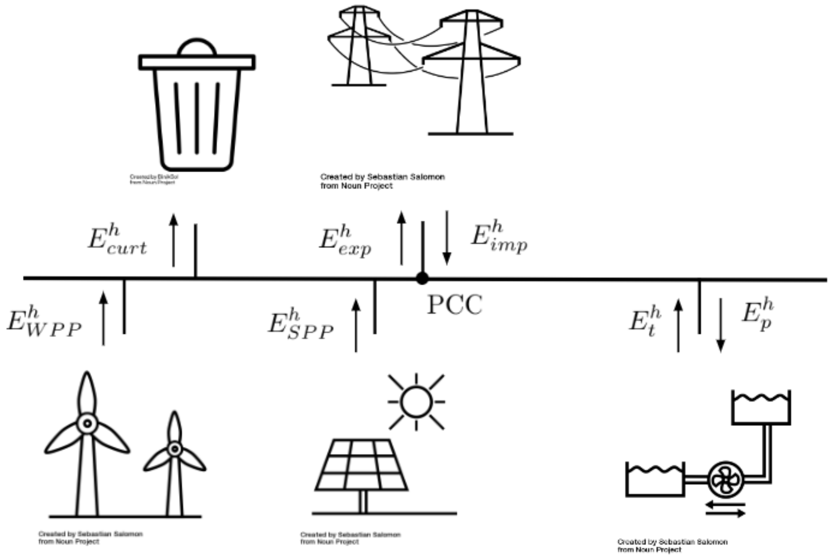


Figure 5.1: Overview of the hybrid power plant with pumped hydro storage system including electricity flows. Icons are sourced from [7] and [49].

5.2 Model data presentation

Model parameters define the system model and set the conditions for the system operation. Model variables are used to define model states and can change during simulations. The parameters and variables that are used in the energy management model are listed in the Nomenclature section. Note that h is an index for number of a specific hour and ΔT represents the time interval between model states, which in this thesis is one hour due to the utilisation of 1-hour resolution data.

5.2.1 Hybrid power plant

The study data on the WPP and SPP system components comprises hourly electricity production data from Project Garpenberg HPP in 2023 (E_{WPP}, E_{SPP}) and operation and maintenance cost (O&M) of the wind and solar power plant (f_{WPP}, f_{SPP}), excluding balancing responsibility and land lease costs. The hybrid power plant input data is presented in Table 5.1.

Table 5.1: Hybrid power plant system modelling parameters

Parameter	Value	Unit	Source
E_{WPP}	Project Garpenberg WPP production data 2023	MWh/h	Eolus Vind
E_{SPP}	Project Garpenberg SPP production data 2023	MWh/h	Eolus Vind
f_{WPP}	12,5	EUR/MWh	Eolus Vind, [4]
f_{SPP}	4	EUR/MWh	Eolus Vind, [4]

5.2.2 Grid connection point

The study data on the grid-connection between the hybrid power plant with pumped hydro storage and the national grid comprises the maximum grid-connection capacity (P_{GCP}) and maximum curtailment capacity (P_{curt}). The latter corresponds to the total hybrid power plant capacity, provided that both electricity production from the wind and solar power plant can be curtailed. Another relevant data input is the electricity price received by the market operator for electricity exported to the grid (E_{exp}), which is the same price the a consumer has to pay for electricity imported from the grid (E_{imp}). The electricity price referred to herein is the spotprice in SE3 in 2023 (ρ). The grid connection point input data is stated in Table 5.2.

Table 5.2: Grid connection point system modelling parameters

Parameter	Value	Unit	Source
ρ	Spotprice SE3 2023	EUR/MWh,h	Eolus Vind
P_{GCP}	140	MW	Predetermined
P_{curt}	Project Garpenberg HPP capacity	MW	Assumption

5.2.3 Pumped hydro energy storage

The energy storage level, also called state of charge (SOC), in the upper water reservoir of the pumped hydro storage plant can vary between a minimum (E_{Smin}) and a maximum (E_{Smax}) energy storage level. In this thesis, the minimum storage level is chosen as 0 MWh and the maximum storage level is the same as the installed storage size (E_{PHES}). The initial energy storage level (E_{init}) is chosen as half of the maximum energy storage level. The pumped hydro storage energy component input data is listed in Table 5.3.

Table 5.3: Pumped hydro storage energy component modelling parameters.

Parameter	Value	Unit	Source
E_{PHES}	Storage size	MWh	Dimensioning attempts
E_{Smin}	0	MWh	Assumption
E_{Smax}	E_{PHES}	MWh	Assumption
E_{init}	$0,5 \cdot E_{Smax}$	MWh	Assumption

In this thesis, it is assumed that variable speed pump and turbine units are used. The operating range of the power component of a pumped hydro storage plant depends on the installed power capacity (P_{PHES}). The maximum power capacity of both the pump (P_{pmax}) and turbine (P_{tmax}) is chosen as the installed power capacity due to the fact that it is not reasonable to install surplus power capacity. The minimum power capacity is determined by the affinity laws and can differ between the two modes: pump (P_{pmin}) and turbine (P_{tmin}) [4]. The affinity laws demonstrate the relation between power components and site variables such as head, flow rate, shaft speed and power capacity. Since these variables are unknown in this thesis, assumptions have been made. It is assumed that a pumped hydro storage configuration with a very short average response time is utilised and that the pump and turbine units can start operate in both pump and turbine mode from 0 MW. The performance of the pump (η_p) and turbine (η_t) is chosen as 90 %, in accordance with the study [4]. The pumped hydro storage power component input data is presented in Table 5.4.

Table 5.4: Pumped hydro storage power component modelling parameters.

Parameter	**Value**	**Unit**	**Source**
P_{PHES}	Power capacity	MW	Dimensioning attempts
P_{pmin}	0	MW	Assumption
P_{tmin}	0	MW	Assumption
P_{pmax}	P_{PHES}	MW	Assumption
P_{tmax}	P_{PHES}	MW	Assumption
η_p	0,9	MW	[4]
η_t	0,9	MW	[4]

The O&M cost of a pumped hydro storage plant is specified as 3,5 EUR/MWh by the authors of [4]. To illustrate that the operation in pump mode is more demanding compared to the operation in turbine mode, the O&M cost of pump operation (f_p) is chosen as slightly higher than the average pumped hydro storage O&M cost and the O&M cost of turbine operation (f_t) is chosen as slightly lower than the average pumped hydro storage O&M cost in this thesis. The start-up of the pump or turbine from standstill is associated with a non-recurrent cost (k_{start}), as specified in the study [4].

All transitions between modes gradually deteriorate the plant performance, and logically the change from pump to turbine mode wears down pumped hydro storage equipment more than the opposite. This is also consistent with the observation that the time required to change from pump to turbine mode is almost twice as long as the time required to change from turbine to pump mode [50]. Response times will be discussed more in the Electrical system simulation method section. In this thesis, the average non-recurrent cost of change between pump and turbine mode is chosen as half of the start-up cost, with the cost of the change from pump to turbine mode (k_{pt}) weighed higher than the cost of change in the other direction (k_{tp}). In other words, a similar approach is taken for the cost of transition between modes as for the O&M cost. The pumped hydro storage operating economic input data is compiled in Table 5.5.

Table 5.5: Pumped hydro storage operating economic modelling parameters.

Parameter	**Value**	**Unit**	**Source**
f_p	4	EUR/MWh	Assumption, [4]
f_t	3	EUR/MWh	Assumption, [4]
k_{start}	10	EUR	[4]
k_{pt}	6	EUR	Assumption
k_{tp}	4	EUR	Assumption

5.3 Operating strategy

The aim of the system operating strategy is to maximise the operating revenue by maximising the profits from electricity arbitrage trading and minimising the operating costs. The model reduce generation curtailment and can interact with electricity markets. The optimisation is conducted on a daily basis, and thus perform well on the day-ahead market. The model takes into account operating costs and wear on pump and turbine units associated with long-term operation at high power levels and frequent start-ups of the units. Technical constraints on system components are considered in the system operating strategy to make sure the system is well-functioning and that no power ratings of the system components are exceeded. The energy management model is formulated in mathematical terms and optimal control of the pump and turbine units is determined by solving the mathematical problem. To investigate the performance of the system model, the optimisation calculations on a daily basis are extended over an entire year.

5.4 Model assumptions

The assumptions made in the energy management model are listed below.

- Generation curtailment occurs when the grid-connection capacity is insufficient to deliver the curtailed electricity, electricity exports to the grid is not profitable, the energy storage is full and/or the maximum power of the pump is insufficient to store the electricity.
- The performance of the PHES system component remains constant throughout the operating range of the pump and turbine units and degradation of these units are not considered.
- Only variable speed pump and turbine units are incorporated in the model and the units are assumed to be able to start operate at 0 MW. The pumped hydro storage system configuration is expected to have a short average response time allowing it to handle rapid variations in electricity production from variable renewable energy sources without affecting the system behaviour.
- The operation of the PHES system component is independent upon energy storage level and is not affect by evaporation losses, which could deteriorate the plant performance over time.
- The pumped hydro storage plant is considered a short-term energy storage solution because the optimisation is conducted for 24 hours at a time starting 12 a.m. each day.
- Only energy arbitrage trading on the day-ahead market is considered and no revenues from trading on the intraday market or frequency regulation markets are included in the optimisation of the maximum daily operating profit.
- No distinctions are made between the operation of a pumped hydro storage plant above ground and the operation of a pumped hydro storage plant in an underground mine.

5.5 Mathematical model representation

The energy management model is formulated as an mathematical optimisation problem. The optimal scheduling of the energy storage operation is found by solving the objective function with respect to optimisation constraints. Technical and economic factors put restrictions on the variables in the objective function and controls the problem solution. Binary variables are used in the problem formulation to indicate if a specific model state is on or off during the intended hour. The mathematical problem is programmed with MatLab using the Optimisation Toolbox. Mixed integer linear programming (MILP) is the mathematical optimisation algorithm that is used. The programming code written in Matlab can be found in the Appendix.

The mathematical problem formulation is inspired by a recent research study by Naval et al.[4] on optimal scheduling and management of a grid-connected hybrid power plant with pumped hydro storage system. In their study, an energy management model was proposed and applied to a case study in Spain. This thesis distinguishes itself by including costs of transition between pump and turbine mode, and also by considering generation curtailment in the system model. Furthermore, the system configuration investigated by the authors of [4] is different from the system in this thesis, as the Spanish system includes an energy demand in the form of an energy-intensive industry. The energy load within their system is directly connected to the PCC before the whole system is connected to the national grid and the renewable power generation is designed to meet the demand of that load.

5.5.1 Objective function

The objective function is to maximise the daily operating profit, which is consistent with the sum of the hourly operating profits over a 24-hour period. This is established by Equation 3. The time step h is the number of a specific hour within the time window N_h, which is 24 hours. The variables and parameters in Equation 3 will be presented with respect to the model constraints and are also listed in the Nomenclature section. The hourly operating revenue is solely derived from selling electricity to the grid, whereas the hourly operating cost is derived from various factors. The operating costs included in the objective function is buying electricity from the grid, operation of pump or turbine units, start-up of pump or turbine from standstill and change from pump to turbine mode and vice versa. The operation of the pumped hydro storage plant is penalised for the reason that frequent start-ups and transitions between modes accelerate degradation of pump and turbine units. In the objective function also the price of the curtailed electricity is considered as an operating cost to achieve desirable system behavior, and hence allow for generation curtailment but preferably only when electricity prices are low.

$$Profit = \sum_{h=1}^{N_H} (\rho^h \cdot E^h_{exp} - (\rho^h \cdot E^h_{imp} + \rho^h \cdot E^h_{curt} + f_p \cdot E^h_p + f_t \cdot E^h_t + C^h_{start} + C^h_{pt} + C^h_{tp})) \tag{3}$$

5.5.2 Energy balance constraint

The energy balance within the whole system must be preserved at every time step. Equation 4 ensures that the electricity input to the PCC equal the electricity output from the same point, in accordance with the electricity flows in Figure 5.1.

$$E^h_{SPP} + E^h_{WPP} + E^h_t + E^h_{imp} = E^h_p + E^h_{exp} + E^h_{curt} \tag{4}$$

5.5.3 Grid connection constraints

Electricity can not be exported to the grid and imported from the grid during one time step, as determined by the binary variables I^h_{imp} and I^h_{exp} and presented in Equation 5. The size of the imported and exported electricity is limited by the grid-connection capacity, as shown in Equation 6 and 7. It is not reasonable for electricity to be both imported from the grid and curtailed during the same time step, as regulated by Equation 8. Equation 9 ensure that the size of the generation curtailment does not exceed the predetermined maximum power capacity of the curtailment .

$$I^h_{imp} + I^h_{exp} \leq 1 \tag{5}$$

$$0 \leq E^h_{imp} \leq I^h_{imp} \cdot P_{GCP} \cdot \Delta t \tag{6}$$

$$0 \leq E^h_{exp} \leq I^h_{exp} \cdot P_{GCP} \cdot \Delta t \tag{7}$$

$$I^h_{imp} + I^h_{curt} \leq 1 \tag{8}$$

$$0 \leq E^h_{curt} \leq I^h_{curt} \cdot P_{curt} \tag{9}$$

5.5.4 Energy storage constraints

The pump and turbine units can not operate simultaneously during one time step, as regulated by the binary variables I^h_t and I^h_t and expressed in Equation 10. The size of electricity to the pump and from the turbine has both a lower limit determined by the minimum power capacity of the units and an upper limit determined by the maximum power capacity of the units, as introduced in Equation 11 and 12. The energy storage level is limited by minimum and maximum values on stored energy, as defined in Equation 13. Equation 14 establishes the energy storage level in the end of each time step.

$$I^h_p + I^h_t \leq 1 \tag{10}$$

$$P_{pmin} \cdot I^h_p \cdot \Delta t/\eta_p \leq E^h_p \leq P_{pmax} \cdot I^h_p \cdot \Delta t/\eta_p \tag{11}$$

$$P_{tmin} \cdot I^h_p \cdot \Delta t \cdot \eta_t \leq E^h_t \leq P_{tmax} \cdot I^h_t \cdot \Delta t \cdot \eta_t \tag{12}$$

$$E_{Smin} \leq E^h_{SOC} \leq E_{Smax} \tag{13}$$

$$E^h_{SOC} = E^{h-1}_{SOC} + E^h_p - E^h_t \tag{14}$$

Based on Equation 15, it is possible to be informed whether or not the pump or turbine starts from standstill (I^h_{start}) during one time step. The start-up of pump or turbine is further linked to a start-up cost (C^h_{start}) in Equation 15. If the operating mode changes from pump to turbine (I^h_{pt}) is investigated in Equation 17 and associated with a change of mode cost (C^h_{pt}) in Equation 18. Similarly, if the operating mode changes from turbine to pump, the binary variable (I^h_{tp}) in Equation 19 will have a value of 1 and be associated with a change of mode cost (C^h_{tp}) in Equation 20.

$$I^h_{start} \geq I^h_p - I^{h-1}_p + I^h_t - I^{h-1}_t \tag{15}$$

$$C^h_{start} = k_{start} \cdot I^h_{start} \tag{16}$$

$$I^h_{pt} \geq I^h_t - I^{h-1}_p - 1 \tag{17}$$

$$C^h_{pt} = k_{pt} \cdot I^h_{pt} \tag{18}$$

$$I^h_{tp} \geq I^h_p - I^{h-1}_t - 1 \tag{19}$$

$$C^h_{tp} = k_{tp} \cdot I^h_{tp} \tag{20}$$

The energy storage constraints are the final constraints in the mathematical model representation.

6 Electrical system simulation method

6.1 Electrical system overview

An illustration of the grid-connected hybrid power plant with pumped hydro storage electrical system configuration is presented in Figure 6.1. The solar power plant generate DC that is converted to AC before integration to the PCC. Both the wind power plant and pumped hydro storage plant generate and/or consume AC, and hence there is no need to connect inverters to these components. With this electrical system configuration, the internal system at the PCC is an AC electrical system. The voltage level at the PCC is lower than in the distribution grid network, and therefore the voltage level must increase before connection to the national grid. This is done by coupling the system to a transformer before integrating the system to the national grid network. The electrical system model is designed in an attempt to reduce the amount of expensive system components without degrading the functionality of the system. Also, by not connecting the pump and turbine units to any power electronics before the grid connection point, the system can provide inertial response to the national grid.

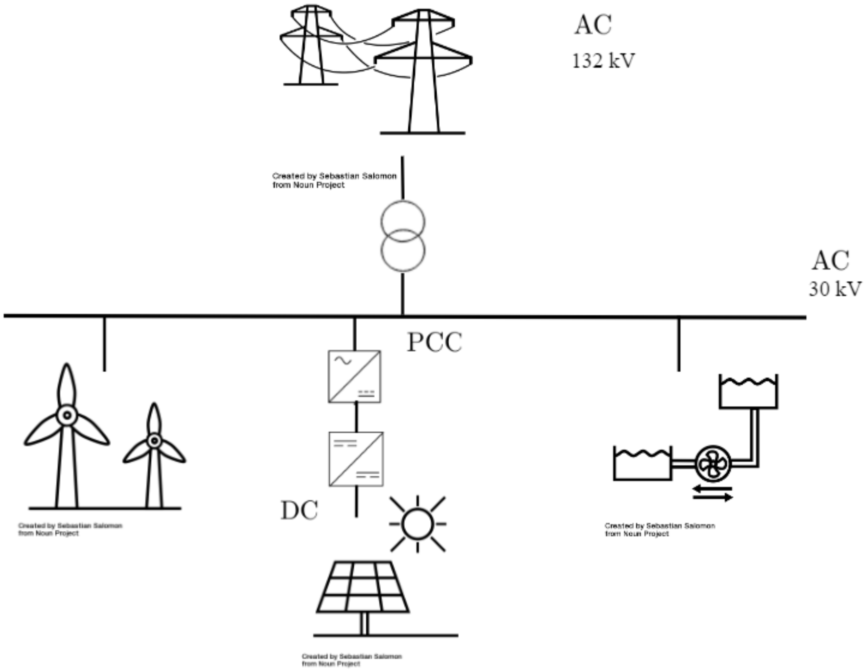


Figure 6.1: Hybrid power plant with pumped hydro storage electrical system overview including types of voltage within the system and large electronic components. Icons are sourced from [7].

6.2 Electrical system model

The modelling of the combined hybrid power plant and pumped hydro storage electrical system was conducted to emulate a real-world electrical system. In particular, the components were modelled to reflect the characteristics and behaviour of the real-world system components. The modelling and simulation environment OpenModelica was used to efficiently model and optimise the electrical system. OpenModelica is a computer tool intended for industrial and academic applications and is an open source software. The implemented OpenModelica system is demonstrated in Figure 6.2.

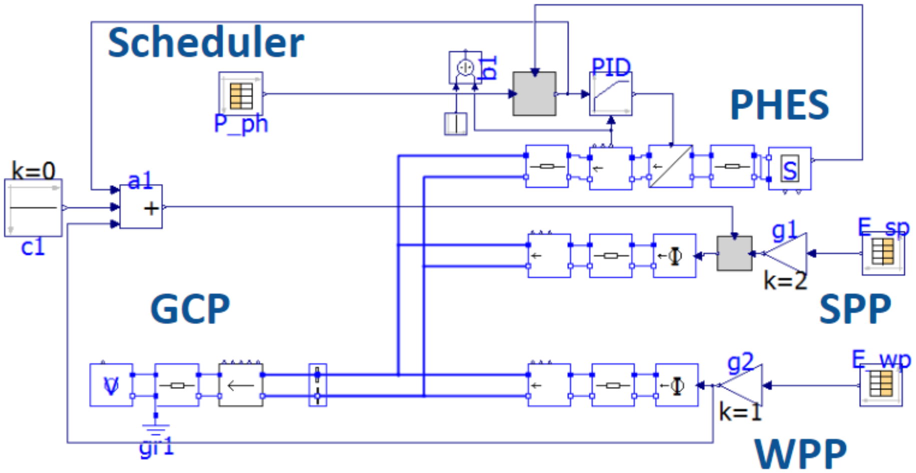


Figure 6.2: Hybrid power plant and pumped hydro storage electrical system model in OpenModelica interface.

6.2.1 Hybrid power plant

The WPP and SPP system components are modelled as two power generator units in OpenModelica. The generator units consist of electricity production data that is linked to a measuring unit via a power unit and a line unit. The wind and solar generator units are both individually connected to the electrical node within the complete OpenModelica model, and thus create the HPP system component.

6.2.2 Pumped hydro energy storage

The PHES system component is modelled as a general energy storage unit in OpenModelica. The energy storage unit consists of a capacitor that can be charged and discharged similar to how the upper water reservoir of a pumped hydro storage plant can be filled and emptied. The charging is managed by converters, which are controlled by PI (Proportional-Integral) controllers. The response times of the PHES system component is determined by the chosen PI parameters in the control algorithm for the specific control loop mechanism. The pumped hydro storage is connected to the electrical node within the complete OpenModelica model.

6.2.3 Grid connection point

The GCP system component is modelled using a voltage source unit, line unit and measuring unit and linked to the electrical node within the OpenModelica model.

6.3 Operating modes

A pumped hydro storage plant has two main operating modes that have previously been referred to as pump and turbine mode. Two other important operating modes are standstill (shutdown with the runner filled with water) and synchronous condenser (spinning-in-air). The required time for transition between the operating modes varies depending on modes and internal pumped hydro storage system configuration. A ternary set generally have a shorter average response time than a binary set. Similarly, a fixed speed configuration has an average response time that is shorter than a variable speed configuration. Accordingly, the tunnel design for moving water between reservoirs is an important factor in terms of response time, but also the type and number of power units affect the required time. The response times of fixed speed, variable speed and ternary set pumped hydro storage configurations are discussed in the Energy Storage Grand Challenge Cost and Performance Assessment 2020 [50], and the response time results of their literature review are re-illustrated in Table 6.1. The data presented in the table is in seconds and is also consistent with data available in the study [18].

Table 6.1: Estimated time in seconds to change between operating modes depending on pumped hydro storage configuration. Re-illustration of table in [50].

Initial mode	Final mode	Fixed speed	Variable speed	Ternary set
Synchronous condenser	Turbine	5-70	60	20-40
Standstill	Turbine	75-120	90	65-90
Synchronous condenser	Pump	50-80	70	25-30
Standstill	Pump	160-360	230	80-85
Turbine	Pump	90-220	280	25-60
Pump	Turbine	240-500	470	25-45

In addition to the mentioned modes in the study [50], modern pumped hydro storage plants can also be designed for an "idle mode". This demands separate turbines and pumps that are connected through a hydraulic short circuit, which allows the plant to circulate the water and have a net zero output to the grid. When needed, this mode can the be changed to either turbine or pump mode in the matter of a few seconds.

6.4 Scheduler

A scheduler is connected to the PHES system component in the implemented OpenModelica model. The aim of the scheduler is to adjust the operation of the energy storage based on electricity production and price forecasts. The scheduler should take economic decisions with respect to internal prognoses on energy storage level and electricity prices for a number of hours ahead. In this thesis, the idea is that the combined hybrid power plant and pumped hydro storage system participate in the day-ahead market, and therefore submit bids 12:00 p.m. each day for operation the next day. The optimisation is managed by the proposed energy management model, which optimises the daily profits. In this way, the simulation result of the energy management model acts as a scheduler and plans the operation of the energy storage by determining when the plant should transition between different modes and at what power level the pump and turbine units should operate.

6.5 Simulation assumptions

The operation of the hybrid power plant and pumped hydro storage system is simplified and assumptions that are made in the electrical system simulations are listed below.

- Actual electricity production and electricity prices align with the forecasts used to submit bids on the day-ahead market and manage the energy storage during the operating day.
- A pumped hydro storage plant configuration is not chosen in the electrical system model. Instead, the PHES system component is modelled as an energy storage unit in general.

- The temporal resolution of the electricity production data is one hour, and therefore also the energy storage is managed on an hourly basis with average values. This is a rough estimate since the electricity production fluctuates within an hour, and for example solar power generation is affected by the movement of clouds across the sky. The electrical system must manage these variations or otherwise system components could be damaged and electricity production be curtailed. It is of great importance for the energy storage response time to be short enough to handle rapid fluctuations, for the energy storage capacity to be large enough to handle second-by-second power variations, and for the energy storage to have room for additional energy in order to avoid generation curtailment.
- What happens within each hour is not considered in this thesis but instead most important is that the electricity production and energy storage level meet expectations by the end of each hour. It is assumed that the grid network can handle fluctuations in electricity production and possible imbalances, which can cause imbalance fees, are not considered in the simulations. The response time of the PHES system component is chosen as very short in the electrical system simulations.
- In light of that the scheduler algorithm is built upon the proposed energy management model, the assumptions listed in the energy management modelling method also apply to the electrical system simulation method.

6.6 Simulation analysis technique

In order to assess the energy management model, the electrical system operation of the PHES system component was managed by the energy management simulation results of the case study. Subsequently, the two simulation results were compared to test the functionality of the system operation. In the comparison, extra focus was placed on electricity to the transformer in relation to the expected generation curtailment. In the electrical system model, solar power was not directly curtailed but instead it was assumed that the surplus electricity production to the transformer; the electricity that exceed the available grid-connection capacity, was managed by solar power generation curtailment. Hence, the surplus electricity production to the transformer should be consistent with the expected generation curtailment from the energy management simulation result.

7 Techno-economic analysis method

7.1 Financial metrics

Financial studies are carried out by companies to examine if an investment in a project will be successful from an economic perspective. Financial metrics are measures that can be utilised to assess the performance and viability of an investment. Examples of quantitative measures that are commonly used as financial indicators are simple payback period, net present value, internal rate of return and levelised cost of electricity. These measures are briefly described below.

7.1.1 Simple payback period

Simple payback, abbreviated as SP, period is the number of years it takes until the initial investment cost is fully paid and the project can start generating profit [51]. The SP period is defined in Equation 21.

$$\sum_{t=1}^{SP} C_t = C_0 \tag{21}$$

t: Number of a specific time window $(-)$
C_0: Total initial investment cost $(MEUR)$
C_t: Net cash flow at time t $(MEUR)$

7.1.2 Net present value

Net present value, abbreviated as NPV, describes the total value of an investment in a project and is an important financial metric to determine if an investment is worthwhile. To calculate the NPV of a project, all current and future cash flows; both revenues and expenses, are summerised and discounted to the present day. A high NPV usually indicates a "good" investment. The NPV formula is presented in Equation 22.

$$NPV = \sum_{t=0}^{T} \frac{C_t}{(1+i)^t} - C_0 \tag{22}$$

T: Final time window $(-)$
i: Discount rate $(\%)$

7.1.3 Internal rate of return

Internal rate of return, abbreviated as IRR, demonstrates whether an investment opportunity can be justified. The IRR value is the discount rate that brings the net present value to zero. The higher the IRR is, the more desirable an investment usually is because the project is more likely to generate high annual growth of the investment. Nevertheless, a high IRR may carry a higher level of risk that can lower the attractiveness of an investment. Equation 23 establishes how the calculation of IRR is performed.

$$NPV = \sum_{t=0}^{T} \frac{C_t}{(1+IRR)^t} - C_0 = 0 \tag{23}$$

7.1.4 Levelised cost of electricity and energy storage

Levelised cost of electricity, abbreviated as LCOE, is a measure of the cost of the electricity produced by a generator. The measure is commonly used to compare different projects and electricity production technologies. To calculate the LCOE, the lifetime cost of the intended project is divided by the average annual electricity production. A low LCOE is adequate in many respects when investments in new power plants are considered. Levelised cost of energy storage, abbreviated as LCOS, is a measure of the cost of the electricity produced by stored energy 24.

$$LCOE = \frac{(CAPEX \cdot FCR) + OPEX}{AEP_{net}} \tag{24}$$

$CAPEX$: Capital expenditures ($MEUR$)
FCR: Fixed charge rate* (%)
$OPEX$: Operating expenditures per year ($MEUR$)
AEP_{net}: Net average electricity production over a year (MWh)

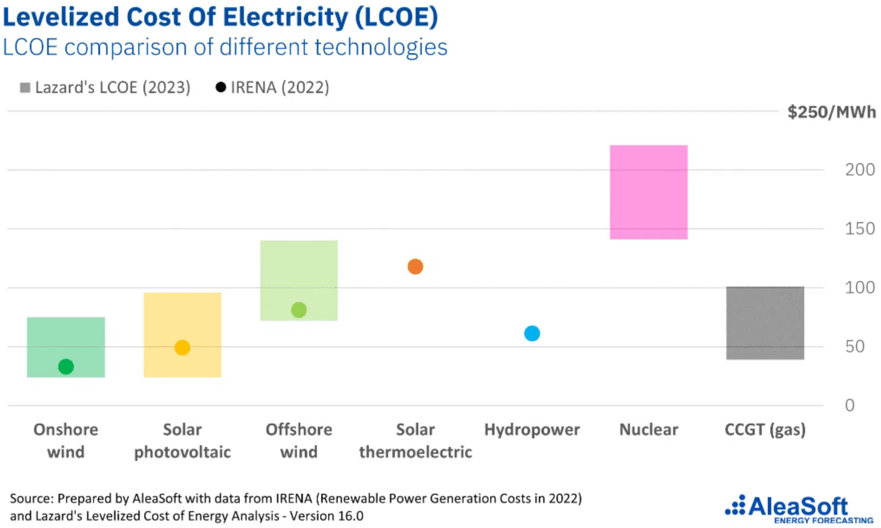
* Not to be confused with FCR-products in frequency regulation markets.

7.2 Economic attributes of technologies

In general, project expenditures are divided into two types: CAPEX and OPEX. The capital expenditures, abbreviated as CAPEX, are the large and long-term expenditures that are associated with the investment in a certain project. While on the contrary, the operating expenditures, abbreviated as OPEX, are the rather small and short-term expenditures that are associated with annually recurring costs [52].

7.2.1 Hybrid power plant

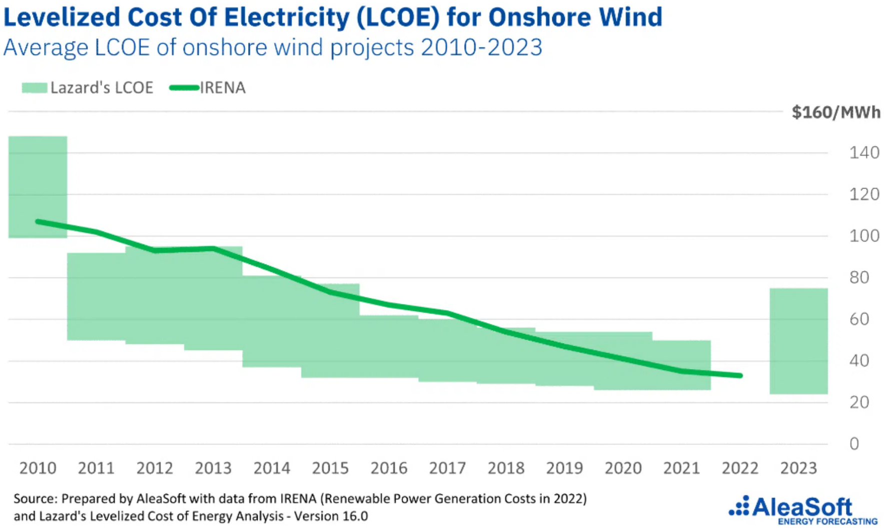
Renewable power plants are characterised by relatively large capital cost and low operation and maintenance cost due to the nonexistent fuel cost. When renewable power plants first were introduced, the lifetime cost of wind power plants and solar power plants were higher than the cost of fossil-based power plants. Nevertheless, this has changed and for today renewable power generation can compete with fossil-based power generation in terms of cost of electricity production. The LCOE for different electricity production technologies in 2022 is presented in Figure 7.1.



Source: Prepared by AleaSoft with data from IRENA (Renewable Power Generation Costs in 2022) and Lazard's Levelized Cost of Energy Analysis - Version 16.0

Figure 7.1: LCOE for power generation projects with various power production technologies. Sourced from [53].

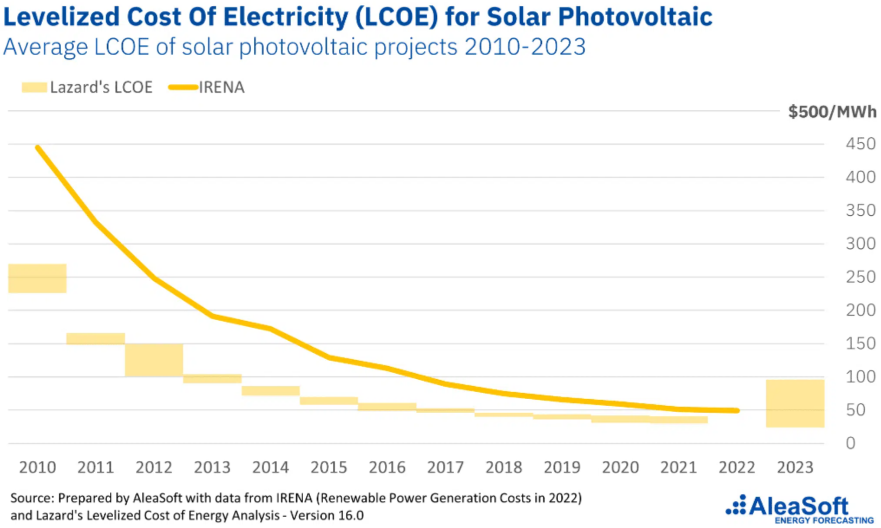
In recent decades, wind turbines have evolved significantly in terms of both performance and cost effectiveness. Wind turbines have become larger and more reliable, resulting in higher annual electricity production and lower construction cost. New onshore wind power plants usually have an expected technical lifetime of 35 years, and possible partial or full repowering of wind turbines can further extend the lifetime. Between 2021 and 2022, IRENA reported a decrease of 5% in global weighted average LCOE for newly commissioned onshore wind power plants. The historical development of LCOE for onshore wind power projects is presented in Figure 7.2.



Source: Prepared by AleaSoft with data from IRENA (Renewable Power Generation Costs in 2022) and Lazard's Levelized Cost of Energy Analysis - Version 16.0

Figure 7.2: Historical development of LCOE for new wind projects. Sourced from [53].

Similar to wind power projects, the LCOE for new solar power projects has decreased in recent years. The primary reason for the decrease is the lower cost of solar panels due to technological improvements and economy-of-scale. Extensive deployment of solar power plants in China, which is the country responsible for most manufacturing of solar panels in the world, is a key factor in the historical and future techno-economic development of solar power plants. The operating lifetime of solar power plants can vary, but a majority of solar power plants are designed to last for more than 25 years with minor updates of electrical equipment and moderately reduced maximum capacity of the solar panels. The historical development of LCOE for solar power projects can be viewed in Figure 7.3.



Levelized Cost Of Electricity (LCOE) for Solar Photovoltaic

Average LCOE of solar photovoltaic projects 2010-2023

Source: Prepared by AleaSoft with data from IRENA (Renewable Power Generation Costs in 2022) and Lazard's Levelized Cost of Energy Analysis - Version 16.0

Figure 7.3: Historical development of LCOE for new solar projects. Sourced from [53].

Hybrid power plants can share parts of the infrastructure since the two power plants are connected to the same grid connection point. The cost of grid-connection is often included in the calculations of LCOE for separate wind power plant and solar power projects, and hence hybrid projects usually have lower LCOE than two stand-alone wind power plant and solar power projects. This makes hybrid power projects cost-effective.

7.2.2 Pumped hydro energy storage

The CAPEX of a stand-alone pumped hydro storage plant consists of multiple factors. A few of the largest expenditures are cost of reservoirs, tunnels, waterways, electrical equipment, mechanical equipment, powerhouse, grid fees and land ownership. The capital investment cost is heavily dependent upon pumped hydro storage plant configuration; including type of set, turbines and machines. In turn, the most suitable plant configuration is dependent upon the required functionality of the plant and the electricity market situation. For example, the utilisation of the idle mode as an operating mode in the plant is particularly important for ancillary revenues and useful for the FCR-N market. Nonetheless, the increased revenues have to be balanced to the increased CAPEX due to the need for separate pumps and turbines with generators and motors. This means that such an installation is not viable for certain markets, where the ancillary services are not yet developed as in the Nordic electricity market. For a pumped hydro storage plant in an decommissioned mine, the construction cost of the storage system may be lower compared to the construction cost of a new pumped hydro storage plant above ground. This is because existing infrastructure of the mine can be utilised. The OPEX of a pumped hydro storage plant depends on the maintenance schedule and operating strategy; including, frequency of changes between operating modes and depth of discharge.

7.2.3 Technical assumptions

Technical assumptions on the lifetime and performance of system components are made in the techno-economic feasibility analysis. As regards the PHES system component, the assumptions are based on the plant being located in an underground mine, as in the case study of Project Garpenberg. Nonetheless, the pumped hydro technology is largely the same no matter if the pumped hydro storage plant is located underground or above ground, and for this reason the technical assumptions could apply to pumped hydro storage plants in general. A compilation of the technical assumptions can be viewed in Table 7.1.

Table 7.1: Technical assumptions regarding system components.

Component	Property	Assumption	Unit	Year	Source
WPP	Lifetime	35	years	2024	Eolus Vind
SPP	Lifetime	35	years	2024	Eolus Vind
	Capacity degradation	2,5	%/year 1	2024	Eolus Vind
		0,4	%/year 2-35	2024	Eolus Vind
PHES	Lifetime	40	years	2024	[21]
	Efficiency	80	%	2024	[19] [17]

7.3 Economic assumptions

To analyse the financial feasibility of a certain project, simplifications have to be made for the economic analysis to be practicable. The assumptions made in the techno-economic analysis of the combined hybrid power plant and pumped hydro storage system are presented in this section.

7.3.1 Capital and operational expenditures

The assumed installation cost and annual service and maintenance cost of the system components can be observed in Table 7.2. The land lease and balancing costs are excluded from the O&M costs. Likewise the technological assumptions, the economic assumptions on the PHES system component are based on the plant being located in an underground mine, but the assumptions can also apply to pumped hydro storage plants above ground. This is because the assumptions on CAPEX and OPEX are rough and apply to pumped hydro storage plants in general since the plant configuration and machines are not specified in this study.

Table 7.2: Economical assumptions regarding system components.

Component	Property	Assumption	Unit	Year	Source
WPP	Installation cost	1460	EUR/kW	2024	Eolus Vind
	Service and maintenance	12,5	EUR/MWh	2023	Eolus Vind
SPP	Installation cost	435	EUR/kW	2024	Eolus Vind, [4]
	Service and maintenance	4	EUR/MWh	2023	Eolus Vind, [4]
GCP	Installation cost	140	EUR/kW	2024	Eolus Vind
PHES	Installation cost	1360	EUR/kW	2024	Confidential
	Service and maintenance	2	% of gross revenues	2024	Confidential

7.3.2 Financial factors

The electricity production and spotprice data used to determine the operating profit in this thesis is from 2023. Therefore, the currency conversion between EUR, SEK and USD is based on the average exchange rate in 2023, as stated in Table 7.3. Presented in the same table is also information on other economic parameters such as compensations, tariffs and taxes.

Table 7.3: Financial assumptions regarding hybrid power plant with pumped hydro storage project.

Type	Property	Assumption	Unit	Year	Source
Comp	Grid benefit Guarantees of Origin etc.	3	SEK/MWh	2024	Eolus Vind
Tariff	Land lease	4	% of Gross revenue	2024	Eolus Vind
	Balancing fees	3	EUR/MWh	2024	Eolus Vind
Tax Incentives	Company tax	20,6	%	2021	Skatteverket
	Economic life	35	years	2024	Assumption
	Depreciation	4	%	2024	Assumption
Inflation	Gross revenue	2	%	2024	Assumption, [54]
	OPEX	2	%	2024	Assumption, [54]
Exchange rate	EUR/SEK	0,087078	n/a	2023	[55]
	EUR/USD	1,089254	n/a	2023	[55]

7.3.3 Electricity market trading

Only profits from electricity sales and electricity arbitrage trading on the day-ahead market and frequency regulation markets are considered in the techno-economic analysis. Revenues from electricity trading on the intraday market, which in reality would be possible for both the hybrid power plant alone and with the pumped hydro storage plant, is not included in the assessment of the project investment attractiveness. Mismatch between renewable power generation forecasts and real-time power generation from the hybrid power plant is likely to occur in some extent. Even though electricity bids on the day-ahead market are assumed to only be placed on an hourly basis and unpredictable weather events could balance each other out within the operating hour, it is difficult to ensure that actual power generation and market bids are perfectly matched every hour. Hence, imbalances are neglected in this thesis and imbalance fees are not included in the techno-economic analysis.

The profits from electricity sales and arbitrage trading used in the techno-economic analysis are derived from the initial data analysis and energy management simulations. In this thesis, the concept is that some of the pumped hydro storage capacity can be offset on the frequency regulation market when the energy storage level allow for it and the pumped hydro storage plant is not planned to be in operation considering optimal scheduling of the plant to maximise profit from electricity arbitrage trading on the day-ahead market only. Revenues from participation of the pumped hydro storage plant in frequency regulation markets are assigned a constant value of 130 kEUR/MW/year in the techno-economic analysis and this assumption is discussed in the text below.

In 2023, Energy Transition Expertise Centre (ENTEC) conducted a study [56] on market value of stored electricity and electricity price gaps. The study shows that participation in FCR markets can generate annual revenue of up to 50 kEUR/MW when the average hourly FCR price is above 6 EUR/MW and annual revenue of 175 kEUR/MW when the average hourly FCR price is above 20 EUR/MW. Last year, when the study [56] was performed, the most beneficial electricity markets for energy storage plants to participate in were frequency regulation markets, and especially the FCR markets. Nevertheless, it is important to mention that the profitability of participation in frequency regulation markets is heavily dependent upon complex trading strategies using complicated mathematical tools for forecasting and optimisation. The average remuneration for the three FCR-products in the whole of Sweden and in electricity area SE3 in 2023 is demonstrated in Figure 7.4. The average call-off price for FCR capacity in 2023 is presented in Table 7.4.

Table 7.4: Average FCR price in the whole of Sweden and in electricity area SE3. Data is sourced from [57].

Type	**Tot**	**SE3**	**Unit**
FCR-N	66	21	EUR/MW
FCR-D up	38	145	EUR/MW
FCR-D down	71	15	EUR/MW

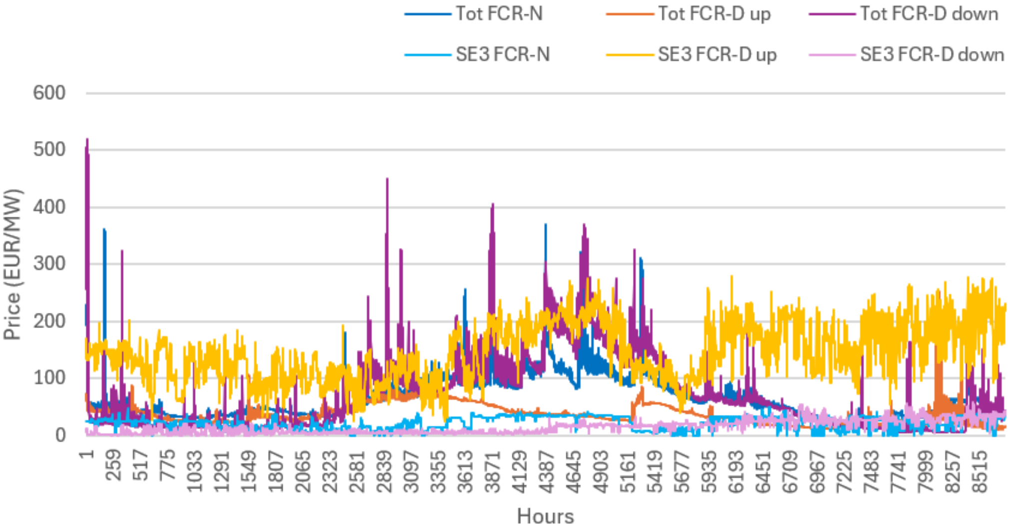


Figure 7.4: Hourly FCR price in the whole of Sweden and in electricity area SE3. Data is sourced from [57].

On the basis of ENTEC's study and the FCR price data, the annual ancillary revenue is estimated as 130 kEUR/MW installed pumped hydro storage power capacity in the techno-economic analysis. If the average FCR price is assumed to be 15 EUR/MW, which is the lowest SE3 price of a FCR-product in 2023, trading on the FCR markets could generate annual revenues of up to 75% of 175 kEUR/MW, in accordance with ENTEC's study, i.e. about 130 kEUR/MW/year. The lowest average FCR is chosen in order to not overestimate the revenue from frequency regulation market trading but still consider that it is the upper limits on generated revenue that is given by ENTEC's study. In the estimate of 130 kEUR/MW/year in ancillary revenues in this study, also participation of the pumped hydro storage plant in other frequency regulation markets are assumed to be included. However, both according to ENTEC's study and the frequency regulation market data in Figure 2.11, it seems reasonable that trading on the FCR markets are expected to contribute to most of the ancillary revenues.

7.4 Investment appraisal

Investment appraisals of the hybrid power plant and pumped hydro storage project were conducted in Excel and the appraisals were based on Project Garpenberg. Project Garpenberg is assumed to be able to start operate in 2030 and have an economic lifetime of 35 years. The annual gross profit was determined by subtracting the annual operating gross cost from the annual operating gross revenue. Beginning with earnings before interest, taxes and amortisation (EBITA), the net profit was calculated. The net pre-tax and post-tax free cash flow to equity (FCFE) was determined and used in the calculations of pre-tax and post-tax IRR. Furthermore, the LCOE was determined with a fixed interest rate of 10%.

To assess the feasibility of coupling pumped hydro storage to a hybrid power plant, two main scenarios were investigated in the techno-economic analysis: hybrid power plant without (1) and with (2) pumped hydro storage.

1. The investment appraisal of the first scenario was based on results of the initial data analysis of Garpenberg HPP (350 MW). Important input data to the investment appraisal was the electricity production from Garpenberg WPP and SPP including curtailed solar electricity production, which corresponds to the exported electricity, and annual revenue from electricity sales on the day-ahead market.
2. The investment appraisals of the second scenario were based on results of simulations of the energy management model of Garpenberg HPP (350 MW) coupled with Garpenberg PHES (X MW, Y MWh), where X and Y are variables that were varied between different attempts in the techno-economic dimensioning. The techno-economic dimensionsing strategy will be described in the next subsection. Important input data to the investment appraisals of scenario 2 is exported, imported and curtailed electricity and revenue from electricity arbitrage trading.

7.5 Dimensioning strategy

If considering only the energy management model, it is evident that the higher the pumped hydro storage power capacity (P_{PHES}) is and the larger the storage size (E_{PHES}) is, the higher the operating profit will be. The only limiting factor for the possible operating profit is the grid-connection capacity. However, this does not necessarily imply that the whole project is most financially feasible when the size of the energy storage is very large since a large pumped hydro storage plant also have a relatively high installation cost and O&M cost. For this reason, it is important to dimension the energy storage based on the techno-economic analysis. In this thesis, different "attempts" in terms of pumped hydro storage power capacity and storage size were simulated using the energy management model and the results of the simulations were used in investment appraisals of scenario 2. The first attempt: Attempt 2A, was based on the size of energy storage suggested in the initial data analysis. The additional attempts were based on the techno-economic analysis results of the previous attempts, and thus it became an iterative process between testing pumped hydro storage dimensions in simulations, inserting the simulation results in financial calculations and analysing those results with the aim of finding another energy storage dimension that could be even more profitable.

8 Results

8.1 Initial data analysis result

The electricity production from the wind power plant and solar power plant is complementary on both a hourly and an annual basis, in accordance with Figure 4.1 and 4.2. The electricity prices are lowest at nighttime and during the summer months, as evident in Figure 4.3 and 4.4. The electricity production from Garpenberg HPP (245 MW) is relatively stable over the year.

8.1.1 Duration curves

From the initial electricity production data, duration curves were created to illustrate the number of hours that a specific amount of electricity is produced from a power plant. In Figure 8.1, duration curves of Garpenberg WPP (140 MW) and SPP (105/160/210 MW) in 2023 are shown together with a constant line demonstrating Garpenberg GCP (140 MW). The plateaus in the beginning of the duration curves of solar power generation indicate the cutting of electricity production by the inverters due to oversizing the solar power plant peak power capacity. Duration curves of Garpenberg HPP (245/300/350 MW) are shown in Figure 8.2. The curtailment of electricity production from Garpenberg HPP (245/300/350 MW) correspond to the areas between each of the three duration curves and the constant line in the beginning of the graphs in Figure 8.2. The size of these areas positively correlates with the installed hybrid power plant capacity, meaning that more power generation is curtailed when the hybrid power plant capacity increase.

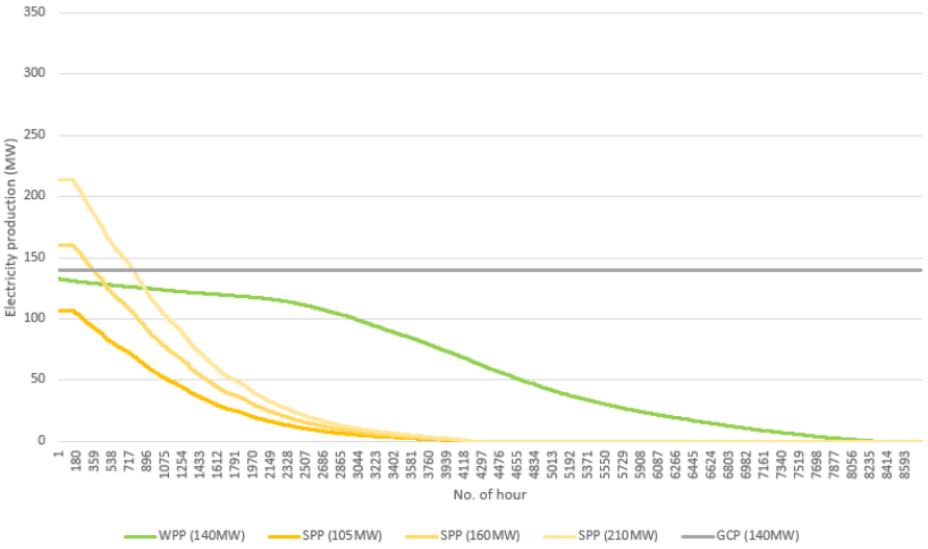


Figure 8.1: Duration curve of electricity production from the wind power plant and different sizes of the solar power plant.

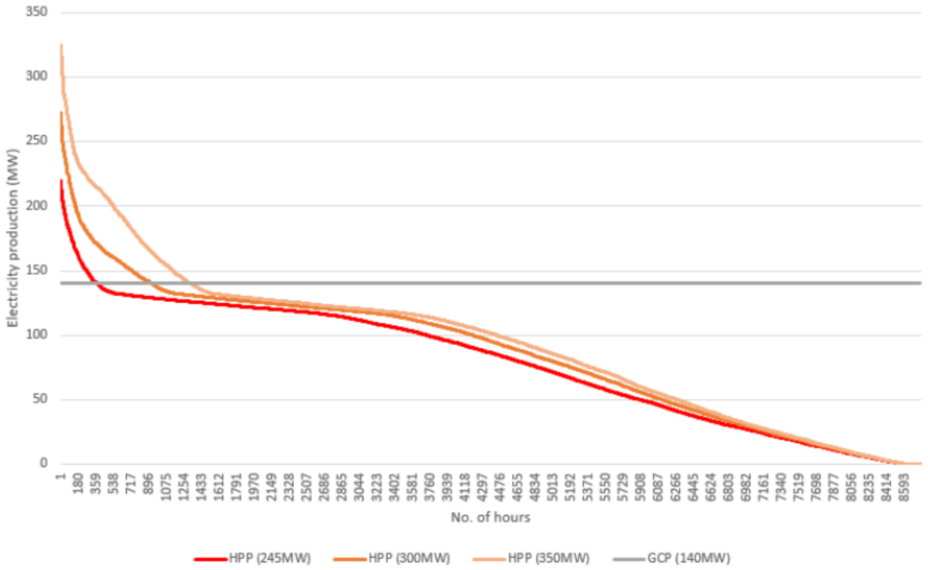


Figure 8.2: Duration curve of electricity production from different sizes of the hybrid power plant.

8.1.2 Hybrid power plant dimension

If the installed capacity of the hybrid power plant increases and the grid-connection capacity remains the same, the grid-connection utilisation increases and more of the total electricity production is curtailed. In turn, this leads to larger revenue losses due to generation curtailment, as evident in Table 8.1. A hybrid power plant with energy storage can reduce the electricity production that is curtailed with respect to the grid-connection capacity. Therefore, it is possible to install a large hybrid power plant without resizing the grid connection point or having high revenue losses. In this thesis, Garpenberg HPP (350 MW) was chosen for further investigation. The reason for not choosing an even larger size of the hybrid power plant, was the basis in reality of Project Garpenberg.

Table 8.1: Grid-connection capacity util, curtailment percentage and lost revenue data for different sizes of the hybrid power plant.

Type	Unit	HPP (245MW)	HPP (300MW)	HPP (350MW)
CF of GCP	%	55,5	59,2	61,4
Tot curtailment	%	1,4	4,0	8,6
SPP curtailment	%	7,1	15,2	26,5
Lost revenue curtailed	%	1,9	2,9	6,7

8.1.3 Curtailment reduction

Power and energy curtailment of electricity production from the hybrid power plant was analysed separately. The result of the curtailment analysis of Garpenberg HPP (350 MW) is presented in Table 8.2. In the table, the upper power and energy curtailment quartiles refer to the values of power and energy curtailment under which 75% of the hours and days per year respectively are found. In Figure 8.3, the frequency distribution of power curtailment per hour is illustrated, excluding the more than 7000 hours with non-existent power curtailment. Similarly, the frequency distribution of energy curtailment per day, excluding the about 100 days with non-existent energy curtailment, is presented in Figure

8.4.

Table 8.2: Information on curtailment of the hybrid power generation.

Curtailment	**Value**	**Unit**
Maximum Power	186	MW/h
Maximum Energy	1280	MWh/day
Upper Power quartile	77	MW/h
Upper Energy quartile	470	MWh/day
Average Power	53	MW/h
Average Energy	270	MWh/day

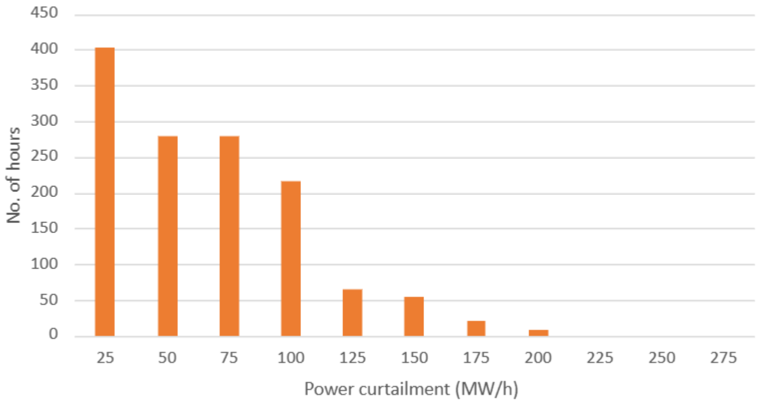


Figure 8.3: Power curtailment of the hybrid power generation.

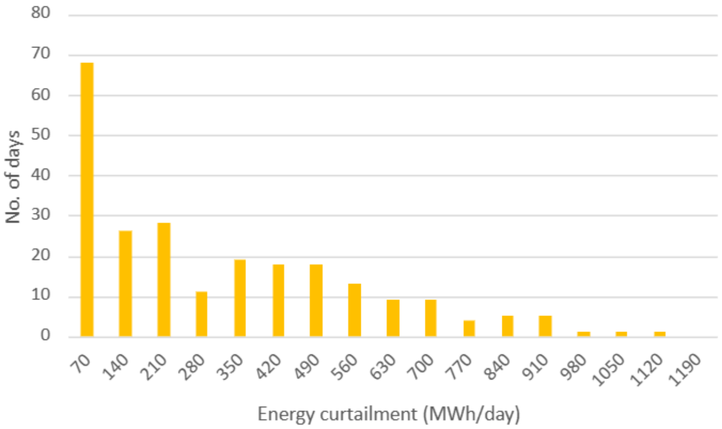


Figure 8.4: Energy curtailment of the hybrid power generation.

8.1.4 Price cannibalisation

In the initial data analysis, it became clear that price cannibalisation affect the operating revenue of the hybrid power plant. It was observed that the lost revenue from generation curtailment of electricity production from Garpenberg HPP (350 MW) is associated with a lower average electricity price than the total average electricity price in 2023; 33 EUR/MWh compared to 52 EUR/MWh. Price cannibalisation is also evident when the percentage of total curtailed electricity production is set against the percentage of total revenue that is lost due to generation curtailment. As expected, the ratio of revenue loss is lower than the ratio of curtailed electricity, and this is shown in Table 8.1. A histogram with the average generation curtailment multiplied with the average electricity price for each hour of a day is presented in Figure 8.5. It is noteworthy that generation curtailment only occurs daytime and that the largest revenue loss due to generation curtailment occurs between 11 a.m. and 2 p.m..

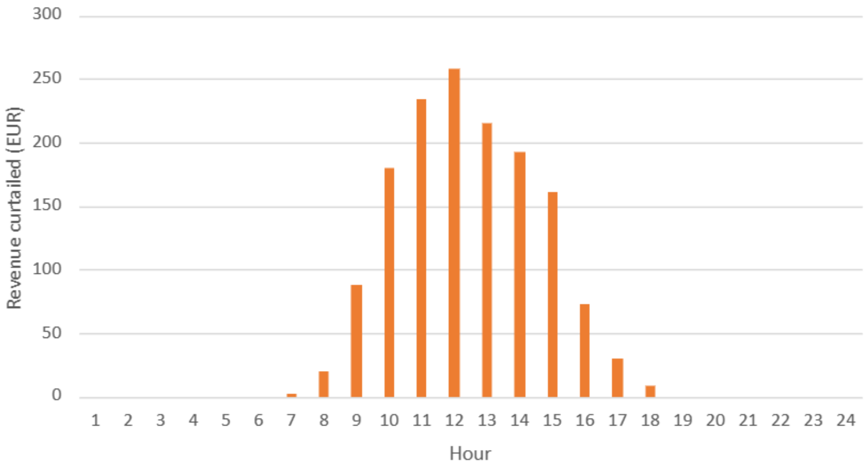


Figure 8.5: Average revenue loss due to generation curtailment for each hour of a day.

8.1.5 Energy storage initial dimensioning

Energy curtailment most commonly occurs several hours in a row since generation curtailment only occurs daytime and follow a similar pattern as the solar power generation, provided that the wind power capacity equal the grid-connection capacity. This was observed in the data analysis of Garpenberg HPP (350 MW) and is the reason why energy curtailment per day can be utilised to indicate a reasonable energy storage size. Due to that this study is written from the perspective of an electricity producer, the primary benefit with coupling a pumped hydro storage plant to a hybrid power plant before the grid connection point is considered as curtailment reduction, and thus generation curtailment was analysed with respect to energy storage dimensioning.

If Garpenberg PHES should be able to manage all renewable power generation that exceed the installed capacity of Garpenberg GCP on a daily basis, the PHES power capacity would have to be at least 190 MW. Moreover, given that the energy storage level is low when energy curtailment occur, the PHES energy storage size would have to be at least 1300 MWh, in accordance with Table 8.2. However, it is not financially reasonable to dimension a pumped hydro storage plant based on an extreme case in terms of generation curtailment, but instead it is more reasonable to dimension the plant based on the power and energy curtailment that about 75% of the hours and days per year, respectively, is below. In this thesis, the upper quartile was utilised to dimension the initial pumped hydro storage plant and it is important to mention that this was only an assumption and had no scientific background.

In Table 8.2, it can be observed that 75% power and energy curtailment corresponds to a power capacity of about 80 MW and a storage size of 470 MWh. Thus, the storage duration is almost 6 hours. For the sake of simplicity, the storage duration of the pumped hydro storage plant was set to 6 hours in the initial data analysis and applied to the subsequent methods. From the literature review on pumped hydro storage systems, multiple pumped hydro storage studies were based on plants with 6-hour storage duration, which confirms the reasonableness of this simplification. The initial energy storage size that was first tested in the energy management model was chosen as 80 MW and 480 MWh.

8.1.6 Energy storage operating strategy

The size of the possible daily revenue from electricity arbitrage trading depends on the price gap between the hours with the lowest and highest electricity prices. In 2023, the electricity price gaps fluctuated greatly; both on a seasonal and daily basis. In electricity area SE3, there were hours when electricity prices were negative in the spring months as well as hours when electricity prices reached above 300 EUR/MWh in the winter months. In Figure 4.4, it can be observed that the hours with the lowest electricity prices; about 35 EUR/MWh, on a daily basis are those in the night from 11pm to 5am. In the same figure, it can be observed that high electricity prices of about 65 EUR/MWh occur twice per day; in the morning from 7 a.m. to 10 a.m. and in the evening from 4 p.m. to 10 p.m.. During the hours in the middle of the day, electricity prices are about 55 EUR/MWh; that is to say in between the lowest and the highest daily electricity price levels.

Derived from the initial data presentation and generation curtailment analysis, it would be reasonable for the pumped hydro storage to be discharged when the grid-connection capacity is not fully utilised in the morning and evening when electricity prices are high. Contrariwise, it would be reasonable for the energy storage to be charged when generation curtailment occurs in the middle of the day as well as in the night when the electricity prices are low. In this way, both revenue losses due to generation curtailment could decrease and revenues from electricity arbitrage trading could increase. By offsetting some of the energy storage to bid on the frequency regulation markets in Sweden, it could further provide operating revenues.

8.2 Energy management simulation result

The result of the energy management simulations of the combined hybrid power plant and pumped hydro storage system is presented using data on Garpenberg HPP (350 MW) and the initial dimension of the pumped hydro storage plant: Garpenberg PHES (80 MW, 480 MWh). The values of the variables that were used in the simulation of the initial system model are presented in Table 8.3.

Table 8.3: Initial pumped hydro storage system modelling data.

Parameter	**Value**	**Unit**
P_{PHES}	80	MW
E_{PHES}	480	MWh
P_{pmin}	0	MW
P_{tmin}	0	MW
P_{pmax}	80	MW
P_{tmax}	80	MW
E_{Smin}	0	MWh
E_{Smax}	480	MWh
E_{init}	240	MWh

The simulation result in terms of annual electricity flows: exported, imported and curtailed electricity and electricity from wind and solar power, can be viewed in Table 8.4. In the table, also the values of operating revenue, operating cost and electricity arbitrage trading profit are stated.

Table 8.4: Energy, revenue and cost data on optimal operation of the hybrid power plant with initial pumped hydro storage system over a year.

Parameter	**Value**	**Unit**
CF of GCP	67,0	%
Electricity from WPP	556 120	MWh
Electricity from SPP	203 422	MWh
Electricity from PHES	143 452	MWh
Exported electricity	790 303	MWh
Imported electricity	30 798	MWh
Curtailed electricity	63 694	MWh
Revenue exported electricity	44 275 262	EUR
Cost imported electricity	1 597 275	EUR
Lost revenue curtailed electricity	244 296	EUR
Profit electricity arbitrage	42 677 987	EUR

The energy management model input data on electricity production from the hybrid power plant and spotprice in 2023 is illustrated in Figure 8.6. The hourly operation of the initial system based on the energy management simulation is demonstrated in Figure 8.7 and 8.8. In the first figure, electricity flows across the grid connection point: generation curtailment, exported and imported electricity, are shown. It is clearly visible that more electricity is exported than imported and that generation curtailment mostly occurs during the summer months and early autumn months. In the second figure, the scheduling of the PHES system component is presented together with the energy storage level. This figure shows that the pumped hydro storage plant transitions between operating modes often.

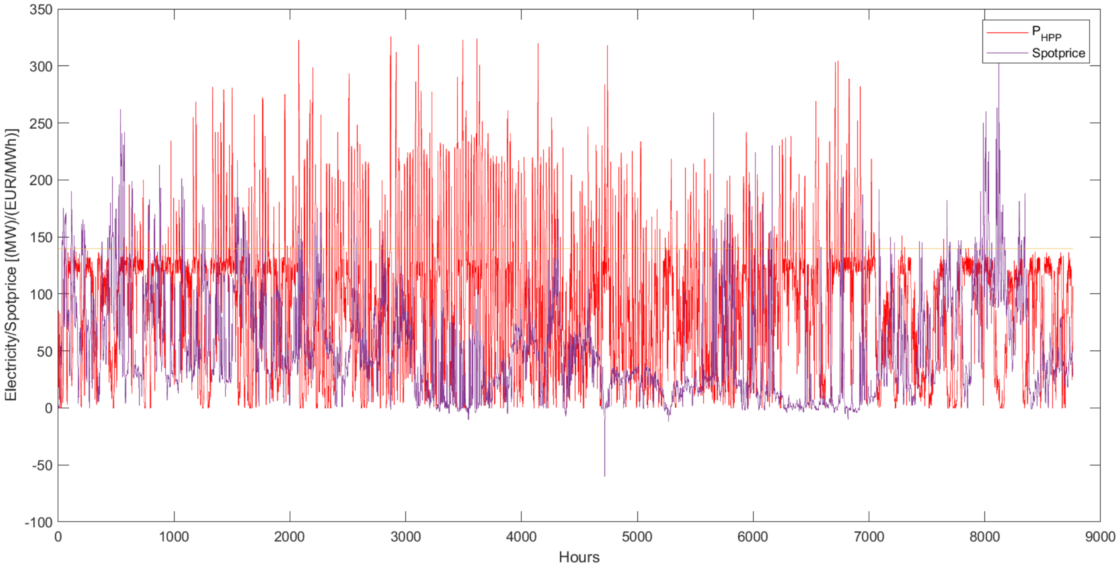


Figure 8.6: Hybrid power plant electricity production and spotprice over a year.

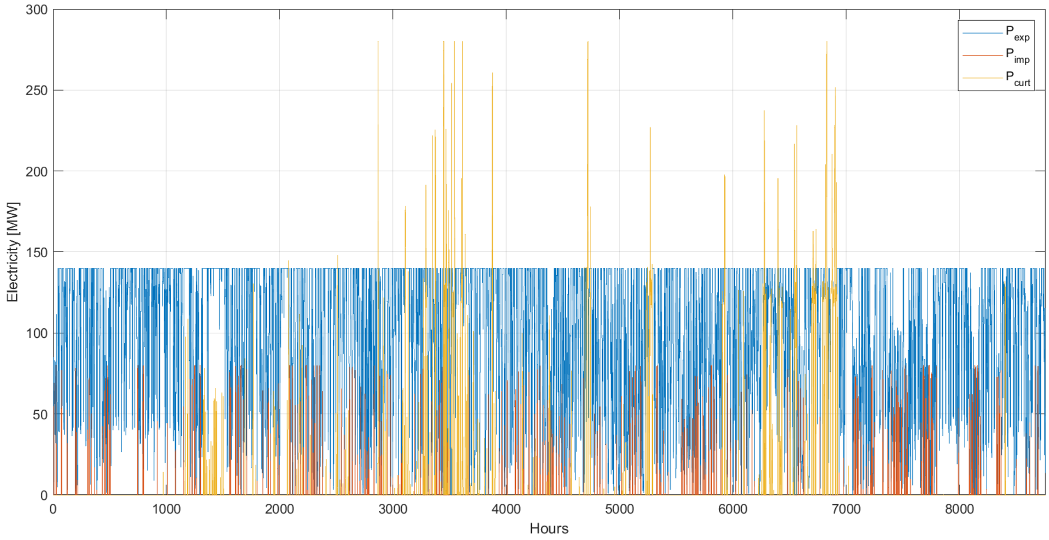


Figure 8.7: Electricity flows across the grid-connection point and generation curtailment over a year.

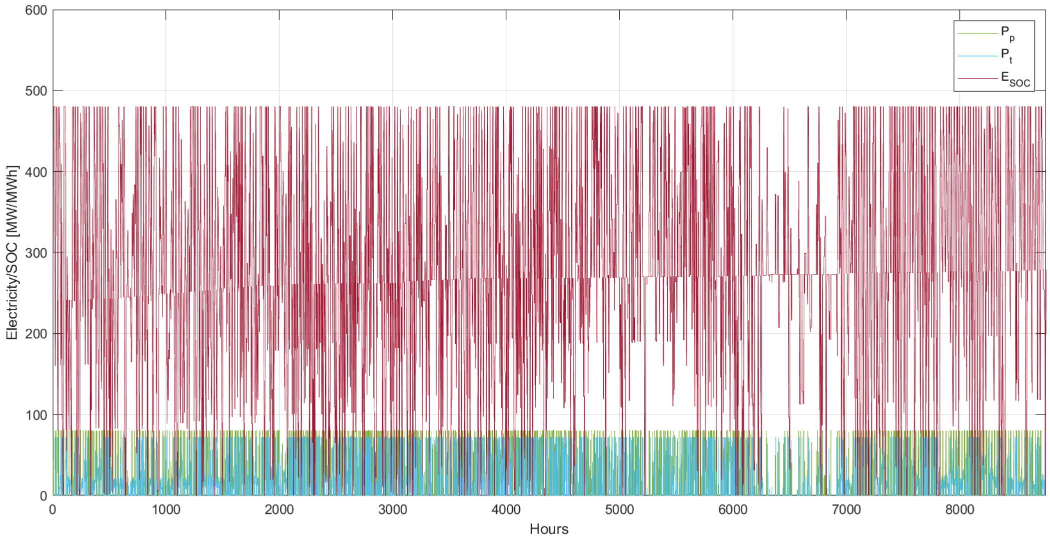


Figure 8.8: Scheduling of the initial pumped hydro storage over a year.

A graph of operation in pump and turbine mode is presented in Figure 8.9. Since the pump consumes electricity and the turbine produces electricity, it is reasonable for pump operation to be displayed with negative values and turbine operation to be displayed with positive values. In the figure, it can be observed that the turbine never operates at maximum turbine power capacity, but at most reaches 72 MW. The turbine operates at 72 MW approximately the same number of hours as the pump operates at 80 MW. The number of hours that the PHES system component operates in standstill during the year is about 3000 hours.

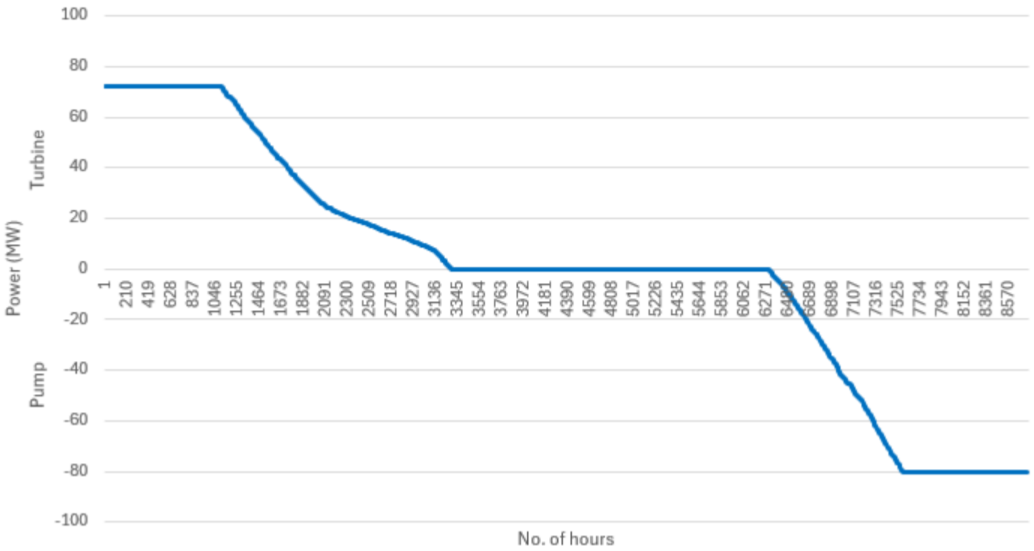


Figure 8.9: Graph of pump and turbine operation over a year.

An example of hourly operation of the initial system for a 10-day period is presented in Figure 8.11 and 8.12. These figures show a closer zoom into the operation during 10 days of the previous result figures that show the operation during an entire year. The input data in terms of electricity production and spotprice during the intended 10-day period is shown in Figure 8.10. By comparing the three figures: 8.10, 8.11 and 8.12, the connections between input and output data in terms of system operation for optimal hourly dispatch of electricity can be analysed. The system operation seems fairly consistent with the simple energy storage operating strategy that was presented earlier in the Result section.

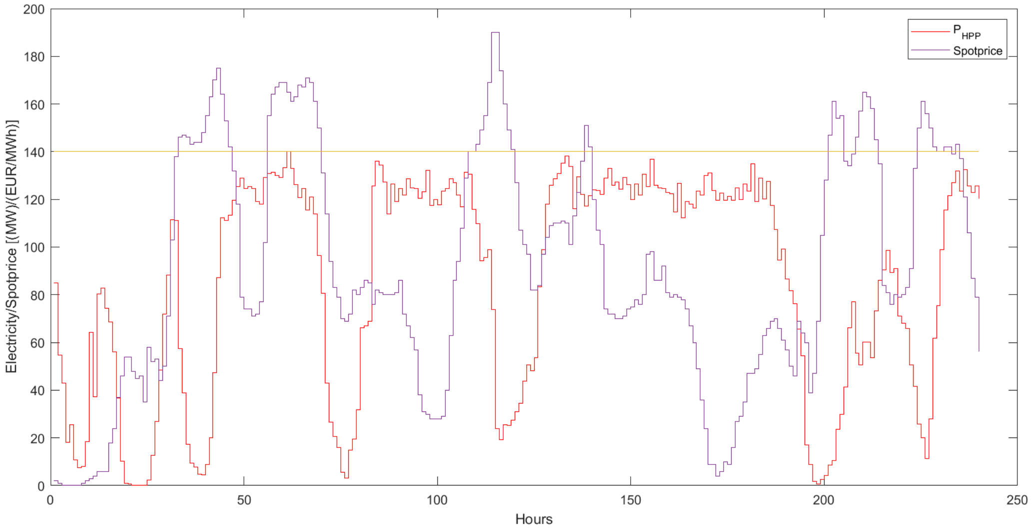


Figure 8.10: Hybrid power plant electricity production and spotprice for a 10-day period.

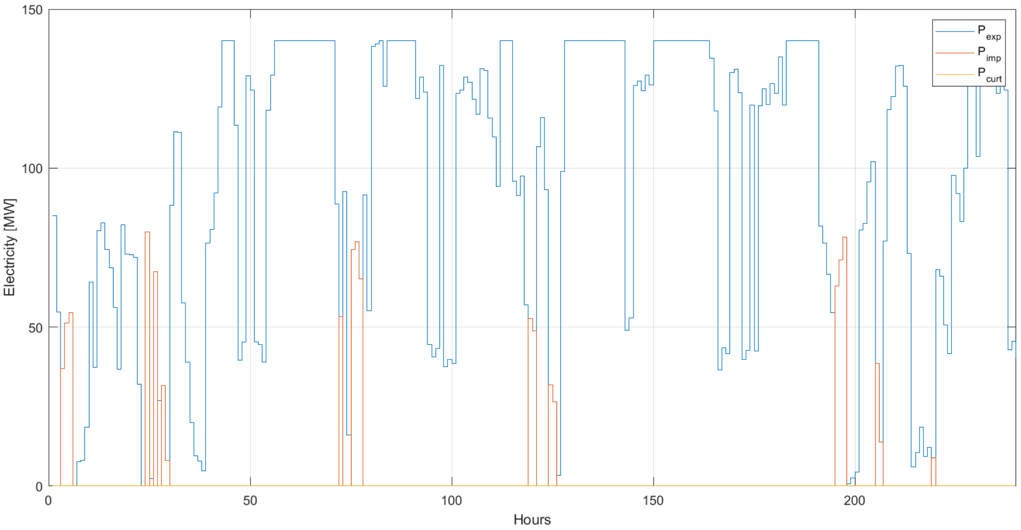


Figure 8.11: Electricity flows across the grid-connection point and generation curtailment for a 10-day period.

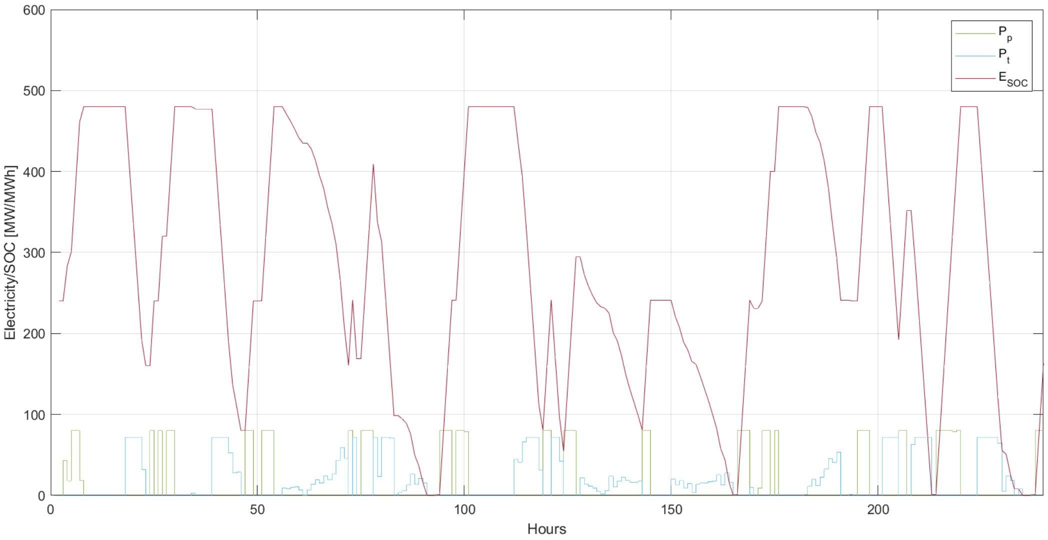


Figure 8.12: Scheduling of the initial pumped hydro storage for a 10-day period.

8.3 Electrical system simulation result

Electrical system simulations were successfully conducted using the implemented OpenModelica model and input data on scheduling of the pumped hydro storage plant from the energy management simulations. Based on the analysis of the electrical system simulations in terms of electricity flows at different nodes within the electrical system model, it was observed that the energy management model could be utilised for good electrical system operation, given the preconditions and assumptions of this study. Therefore, the energy management simulation results, and not the electrical system simulation results, were utilised in the techno-economic analysis of the combined hybrid power plant and pumped hydro storage project.

The electrical system simulation result is presented using data on Garpenberg HPP (350 MW) and the initial dimension of the pumped hydro storage plant: Garpenberg PHES (80 MW, 480 MWh). An example of the two generation curtailment graphs, corresponding to each of the two simulation methods that were compared in the analysis of the simulation results, can be viewed in Figure 8.13. Small fluctuations in electricity production around the capacity limit of the transformer, which do not align with the energy management simulation results, were noted in the electrical system simulation results. In other respects, the similarities between the simulation results are apparent. The small fluctuations can be deduced to the addition of short response times in the electrical system model compared to the infinitely short response times of the PHES system component in the energy management model.

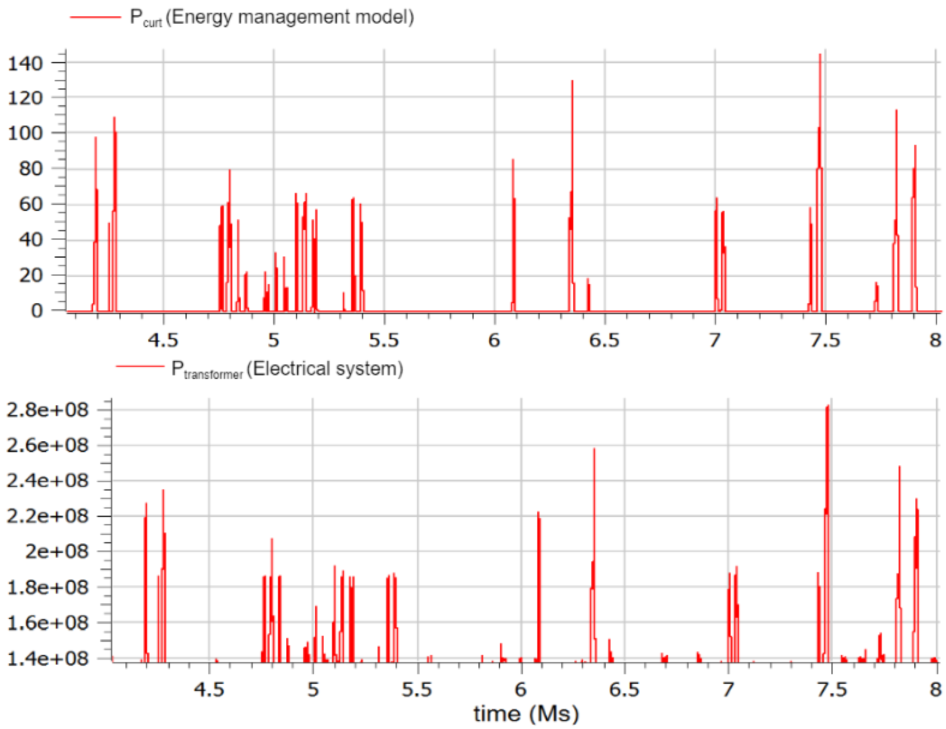


Figure 8.13: Energy management system and electrical system operation in the matter of generation curtailment.

8.4 Techno-economic analysis result

The financial feasibility of combined hybrid power plant and pumped hydro storage projects was evaluated by comparing the techno-economic results of a combined project with the techno-economic results of a stand-alone hybrid power project. Initially, the investment in Garpenberg HPP (350 MW) without a pumped hydro storage plant: scenario 1 - Attempt 1A, was analysed and the result is presented in Table 8.5. Subsequently, the investment in Project Garpenberg HPP (350 MW) with Garpenberg PHES: scenario 2, was analysed based on different dimensions of the energy storage in terms of power capacity and storage size, provided that the storage duration is 6 hours. The results of the various dimensioning attempts that were conducted can be viewed in Table 8.5 and 8.6.

In the first attempt: Attempt 2A, the pumped hydro storage dimension that corresponds to the initial energy storage dimension was analysed based on results of energy management simulations. In the next attempt: Attempt 2B, the size of the power capacity and the energy storage was decreased to 60 MW and 360 MWh respectively. In comparison to the first attempt, the second attempt resulted in higher LCOE and lower IRR. It appeared as if the size of the energy storage was too small, and therefore a larger energy storage dimension of 100 MW, 600 MWh was tested in the third attempt: Attempt 2C. The result of this attempt was slightly better than Attempt 2B and very similar to Attempt 2A. To investigate if the project profitability may increase if the size of the energy storage increases even more, also energy storage dimensions of 120 MW, 720 MWh and 140 MW, 840 MWh were analysed in two additional attempts: Attempt 2D and 2E.

Table 8.5: Part 1: Techno-economic analysis of the hybrid power plant projecy without and with different sizes of the pumped hydro storage.

Type	Unit	Attempt 1A	Attempt 2A	Attempt 2B
HPP capacity	MW	350	350	350
PHES power capacity	MW	0	80	60
PHES storage size	MWh	0	480	360
CF of GCP	%	61,0	67,0	64,4
Total arbitrage trading revenue	MEUR	37,4	42,7	41,4
Lost revenue curtailed	kEUR	2 556	244	537
Rate of lost revenue	%	7,1	0,6	1,3
PHES arbitrage trading revenue	kEUR/MW/year	0	86,3	93,3
PHES ancillary trading	kEUR/MW/year	0	130,0	130,0
PHES total revenue	kEUR/MW/year	0	216,3	223,2
SP period	years	7	6	6
LCOE	EUR/MWh	61	75	72
Pre-tax IRR	%	9,8	11,8	11,5
Post-tax IRR	%	5,8	7,7	7,4

Table 8.6: Part 2: Techno-economic analysis of the hybrid power plant with different sizes of the pumped hydro storage.

Type	Unit	Attempt 2C	Attempt 2D	Attempt 2E
HPP capacity	MW	350	350	350
PHES power capacity	MW	100	120	140
PHES storage size	MWh	600	720	840
CF of GCP	%	69,2	71,5	74,1
Total arbitrage trading revenue	MEUR	43,8	44,7	45,5
Lost revenue curtailed	kEUR	92,9	18,2	-26,8
Rate of lost revenue	%	0,2	0,05	-0,06
PHES arbitrage trading revenue	kEUR/MW/year	80,0	74,6	69,4
PHES ancillary trading	kEUR/MW/year	130,0	130,0	130,0
PHES total revenue	kEUR/MW/year	210,0	204,6	199,4
SP period	years	6	6	6
LCOE	EUR/MWh	75	78	80
Pre-tax IRR	%	11,8	11,9	11,9
Post-tax IRR	%	7,7	7,8	7,8

The SP period of all scenario 2 attempts are 6 years, which is one year less than the SP period of scenario 1. Given that the total installation cost is much lower without a pumped hydro storage plant coupled to the hybrid power plant, it is not surprising that the LCOE of scenario 1: 61 EUR/MWh, is lower than the LCOE of all scenario 2 attempts and that the LCOE of scenario 2 generally increase with increased installed pumped hydro storage power capacity. In terms of IRR, the pre-tax IRR of scenario 1 is 9,8%, which is lower than the pre-tax IRR of all scenario 2 attempts. The IRR of all scenario 2 attempts are quite similar; almost 12%, and this indicates that it can be more profitable with combined hybrid power plant and pumped hydro storage projects compared to stand-alone hybrid power projects. The scenario 2 attempt that differs the most from the average scenario 2 pre-tax IRR and have the lowest IRR is Attempt 2B. Attempt 2A can be considered to have a good balance between low LCOE and relatively high IRR and this system was chosen as the final system with the best financial feasibility result. Attempt 2A corresponds to Garpenberg HPP (350 MW) coupled with Garpenberg PHES (80 MW, 480 MWh), and thus the initial pumped hydro storage dimension is also the final pumped hydro storage dimension.

9 Discussion

9.1 Initial data analysis

Prominent in the initial data analysis is the high complementarity between wind power generation and solar power generation. Despite having an installed hybrid power plant capacity of 350 MW and an available grid-connection capacity of 140 MW with no energy storage system installed, only 9% of the average hourly generation from Garpenberg HPP was curtailed. Nevertheless, generation is curtailed and causes revenue losses that would not be necessary if an energy storage system is coupled to the hybrid power plant.

The decreasing trend in power and energy curtailment, as shown in Figure 8.3 and 8.4, was expected since it is logical that a small amount of electricity is curtailed more often than a large amount of electricity. The upper quartile of power and energy curtailment, as stated in Table 9, was only used to find a starting point for the techno-economic dimensioning of the pumped hydro storage plant. As previously mentioned, the storage duration was chosen based on this initial energy storage dimension, which is a simplification. It is certainly noteworthy that another storage duration could prove more profitable in the techno-economic analysis.

9.2 Energy management analysis

The energy management simulations perform in accordance with what was expected from the energy management model. The similarities between optimal scheduling of the combined hybrid power plant and pumped hydro storage system from the energy management simulations and the suggested operating strategy from the initial data analysis are clear. In Figure 8.12, it seems that the pumped hydro storage generally undergoes one charge cycle per day, which implies that the energy storage is charged and discharged once every 24-hour period. Generally, the energy storage is charged during the middle of the day when a lot of electricity is produced and discharged in the evening when the sun is not shining and the spotprice is high. However, both the operation of the PHES system component and the depth of discharge varies greatly depending on the day-to-day weather and electricity price conditions.

It is concluded that the ratio of revenue loss is lower for the hybrid power plant system with energy storage solution than the system without energy storage solution; 7,1 % for Garpenberg HPP (350 MW) compared to 0,6% for Garpenberg HPP (350 MW) coupled with Garpenberg PHES (80 MW, 480 MWh). Also, the CF of the grid connection point is higher for the combined hybrid power plant and pumped hydro storage system than for the stand-alone hybrid power plant system; 67% compared to 61%. This is shown in the Table 8.5.

An interesting result is that the ratio of revenue loss can be negative, as in the case of Attempt 2E. This is evident in Table 8.6 and implies that when the energy storage dimension is large enough, generation curtailment only occurs when the electricity prices are negative, and therefore the system can generate revenue from curtailment of electricity production. Another interesting result in terms of generation curtailment is that the generation curtailment is higher than the installed solar power plant capacity on a few occasions, as evident in Figure 8.7. This indicates that optimal operation of the combined hybrid power plant and pumped hydro storage system may involve generation curtailment of also wind power generation. Generation curtailment of electricity production from a wind power plant is possible, but it should be mentioned that the response time of a wind power plant to decrease its electricity production is longer than the response time of a solar power plant to do likewise.

In order to control how the PHES system component is scheduled in the energy management model, the operation of the pumped hydro storage is penalised with fixed values on start-up of turbine or pump from standstill and change from pump to turbine mode or vice versa. Thus, the system operation is dependent upon the chosen fixed values, and in turn, these values are assumptions based on the study [4] on optimal management of a hybrid power plant coupled with pumped hydro storage. Naturally, there is uncertainty in the optimal scheduling results that can be derived to the chosen values of the cost parameters in the objective function. Additionally, it could be relevant in the model to distinguish between the start-up of pump and the start-up of turbine since it would require more power to build up pressure for the pump to start pumping water upwards than for the turbine to allow water to flow through the turbine runner.

9.3 Electrical system analysis

Both in terms of energy storage level and generation curtailment, the similarities between the energy management simulations with MatLab and the electrical system simulations with OpenModelica are great. For real-world application of the combined hybrid power plant and pumped hydro storage system, it is particularly important that the transformer is protected against overpower, and thus that the solar power plant can reduce its electricity production quick enough so that the power limit of the transformer is not exceeded. Considering that it is mainly solar power generation that is curtailed and it is definitely possible to regulate the power output from a solar power plant rapidly, the simplification in terms of generation curtailment at the transformer in the electrical system simulations is reasonable.

Based on the basic conditions of this study, the hybrid power plant with pumped hydro storage system is well-functioning when the system operation is determined by the energy management simulations. Nevertheless, it is important to repeat that all data used in the simulations are average hourly values, and also the operation of the PHES system component is managed by average hourly values on operating power of pump and turbine. Certainly, this is inconsistent with real-world operation of a combined hybrid power plant and energy storage system because of the intermittent electricity production by wind and solar power. Within each hour, large fluctuations in electricity production are likely to occur, and the amplitude of the fluctuations as well as how frequent the fluctuations are affect the pumped hydro storage system operation. The PHES system component may not be able to manage the transitions between operating modes and from one operating power of the pump or turbine to another operating power of the pump or turbine fast enough to handle the intermittent electricity production. This applies even if the plant configuration with the shortest average response time: ternary set, is utilised. If this is the case, power and energy curtailment would occur also hours when electricity would not be curtailed on the basis of the average hourly values.

One approach to manage the problem with wind and solar power generation is to change the operating strategy due to forecasts. The operating strategy could be adjusted so that the responsibility to handle the fluctuations are put on the national grid instead of the pumped hydro storage plant. This is achieved by reducing the overall operating level to ensure that there is always some available grid-connection capacity that can handle the small power fluctuations. In the energy management model, the size of the grid-connection capacity could, for example, be reduced to 120 MW even if the capacity is 140 MW in reality. Consequently, some available grid-connection capacity is offset to handle the power variations. An negative aspect of this operating strategy is that it set restrictions on the operation of the pumped hydro storage plant and the possible revenues from electricity arbitrage trading. Furthermore, the risk of imbalances is likely to increase, and for this reason the imbalance fees may become higher depending on which party has the balance responsibility.

The operating strategy could also be adjusted in another way in order to handle the intermittent electricity production. By reducing the operating range of the PHES system component in the energy management model, and thus decrease the maximal operating pump power and the upper limitation on the energy storage level, the reduced pump power capacity and energy storage could be offset to handle the small fluctuations in electricity production. However, this applies only if the pumped hydro storage can respond instantly to the rapid power variations. For the purpose of assessing if this operating strategy suits a hybrid power plant coupled with pumped hydro storage, higher resolution data is needed. Also, the impact on the pumped hydro storage plant in terms of accelerated deterioration of the plant, is an important factor to consider in the evaluation of this new operating strategy.

Another approach to manage the issue with variable renewable power generation is to add another energy storage component to the system configuration. Batteries have short response time to reach full power and are therefore well-suited to handle power fluctuations. Also, batteries have the opportunity to participate in all frequency regulations markets in Sweden, and can for this reason increase the flexibility in operationality of the system. Pumped hydro storage is characterised by low installed power capacity compared to energy storage size, whereas batteries commonly have about the same size of power capacity and energy storage. In this sense, these two energy storage systems complement each other well and in a hybrid energy storage system the power fluctuations by wind and solar power generation can be managed by the batteries and the majority of the energy can be stored in the upper water reservoir of the pumped hydro storage plant.

The utilisation of batteries could decrease the depreciation rate of the pumped hydro storage plant, and thus possibly extend the lifetime and increase the availability of the plant. A battery energy storage system was initially added to the electrical system model of the combined hybrid power plant and pumped hydro storage system in OpenModelica. This was done before the study on batteries in a hybrid energy storage system was excluded from this thesis. An overview of the electrical system configuration with batteries is presented in Figure 9.1. Batteries produce DC and can therefore be connected to the solar power plant before the conversion to AC. The more advanced OpenModelica system model can be viewed in Figure 9.2.

Despite the many advantages of batteries in a hybrid energy storage system, the installation of batteries is associated with additional costs in terms of both capital and operational expenditures. Also, the lifetime of batteries is shorter than the lifetime of pumped hydro storage plants, and for this reason the batteries would need to be replaced at least once during the lifetime of a pumped hydro storage plant. The lifetime of batteries is usually specified by number of cycles the batteries can be charged and discharged and if assuming normal utilisation of the batteries, the lifetime can be estimated to about 15 years.

The approach to handle the problem with intermittent power generation by changing the operating strategy is likely to decrease the operating profit in comparison to what can be expected from the energy management model that has been proposed in this thesis, given the 1-hour resolution data. However, for the system to function in reality and to generate profit, it is of great importance to review the pumped hydro storage functionality and system operating strategy in the time frame of seconds. The addition of batteries to the system configuration, will increase the operating profit due to curtailment reduction but also increase the capital expenditures. It would be highly relevant to investigate both the curtailed revenue that can be associated with too long response time of the pumped hydro storage plant and the deterioration of plant performance.

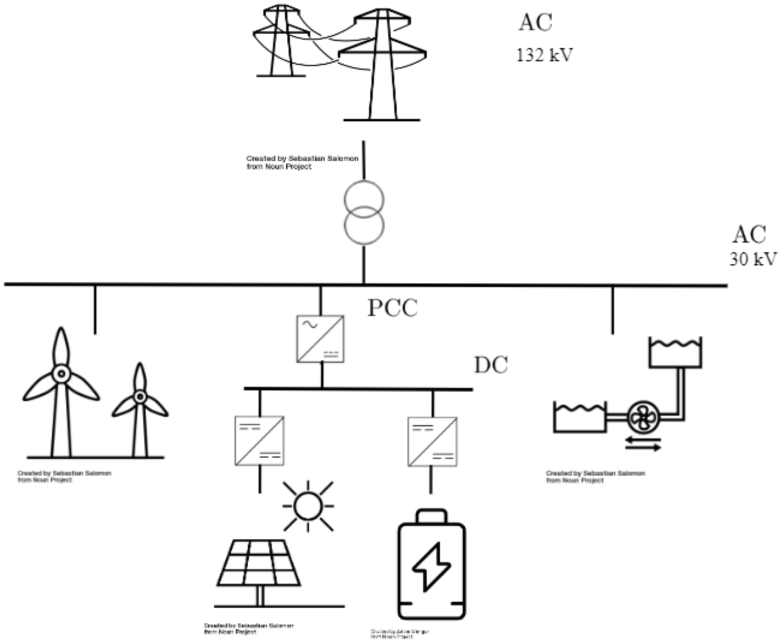


Figure 9.1: Hybrid power plant with pumped hydro storage and battery storage electrical system overview including types of voltage within the system and large electronic components. Icons are sourced from [7] and [58].

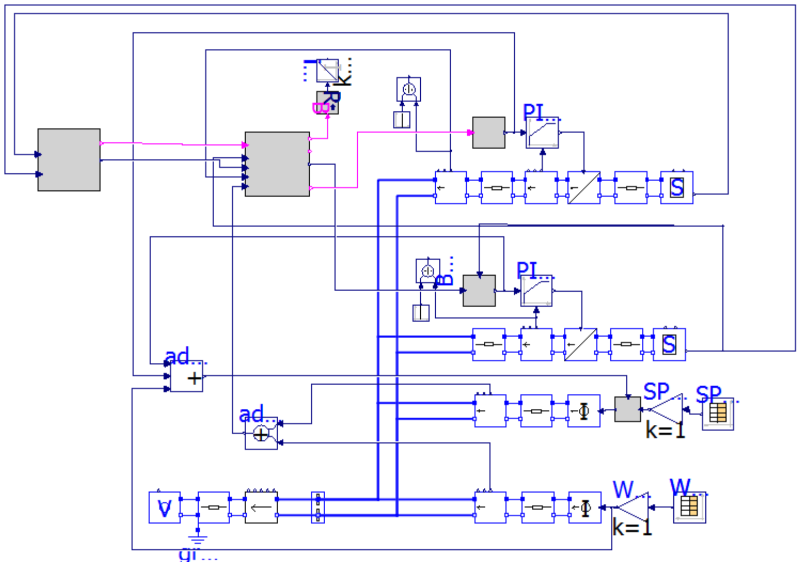


Figure 9.2: Hybrid power plant and hybrid energy storage system model in OpenModelica interface.

9.4 Techno-economic analysis

The techno-economic analysis shows better profitability of combined hybrid power plant and pumped hydro storage projects in relation to stand-alone hybrid power projects. In the analysis result, it was found that the pumped hydro storage plant investigated in this study can be expected to generate revenues of about 200 kEUR/MW/year. Of this revenue, approximately 70 kEUR/MW can be derived from electricity arbitrage trading on the day-ahead market and 130 kEUR/MW can be derived from participation in frequency regulation markets. Consequently, ancillary revenues correspond to about 65% of the total pumped hydro storage plant operating revenue. Considering that remuneration for provision of ancillary services is usually the main revenue stream for pumped hydro storage projects, 65% seems as a reasonable percentage. Nonetheless, it should be repeated that the reserves a pumped hydro storage plant can provide and how much energy storage is offset on the frequency regulation markets affect the ancillary revenues.

Furthermore, frequency regulation markets are based on reserve providers placing competitive bids and the Swedish TSO determining whether or not to accept the bids. Consequently, there is already a great amount of uncertainty surrounding the ancillary revenues from a conventional pumped hydro storage plant and even more uncertainty regarding the revenue that can be expected from a pumped hydro storage plant coupled with a hybrid power plant. However, after discussions with experts on pumped hydro storage plants, it became apparent that a general plant can be expected to generate operating revenues of 100 to 300 kEUR/MW/year, and for this reason, this study's techno-economic analysis result in terms of operating profit is in the middle of the aforementioned interval. Naturally, this strengthens the result of this thesis and makes it more credible. Moreover, the economic life is determined as 35 years due to the lifetime of wind and solar power plants, but in fact the pumped hydro storage plant would be able to operate and generate profit for at least five more years.

9.5 Project incentives

In addition to the purely financial incentives on grid-connected hybrid power plant with pumped hydro storage projects, there are other incentives with regard to the time required for project development and the commercial attractiveness of the projects. These incentives appeared during the course of this study.

9.5.1 Project development process

In Sweden, the permit-to-granting process for large renewable energy projects can take up to 9 years. The percentage of wind power projects that is rejected in any part of the application process is currently about 80%. The problems related to long permit applications and few granted applications do not fall within the scope of this thesis. Anyhow, enabling more projects to successfully proceed with the application process and shortening the time required for each step in the process, are important considerations in the realisation of the case study and similar renewable energy projects. These factors can both enable revenue streams from more projects and enable revenue streams at an earlier stage from the perspective of an electricity producer.

The development of renewable energy projects include discussions and agreements between multiple parties. In the initial site assessment, it is crucial to investigate the available grid-connection capacity and closeness to the project area. An application for connection of wind and solar power generation must be submitted to the distribution system operator (DSO) in early stages of the project development process. The DSO is responsible for assessment of suitable grid connection point and guaranteeing that the grid-connection comply with regulatory requirements. The grid-connection application process can take several years and is expensive. Furthermore, if an approved grid-connection would require large distribution grid reinforcements, the grid-connection part of the project is likely to entail long construction time and high installation cost.

A possible approach for electricity producers to simplify the grid-connection application process and increase the chances of a successful project, is to reduce the demands on the national grid by managing the power fluctuations within the internal system. Also, optimal operation of energy storage coupled to a renewable power plant before the grid connection point could reduce the required grid-connection capacity, and thereby reduce time and costs related to the installation of a large grid connection point. Moreover, a solar power plant can be installed close to an already existing grid-connected wind power plant, and thus create a hybrid power plant and increase the utilisation of an already existing grid connection point.

As of today, there is uncertainty about whether or not electricity producers are allowed to install a higher capacity of the primary electricity source than the grid-connection capacity. However, if mutual advantages of such a system configuration would be found, the regulations might be re-considered. Furthermore, having a much smaller grid-connection capacity than hybrid power plant capacity require an energy storage solution to reduce generation curtailment, and more investments in energy storage systems are requested by many DSOs in Sweden.

9.5.2 Commercial attractiveness

PPAs provide a certain revenue stability and are often required in renewable energy projects to secure financing from investors. The fixed electricity price is, however, an important factor with regard to bankability since a low electricity price also lower the profitability. For electricity producers of wind and solar power, pay-as-produced PPAs are commonly the most attractive agreements. Nonetheless, if an energy storage system is coupled to the renewable power plant, the potential benefits of general baseload PPAs increase. Energy storage systems can help provide reliable electricity supply to consumers and optimal operation of the systems would help mitigate the risk of having to buy expensive electricity from the day-ahead market in times of bad natural wind and solar resources. Additionally, if the electricity production and consumption is closely located, it would be possible for the power plants and the energy-intensive industry to be connected through internal cables before the grid connection point. In spite of this opportunity to decrease electricity losses and facilitate the connection to the national grid, regulations do currently not allow for power line construction projects within an internal electricity production system.

9.6 Future development

The future is uncertain and one can only speculate about what the future will hold. Historical data and statistical methods are commonly used in forecast and simulation tools in an attempt to predict the future development. For renewable energy projects it is of great interest to investigate the possible future electricity prices and the development of electricity markets.

9.6.1 Electricity price development

Historically, both the highest average electricity prices and the largest electricity price gaps in Sweden have appeared in electricity area SE3. As aforementioned, this is the electricity area where Project Garpenberg is located. Due to the large size of the proposed hybrid power plant, the completed project could possibly have a small impact on the price picture in the area if assuming that the price situation is the same as of today when the power plant is in operation.

The average electricity price in Sweden has doubled twice in just the last ten years, as seen in Table 2.9. The upward trend in electricity prices is expected to continue in the near future. The current price development is not just a consequence of the electrification and transition to higher share of variable renewable energy sources in the Swedish electricity mix, but is also dependent upon the development in other European countries. The Swedish electricity market and national grid network is closely linked to the Finnish, Danish, Norwegian and German electricity system, for instance. Especially, the high share of renewable power generation in the German electricity supply together with the Russian invasion of Ukraine caused excessive electricity price spikes in Germany in 2022. In turn, the average electricity price during the same time period was also very high in the southern Swedish electricity areas. In this sense, the liberalisation and internationalisation of the European electricity system can to some extent have negative impact on the Swedish electricity price situation. Nevertheless, it is important to mention that electricity area SE3 and SE4 are net-importers of electricity on an annual basis. Hence, these areas are occasionally dependent upon electricity produced in northern Sweden as well as in other European countries to meet the electricity demand.

From an electricity producers point of view, electricity prices must be higher than the cost of electricity production from a power plant to generate profit. As regards new investments in renewable energy projects, it is of great interest to analyse long-term scenarios on electricity price development. In 2022, the Swedish TSO performed a long-term market analysis on electricity price development until 2050 [59]. In the report, four scenarios on the future Swedish electricity mix were presented and the future electricity price situation was investigated based on those scenarios. The study concluded that in all of the investigated scenarios the average electricity price in 2050 was higher than the average electricity price in 2021 [59].

Another conclusion of the report [59] was that the electricity price gaps will most likely be large in the future. The increased electricity production from wind and solar power will reduce the predictability of the power system and make the electricity prices more volatile. New investments in energy storage systems that generate profit through electricity arbitrage trading are dependent upon the existence of price gaps to be economically feasible. In a similar manner to how price cannibalisation decreases the profitability of new investments in renewable energy projects as the total installed wind power plant and solar power plant capacity in Sweden increases, more grid-connected energy storage systems will decrease the electricity price gaps and counteract its own profitability. An additional factor that may decrease the size of the electricity price gaps in the future are large-scale implementation of flexibility solutions such as flexible production and demand. Flexibility solutions are discussed more in depth by the authors of [6] in their study on solutions for increased flexibility in the Swedish grid network.

9.6.2 Electricity market development

The development of electricity markets is constantly ongoing; new markets are introduced, other markets are changed and the entire Nordic electricity market is moving towards being more and more common to the whole of Europe.

As previously mentioned, the trading volume on the intraday market in Sweden is expected to increase in relation to the trading volume on the day-ahead market and 15-minutes bidding periods are currently being introduced. In the matter of frequency regulation markets, the Swedish TSO is responsible for developing these markets to adapt to the changing Swedish electricity system. An example of a frequency regulation market adjustment is the introduction of the FCR-product: FCR-D downward, in the beginning of 2022 [57]. After the introduction of this specific market, a bidding strategy that involves bidding simultaneously on the two markets: FCR-D upward and downward, has proven to generate great profit. However, this could change if additional markets are introduced or if the FCR markets become saturated.

For new renewable energy projects, it is important to make an effort to predict market changes and develop projects that can adapt their system operation to different future market scenarios. For energy storage projects, which generally are more dependent upon procurement of reserves than wind and solar power projects, it is even more important to have flexibility in operationality since frequency regulation market development happens faster than day-ahead and intraday market development. Two examples of points of electricity market development that would affect the profitability of combined hybrid power plant and pumped hydro storage projects are implementation of capacity mechanisms and compensation for grid services such as inertial response.

9.7 Subsequent research

To achieve 100% renewable power generation in the near future more renewable power plants and energy storage systems must be integrated to the power grid. The interest in renewable energy projects with renewable power plants co-integrated with pumped hydro storage plants has flared up recently and this is reflected on the fact that most studies on combined wind and/or solar power plant and pumped hydro storage systems have been published in the 2020s. The newness of the research area of this thesis and the certainty that large changes in electricity systems and markets are ongoing has provided a challenge in the execution of this study but also opened up for innovative thinking. During the thesis process many interesting topics for future studies were gathered and many of the assumptions in this study can be considered as research opportunities. In the list below, three selected research ideas are briefly explained.

- **Operating strategy involving multiple electricity markets**: Finding the optimal scheduling of a system is a complex task. In spite of that, to be able to investigate the true potential of coupling pumped hydro storage to hybrid power plants before the grid connection point, it is important to include multiple electricity markets in the operating strategy. The energy management model proposed in this thesis is simplified and includes only participation in the day-ahead market but could be developed to integrate also the intraday market and some of the frequency regulation markets.
- **System analysis in the time-frame of seconds**: To ensure the system functionality is maintained during real-world system operation, it is important to conduct simulations with high temporal resolution data. In this thesis, the data used in the simulations consists of average hourly values, and thus it is difficult to understand if the pumped hydro storage plant is able to handle large power fluctuations within each hour. In other words, it would be interesting to analyse 1-second resolution data on wind and solar power generation, and use this new data in simulations of the electrical system model with correct response times of the intended pumped hydro storage plant.

- **Simulations of future electricity price scenarios**: Data-driven investigation of how different future electricity price scenarios affect the profitability of new combined hybrid power plant and pumped hydro storage projects is desirable in the techno-economic analysis. The financial feasibility of coupling a pumped hydro storage plant to a hybrid power plant is heavily dependent upon what electricity price levels and price gaps can be expected in the future. In this thesis, the future development of prices and markets are discussed but no simulations on different price scenarios are conducted.

10 Conclusion

The operation and dimension of a grid-connected hybrid power plant with pumped hydro storage system was successfully optimised on the basis of the study assumptions. An overall final hybrid power plant with pumped hydro storage system configuration and dimension that provides better financial profitability than a stand-alone hybrid power plant was found. Combined hybrid power plant and pumped hydro storage projects have the potential to accelerate the energy transition by contributing to grid stability and flexibility. This type of innovate renewable energy projects are necessary in order to increase the share of variable renewable power generation in the electricity mix and meet the increasing electricity demand. Furthermore, solar power plants and pumped hydro storage plants can be installed to already existing grid-connected wind power plants, and accordingly increase the utilisation of current grid connection points.

The proposed energy management model on optimal hourly operation of a combined hybrid power plant and pumped hydro storage system determines how the entire system is managed. It is evident from the results that a pumped hydro storage plant lower the generation curtailment from the hybrid power plant and increase power balance on the grid by enabling both time shifts in electricity sales and the possibility to buy electricity from the grid when the electricity prices are low.

The response times of a pumped hydro storage plant are important to consider in the functionality evaluation of a combined hybrid power plant and pumped hydro storage system. Depending on response times and fluctuations in wind and solar power generation, the electrical system model may be more or less well-functioning. On an hourly basis, the result of the proposed energy management model can be advantageously used to schedule the electrical system operation. In spite of that, for real-world applications the system functionality must be reviewed and the benefits of changing operating strategy or installing an additional energy storage system, such as a battery system, to the combined hybrid power plant and pumped hydro storage system should be examined.

A combined hybrid power plant and pumped hydro storage project is more financially feasible than the hybrid power project alone. Nonetheless, it must be mentioned that the profitability depends on multiple factors of which electricity price level, electricity price gap and remuneration for provision of ancillary services, are some of the most important factors. Also, the profitability hinge upon the chosen dimension of the pumped hydro storage and the best financial result is obtained when there is a good balance between operating profit and installation cost.

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A Energy management model computer code

Energy management model - Optimisation function in MatLab

```
function [GCP_expV, GCP_impV, PHES_pV, PHES_tV, PHES_SOCV, CURT_EV, f_p, f_t,
kstart, kchangetp, kchangept, IstartV, IchangeptV, IchangetpV, IPHES_tV, IPHES_pV]
= optimDay(WPP_E, SPP_E,Price, SOCinit, IPHES_pinit, IPHES_tinit)

prob=optimproblem;
T=length(WPP_E);

% Decision variables
PHES_p_Pmax=80; %Max power in pump mode (MW)
PHES_t_Pmax=80; %Max power in turbine mode (MW)
PHES_p_Pmin=0; %Min power in pump mode (MW)
PHES_t_Pmin=0; %Min power in turbine mode (MW)
PHES_Emin=0; %Min SOC (MWh)
PHES_Emax=480; %Max SOC (MWh)
GCP_Pmax=140; %Max transformer power (MW)
f_p=4; %Cost in pump mode (EUR/MWh)
f_t=3; %Cost in turbine mode (EUR/MWh)
eff_p=0.9; %Efficiency in pump mode
eff_t=0.9; %Efficiency in turbine mode
kstart=10; %Cost start up pump/turbine (EUR)
kchangetp=6; %Cost change turbine to pump (EUR)
kchangept=4; %Cost change pump to turbine (EUR)

% Pump/turbine decision variables
PHES_p = optimvar('PHES_p',T,'LowerBound',0,'UpperBound',PHES_p_Pmax);
IPHES_p = optimvar('IPHES_p',T,'Type','integer','LowerBound',0,'UpperBound',1);
PHES_t = optimvar('PHES_t',T,'LowerBound',0,'UpperBound',PHES_t_Pmax);
IPHES_t = optimvar('IPHES_t',T,'Type','integer','LowerBound',0,'UpperBound',1);

% Pump/turbine constraints
prob.Constraints.PHES_pReal1 = PHES_p >= PHES_p_Pmin.*IPHES_p/eff_p  ;
prob.Constraints.PHES_pReal2 = PHES_p <= PHES_p_Pmax.*IPHES_p/eff_p;
prob.Constraints.PHES_tReal1 = PHES_t >= PHES_t_Pmin.*IPHES_t*eff_t  ;
prob.Constraints.PHES_tReal2 = PHES_t <= PHES_t_Pmax.*IPHES_t*eff_t;
prob.Constraints.IPHESreal = IPHES_p + IPHES_t <= 1;

% GCP decision variables
GCP_imp = optimvar('GCP_imp',T,'LowerBound',0,'UpperBound',GCP_Pmax);
IGCP_imp = optimvar('IGCP_imp',T,'Type','integer','LowerBound',0,'UpperBound',1);
GCP_exp = optimvar('GCP_exp',T,'LowerBound',0,'UpperBound',GCP_Pmax);
IGCP_exp = optimvar('IGCP_exp',T,'Type','integer','LowerBound',0,'UpperBound',1);

% GCP constraints
prob.Constraints.GCP_impReal = GCP_imp <= GCP_Pmax.*IGCP_imp;
prob.Constraints.GCP_expReal = GCP_exp <= GCP_Pmax.*IGCP_exp;
prob.Constraints.IGCPreal  = IGCP_imp + IGCP_exp <= 1;
```

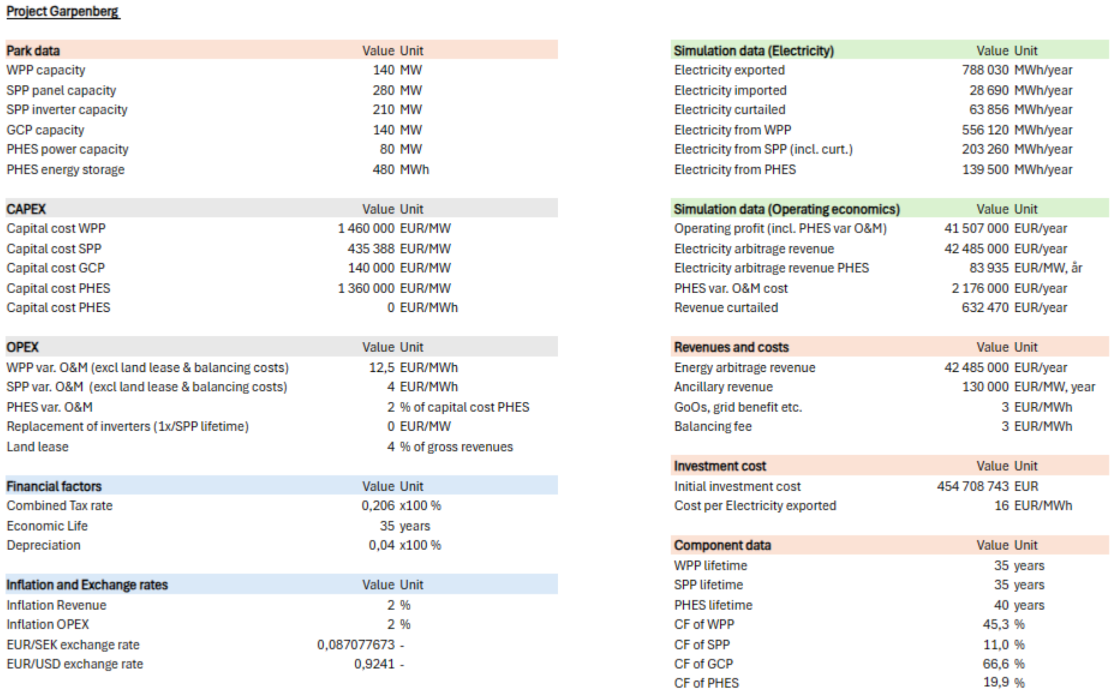
```matlab
% Energy storage decision variable
PHES_SOC = optimvar('PHES_SOC',T,'LowerBound',PHES_Emin,'UpperBound',PHES_Emax);

% Energy storage operating constraints
prob.Constraints.energyStorage  = optimconstr(T);
prob.Constraints.energyStorage(1) = PHES_SOC(1) == SOCinit+PHES_p(1)-PHES_t(1);
prob.Constraints.energyStorage(2:T)
= PHES_SOC(2:T) == PHES_SOC(1:T-1)+PHES_p(2:T)-PHES_t(2:T);
SOCend = PHES_SOC(T)-IPHES_t(T-1)+IPHES_p(T)-IPHES_p(T) == SOCinit;
prob.Constraints.energyStorageReal = SOCend;

% Curtailment decision variables
CURT_E = optimvar('CURT_E',T,'LowerBound',0,'UpperBound',2*GCP_Pmax);
ICURT_E = optimvar('ICURT_E',T,'Type','integer','LowerBound',0,'UpperBound',1);

% Curtailment constraints
prob.Constraints.CURTreal = CURT_E <= 350.*ICURT_E;
prob.Constraints.ICURTreal = IGCP_imp+ICURT_E <= 1;

% Energy balance constraint
prob.Constraints.energyBalance
= WPP_E+SPP_E+GCP_imp+PHES_t == PHES_p+GCP_exp+CURT_E;

% Start up turbine decision variable
Istart = optimvar('Istart',T,'Type','integer','LowerBound',0,'UpperBound',1);

% Start up turbine constraints
start1 = Istart(1) >= IPHES_t(1)-IPHES_tinit+IPHES_p(1)-IPHES_pinit;
prob.Constraints.IstartReal1 = start1;
start2 = Istart(2:T) >= IPHES_t(2:T)-IPHES_t(1:T-1)+IPHES_p(2:T)-IPHES_p(1:T-1);
prob.Constraints.IstartReal2 = start2;

% Change pump to turbine decision variable
Ichangept = optimvar('Ichangept',T,'Type','integer','LowerBound',0,'UpperBound',1);

% Change pump to turbine constraints
change1 = Ichangept >= IPHES_t(1)+IPHES_pinit-1;
prob.Constraints.IchangeReal1 = change1;
change2 = Istart(2:T) >= IPHES_t(2:T)+IPHES_p(1:T-1)-1;
prob.Constraints.IchangeReal2 = change2;

% Change turbine to pump decision variable
Ichangetp = optimvar('Ichangetp',T,'Type','integer','LowerBound',0,'UpperBound',1);

% Change turbine to pump constraints
change3 = Ichangetp(1) >= IPHES_t(1) + IPHES_pinit - 1;
prob.Constraints.IchangeReal3 = change3;
change4 = Ichangetp(2:T) >= IPHES_t(2:T) + IPHES_p(1:T-1) - 1;
prob.Constraints.IchangeReal4 = change4;

% Objective function
prob.ObjectiveSense = 'maximize';
```

```
prob.Objective = sum(GCP_exp.*Price)-sum(GCP_imp.*Price)-sum(f_p*PHES_p)
-sum(f_t*PHES_t)-sum(CURT_E.*Price)-sum(kstart*Istart)
-sum(kchangetp*Ichangetp)-sum(kchangept*Ichangept);

%Solve optimisation problem
options=optimoptions(prob.optimoptions,'Display','none');
[values,~,exitflag] = solve(prob,'Options',options);

% Show optimisation results
if exitflag <= 0
PHES_pV = zeros(T,1);
PHES_tV = zeros(T,1);
GCP_expV = zeros(T,1);
GCP_impV = zeros(T,1);
PHES_SOCV = zeros(T,1);
IstartV=zeros(T,1);
IchangeptV=zeros(T,1);
IchangetpV=zeros(T,1);
CURT_EV=zeros(T,1);
else
PHES_pV = values.PHES_p;
PHES_tV = values.PHES_t;
GCP_expV = values.GCP_exp;
GCP_impV = values.GCP_imp;
PHES_SOCV = values.PHES_SOC;
IstartV=values.Istart;
IchangeptV=values.Ichangept;
IchangetpV=values.Ichangetp;
CURT_EV=values.CURT_E;
IPHES_tV=values.IPHES_t;
IPHES_pV=values.IPHES_p;
end
```

Energy management model - System script in MatLab

```
% Optimisation input data
D=365; %No. of Days
SOCinit=240; %Initial SOC (MWh)
IPHES_tinit=0; %Initial PHES turbine operation (binary variable: off=0, on=1)
IPHES_pinit=0; %Initial PHES pump operation (binary variable: off=0, on=1)

% Optimisation process
for day=1:D
    WPP_E=WPP_140MW_2023_MatLab((day-1)*24+1:(day-1)*24+24,2);
    SPP_E=SPP_105MW_2023_MatLab((day-1)*24+1:(day-1)*24+24,2)2;
    Price=Prices_2023_MatLab((day-1)*24+1:(day-1)*24+24,2);
    [GCP_expV, GCP_impV, PHES_pV, PHES_tV, PHES_SOCV, CURT_EV, f_p, f_t, kstart,
    kchangetp, kchangept, IstartV, IchangeptV, IchangetpV, IPHES_tV, IPHES_pV]
    = optimDay2(WPP_E, SPP_E,Price,SOCinit,IPHES_pinit,IPHES_tinit);
    WPP_EY((day-1)*24+1:(day-1)*24+24,1)=WPP_E;
    SPP_EY((day-1)*24+1:(day-1)*24+24,1)=SPP_E;
    GCP_expY((day-1)*24+1:(day-1)*24+24,1)=GCP_expV;
    GCP_impY((day-1)*24+1:(day-1)*24+24,1)=GCP_impV;
    CURT_EY((day-1)*24+1:(day-1)*24+24,1)=CURT_EV;
    PHES_pY((day-1)*24+1:(day-1)*24+24,1)=PHES_pV;
    PHES_tY((day-1)*24+1:(day-1)*24+24,1)=PHES_tV;
    IstartY((day-1)*24+1:(day-1)*24+24,1)=IstartV;
    IchangeptY((day-1)*24+1:(day-1)*24+24,1)=IchangeptV;
    IchangetpY((day-1)*24+1:(day-1)*24+24,1)=IchangetpV;
    PHES_SOCY((day-1)*24+1:(day-1)*24+24,1)=PHES_SOCV;
    SOCinit=PHES_SOCY(end);
      if PHES_tY(end)>0
          IPHES_tinit=1;
      else
          IPHES_tinit=0;
      end
      if PHES_pY(end)>0
          IPHES_pinit=1;
      else
          IPHES_pinit=0;
      end
end
```

B Investment appraisal



Project Garpenberg

Park data	Value	Unit
WPP capacity	140	MW
SPP panel capacity	280	MW
SPP inverter capacity	210	MW
GCP capacity	140	MW
PHES power capacity	80	MW
PHES energy storage	480	MWh

CAPEX	Value	Unit
Capital cost WPP	1 460 000	EUR/MW
Capital cost SPP	435 388	EUR/MW
Capital cost GCP	140 000	EUR/MW
Capital cost PHES	1 360 000	EUR/MW
Capital cost PHES	0	EUR/MWh

OPEX	Value	Unit
WPP var. O&M (excl land lease & balancing costs)	12,5	EUR/MWh
SPP var. O&M (excl land lease & balancing costs)	4	EUR/MWh
PHES var. O&M	2	% of capital cost PHES
Replacement of inverters (1x/SPP lifetime)	0	EUR/MW
Land lease	4	% of gross revenues

Financial factors	Value	Unit
Combined Tax rate	0,206	x100 %
Economic Life	35	years
Depreciation	0,04	x100 %

Inflation and Exchange rates	Value	Unit
Inflation Revenue	2	%
Inflation OPEX	2	%
EUR/SEK exchange rate	0,087077673	-
EUR/USD exchange rate	0,9241	-

Simulation data (Electricity)	Value	Unit
Electricity exported	788 030	MWh/year
Electricity imported	28 690	MWh/year
Electricity curtailed	63 856	MWh/year
Electricity from WPP	556 120	MWh/year
Electricity from SPP (incl. curt.)	203 260	MWh/year
Electricity from PHES	139 500	MWh/year

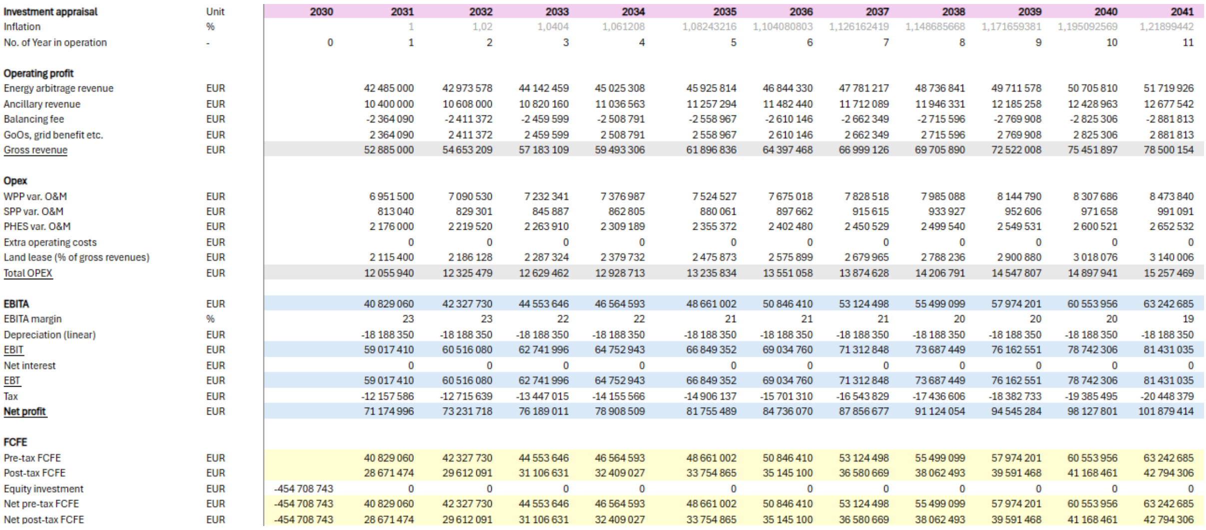
Simulation data (Operating economics)	Value	Unit
Operating profit (incl. PHES var O&M)	41 507 000	EUR/year
Electricity arbitrage revenue	42 485 000	EUR/year
Electricity arbitrage revenue PHES	83 935	EUR/MW, år
PHES var. O&M cost	2 176 000	EUR/year
Revenue curtailed	632 470	EUR/year

Revenues and costs	Value	Unit
Energy arbitrage revenue	42 485 000	EUR/year
Ancillary revenue	130 000	EUR/MW, year
GoOs, grid benefit etc.	3	EUR/MWh
Balancing fee	3	EUR/MWh

Investment cost	Value	Unit
Initial investment cost	454 708 743	EUR
Cost per Electricity exported	16	EUR/MWh

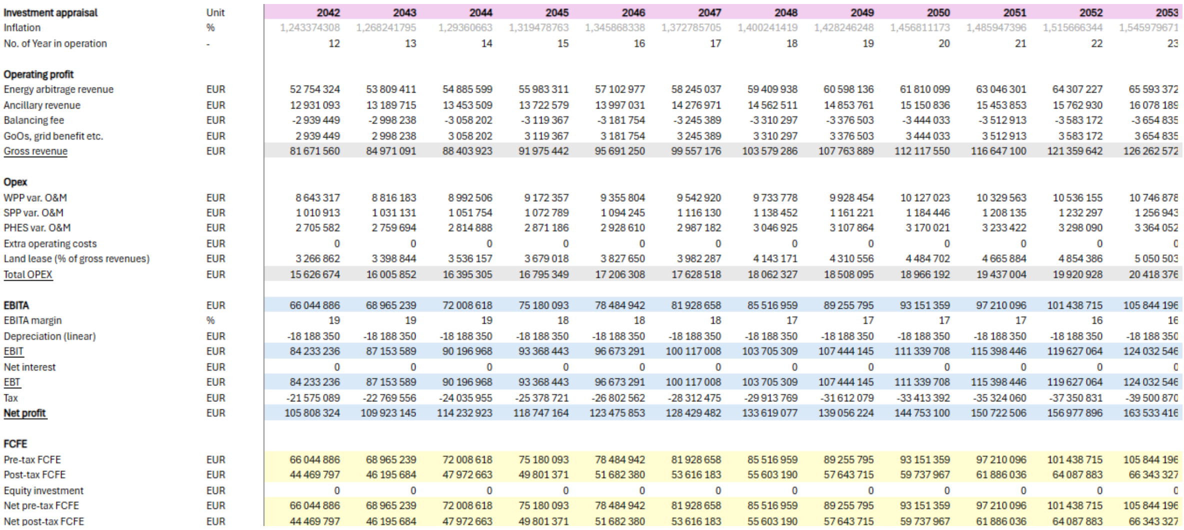
Component data	Value	Unit
WPP lifetime	35	years
SPP lifetime	35	years
PHES lifetime	40	years
CF of WPP	45,3	%
CF of SPP	11,0	%
CF of GCP	66,6	%
CF of PHES	19,9	%

Figure B.1: Part 1: Investment appraisal of final hybrid power plant with pumped hydro storage system.



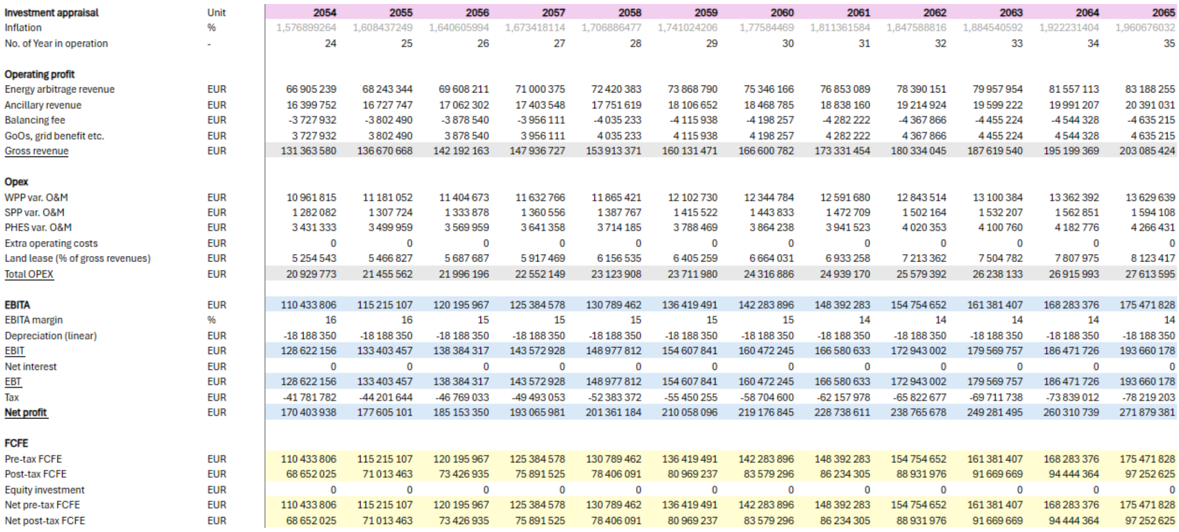
Investment appraisal	Unit	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041
Inflation	%		1	1,02	1,0404	1,061208	1,08243216	1,104080803	1,126162419	1,148685668	1,171659381	1,195092569	1,21899442
No. of Year in operation	-	0	1	2	3	4	5	6	7	8	9	10	11
Operating profit													
Energy arbitrage revenue	EUR		42 485 000	42 973 578	44 142 459	45 025 308	45 925 814	46 844 330	47 781 217	48 736 841	49 711 578	50 705 810	51 719 926
Ancillary revenue	EUR		10 400 000	10 608 000	10 820 160	11 036 563	11 257 294	11 482 440	11 712 089	11 946 331	12 185 258	12 428 963	12 677 542
Balancing fee	EUR		-2 364 090	-2 411 372	-2 459 599	-2 508 791	-2 558 967	-2 610 146	-2 662 349	-2 715 596	-2 769 908	-2 825 306	-2 881 813
GoOs, grid benefit etc.	EUR		2 364 090	2 411 372	2 459 599	2 508 791	2 558 967	2 610 146	2 662 349	2 715 596	2 769 908	2 825 306	2 881 813
Gross revenue	EUR		52 885 000	54 653 209	57 183 109	59 493 306	61 896 836	64 397 468	66 999 126	69 705 890	72 522 008	75 451 897	78 500 154
Opex													
WPP var. O&M	EUR		6 951 500	7 090 530	7 232 341	7 376 987	7 524 527	7 675 018	7 828 518	7 985 088	8 144 790	8 307 686	8 473 840
SPP var. O&M	EUR		813 040	829 301	845 887	862 805	880 061	897 662	915 615	933 927	952 606	971 658	991 091
PHES var. O&M	EUR		2 176 000	2 219 520	2 263 910	2 309 189	2 355 372	2 402 480	2 450 529	2 499 540	2 549 531	2 600 521	2 652 532
Extra operating costs	EUR		0	0	0	0	0	0	0	0	0	0	0
Land lease (% of gross revenues)	EUR		2 115 400	2 186 128	2 287 324	2 379 732	2 475 873	2 575 899	2 679 965	2 788 236	2 900 880	3 018 076	3 140 006
Total OPEX	EUR		12 055 940	12 325 479	12 629 462	12 928 713	13 235 834	13 551 058	13 874 628	14 206 791	14 547 807	14 897 941	15 257 469
EBITA	EUR		40 829 060	42 327 730	44 553 646	46 564 593	48 661 002	50 846 410	53 124 498	55 499 099	57 974 201	60 553 956	63 242 685
EBITA margin	%		23	23	22	22	21	21	21	20	20	20	19
Depreciation (linear)	EUR		-18 188 350	-18 188 350	-18 188 350	-18 188 350	-18 188 350	-18 188 350	-18 188 350	-18 188 350	-18 188 350	-18 188 350	-18 188 350
EBIT	EUR		59 017 410	60 516 080	62 741 996	64 752 943	66 849 352	69 034 760	71 312 848	73 687 449	76 162 551	78 742 306	81 431 035
Net interest	EUR		0	0	0	0	0	0	0	0	0	0	0
EBT	EUR		59 017 410	60 516 080	62 741 996	64 752 943	66 849 352	69 034 760	71 312 848	73 687 449	76 162 551	78 742 306	81 431 035
Tax	EUR		-12 157 586	-12 715 639	-13 447 015	-14 155 566	-14 906 137	-15 701 310	-16 543 829	-17 436 606	-18 382 733	-19 385 495	-20 448 379
Net profit	EUR		71 174 996	73 231 718	76 189 011	78 908 509	81 755 489	84 736 070	87 856 677	91 124 054	94 545 284	98 127 801	101 879 414
FCFE													
Pre-tax FCFE	EUR		40 829 060	42 327 730	44 553 646	46 564 593	48 661 002	50 846 410	53 124 498	55 499 099	57 974 201	60 553 956	63 242 685
Post-tax FCFE	EUR		28 671 474	29 612 091	31 106 631	32 409 027	33 754 865	35 145 100	36 580 669	38 062 493	39 591 468	41 168 461	42 794 306
Equity investment	EUR	-454 708 743	0	0	0	0	0	0	0	0	0	0	0
Net pre-tax FCFE	EUR	-454 708 743	40 829 060	42 327 730	44 553 646	46 564 593	48 661 002	50 846 410	53 124 498	55 499 099	57 974 201	60 553 956	63 242 685
Net post-tax FCFE	EUR	-454 708 743	28 671 474	29 612 091	31 106 631	32 409 027	33 754 865	35 145 100	36 580 669	38 062 493	39 591 468	41 168 461	42 794 306

Figure B.2: Part 2: Investment appraisal of final hybrid power plant with pumped hydro storage system.



Investment appraisal	Unit	2042	2043	2044	2045	2046	2047	2048	2049	2050	2051	2052	2053
Inflation	%	1,243374308	1,268241795	1,29360663	1,319478763	1,345868338	1,372785705	1,400241419	1,428246248	1,456811173	1,485947396	1,515666344	1,545979671
No. of Year in operation	-	12	13	14	15	16	17	18	19	20	21	22	23
Operating profit													
Energy arbitrage revenue	EUR	52 754 324	53 809 411	54 885 599	55 983 311	57 102 977	58 245 037	59 409 938	60 598 136	61 810 099	63 046 301	64 307 227	65 593 372
Ancillary revenue	EUR	12 931 093	13 189 715	13 453 509	13 722 579	13 997 031	14 276 971	14 562 511	14 853 761	15 150 836	15 453 853	15 762 930	16 078 189
Balancing fee	EUR	-2 939 449	-2 998 238	-3 058 202	-3 119 367	-3 181 754	-3 245 389	-3 310 297	-3 376 503	-3 444 033	-3 512 913	-3 583 172	-3 654 835
GoOs, grid benefit etc.	EUR	2 939 449	2 998 238	3 058 202	3 119 367	3 181 754	3 245 389	3 310 297	3 376 503	3 444 033	3 512 913	3 583 172	3 654 835
Gross revenue	EUR	81 671 560	84 971 091	88 403 923	91 975 442	95 691 250	99 557 176	103 579 286	107 763 889	112 117 550	116 647 100	121 359 642	126 262 572
Opex													
WPP var. O&M	EUR	8 643 317	8 816 183	8 992 506	9 172 357	9 355 804	9 542 920	9 733 778	9 928 454	10 127 023	10 329 563	10 536 155	10 746 878
SPP var. O&M	EUR	1 010 913	1 031 131	1 051 754	1 072 789	1 094 245	1 116 130	1 138 452	1 161 221	1 184 446	1 208 135	1 232 297	1 256 943
PHES var. O&M	EUR	2 705 582	2 759 694	2 814 888	2 871 186	2 928 610	2 987 182	3 046 925	3 107 864	3 170 021	3 233 422	3 298 090	3 364 052
Extra operating costs	EUR	0	0	0	0	0	0	0	0	0	0	0	0
Land lease (% of gross revenues)	EUR	3 266 862	3 398 844	3 536 157	3 679 018	3 827 650	3 982 287	4 143 171	4 310 556	4 484 702	4 665 884	4 854 386	5 050 503
Total OPEX	EUR	15 626 674	16 005 852	16 395 305	16 795 349	17 206 308	17 628 518	18 062 327	18 508 095	18 966 192	19 437 004	19 920 928	20 418 376
EBITA	EUR	66 044 886	68 965 239	72 008 618	75 180 093	78 484 942	81 928 658	85 516 959	89 255 795	93 151 359	97 210 096	101 438 715	105 844 196
EBITA margin	%	19	19	19	18	18	18	17	17	17	17	16	16
Depreciation (linear)	EUR	-18 188 350	-18 188 350	-18 188 350	-18 188 350	-18 188 350	-18 188 350	-18 188 350	-18 188 350	-18 188 350	-18 188 350	-18 188 350	-18 188 350
EBIT	EUR	84 233 236	87 153 589	90 196 968	93 368 443	96 673 291	100 117 008	103 705 309	107 444 145	111 339 708	115 398 446	119 627 064	124 032 546
Net interest	EUR	0	0	0	0	0	0	0	0	0	0	0	0
EBT	EUR	84 233 236	87 153 589	90 196 968	93 368 443	96 673 291	100 117 008	103 705 309	107 444 145	111 339 708	115 398 446	119 627 064	124 032 546
Tax	EUR	-21 575 089	-22 769 556	-24 035 955	-25 378 721	-26 802 562	-28 312 475	-29 913 769	-31 612 079	-33 413 392	-35 324 060	-37 350 831	-39 500 870
Net profit	EUR	105 808 324	109 923 145	114 232 923	118 747 164	123 475 853	128 429 482	133 619 077	139 056 224	144 753 100	150 722 506	156 977 896	163 533 416
FCFE													
Pre-tax FCFE	EUR	66 044 886	68 965 239	72 008 618	75 180 093	78 484 942	81 928 658	85 516 959	89 255 795	93 151 359	97 210 096	101 438 715	105 844 196
Post-tax FCFE	EUR	44 469 797	46 195 684	47 972 663	49 801 371	51 682 380	53 616 183	55 603 190	57 643 715	59 737 967	61 886 036	64 087 883	66 343 327
Equity investment	EUR	0	0	0	0	0	0	0	0	0	0	0	0
Net pre-tax FCFE	EUR	66 044 886	68 965 239	72 008 618	75 180 093	78 484 942	81 928 658	85 516 959	89 255 795	93 151 359	97 210 096	101 438 715	105 844 196
Net post-tax FCFE	EUR	44 469 797	46 195 684	47 972 663	49 801 371	51 682 380	53 616 183	55 603 190	57 643 715	59 737 967	61 886 036	64 087 883	66 343 327

Figure B.3: Part 3: Investment appraisal of final hybrid power plant with pumped hydro storage system.



Investment appraisal	Unit	2054	2055	2056	2057	2058	2059	2060	2061	2062	2063	2064	2065
Inflation	%	1,576899264	1,608437249	1,640605994	1,673418114	1,706886477	1,741024206	1,77584469	1,811361584	1,847588816	1,884540592	1,922231404	1,960676032
No. of Year in operation	-	24	25	26	27	28	29	30	31	32	33	34	35
Operating profit													
Energy arbitrage revenue	EUR	66 905 239	68 243 344	69 608 211	71 000 375	72 420 383	73 868 790	75 346 166	76 853 089	78 390 151	79 957 954	81 557 113	83 188 255
Ancillary revenue	EUR	16 399 752	16 727 747	17 062 302	17 403 548	17 751 619	18 106 652	18 468 785	18 838 160	19 214 924	19 599 222	19 991 207	20 391 031
Balancing fee	EUR	-3 727 932	-3 802 490	-3 878 540	-3 956 111	-4 035 233	-4 115 938	-4 198 257	-4 282 222	-4 367 866	-4 455 224	-4 544 328	-4 635 215
GoOs, grid benefit etc.	EUR	3 727 932	3 802 490	3 878 540	3 956 111	4 035 233	4 115 938	4 198 257	4 282 222	4 367 866	4 455 224	4 544 328	4 635 215
Gross revenue	EUR	131 363 580	136 670 668	142 192 163	147 936 727	153 913 371	160 131 471	166 600 782	173 331 454	180 334 045	187 619 540	195 199 369	203 085 424
Opex													
WPP var. O&M	EUR	10 961 815	11 181 052	11 404 673	11 632 766	11 865 421	12 102 730	12 344 784	12 591 680	12 843 514	13 100 384	13 362 392	13 629 639
SPP var. O&M	EUR	1 282 082	1 307 724	1 333 878	1 360 556	1 387 767	1 415 522	1 443 833	1 472 709	1 502 164	1 532 207	1 562 851	1 594 108
PHES var. O&M	EUR	3 431 333	3 499 959	3 569 959	3 641 358	3 714 185	3 788 469	3 864 238	3 941 523	4 020 353	4 100 760	4 182 776	4 266 431
Extra operating costs	EUR	0	0	0	0	0	0	0	0	0	0	0	0
Land lease (% of gross revenues)	EUR	5 254 543	5 466 827	5 687 687	5 917 469	6 156 535	6 405 259	6 664 031	6 933 258	7 213 362	7 504 782	7 807 975	8 123 417
Total OPEX	EUR	20 929 773	21 455 562	21 996 196	22 552 149	23 123 908	23 711 980	24 316 886	24 939 170	25 579 392	26 238 133	26 915 993	27 613 595
EBITA	EUR	110 433 806	115 215 107	120 195 967	125 384 578	130 789 462	136 419 491	142 283 896	148 392 283	154 754 652	161 381 407	168 283 376	175 471 828
EBITA margin	%	16	16	15	15	15	15	15	14	14	14	14	14
Depreciation (linear)	EUR	-18 188 350	-18 188 350	-18 188 350	-18 188 350	-18 188 350	-18 188 350	-18 188 350	-18 188 350	-18 188 350	-18 188 350	-18 188 350	-18 188 350
EBIT	EUR	128 622 156	133 403 457	138 384 317	143 572 928	148 977 812	154 607 841	160 472 245	166 580 633	172 943 002	179 569 757	186 471 726	193 660 178
Net interest	EUR	0	0	0	0	0	0	0	0	0	0	0	0
EBT	EUR	128 622 156	133 403 457	138 384 317	143 572 928	148 977 812	154 607 841	160 472 245	166 580 633	172 943 002	179 569 757	186 471 726	193 660 178
Tax	EUR	-41 781 782	-44 201 644	-46 769 033	-49 493 053	-52 383 372	-55 450 255	-58 704 600	-62 157 978	-65 822 677	-69 711 738	-73 839 012	-78 219 203
Net profit	EUR	170 403 938	177 605 101	185 153 350	193 065 981	201 361 184	210 058 096	219 176 845	228 738 611	238 765 678	249 281 495	260 310 739	271 879 381
FCFE													
Pre-tax FCFE	EUR	110 433 806	115 215 107	120 195 967	125 384 578	130 789 462	136 419 491	142 283 896	148 392 283	154 754 652	161 381 407	168 283 376	175 471 828
Post-tax FCFE	EUR	68 652 025	71 013 463	73 426 935	75 891 525	78 406 091	80 969 237	83 579 296	86 234 305	88 931 976	91 669 669	94 444 364	97 252 625
Equity investment	EUR	0	0	0	0	0	0	0	0	0	0	0	0
Net pre-tax FCFE	EUR	110 433 806	115 215 107	120 195 967	125 384 578	130 789 462	136 419 491	142 283 896	148 392 283	154 754 652	161 381 407	168 283 376	175 471 828
Net post-tax FCFE	EUR	68 652 025	71 013 463	73 426 935	75 891 525	78 406 091	80 969 237	83 579 296	86 234 305	88 931 976	91 669 669	94 444 364	97 252 625

Figure B.4: Part 4: Investment appraisal of final hybrid power plant with pumped hydro storage system.

Financial metrics		
Simple payback	years	6
LCOE	EUR/MWh	75
Pre-tax Equity IRR	x100%	0,118
Post-tax Equity IRR	x100%	0,070

Figure B.5: Part 5: Investment appraisal of final hybrid power plant with pumped hydro storage system.