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Industrial Electrical Engineering and Automation

Unlocking the Potential of Solar-Hydro Hybrid Solutions: Feasibility and Economic Analysis

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Abstract

Hybrid solutions that combine multiple renewable energy sources, such as solar power and hydro power, are gaining popularity as a means of meeting the growing energy demands while minimising environmental impacts, but also as an opportunity of connecting solar power plants to the grid in areas where this might not be possible unless large investments are made. This master thesis aims to evaluate the feasibility and economic viability of integrating solar panels with an existing grid connection point at a hydro power plant, along with the introduction of an energy storage solution using a hydro power plant reservoir. The study is conducted in cooperation with Eolus Vind AB and focuses on a selected site at Karsefors in southern Sweden, but also discusses hybrid solutions in a broader context, considering other solar and hydro power technologies such as pumped hydro power and floating PV, emphasising their potential advantages and challenges.

Four different scenarios are simulated and analysed, including standalone hydro power production, standalone solar power production, and two hybrid solar-hydro power production scenarios with and without an implemented refinement method. The simulations provide insights into the benefits and disadvantages of implementing a hybrid system compared to standalone solar and hydro power plants. The study examines technical aspects such as grid utilisation, curtailment and refinement methods, as well as economic factors such as income generation, net present value (NPV), internal rate of return (IRR) and payback time.

The results indicate that the technical and operational feasibility of a solar-hydro hybrid system at a shared grid connection point was found to be viable. The study highlights the potential to reduce curtailment and grid capacity limitations through refinement methods. However, curtailment may still be necessary during certain periods. The economic analysis revealed mixed results with suboptimal financial metrics but higher income for the hybrid scenarios compared to standalone systems. Alternative hybrid solutions like pumped hydro power and floating PV offer additional possibilities for storage and synergies, but require trade-offs and consideration of implementation costs and environmental impacts.

Preface

This master thesis is the result of a collaboration with Eolus Vind AB, with the purpose of investigating the feasibility and financial viability of integrating a solar power plant to an existing hydro power plant at its grid connection point. The specific site examined in this report is the Karsefors hydro power plant, situated along the river Lagan in bidding area SE4.

To obtain crucial production and economic data for the solar power plant, Eolus Vind AB kindly provided data through simulations using PVsyst. Gratitude is also owed to Statkraft Sverige AB for sharing data on the Karsefors hydro power plant, as well as Nord Pool for granting access to their historical day-ahead and intraday spot prices.

I would like to express special appreciation to my supervisor at Lund University, Jörgen Svensson, and my supervisor at Eolus Vind AB, Fredrik Liljehov, along with the entire staff at Eolus Vind AB, for their support throughout this master thesis. Their guidance and assistance have been invaluable in the completion of this research.

Nomenclature

AC	Alternating current
DC	Direct current
Degradation factor	Efficiency decrease per year
GCR	Ground coverage ratio
IRR	Internal rate of return
Irradiance	Solar power per unit area $[W/m^2]$
MPPT	Maximum power point tracking
NPV	Net present value
PV	Photovoltaic
PVGIS	European Commission database for solar irradiation
PVsyst	Solar power simulation program
Photon	Particle of light that carries energy

Contents

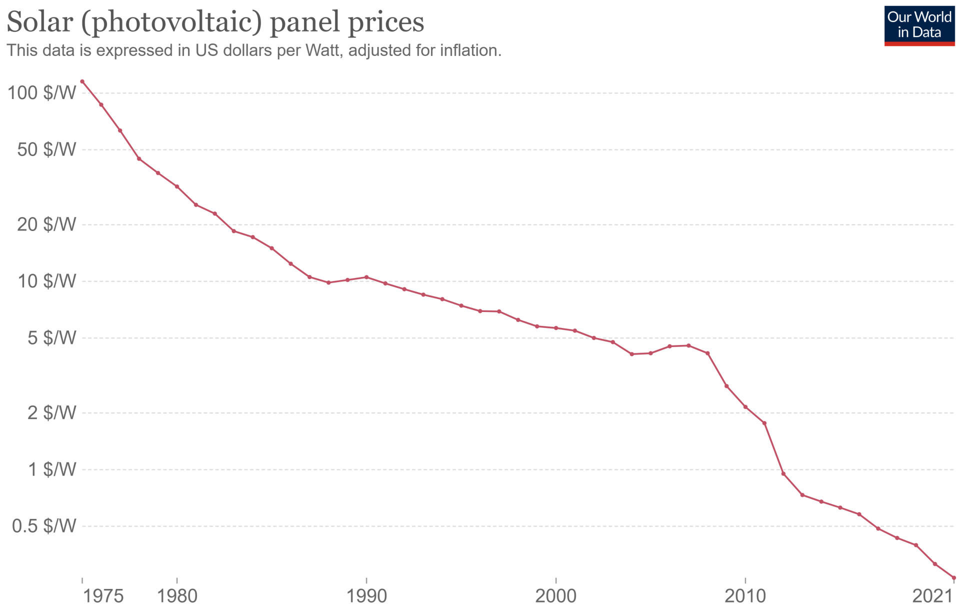
1 Introduction

This section provides an overview of the background, objectives, research questions, methodology, and limitations of the study. It acts as a basis for the subsequent analysis by discussing the context, goals, approach, and boundaries of the research.

1.1 Background

Hybrid solutions that combine multiple renewable energy sources have become an increasingly popular option for meeting the rising energy demands of modern society. The integration of solar power and hydro power has the potential to produce a stable and reliable energy supply with low environmental impacts. From an economical perspective it could also act as a means to decrease investment costs as the two power plants could share grid connection and thus removing part of the investment costs related to building a new transformer at a grid connection point.

The utilisation of solar power has gained considerable attention in recent years due to its clean, sustainable, and renewable nature. Solar power generation is also becoming increasingly cost-effective with a continuous decrease in costs over the recent years reaching as low as 0.27$/W in 2021, which can be seen in figure 1, making it a viable option for energy production. Hydropower, on the other hand, is one of the most established renewable energy source in the world and has been utilised for many years. Hydro power has the potential to generate large amounts of electricity, particularly in areas with significant water resources.


Solar (photovoltaic) panel prices
This data is expressed in US dollars per Watt, adjusted for inflation.

Source: Nemet (2009); Farmer & Lafond (2016); International Renewable Energy Agency (IRENA)
OurWorldInData.org/energy • CC BY
Note: Data is expressed in constant 2021 US$ per Watt.

Figure 1: Solar panel cost in US dollars per watt (Our World in Data, 2023). Note that the scale is non-linear.

The combination of these two sources can provide a reliable and consistent energy supply that can be utilised throughout the day and across different seasons. By utilising both sources the drawbacks of each energy source can be reduced and in turn the benefits can be increased.

For instance, hydro power may be limited in its electricity production during periods of drought while solar power will be less efficient during periods of less solar irradiation, such as during night time, during the winter season or when large clouds cover the sky. Combining the two sources can increase the insurance of a reliable energy supply and reduce the need for backup generation sources. Given the potential benefits of hybrid solutions with solar and hydro power, it is important to examine the feasibility and economic viability of such systems, which is why this study is being made.

1.2 Objective

The objective of this study is to evaluate the profitability and feasibility of connecting solar panels to an existing grid connection point at a hydro power plant, in order to reduce the costs associated with grid connection, as well as introducing an energy storage solution in the form of stored water in a hydro power plant reservoir. The study will focus on integrating solar and hydro power into the grid connection point of a selected site, but will also discuss the hybrid solution independent of site and investigate different solar and hydro power technologies. The site specific investigation will examine the potential of a solar-hydro hybrid system by analysing four different scenarios that will cover all base cases as well as the hybrid case with and without an implemented refinement method. The four scenarios are as follows:

- Scenario 0: Standalone Hydro power production.
- Scenario 1: Standalone Solar power production.
- Scenario 2: Hybrid Solar-Hydro power production - Without refinement.
- Scenario 3: Hybrid Solar-Hydro power production - With refinement.

The hybrid simulation scenarios will be compared to a standalone grid connected solar and hydro power plant with the purpose of displaying the benefits or disadvantages of implementing a hybrid system. A more thorough overview of the different scenarios are explained in section 5. Overall, this study seeks to provide insights into the feasibility and economic viability of hybrid solutions with solar and hydro power. The findings of this study are meant to contribute to the development of sustainable and reliable energy systems that can meet the rising energy demands of modern society while minimizing environmental impacts.

1.3 Research questions

Below follows the research questions that this study will aim to answer.

- What are the technical and operational feasibility aspects of integrating solar power and hydro power into a hybrid system at the same grid connection point?
- How does a hybrid system perform in terms of electricity generation and energy supply compared to standalone solar power and standalone hydro power in Sweden?
- What are the economic implications of implementing solar power plant to the same grid connection point as a hydro power plant compared to the standalone solar power system in terms of Net Present Value (NPV), Internal Rate of Return (IRR), and payback time.
- What are the potential benefits and challenges of alternative solar-hydro hybrid solutions?

1.4 Methodology

This master thesis mainly focuses on two areas regarding hybrid solutions with solar and hydro power. The first is an in depth literature review of already existing hybrid solutions, future potential solutions, and the theoretical aspects of both types of power plants respectively and when operating in a hybrid system. This background study is essential to gain a comprehensive and necessary understanding of the complexity of solar-hydro hybrid power plants.

The second part of this study involves a series of simulations using the softwares PVsyst and Microsoft Excel. PVsyst is used for simulating the solar power plants and Microsoft Excel for further refinement and related calculations. The simulations have been customised to fit the selected simulation site and to fit the objective of this master thesis. The simulations are meant to provide vital information that can be used to discuss the feasibility and profitability of the hybrid system.

1.5 Limitations

Although this report discuss storage possibilities in a hydro power plant it does not analyse or discuss the possibility of implementing battery storage to the system. Additionally this master thesis explore the profitability and feasibility of a solar-hydro hybrid system but does not go in to the specifics of the electrical design requirements in the components related to such a system.

The results are limited to simulations based on a specific site at Karsefors in the river Lagan for the years 2018 and 2020. They are also limited to four scenarios, described in section 5, which include standalone projects as well as hybrid projects. No other scenarios are simulated or calculated for in this report.

2 Theory

This section will introduce comprehensive overview of the theoretical background necessary for the analysis of a solar-hydro hybrid power plant. First, the principles of hydro and solar power generation will be introduced, highlighting their individual characteristics and operating mechanisms. Thereafter the synergies and complementarities between these two sources in a hybrid system will be explained, along with an overview of the Swedish electricity market. As the main focus of this study is to examine the possibility and viability of a solar-hydro hybrid power plant the different technologies are explained in a moderate level of profoundness.

2.1 Conventional hydro power

When water evaporates from the surface of the earth it gathers in the atmosphere as clouds. The water then returns to earths surface by rain and snow and flows through streams by converting its potential energy to kinetic energy. A hydro power plant can therefore be installed in conditions where the potential energy can be converted to kinetic energy which in turn can be utilised to produce electrical energy. Since both the potential energy and the volume of the flowing water is utilised, a large difference in elevation between the reservoir and turbine as well as higher water flow is optimal. (EERE, n.da)

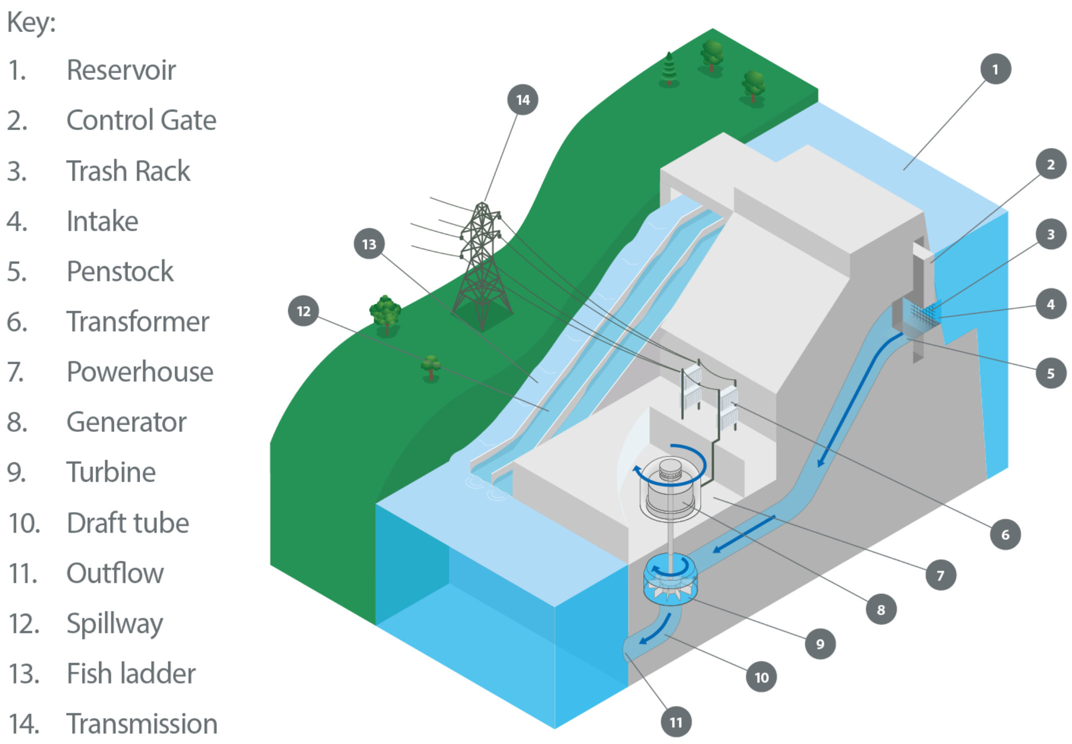


Figure 2: Visualisation of a hydro power plant (IHA, n.d)

1. *Reservoir*
   The reservoir carry the water used for production in the hydro power plant. It is elevated at a higher level to make use of the potential energy of the water. Higher

elevation means higher potential energy and higher potential energy is desired to generate electricity from the descending water. The elevation between the turbine and reservoir is called the head. (Energy Education, n.dc) In a run of the river hydro power system the reservoir is usually called a pondage, hinting at the smaller size of the reservoir as it is not to disturb the natural run of the river. The reservoir can be seen as the energy storage of a hydro power plant as it contains water that can be used for power production. When used as a storage, the volume and limits for water levels of the reservoir are important as it regulates the amount of available water that can be stored. (Energy Education, n.db)

2. *Control gate*
   The amount of water flowing from the reservoir or pondage through the penstock towards the turbine is controlled by the control gate. Maximum water flow means the control gate is fully open. The control gate therefore also controls the water level of the reservoir or pondage. (Daware, n.d)

3. *Trash rack*
   Trash racks in the intake system of hydro power plants provide protection against large debris that can cause damage to turbine parts and disrupt the overall operations of the power plant. These structures are strategically placed to prevent the entrance of unwanted materials into the intake system. (Rahman, n.d)

4. *Intake*
   The intake correctly directs the water in the right direction for power production and serves as the connection between the river and penstock (Anupoju, n.d)

5. *Penstock*
   Penstocks serves as large pipes with a sloping gradient that transport the water from the intake structure to the turbines. As these pipes operate under pressure, sudden opening or closing of the penstock gates can result in quick changes in water flow and pressure causing a water hammer effect, which can damage the penstocks. To prevent such effects, penstocks are designed to resist water hammer, while also functioning similarly to conventional pipes. To accommodate the pressure, penstocks with heavy walls are used for short lengths, while long penstocks are equipped with surge tanks. Surge tanks are water filled tanks that are used to regulate the pressure within the penstock. (Anupoju, n.d)

6. *Transformer*
   Transformers use electromagnetic induction to change the voltage and current of an alternating current (AC) signal, allowing it to be passed between circuits. They increase, or ”step up”, the voltage leaving power plants and decrease it, or ”step down”, at substations and distribution transformers. By changing the voltage, transformers reduce energy loss during transmission. Transformers maintain the same power level by decreasing current when voltage is increased, and vice versa. However, they do not allow direct current (DC) input to pass through due to its absence of a changing magnetic field to induce a voltage across the secondary component. (Energy Education, n.de) The efficiency of a transformer is usually in the range of 95% - 99%. (Linquip, 2023)

7. *Powerhouse*
   To protect the hydraulic and electrical equipment a powerhouse is built around it. Depending on the layout of the hydro power plant the power house have different dimensions and structural properties. (Anupoju, n.d)

8. *Generator*
   The purpose of a generator in a hydro power plant is to convert mechanical energy from

the turbine shaft to electrical energy. A generator comprises two essential components: a rotor with an axle, which is linked to the turbine, and a stationary stator that surrounds the rotor. During the operation of the generator, the rotor rotates, and direct current is supplied to its poles, which produce an electromagnetic field. This electromagnetic field, in turn, generates the desired electricity in the windings of the stator. The stator's windings are responsible for converting the electromagnetic energy into electrical energy. This process is fundamental to the operation of a generator. (Energy Education, n.da)

9. *Turbine*
   The turbine is a device that converts hydraulic energy into mechanical energy, which is then converted into electrical energy by coupling the turbine shaft to a generator. The turbine operates by allowing water, under high pressure, to strike the circular blades or runner, thereby causing the central shaft to rotate and generate electrical power through the connected generator. There are mainly three types of turbines that are used in conventional hydro powe plants. The Pelton turbine, which classifies as an impulse turbine, and the Francis- and Kaplan turbine, which both classifies as a reaction turbine. (Anupoju, n.d)

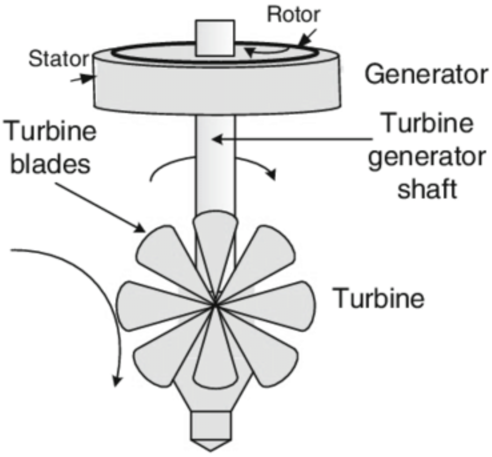


Figure 3: Visualisation of a generator connected to a turbine (Demirel, 2012)

10. *Draft tube*
    When utilising reaction turbines, such as Francis or Kaplan turbines, the inclusion of a draft tube is essential, as it serves to connect the turbine outlet to the outflow. The draft tube is designed with a gradually increasing diameter to ensure the safe and efficient discharge of water into the outflow at a velocity that does not damage the turbine or surrounding infrastructure. Furthermore, at the termination point of the draft tube, outlet gates are installed, which can be utilised to close off the water flow during maintenance or repair operations. (Anupoju, n.d)

11. *Outflow*
    The water that has been utilised for power generation is transported through an outlet conduit known as the tailrace and is subsequently discharged downstream of the dam back into the river. (EDCL, n.d)

12. *Spillway*
    A spillway, an essential component of a hydro power plant, plays a critical role in facilitating the safe passage of floodwaters downstream back into the river on which the plant is placed on. Without these spillways the excess water from the water source

can damage or destroy parts of the plant, such as the turbines. The spillways are also used to prevent the dam from having an overflow of water in the reservoirs if maximum reservoir capacity has been reached. In such instances the spillway instead draws water from the top of the reservoir to preserve a constant water level equal to the maximum water level of the reservoir.(Energy Education, n.dd)

13. *Fish ladder*
    Fish ladders are essential for facilitating safe fish migration up and downstream, particularly in the vicinity of operating hydro turbines. During the breeding period, fish tend to migrate upstream to small rivers, and dams can impede their habitat, making the fish ladder a crucial navigational tool for fish. While fish ladders provide a safe and relatively easy means of navigation alongside the dam, they still require a significant effort for fish to pass through them. (Belyakov, 2019)

14. *Transmission*
    Electrical transmission delivers generated electricity to populated areas via the distribution grid. Transformers are essential to increasing voltage levels for long distance transmission. This system, along with power plants, distribution systems and substations, form the electrical grid which is essential to the society's electricity demands. (Energy Education, n.df)

In Sweden, hydro power companies can more or less accurately predict the inflows into reservoirs during the spring flood season by measuring snow depths in the mountains during the winter. For the annual cycle of hydro power, three main factors come into play: winter snow depth, spring flooding, and precipitation levels during summer and autumn. By predicting the amount of flowing water to the reservoirs, an effective water storage plan during periods of high inflow, particularly during the spring flood that arises from melting snow in the mountains, can be made. Instead of being wasted during periods of heavy precipitation and spring floods when inflows are high, electricity production can be conserved for later times when demand for electricity rises. (Uniper, n.d)

As mentioned, water flow in Sweden is highly seasonal with peaks occurring during spring, as the snow and ice melts from higher elevation points such as the mountains, and during autumn and winter when precipitation increases. During summer the water flow is generally at its lowest due to water evaporation and lower precipitation. Figure 4 shows the average flow of water at a point in the river Lagan in southern Sweden, based on daily modelling data from SMHI, where the seasonal variations can be seen.

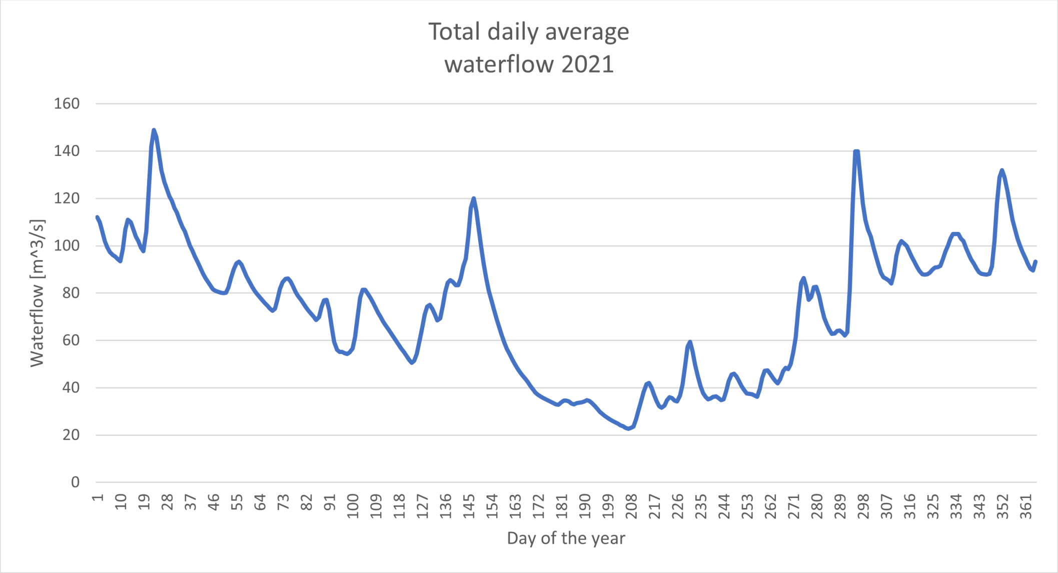


Figure 4: Daily average water flow in Lagan based on modeling data from SMHI (SMHI, 2023)

The electricity production from hydro power in Sweden usually varies between 50-80 TWh depending on the amount of water runoff in a given year. Figure 5 shows the yearly total electricity production of hydro power in Sweden, where the zero line corresponds to the normal annual electricity production of 65.5 TWh. The years above the zero line are considered "wet years" with high water runoff, while the years below the line are "dry years." The chart depicts the variations in electricity production from hydro power from year to year which indicates the dependency on water runoff from precipitation and snowmelt. The use of reservoirs can mitigate variations in electricity production caused by changes in water runoff by storing water, both long-term and short-term depending on the size of the reservoir. (Energiföretagen, 2023)

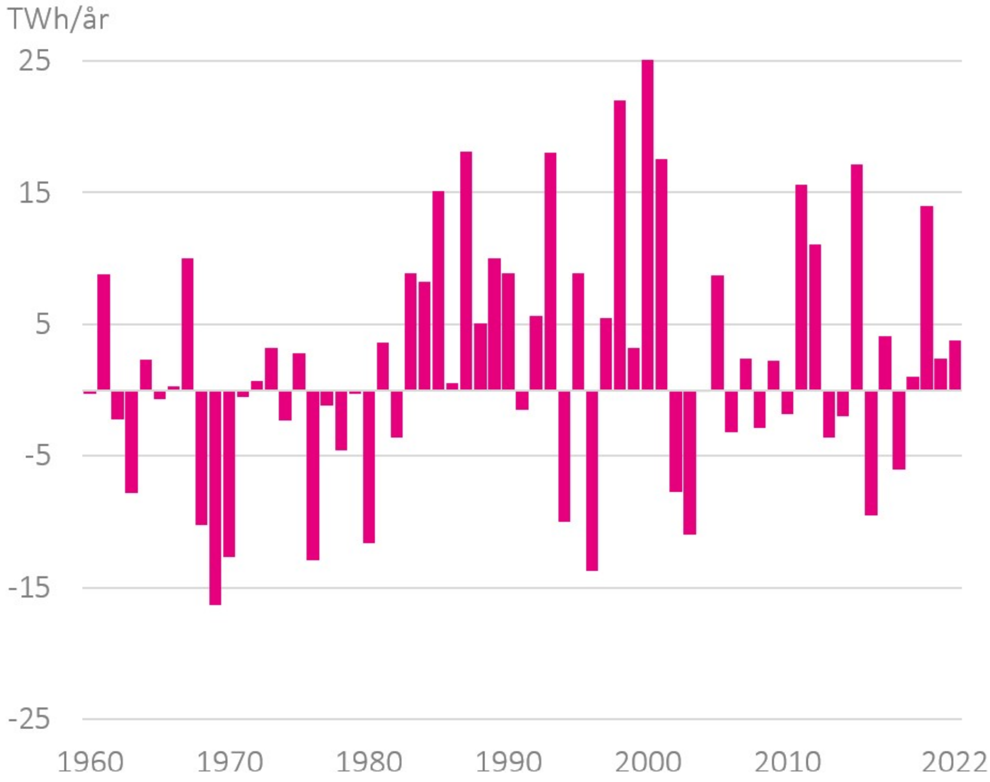


Figure 5: Electricity production from hydro power per year where the zero line equals the annual average electricity production of 65.5 TWh/year (Energiföretagen, 2023)

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2.2 Pumped hydro power

Extracting electrical energy through pumped hydro power works on the same principle as conventional hydro power by using the flow of water released from a certain height, with the addition of being able to pump the water back up to the elevated reservoir again. It stores energy by pumping water to a high elevation reservoir during off-peak periods and times of high production at renewable power plants. The stored water is then released to drive hydraulic turbines and generate electricity when demand increases in the same way normal hydro power plants work. It is considered to have one of the highest efficiencies among mechanical energy storage technologies with an efficiency reaching up to 85% depending on several factors such as height differences, technology used and water availability, and can have a capacity of up to a few thousand megawatts. However, pumped hydro power systems can face challenges as it requires specific geological structures to be viable. Despite these challenges, pumped hydro power is one of the most widely implemented mechanical energy storage technologies in the world in terms of installed MW. (Arabkoohsar and Nami, 2020)

Open-loop and closed-loop pumped hydro power are the two most common types of pumped hydro power systems. In an open-loop system the water used for energy storage and electricity production is taken from a nearby natural flows of water, while a closed-loop system uses reservoirs within a closed system and the water is thus recycled between an upper and lower reservoir. Both open-loop and closed-loop systems have drawbacks and benefits. Usually open-loop systems have lower capital costs but require access to a nearby natural water source. A closed-loop system does not necessarily require a natural water source, but instead can have a higher capital cost due to the need for additional infrastructure, such as the construction of the reservoirs. Finding suitable locations for implementing pumped hydro power can be difficult due to the specific geographical requirements. (EERE, n.dc)

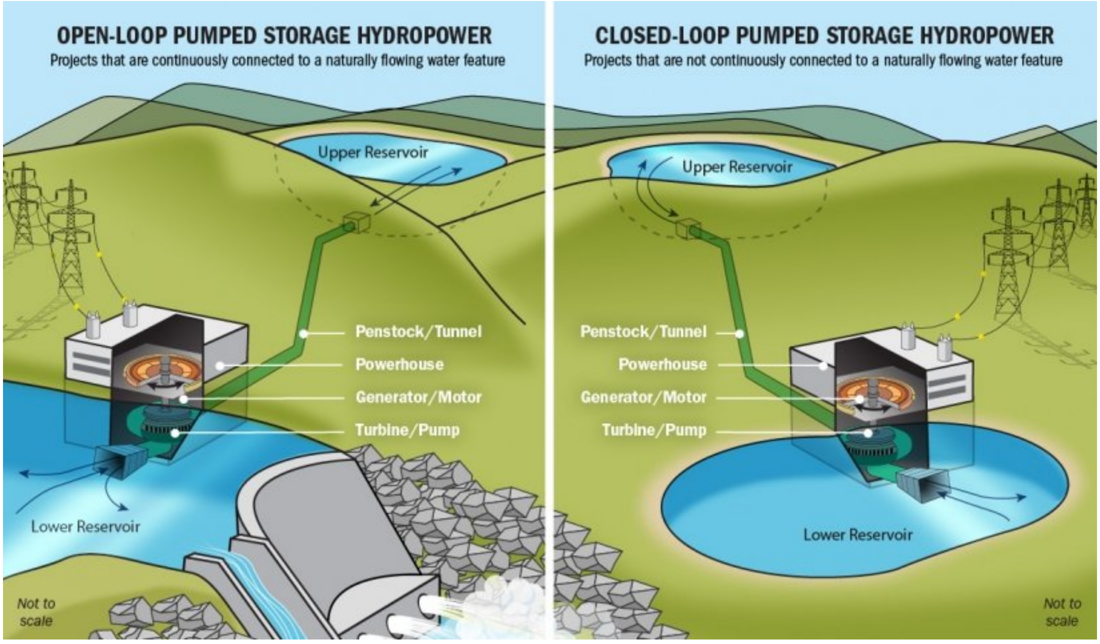


Figure 6: Open and closed pumped hydro power systems (EERE, n.dc)

2.3 Hydro power turbines

There are three main types of turbines used in hydro power plants, the Francis, Kaplan and Pelton turbines. Below follows an introduction to each of them as well as a description of their optimal operation points.

2.3.1 Francis turbine

The Francis turbine was invented by James Francis in 1848. It is classified as a reaction turbine which means it uses the pressure and velocity change of water when flowing through the rotor. The pressure is reduced with an increase in velocity, causing a reaction on the turbine. (Kamran, 2021) In the Francis turbine water changes direction as it passes through the turbine as flow enters the turbine in a radial direction and exits along the direction of its axis after interacting with the turbine blades. The turbine operates efficiently when water reaches all blades uniformly, and the spiral casing controls the flow of water. This casing feeds water through a set of valves and fixed blades into the moving blades of the turbine rotor. The rotor blades are specially shaped to extract the maximum amount of energy from the flowing water, with blade design being dependent on water head and flow. This means the Francis turbine is often built specifically for one site and its specific mean water flow and head height. A Francis turbine can capture 90%–95% of the energy in the water, with optimal performance achieved between 100 and 300 meters of head height. A Francis turbine can also be used in reverse, as a pump, due to its specific closed design. While the Francis turbine is versatile in this aspect, it is typically not used for very high or low head applications as these require specialized turbine designs due to flow rate limitations and fabrication difficulties. (Breeze, 2018)

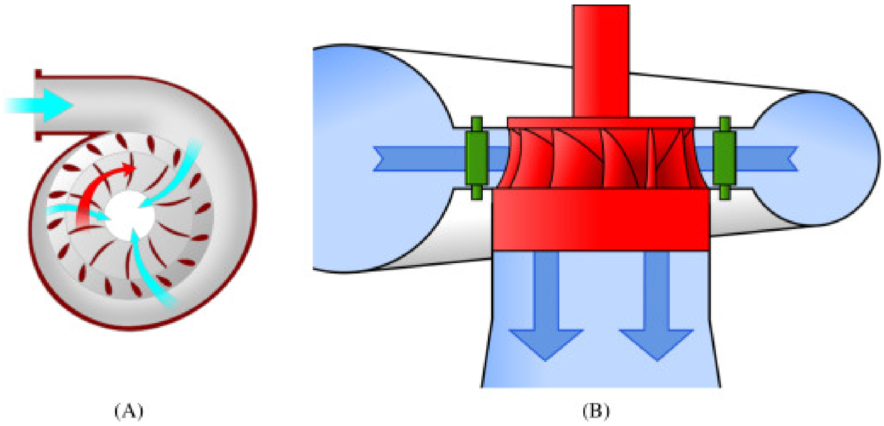


Figure 7: Top and side schematics of a Francis turbine (Breeze, 2018)

2.3.2 Kaplan turbine

Austrian professor Viktor Kaplan developed the Kaplan turbine in 1913 and is just like the Francis turbine classified as a reaction turbine. The penstock delivers water to the scroll casing, which is designed to maintain flow pressure. The scroll casing can be seen on the left and right of figure 8. Adjustable guide vanes direct the water to the runner blades, which are twisted along their length to maintain an optimal angle of attack for all blade cross-sections, maximising efficiency. The runner blades are oriented axially to the direction of the water, which turns 90 degrees upon entering the runner. The force of the water striking the runner blades causes them to rotate. The water then enters the draft tube, where its pressure and kinetic energy are reduced. This reduction in kinetic energy results in an increase in water pressure, as kinetic energy is converted to pressure energy. Kaplan turbines works more optimally at lower head heights and higher flow rates compared to other turbines. The efficiency of a Kaplan turbine is considered very high as is the general case for hydro turbines. (Mishra, n.d)

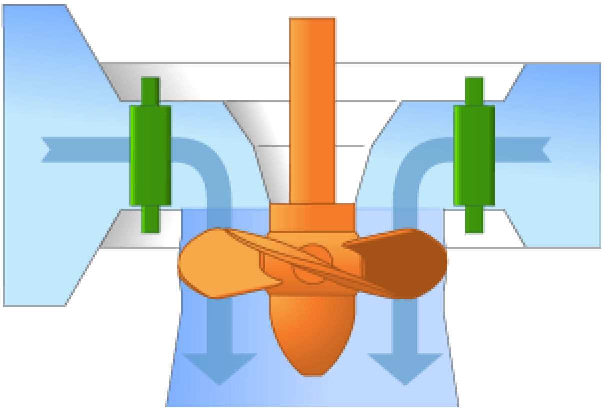


Figure 8: Schematic of a Kaplan turbine (EERE, n.db)

2.3.3 Pelton turbine

The Pelton turbine was invented by Lester Allan Pelton in 1879 and is considered an impulse turbine. In a Pelton turbine there is a spray nozzle at the end of the penstock. The spray nozzle is aimed towards the Pelton turbines buckets and impacts each of the buckets tangentially. When force is applied during a period of time, as is the case for the Pelton turbine, it is called an impulse, which is why the Pelton turbine is classified as an impulse turbine. This impulse is what causes the Pelton turbine to rotate and thus generate electrical energy. Pelton turbines are generally used for higher head and lower flow rates compared to the Francis and Kaplan turbines. (Savree, n.d)

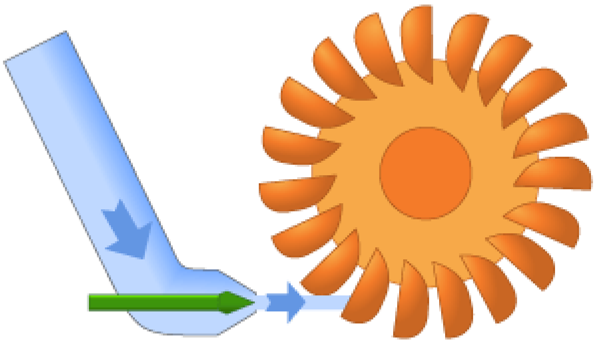


Figure 9: Schematic of a Pelton turbine (EERE, n.db)

2.3.4 Optimal operation

The nature of turbine selection is displayed in figure 10, which presents two important parameters used when selecting turbines for a hydro power plant, the head height of the site (H) and a dimensionless coefficient (σ). As shown in figure 10, Kaplan and Francis turbines are typically utilized for low and medium heads, while Pelton turbines are predominantly used for high heads. The dimensionless coefficient σ is a critical parameter in the selection of a turbine and depends on multiple factors, such as the volumetric flow rate, the rotational speed of the wheel and gravitational constant, which are all important to the efficiency of the turbine. Equation 1 shows how σ is determined.

$$\sigma = \frac{2 \cdot N \cdot \sqrt{\pi \cdot Q}}{(2 \cdot g \cdot H)^{3/4}} \tag{1}$$

N	Rotational speed of the wheel $[rad/s]$
H	Head height $[m]$
g	Gravitational constant $[m/s^2]$
Q	Volumetric flow rate $[m^3/s]$

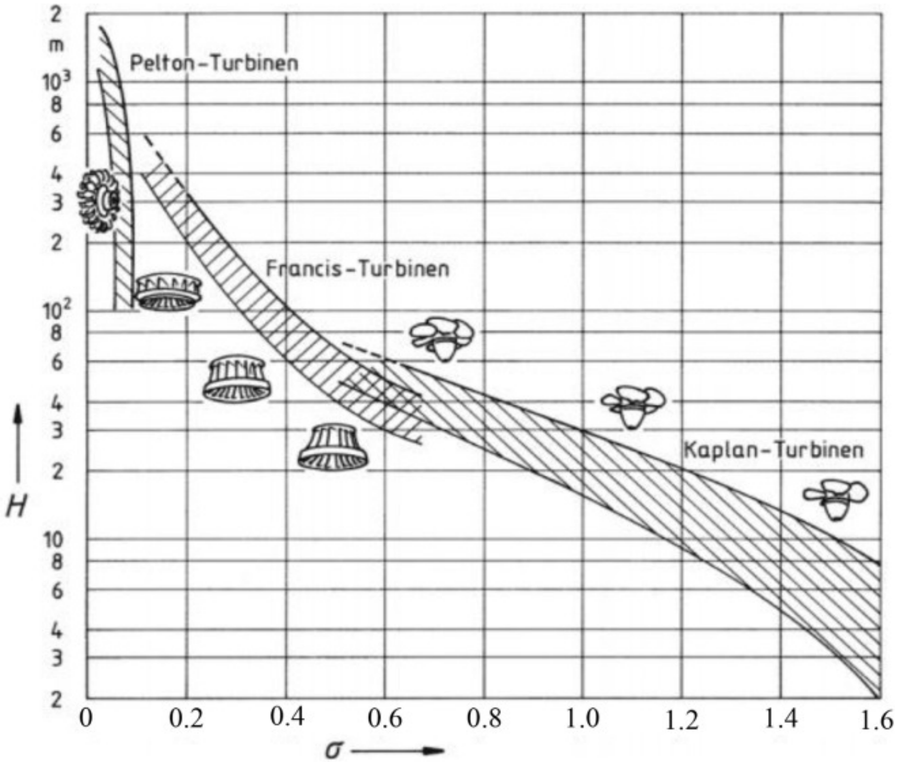


Figure 10: Optimal operation for different turbine types depending on H and σ (Abeykoon, 2022)

2.4 Hydro power calculations

To find the maximum power that can be extracted from a hydro power plant the following formula can be used. (Renewables first, n.d)

$$P = \dot{m} \cdot g \cdot H_{net} \cdot \eta \tag{2}$$

The system efficiency corresponds to all of the internal efficiencies in the hydro power plant.

The unit for mass flow rate $\dot{m}$ is kg/s. It can be rewritten with the purpose to use the more common unit m^3/s by the following formula:

$$m = \rho \cdot V \Rightarrow \dot{m} = \rho V/s = \rho Q \tag{3}$$

Where ρ is the density of the fluid, V is the volume and Q is the volumetric flow rate. This gives an updated version to equation 2:

$$P = \rho \cdot Q \cdot g \cdot H_{net} \cdot \eta \tag{4}$$

P	Power $[W]$
$\dot{m}$	Mass flow rate $[kg/s]$
m	Mass $[kg]$
g	Gravitational constant $[m/s^2]$
H_{net}	Net head $[m]$
η	System efficiency $[\%]$
V	Volume $[m^3]$
Q	Volumetric flow rate $[m^3/s]$
ρ	Density $[kg/m^3]$

If a hydro power plant has a flow of $100m^3/s$, head height of $20m$, a total efficiency of 80% and standard values for the density of water ρ and gravitational constant g, the resulting power output from the power plant becomes:

$$P = 997kg/m^3 \cdot 100m^3/s \cdot 9.82m/s^2 \cdot 20m \cdot 0.8 = 15\ 664\ 864W$$

Examining this formula it can be seen that the mass flow rate and net head height are the parameters that will influence the location choice of a hydro power plant the most. With a low net head height a larger mass flow rate is required to reach the same power output as for a hydro power plant with higher net head height, and vice versa. An optimal location would have both a high net head height and mass flow rate.

The reservoir storage capability of a hydro power plant can also be calculated. Equation 5 shows the relationship between the volume (V), surface area (A) and height (h) and figure 11 illustrates this. With the knowledge of two of these parameters the third can be calculated. The simplified formula assumes a reservoir with flat surfaces and straight edges, which does not correspond to the actual topography of a hydro power reservoir, since it has varying contours and shapes.

$$V = A \cdot h \tag{5}$$

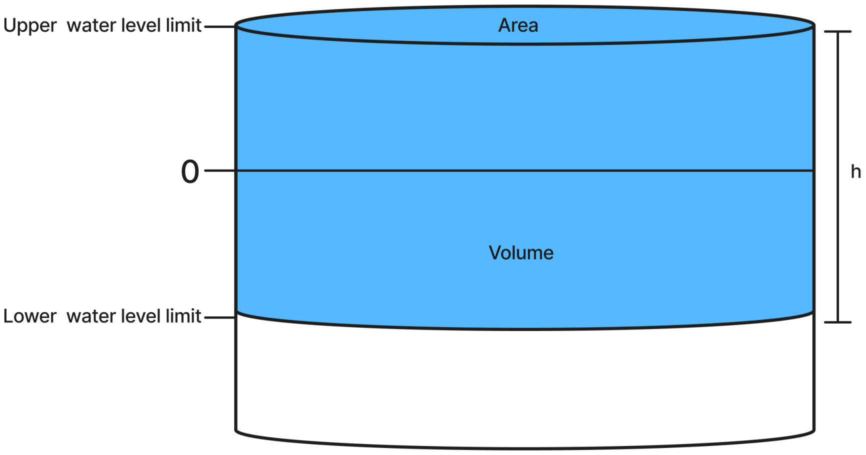


Figure 11: Illustration of a water reservoir.

If the water storage volume is calculated, the potential energy storage (E) can also be calculated using equation 6.

$$E = \int_{H_0}^{H} \rho \cdot V \cdot g \cdot hdh \tag{6}$$

Assuming a volume of a reservoir to be 10 000m^3, height going from 15 to 25m and using the same values as the previous example, the energy capacity of the reservoir can be calculated using equation 6.

$$E = \int_{15}^{20} 997kg/m^3 \cdot 10000m^3 \cdot 9.82m/s^2 \cdot hdh \approx 8.57GJ = 2.38MWh$$

2.5 Photovoltaic (PV)

This section aims to provide sufficient background theory regarding electricity production from photovoltaic technology as well as introducing formulas used when calculating production of electricity. Photovoltaic, or PV, technology utilise the solar irradiation on earth to produce electrical energy. Its construction consists of cells, modules and arrays, which can be seen in figure 12.

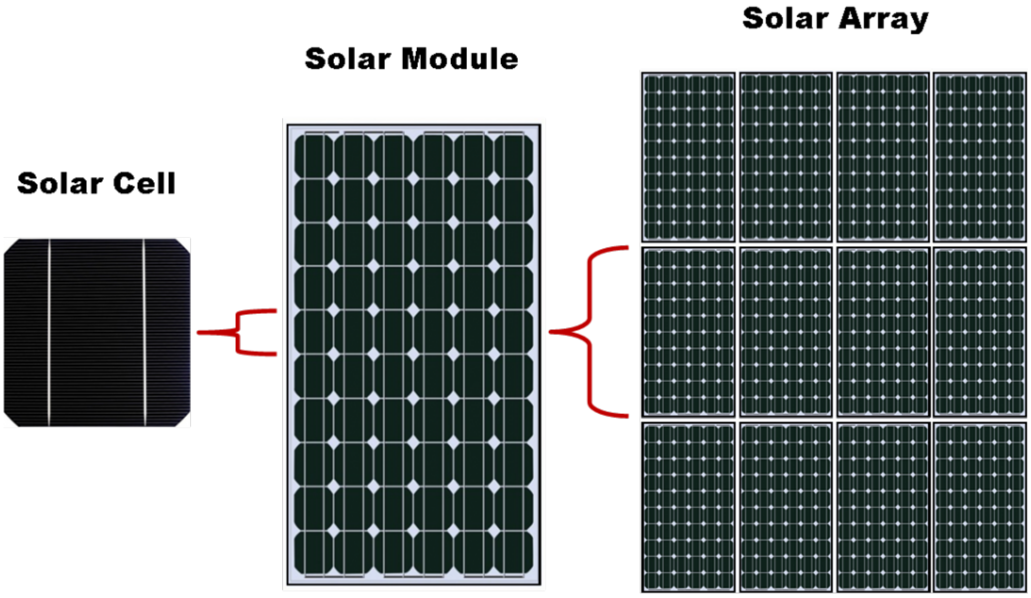


Figure 12: Photovoltaic cell, module and array (PVeducation, n.d)

2.5.1 Cells

Solar cells are most commonly made of semiconductor materials, such as silicon. A thin semiconductor wafer is treated by doping the layers to create one side with a surplus of electrons and the other with a deficit, resulting in a positive charge on one side and a negative charge on the other, which creates an electrical field. This is called a P-N junction because of the doped semiconductors being Positive and Negative respectively. As photons strike the surface of the solar cell, they dislodge electrons from the atoms in the semiconductor material and when the positive and negative sides of the solar cell are connected to electrical conductors, an electrical circuit is formed, allowing the electrons to flow as an electric current. (Knier, n.d)

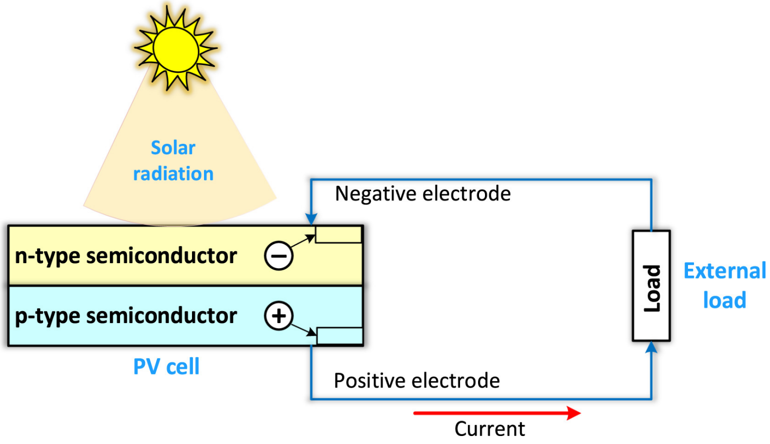


Figure 13: Simplified illustration of a solar cell (El Hammoumi et al., 2022)

2.5.2 Modules

A photovoltaic module refers to a group of interconnected solar cells, mounted in a structural framework or support. These modules are engineered to provide electricity at a specific voltage. The amount of current generated by the module is directly proportional to the intensity of light falling on its surface, which can be seen in equation 8. (Knier, n.d)

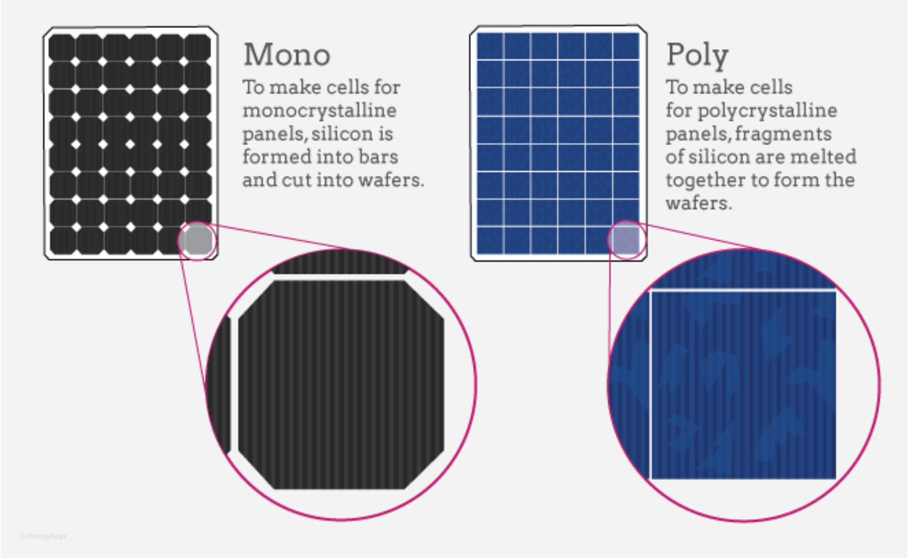
2.5.3 Arrays

To create an array, multiple photovoltaic modules can be interconnected. Generally, a larger module or array size generates greater amounts of electricity. These modules and arrays produce direct-current (DC) electricity and can be wired in series or parallel configurations to achieve the desired voltage and current output. (Knier, n.d)

2.5.4 Monocrystalline and polycrystalline solar panels

Todays market includes several types of solar panels and development in the area is continous. The most common types of solar panels are monocrystalline and polycrystalline solar panels. Although they both produce electricity from solar irradiation they operate with different properties. The most refined type of solar panels available today are those made of monocrystalline silicon, which are produced by cutting silicon bars in to wafers. They are easily identifiable by their uniform dark appearance and rounded edges. Their superior efficiency rates, which can surpass 20%, are attributed to the high purity of the silicon used when producing the panels. The degradation factor, which is the factor of the total decrease in power output of the panel, of monocrystalline solar panels are usually considered to be around 0.5% per year and slightly higher for polycrystalline panels. Monocrystalline solar panels offer a lifespan of 25-30 years while polycrystalline solar panels have a larger uncertainty in lifespan, due to increased degradation factor, of 20 to 30 years.

Monocrystalline panels offer several advantages such as high power output, smaller space requirement, lower degradation factor and extended lifespan. However, they are also the most expensive option. Additionally, they are relatively less affected by high temperatures when compared to polycrystalline panels, making them a practical choice for areas with hot climates which usually is the case in areas with high irradiance. The polycrystalline solar panels are easily recognised by their square shape and blue-speckled appearance. The panels are created by melting raw silicon which is a process that is both faster and less expensive than the method used to manufacture monocrystalline panels. While polycrystalline panels are less expensive than monocrystalline panels, they do have lower efficiency rates at around 15%, as well as a reduced space efficiency and shorter lifespan, specifically in high-temperature environments as polycrystalline panels are more sensitive to heat. It is important to note that the choice between them in the end depends on site specific circumstances as the power outputs are fairly similar between them. (Greenmatch, 2023) (ASES, 2021)



To make cells for monocrystalline panels, silicon is formed into bars and cut into wafers.

To make cells for polycrystalline panels, fragments of silicon are melted together to form the wafers.

Figure 14: Illustration of monocrystalline and polycrystalline solar panels (ASES, 2021)

2.6 Floating PV

Floating solar PV has emerged as a promising technology and in the past years it has grown significantly, from 61 MW installed capacity in 2015 to over 3 GW in 2021. The large growth in floating solar PV highlights the potential in the technology to scale rapidly, making it a compelling option for addressing global energy needs.(Iberdrola, n.d)

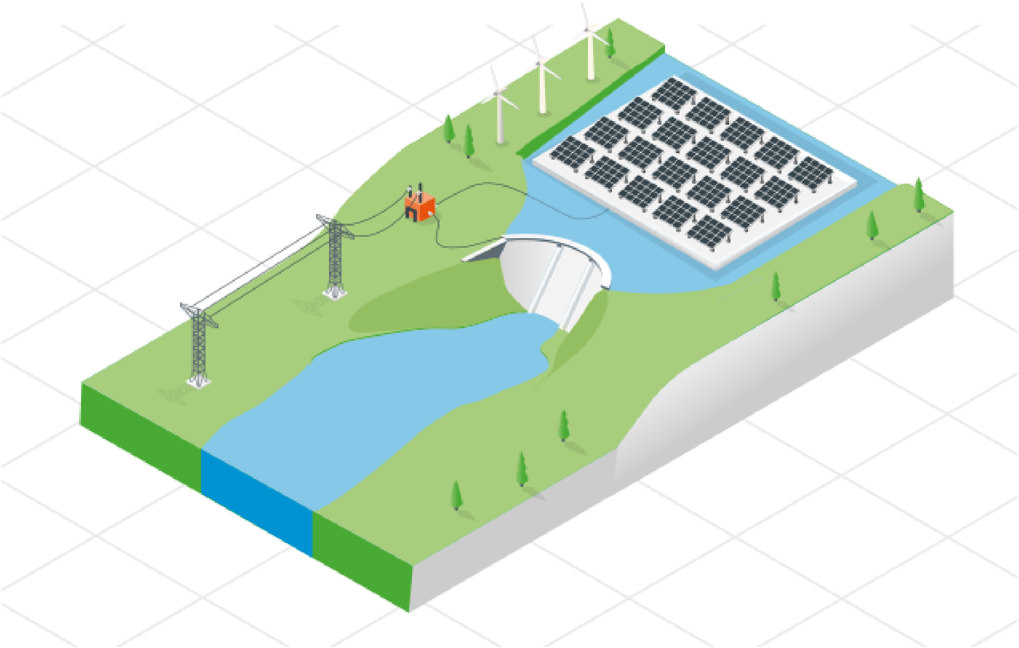


Figure 15: Illustration of floating PV installation on a hydro power reservoir (Iberdrola, n.d)

When installing floating PV it is important that the water is not moving as it might damage the construction. This means a reservoir with a steady water source is preferred. The arrays are installed on floating plastic constructions that are placed along the edges of the panels which means there can be an opening towards the surface of the water below the panels. This feature can be utilised by installing bifacial solar panels, meaning it can react to photons on both sides of the panel, and thus producing energy from photons reflected from the surface of the water. The panels can also be tilted and oriented for optimal power production for the specific site. (Maciejewski, 2023)

The floating construction are then anchored in place to avoid movements in the construction that could shift the orientation. The anchoring can be done in different ways where the most common ones are anchoring to the bottom, anchoring to the shore or anchoring to piles. An illustration of these methods can be seen in figure 16. Iberdrola (n.d)

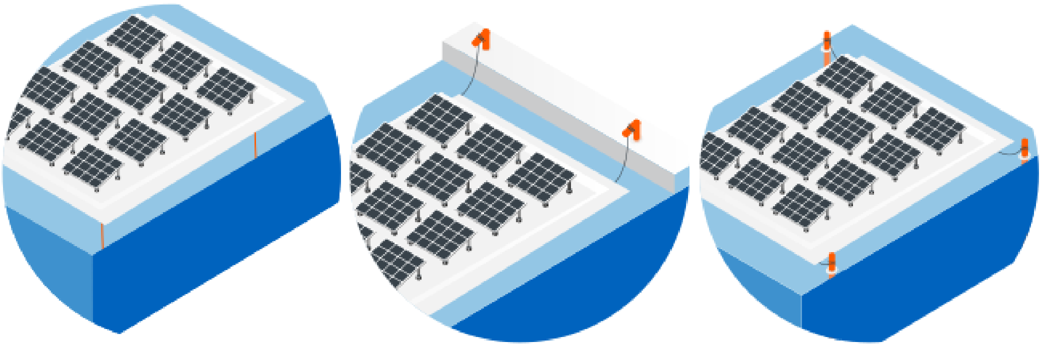


Figure 16: Illustration of anchoring methods for floating PV installations.
From left to right: bottom anchoring, shore anchoring, pile anchoring. (Iberdrola, n.d)

When anchoring to the bottom the depth of the reservoir is important due to the fact that increased length of anchoring ropes allows for a larger unwanted movement. The depth of the reservoir is also important when using the pile anchoring method because of the increased costs of longer and larger piles. Depth is not as important for the shore anchoring method but the principle of not having too long anchoring ropes still applies. (Maciejewski, 2023) (Iberdrola, n.d)

There are both postive and negative sides with floating PV systems compared to on-shore PV systems. The water can act as a coolant for the PVs, hindering them from getting too hot. As efficiency decreases with increased heat this is a positive effect. Another positive aspect is the possibility for bifacial modules which increases power production by using the photons reflected from the surface of the water and thus increasing the produced power per occupied area. 1MW installed floating PV capacity fits on an estimate of 1 hectare, or 10 $000m^2$, compared to on-shore PV that can fit around 1MW of installed capacity on 1.2 hectares, or 12 000 m^2 . However, the planning phase for floating PV generally takes longer because water level changes must be taken into account so that the modules are constantly floating, aswell as implementing a suitable anchor solution that works for altering water levels. The research regarding environmental impacts for floating PV are also less developed since it is a less developed technology compared to on-shore PV which can make permits harder to get and thus prolong the planing phase. Investment costs are also higher for floating PV due to increased infrastructure, around 30% more expensive than that for on-shore PV systems. (Maciejewski, 2023) (Iberdrola, n.d)

2.7 PV design and operation

The vertical tilt angle of solar panels in a PV system is an important factor in the amount of electricity generated. Efficient solar radiation collection occurs when the rays from the sun are perpendicular to the surface of the panel, but this angle varies throughout the year as earth rotates around the sun. As a result, the optimal tilt angle for a PV panel changes over the year and depends on the latitude of the location. There is no universal optimal tilt angle because the natural tilt and orbit of the earth influence the way the sun moves across the sky in different locations worldwide. The geographical latitude of a solar installation is a crucial factor in determining the ideal vertical angle at which the panels should be installed to generate the most energy from the rays of the sun. As the location moves further from the equator and closer to the poles, the tilt angle should increase to allow the panel to face the sun better. However, solar electricity output is not only affected by the position of the sun but also by climatic and environmental conditions. Accumulation of snow on panels during winter in regions closer to the poles can block sunlight from reaching the solar cells. Increasing the tilt angle of the panels can limit the amount of snow and ice that accumulates on the surface of the panels by allowing snow and rainfall to slide off. In dry, polluted, or desert areas, a higher tilt can limit soiling from dust, sand, and dirt that can block sunlight and reduce energy conversion. (Negro, 2022)

Interrow shading is a consequence of the physical positioning of PV modules within an array. Ground coverage ratio, or GCR, represents the ratio of module area to total land area, or the length along the array divided by the row pitch. Figure 17 illustrates this and the GCR is defined as:

$$GCR = \frac{L}{R} \tag{7}$$

Where L is the array length and R is the row pitch. In PV systems with a high GCR, the spacing between rows are typically reduced resulting in the modules being closer together and thus increasing the likelihood of shadows being cast by one row onto the rows behind it. These shadows obstruct the incident sunlight and restrict the light absorption capacity of the panels, reducing their energy output. Interrow shading can impact the overall performance and efficiency of a PV system. Designers and operators of PV installations can optimise the GCR in system layouts to reduce shading effects. Careful consideration of the GCR allows for proper spacing between rows, thereby reducing the occurrence and severity of interrow shading and maximising power production. (Deline et al., 2014)

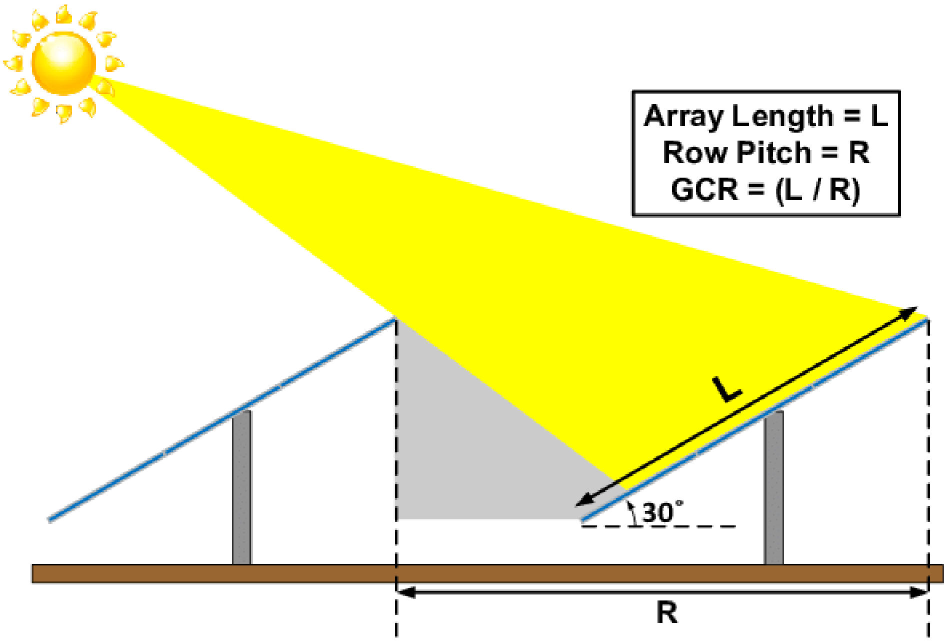


Figure 17: Illustration of how to calculate GCR (Deline et al., 2014)

2.8 PV System components & control

The DC/AC inverter is a component in solar power systems, responsible for converting the direct current (DC) generated by solar panels into alternating current (AC) suitable for use in electrical grids and appliances. Inverters integrate solar energy with existing power systems. They employ power electronics and control algorithms to efficiently convert the DC input into an AC output. High conversion efficiency, often exceeding 95%, ensures minimal power losses during the conversion process. Inverters also incorporate maximum power point tracking (MPPT) algorithms to optimise solar panel output under varying conditions. MPPT works by continuously monitoring and adjusting the operating voltage and current of the solar panels. By dynamically finding the maximum power point (MPP), where the panels operate at their highest efficiency, MPPT algorithms ensure that the panels can extract the maximum available power under changing environmental conditions. This results in improved energy generation from solar sources. Figure 18 displays the relationship between the voltage and current for a solar cell and how the MPP is found. Apart from this they offer various protection mechanisms such as overvoltage and undervoltage protection, overcurrent protection and ground fault detection. DC/AC inverters play a vital role in optimising power production, enhancing system efficiency, and ensuring safe and reliable operation in solar power systems. (Bruce, 2022) (Spirit Energy, 2023)

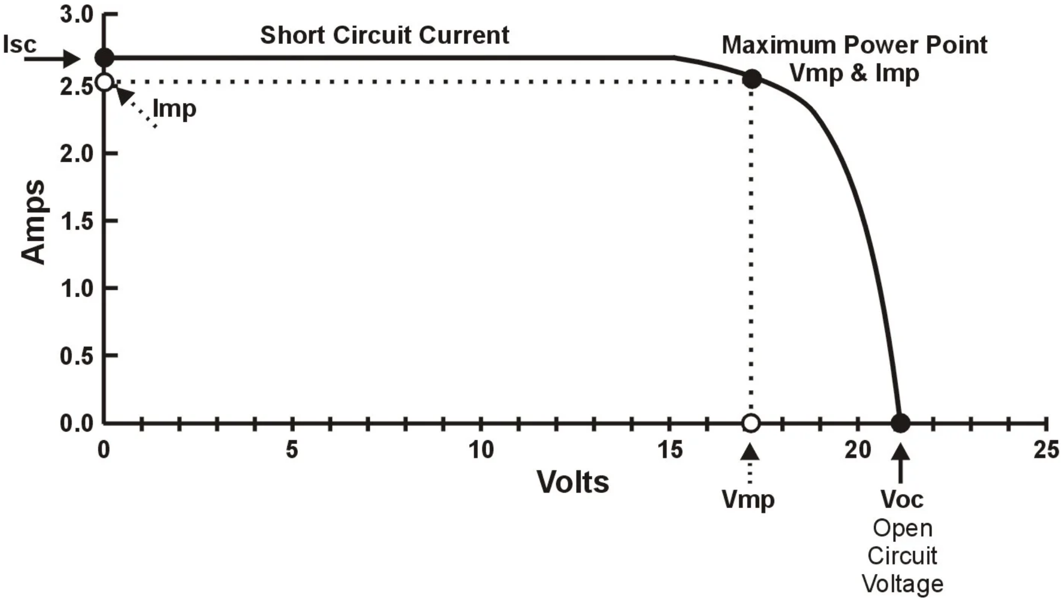


Figure 18: Example of an I-V curve and the MPP of a solar cell (Spirit Energy, 2023)

Switchgears are an essential component in electrical power systems that controls, protects, and isolates equipment and circuits to ensure safe and efficient energy distribution. Its primary function is to detect and interrupt faults and abnormal conditions, preventing damage to the system. Switchgears allows for selective disconnection and reconnection of equipment or sections of the system. It incorporates protective relays and devices to monitor the power system, detecting faults and coordinating circuit protection for stable power flow. They operate across various voltage levels, and can be used for different power system configurations.

2.9 Solar power calculation

To calculate the generated power output of a solar cell equation 8 can be utilized. As can be seen, solar irradiation plays a large part in the amount of power that can be generated. The efficiency η corresponds to the cells total efficiency and is, as mentioned, around 15-20% depending on what type of solar panel is used.

$$P = \eta \cdot G \cdot A \tag{8}$$

To get a greater view on the scale of power production from solar panels an example can be made. If solar panels are located in southern Sweden the average solar radiation on a sunny day is about 1000 W/m^2, if the area of the solar panels is 4 m^2 and efficiency is 20%, the power output can be calculated using equation 8.

P	Power $[W]$
η	Efficiency [%]
G	Irradiance $[W/m^2]$
A	Area $[m^2]$

$$P = 0,2 \cdot 1000 \cdot 4 = 800W$$

Incorporating this in to a solar power system, further calculations for the total power production of a solar park can be made. When the solar panels produce power it is sent through a series of components and controllers, such as the ones described in section 2.8, as well as the transformer at the grid connection point and all the cables in the system. While these components operate at high efficiency, losses still occur. Some examples of typical system power losses can be seen in table 1, but the values might vary depending on environment, system configuration, components and cable lengths.

Shading	7%
Dust and Dirt	2%
Array Mismatch	0.7%
DC Cable Losses	1%
Inverter Losses	3%
AC Cable Losses	0.5%
Transformer losses	3%

Table 1: Example of typical losses in a solar power system (Bruce, 2023)

Continuing the previous example, the power output to the grid of a solar power plant can be calculated using equation 9.

$$P_{tot} = \eta_{sys} \cdot n \cdot P_{panel} \tag{9}$$

P_{tot}	Total power output to the grid $[W]$
η_{sys}	Total system efficiency [%]
n	Number of panels [Unit]
P_{panel}	Total power output of a solar panel $[W]$

If 10 of the previously calculated solar panels are installed and the total system efficiency η_{sys} is 85%, the total power output to the grid can be calculated as follows.

$$P_{tot} = 0.85 \cdot 10 \cdot 800W = 6800W$$

2.10 Solar & hydro hybrid power generation

Solar-hydro hybrid power plants are power plants that combine the use of the solar energy and hydro power to generate electricity. The basic principle behind a solar-hydro hybrid power plant is to use the excess power during peak hours to store water in the reservoir, or pump water from a lower elevation to a higher elevation reservoir. The stored water can then be released during off-peak hours to generate electricity when electricity prices are higher. Figure 19 illustrates an example of a connection diagram of a simple solar-hydro hybrid power plant.

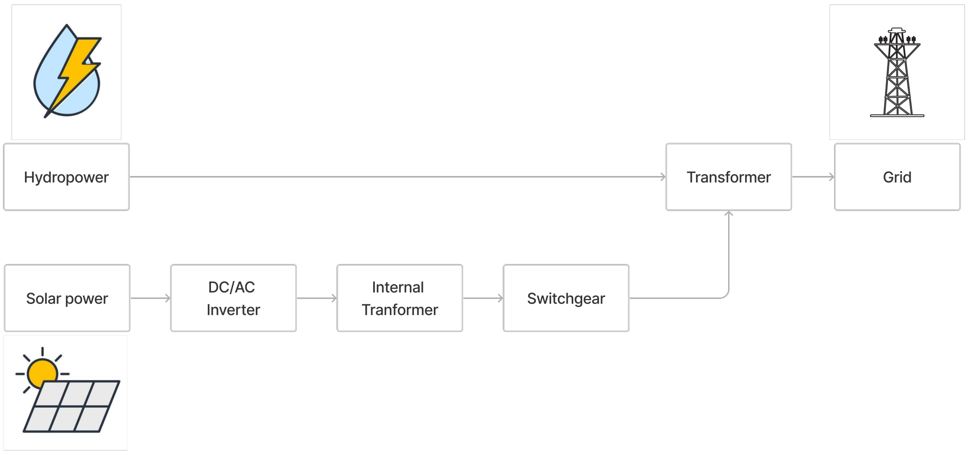


Figure 19: Connection diagram of a solar-hydro hybrid solar plant

Compared to standalone solar or hydro power plants, solar-hydro hybrid power plants offer a more stable and dependable source of electricity. Solar energy is known to be intermittent and depends on factors like weather conditions and time of day. Hydro power on the other hand, although also being influenced by seasonal fluctuations, is considered to be more consistent and controllable and can therefore act as a stabiliser in the hybrid system.

One of the key design considerations for a solar-hydro hybrid power plant is the sizing of the solar panels and the hydro power turbine. The solar panels can be sized to meet certain criteria. It can as an example be sized to either meet the demand at its peak hours or to meet the grid connection capacity at its peak hours, but can also be sized after the available storage capacity in the hydro power reservoir. As the hydro power plant is more controllable it can for example be designed to meet the electricity demands at off-peak hours, or to maximise the grid connection capacity at peak water flow. Sizing the hybrid plant can be done in many ways and is often dependent on the specific site due to limitations in available area, solar irradiance, water sources, water flow and supply and demand. The location of the hybrid system is thus very important as it is greatly affected by the surrounding environment. The surrounding environment also plays a large role as regulations, environmental impact assessments, and obtaining permits are essential when installing a power plant, which can be time-consuming to achieve, spanning several years. If a project gets denied after these processes has been started, a lot of investments would be lost.

Solar-hydro hybrid power plants are ideally suited for locations that receive ample sunlight and have access to a reliable source of water. In addition, the geographical location should also be suitable for the construction of a reservoir at a high altitude. The choice of turbine is also important in this aspect as the different turbines operate with different effectiveness depending on head height and water flow, which is dependent on the location. If the hydro power plant is a pumped hydro power plant the choice of turbine is specially important as it needs to be able to work in reverse, as a pump, like the Francis turbine. Another important aspect of the sizing of the hybrid power plant is the available capacity in the transformer at the grid connection point. As both power plants produce power it is important to make sure that the transformer can handle the total power from the two plants, otherwise energy will be wasted or curtailed.

Additionally, the energy storage and control systems are also an important aspect when dimensioning a solar-hydro hybrid power plant. It ensures reliable power supply by the possibility to implement refinement methods for power production. Larger reservoirs implies that larger solar power plants can be installed as more energy can be stored and utilised when demand increase or solar irradiation is low, while smaller reservoirs could suggest a smaller solar power plant installation as energy can not be stored in the same manner. Refinement methods can be implemented in several ways. Water can be stored for longer or shorter periods of time and the utilisation of the stored water can be utilised in dependency of many factors, such as maximising profits or having consistent power output throughout the day.

There is no clear right or wrong way to implement a solar-hydro hybrid power plant. It is dependent on a lot of different factors, as described in this section. Simulations and tests which can help with finding the most suitable location and refinement method for a hybrid power plant has to be made before deciding how to implement it.

2.11 Swedish electricity market

The Swedish electricity market has been deregulated since 1996, allowing for free competition amongst electricity traders and suppliers. Sweden is part of the European electricity market, which also enables the trade of electricity across borders on a deregulated market. Approximately 120 suppliers of electricity exists in the Swedish electricity market. The distribution of electricity is however monopolised through different companies being responsible for the distribution in separate parts of Sweden.(Energimarknadsinspektionen, 2021a) Svenska kraftnät is responsible for creating and evaluating regulations, agreements and different procedures for the electricity market within Sweden. When it comes to trading across borders the responsibility is instead shared between the operators affected by the trade. (Svenska kraftnät, 2023). Nord Pool is the Nordic market for electricity prices and is managed by Svenska kraftnät and their respective counterparts in the other Nordic and Baltic countries sharing the market. The market has a spot market for electricity per hour. The majority of trading takes place at Nord Pool but it can also occur directly between generators and suppliers. Nord Pool is divided in two separate markets, day-ahead market and intraday market.(Svenska kraftnät, 2021)

2.11.1 Day-ahead market

The day-ahead spot market on Nord Pool is where trading for electricity prices per hour one day-ahead of delivery occurs. The trading is done by anonymous auction with both producers and consumers and starts at 10:00 with the publishing of the available capacities and ends at 12:00 every day. The bidding is done by customers specifying the energy they are willing to either buy or sell for a specific hour at a price in EUR/MWh. With this information prices for every hour can be set. The day-ahead market is used when planning the next 24 hours of electricity supply and demand and is meant to balance them out in the power market. Figure 20 illustrates the change in day-ahead prices through the years 2018-2022.(Nord Pool, n.da)

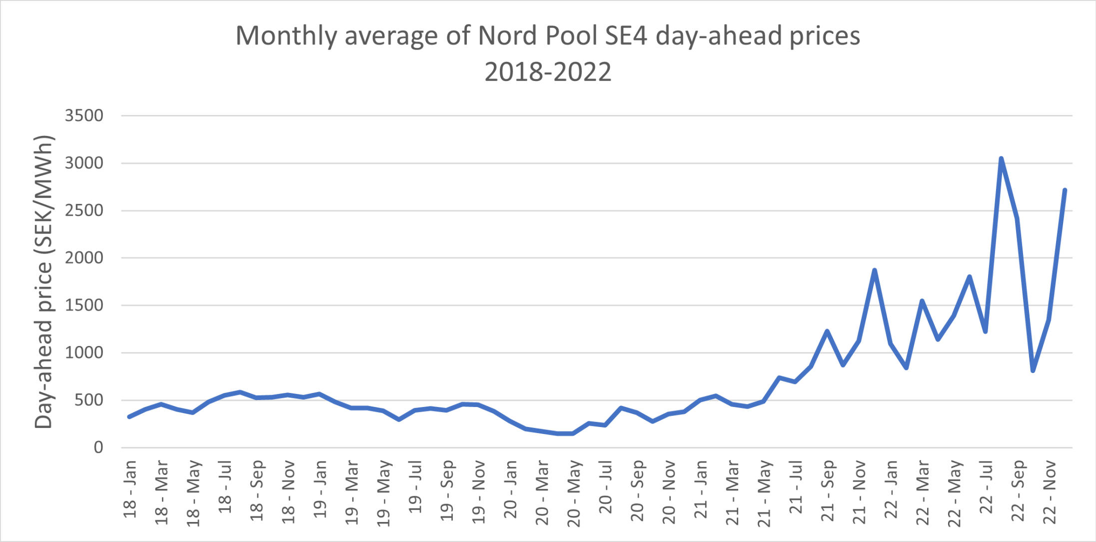


Figure 20: Change in day-ahead prices in SE4 through 2018-2022 based on monthly average prices. (Nord Pool, 2023)

Figure 21 illustrates the day-ahead prices for bidding area SE4 in Sweden for four different days, representing each season, during 2022.

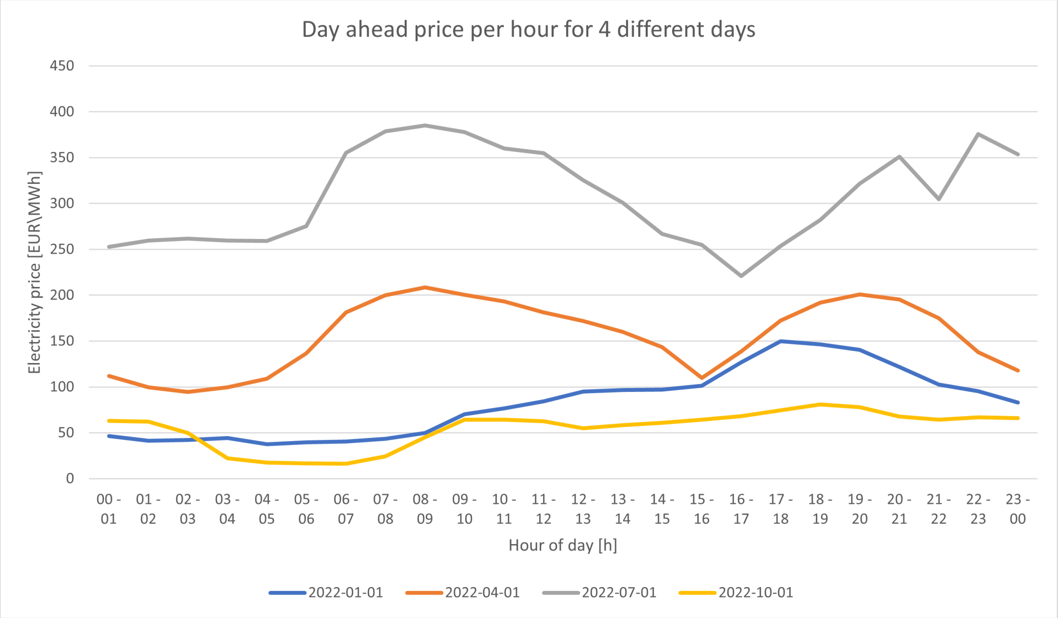


Figure 21: Day-ahead prices for SE4 on 2022-01-01, 2022-04-01, 2022-07-01, 2022-10-01 based on hourly prices. (Nord Pool, 2023)

2.11.2 Intraday market

Intraday market, or same day market, works as a compliment to the day-ahead market. It acts to adjust the orders made on the day-ahead market if there might be any unexpected changes in either supply or demand of electricity that could not have been anticipated when placing bids in the day-ahead market. Increasing amount of intermittent renewable power production that is dependent on more unpredictable aspects has introduced new challenges for the market costumers and thus the interest in the intraday market has increased. The intraday market, compared to the day-ahead market, does not have specific deadlines and is continuously open every day of the year. This market is based on the principle that the highest buy price and lowest sell price are prioritised. (Nord Pool, n.db)

2.11.3 Bidding areas

Since 2011 Sweden has been divided into four bidding areas, or electricity price areas, where SE1 is the area located furthest north and SE4 is the area located furthest south. These areas were created due to bottlenecks on the transmission lines and with the purpose of improving the national grid to supply electricity and to easier pinpoint areas that need further development. The location of these areas are continuously evaluated by Svenska kraftnät and affected operators in other countries with the help of regulations set by the EU. Svenska kraftnät do not alter the areas themselves but provide suggestions for the government to decide about possible changes. (Energimarknadsinspektionen, 2021b) Price differences occur in the different bidding areas as energy flows from low cost areas to higher cost areas in relation to supply and demand. When the transmission capacity is sufficient a joint price is set for the entire bidding area which then works as a reference price for the entire market. The price differences occurs when the transmission capacity between bidding areas is limiting, which means the demand is higher than the supply, and energy needs to be transferred between the areas with excess electricity supply and the ones with a deficit. (Svenska kraftnät, 2023, 2021)

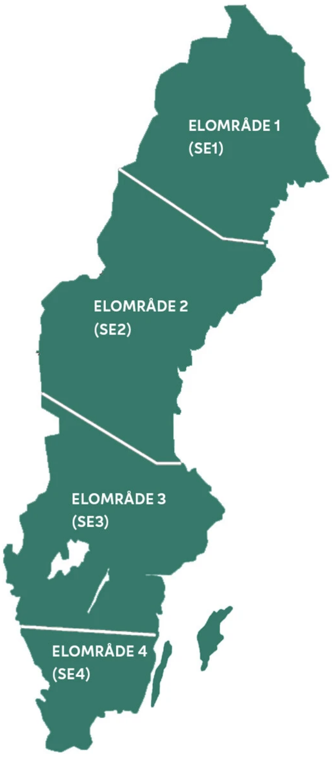


Figure 22: Map of the four different bidding areas of Sweden (elområde = bidding area) (Energimarknadsinspektionen, n.d)

2.11.4 Swedish electricity mix

In Sweden, the annual electricity production typically ranges between 150 and 165 TWh, while our electricity consumption falls within the range of 135 to 145 TWh per year. As a result, Sweden has a net surplus of electricity, exporting the excess power. The contribution of different power sources to the overall electricity production can vary from year to year due to limiting factors such as available water and wind, as well as shutting down different power plants. For instance, in 2019, nuclear power reached a production of over 64 TWh, only to decrease to 47 TWh the following year due to the closing of nuclear power plants. On the other hand, hydroelectric power generated slightly over 64 TWh in 2019, which increased to over 71 TWh in 2020. Nuclear power accounts for approximately 30 percent of the electricity production in a typical year after 2020. Hydroelectric power represents 35-45 percent of the production, varying depending on wet and dry years. Meanwhile, wind power contributes 15-20 percent, with its share steadily growing. The remaining electricity is derived from biomass-fired combined heat and power plants, with an increasing presence of solar power installations. These figures emphasise the significant role played by nuclear and hydro power within Swedish power production, as well as the increasing importance of wind and solar power. (Lindholm, 2023)

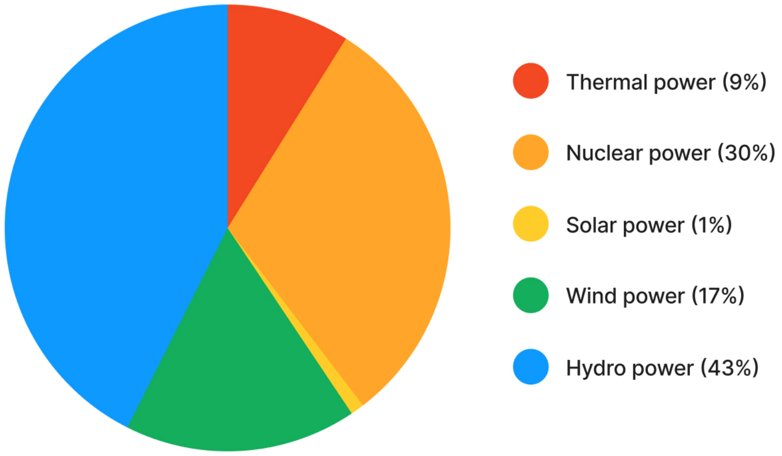


Figure 23: Swedish electricity mix 2021, based on informarion from Statistiska centralbyrån. (Statistiska centralbyrån, 2022)

3 Economical calculation methods

This section introduces the three financial calculation methods used to evaluate profitability in this study, namely NPV, IRR and payback time.

3.1 Net Present Value (NPV)

The Net Present Value (NPV) method is a financial analysis technique used to determine the value of an investment by comparing the present value of the expected cash inflows to the present value of the expected cash outflows. The NPV method is widely used as a tool in decision-making, as it takes into account the time value of money and the uncertainty of future cash flows. The theoretical framework of the NPV method also provides a foundation for understanding other financial metrics, such as the internal rate of return (IRR) and payback period. But it is important to consider the assumptions and limitations of the model. For example, the accuracy of the estimated future cash flows and the choice of discount rate can significantly impact the results. Therefore, it is important to remember that the NPV method is not perfect and only an estimation. However, the method is fairly simple to use and can be applied in various fields such as finance, engineering and environmental studies, making it a versatile tool for comparing and evaluating the economic value of different projects in different fields.

The following equation is used when calculating NPV:

$$NPV = (\sum_{t=0}^{T} \frac{C_t}{(1+i)^t}) - C_0 \tag{10}$$

C_t	Net cash flow at time period t
i	Discount rate
t	Time period
C_0	Investment cost

If we consider the following data:

i	10%
t	3 years
C_0	150 0000 SEK

	Year 0	Year 1	Year 2	Year 3
C_t	0 SEK	50 000 SEK	75 000 SEK	100 000 SEK
C_0	-150 000 SEK	0 SEK	0 SEK	0 SEK

The NPV can be calculated using equation 10 and becomes as follows:

$$NPV = (\sum_{t=0}^{T} \frac{C_t}{(1+i)^t}) - C_0 = (\frac{0}{(1+0.1)^0} - 150000) + (\frac{50000}{(1+0.1)^1}) + (\frac{75000}{(1+0.1)^2}) + (\frac{100000}{(1+0.1)^3}) = 32600 SEK \tag{11}$$

In equation 11 an investment of 150 000 SEK is made and the cash flow for year 0 is considered to be 0 SEK. On year 1 there is no additional investment costs and the investment is starting to generate an income, which reaches a cash flow of 50 000 SEK. The cash flow increases each year and reaches up to 100 000 SEK on year 3. The value of the investment, or the NPV, then becomes 32 600 SEK. This value is positive, which means that the investment can be considered a good investment according to the NPV method. A negative value on NPV generally means that the investment is not considered as good.

3.2 Internal Rate of Return (IRR)

The Internal Rate of Return (IRR) is connected to NPV and is a financial metric used to evaluate the profitability of an investment. It is the discount rate at which the NPV of the cash inflows of an investment equals the NPV of the cash outflows of the investment. In other words, the IRR is the rate of return that makes the NPV of an investment equal to zero.

The following formula shows the relationship between NPV and IRR:

$$0 = NPV = \sum_{t=0}^{T} \frac{C_t}{(1+IRR)^t} - C_0 \tag{12}$$

C_t	Net cash flow at time period t
IRR	Internal rate of return
t	Time period
C_0	Investment cost

Using the same values given in equation 11 the IRR can be calculated for a project. 13 shows the calculation.

$$O = (\sum_{t=0}^{T} \frac{C_t}{(1+IRR)^t}) - C_0 = (\frac{0}{(1+IRR)^0} - 150000) + (\frac{50000}{(1+IRR)^1}) + (\frac{75000}{(1+IRR)^2}) + (\frac{100000}{(1+IRR)^3}) \Rightarrow$$
$$\Rightarrow IRR = 20.6\% \tag{13}$$

The value of IRR is in this case 20.6 %. This indicates that the NPV will be positive, and thus also indicating on a profitable investment, when as long as the discount rate is lower than 20.6%. Higher IRR indicates a safer or more profitable investment compared to a low value.

3.3 Payback time

The payback time method is a simpler financial analysis technique than NPV and is used to evaluate the time it takes to recover an investment. It calculates time required for the cash inflows from an investment project to equal the initial cash outlay, or in other words when the total income of a project has passed the total investment costs of said project. The payback period is a measure of the liquidity or short-term risk associated with an investment. A shorter payback period indicates a faster recovery of the initial investment and is generally considered more favorable. However, the payback method does not consider the time value of money, which is an important factor in investment decision making.

Continuing the previous example one can calculate the time it takes to recover the investment using the payback time method. Table 3.3 shows the calculation. The resulting payback time then becomes 3 years as it takes 3 years to pay back the initial investment.

	Year 0	Year 1	Year 2	Year 3
C_t	0 SEK	50 000 SEK	75 000 SEK	100 000 SEK
C_0	-150 000 SEK	0 SEK	0 SEK	0 SEK
Cashflow	-150 000 SEK	-100 000 SEK	-25 000 SEK	75 000 SEK

4 System site and configuration

This section provides information about the site chosen for simulation. Information about the hydropower plant will first be introduced and then the solar power plant will be explained. Lastly, information about the economical calculations as well as cost assumptions will be introduced.

4.1 Karsefors hydro power plant

Figure 24: Karsefors hydro power plant from above (Statkraft, n.d)

Karsefors hydropower plant is located in bidding area 4, in the river Lagan near the city of Laholm in Halland County. This site was chosen as simulation site due to the capacity of the hydro power plant being reasonably large to be able to match a respective solar power plant with the same sizing, thus having a 1:1 relation in energy sent to the grid between them. It was also chosen because Eolus Vind AB has an available site near Karsefors hydro power plant and therefore could provide with more concrete information which reduced assumptions. Some information about Karsefors hydro power plant can be seen in the table below.

Karsefors	
Owner	Statkraft Sverige AB
Year built	1930
Year rebuilt	2016
Turbine type	Francis
Amount of turbines	2
Head height	25,6 m
Maximum power	31,4 MW
Normal annual production	129 $GWh/year$
Maximum flow rate	155 m^3/s
Grid connection capacity	31,4 MW
Water storage capacity	1,4 Mm^3
Total system efficiency	88%

Table 2: Information about Karsefors hydro power plant (Khulin, 2021; Lejdstrand, 2023)

To calculate the allowed changes in water level in the reservoir the provided water storage capacity together with an assumption of the size of the reservoir based on areal footage of the site was used. The measured area of the size of the reservoir can be seen in figure 25. The areal footage gives an approximate area of 792 500 m^2 and the formula for calculating the allowed change in water level can be seen in equation 14.

$$h = \frac{V}{A} = \frac{1.4 \cdot 10^6}{792.500 \cdot 10^3} \approx 1.8m \tag{14}$$

This assumption gives a water level change of approximately ± 0,9m from a supposed standard value of 0m in reservoir water level. Note that the values are rounded.

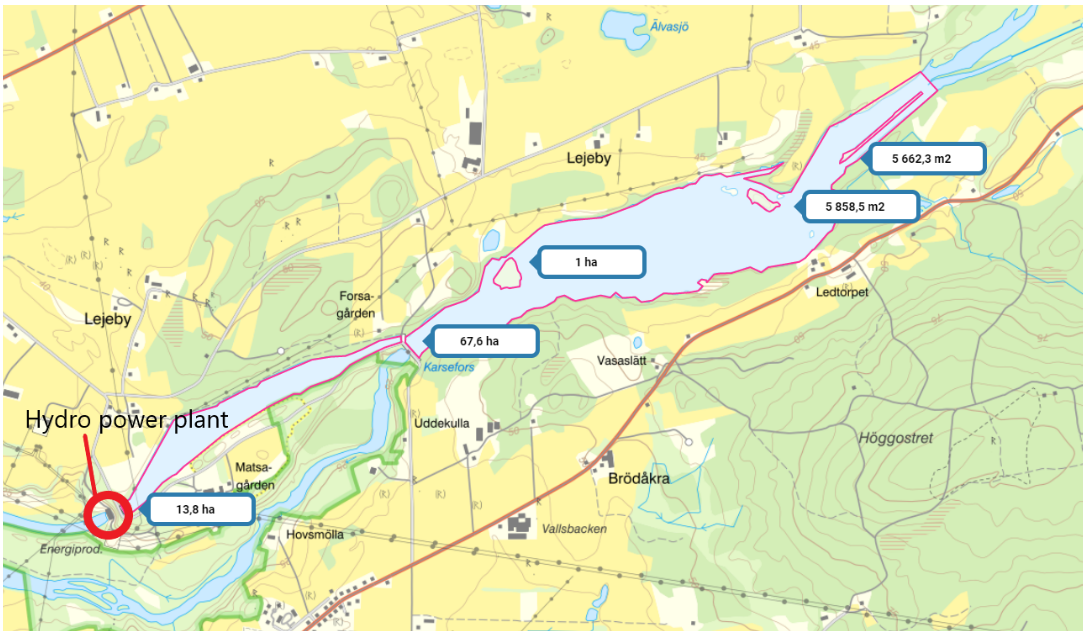


Figure 25: Reservoir size of Karsefors hydro power station (Lanmäteriet, 2023)

4.2 PV installation

For PV simulations a site close to Säbyholm farm near Karsefors hydro power plant was chosen for installing the solar power plant. The specific site was chosen due to Eolus Vind

AB having permission to install a solar power plant in that area, which can be seen in figure 27. The distance from the solar power plant to the transformer at the grid connection point can also be seen in this figure.

Site specifications for the PV installation used in the PVsyst simulation can be seen in table 3. The site specifications used for simulation is that of a solar power plant with installed capacity of approximately 58 MW which produce a maximum power of roughly 46 MW to the transformer. The reason for the lower value of power sent to the grid is due to inverter limitations. The simulated results are then scaled to to get a 1:1 relation between maximum power sent to the grid connection point from the solar power plant and hydro power plant. The scaling results in an installed capacity of the solar power plant of approximately 40 MW, which give a relation of about 1.27:1 in installed capacity between the solar power plant and the hydro power plant. This means that the installed capacity of the solar power plant is 27% larger than that for the hydro power plant. These scaled characteristic data can be seen in table 4

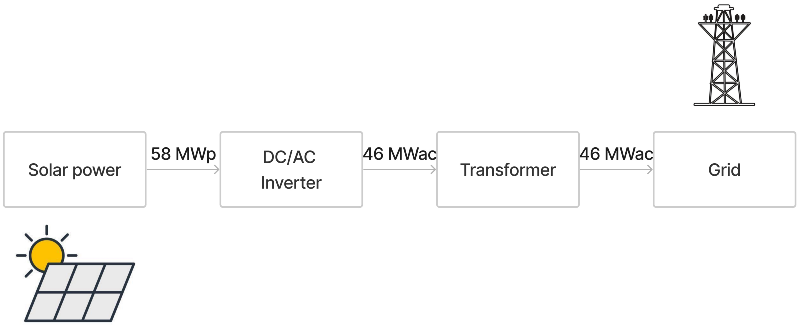


Figure 26: Illustration of the inverter limit in a solar power system.

Another scaling is also made to get a relation of 1.25:1 between the maximum possible power sent to the grid connection point from the solar power plant and hydro power plant, resulting in approximately 39 MW. This gives an installed capacity of approximately 50 MW and a relation of 1.59:1 in installed capacity between the two power plants. Table 5 indicates the scaled characteristics for these simulations.

The total system efficiency is approximately 85% and all losses before the energy is sent to grid is taken in to account in this value.

Installed capacity	58 MWp
Inverter power	46 MWac
P_nom ratio	1.27
Tilt angle	25°
Shading	Linear shading
GCR	53%
Nbr of inverters	365 units
Solar cell type	Monocrystalline
Nbr of modules	87812 modules
Solar panel efficiency	20%
System efficiency	85%

Table 3: Characteristics for simulation of the solar power plant in Säbyholm. Note that the values in the table are rounded.

Installed capacity	40 MWp
Inverter power	31,4 MWac
P_nom ratio	1.27
Tilt angle	25°
Shading	Linear shading
GCR	53%
Nbr of inverters	251 units
Solar cell type	Monocrystalline
Nbr of modules	47576 modules
Solar panel efficiency	20%
System efficiency	85%

Table 4: 1:1 scaled characteristics for simulation of the solar power plant in Säbyholm. Note that the values in the table are rounded.

Installed capacity	50 MWp
Inverter power	39 MWac
P_nom ratio	1.27
Tilt angle	25°
Shading	Linear shading
GCR	53%
Nbr of inverters	314 units
Solar cell type	Monocrystalline
Nbr of modules	59470 modules
Solar panel efficiency	20%
System efficiency	85%

Table 5: 1.25:1 scaled characteristics for simulation of the solar power plant in Säbyholm. Note that the values in the table are rounded.

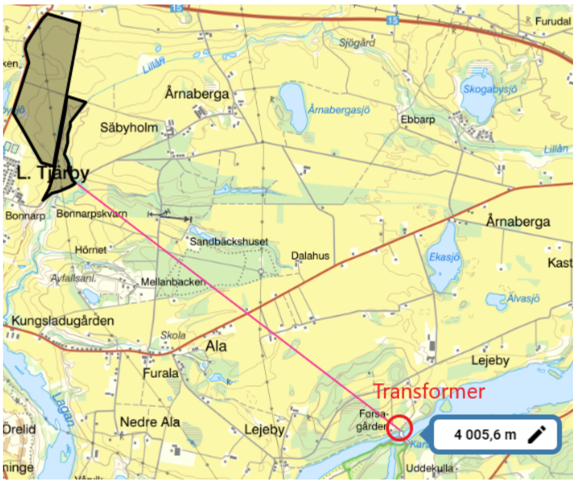


Figure 27: Aerial view of the solar power plant and the distance, as the crow flies, to the grid connection point

4.3 Economical calculations

Nord Pool day-ahead prices are used when calculating the income from electricity production for the four scenarios for each hour of the year. Since the years in question are 2018 and 2020 the day-ahead prices for these two years are used and figure 28 illustrates the monthly average day-ahead price for each year, showcasing the difference in electricity price between the two years. Together with the tariffs from Södra Hallands Kraft AB from table 6 the total income from electricity sold to the grid for each hour can be calculated. The tariff costs and compensations are, for all four scenarios, evenly distributed on an hourly basis to make calculations more comprehensible as both electricity production and day-ahead prices are used on an hourly basis for the calculations.

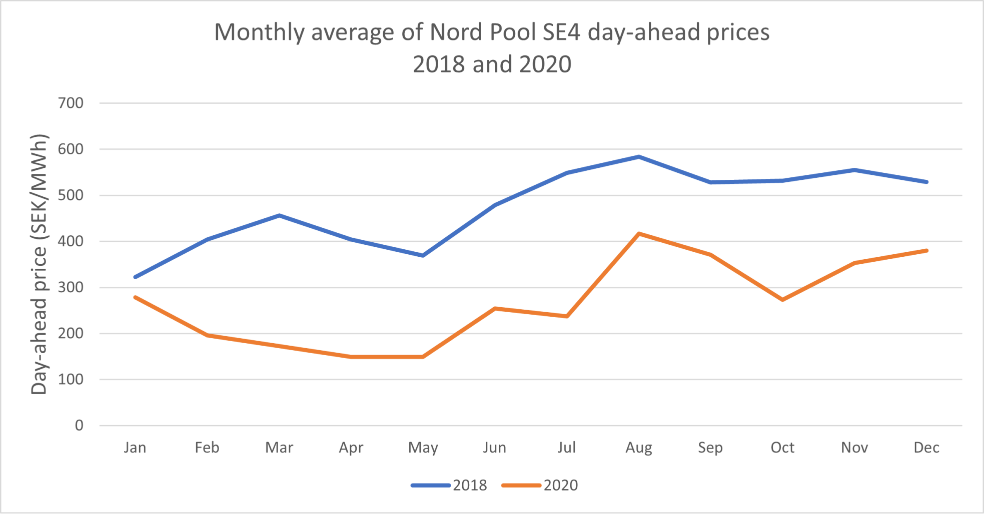


Figure 28: Difference in monthly average day-ahead prices for 2018 and 2020 (Nord Pool, 2023)

Feed-in tariff	
Monthly fee	2481 kr/month
Power fee	11.8 kr/kW, month
Compensation (high load)	0.5 öre/kWh (Jan-Mar and Nov-Dec)
Compensation network loss	7.4 öre/kWh

Table 6: Tariff information at grid connection for Karsefors hydropower plant (Södra Hallands Kraft AB, 2023)

The economical calculations used during the simulation process are NPV, IRR and payback time, which are all explained in section 3. To calculate the yearly income for each scenario and year of simulation the tariffs together with the day-ahead prices provided by Nord Pool are used. The time period t in which both NPV and IRR are calculated is 30 years, to match the lifespan of the solar power plant. All economical calculations were performed in Excel. It is assumed that it is the same owner of both power plants while doing the financial calculations.

4.3.1 Cost assumptions

To do the economical calculations some assumptions regarding costs of installing and operating a solar park as well as different factors and rates are made. The assumptions are based on information given through past project plans and discussions with employees at Eolus Vind AB. Table 7 shows the assumptions used for the economical calculations in the simulations.

Installation cost (SEK/W)	6
Opex (SEK/W)	0,075
Grid connection (MSEK)	5
Transformer (MSEK)	25
Cables 4km (MSEK)	12
Degredation factor	0,995
Inflation rate	0,02
Discount rate	0,08
Installed capacity, ratio 1:1 (MW)	40
Installed capacity, ratio 1.25:1 (MW)	50

Table 7: Economical assumptions for simulation

The installation cost includes the entire internal system of internal transformers, cables, inverters, switchgears and solar panels. This is considered to be a one time investment cost made on the first year during the economical calculations. The opex includes all the operation and maintenance costs and is a reoccurring cost. Grid connection costs is the total cost for connecting the solar power plant to an existing transformer. The transformer cost is the total cost for a new transformer and cables are the total cost for cables from the internal system to the transformer and grid. Grid connection, transformer and cable costs are also considered a one time investment cost made on the first year. Degradation factor refers to the gradual decrease in the performance or efficiency of the panels over time. The inflation rate denotes the rate at which the general level of money is rising and the discount rate represents the interest rate used to determine the present value of future cash flows.

5 Simulation methodology

In this section the simulations will be described and explained. Limitations regarding the simulations are also brought up. Some details of the simulations are left out due to secrecy from the involved parties.

5.1 Simulation limitations

The simulations are based of data collected from two years, 2018 and 2020. The obtained results from the simulation might differ compared to results for similar simulations made for other years as fluctuations in electricity price, variations in wet and dry years and changes in assumptions made for costs and different rates can contribute to different outcomes. The selected years, 2018 and 2020, are considered extremes in terms of hydro power production, with one year being dry and the other wet. Therefore, the results do not represent an average year in terms of hydro power production. As the simulations are based on the specific site of Karsefors, results from the simulations are specific to that site and will differ if made on other sites as solar irradiation and water flow differs depending on site.

The simulations assume that the hybrid system is an isolated system with a common owner of both power plants. This means it is not dependant on other systems in the nearby area, such as hydro power plants higher upstream or lower downstream that could influence the water flow and subsequently impact the production and storage capabilities of the hydro power plant. Additionally, it is implied that the owner has full control over the production and refinement of the system, as it is owned by the same actor.

In scenario 3 the refinement method is based on storing energy from one day to the next rather than longer periods of time. In reality, storage may not always be possible during certain periods of the year, while storage over longer periods, such as seasons, may be possible for other periods. Neither is it known if the hydro power plant already utilise a refinement method to increase profits or store energy. For the purpose of the simulation it was assumed not to have such an implementation, while in reality it is likely that some form of refinement method is implemented. No changes were made to the power production from the hydro power plant production data unless it exceeds the grid capacity limitation. The water level limit was not considered as a limiting factor in the refinement method as information regarding the water level at the start of each year was unavailable.

5.2 Simulation scenarios

There are a total of four scenarios analysed in the simulation. Below follows a description of each scenario and how they are evaluated. Calculations and simulations for all four scenarios will be made for two different years, 2018 and 2020, as 2018 was considered a dry year and 2020 a wet year. These years were chosen based on available data for the hydro power plant. The grid capacity is assumed to be of the same size as the hydro power plant maximum capacity for all scenarios, which is 31.4MW. Scenario 1, 2 and 3 will be simulated for two different sized solar power plants, where one is sized 1:1 in regards to the grid connection capacity and the other 1.25:1, as describe in section 4.2.

5.2.1 Scenario 0 - Standalone hydro power production

Scenario 0 serves as the reference point for analyzing the operational and financial aspects of the hydro power plant on its own, as it represents the current configuration at the site of interest. The production data for Karsefors hydro power plant is provided by Statkraft Sverige AB and is therefore based on actual measurements rather than simulated or calculated values. Further analysing of the data and financial calculations are made in Microsoft Excel.

The provided production data was gathered at a point before reaching the transformer and thus a transformer efficiency of 97% was assumed based on information on typical efficiency rates for transformers. This efficiency rate is applied to the production data to determine the amount of electrical energy sent to the grid.

Financial calculations are conducted by combining the production data with Nord Pool day-ahead prices and the tariffs from Södra Hallands Kraft AB, as indicated in table 6. No curtailed energy will occur in this scenario as the hydro power plant is designed to produce according to the grid connection capacity of 31,4 MW. Given that the production data is provided by Statkraft Sverige AB it is assumed that factors such as water flow and reservoir water levels have already been taken into account. It is unknown whether the production data provided by Statkraft Sverige AB has been refined for the two years. Additionally, the hydro power plant is assumed to be isolated an not dependent on other hydro power plants within the river Lagan.

Figure 29 illustrates the relevant parameters required for calculating hydro power plant production. In this simulation the parameters are not taken in to account as the provided production data from Statkraft Sverige AB does not include information related to them.

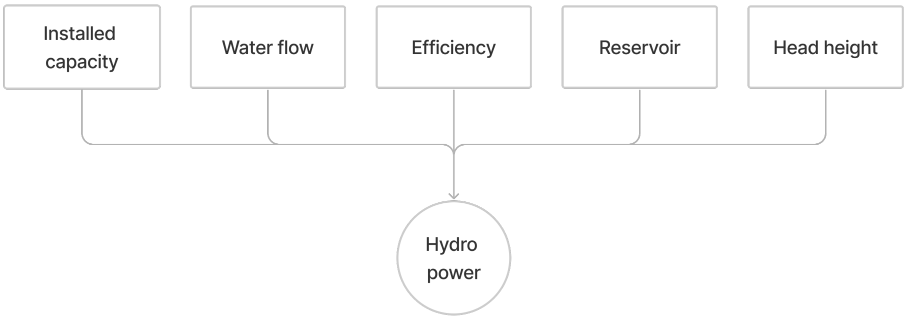


Figure 29: Block diagram of parameters and variables for simulation scenario 0.

Figure 30 illustrates how the hydro power plant is connected to the grid via a transformer.

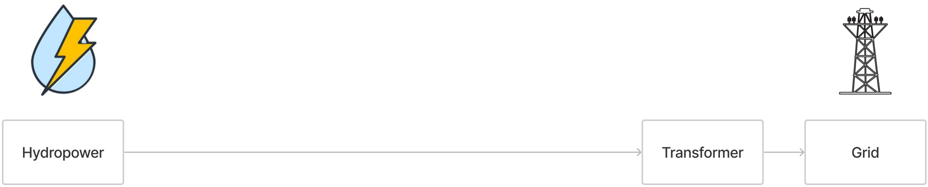


Figure 30: Connection diagram of scenario 0.

5.2.2 Scenario 1 - Standalone solar power production

Scenario 1 analyse the solar PV installation independent of the hydropower plant. This scenario also serves as a basis for comparison towards the hybrid systems, particularly from an economical perspective.

The solar power plant is simulated using PVsyst, incorporating the specifications described in section 4.2. Further analysing of the data and financial calculations are performed in Microsoft Excel. Similar to scenario 0, financial calculations in Scenario 1 utilize the production data, assumptions from Section 4.3.1, Nord Pool day-ahead prices and the tariffs from Södra Hallands Kraft AB, represented in table 6. In this scenario, the financial analysis includes the cost of a new transformer at the grid connection point, while the cost of connecting to an existing transformer is not considered since it is not applicable to this specific simulation scenario. No curtailment occurs in scenario 1 for the 1:1 scaled power plants, as the solar power plant is designed to operate at a maximum capacity of 31.4 MW, aligning with the grid connection capacity. However, curtailment will occur for the 1.25:1 scaled power plant as it can exceed the grid connection capacity for certain periods of the year.

Figure 31 illustrates the relevant parameters that are used to calculate the production of the solar power plant and table 4 in section 4.2 show some of these values. The solar irradiation is gathered on an hourly basis from the European Commission database for solar irradiation, PVGIS.

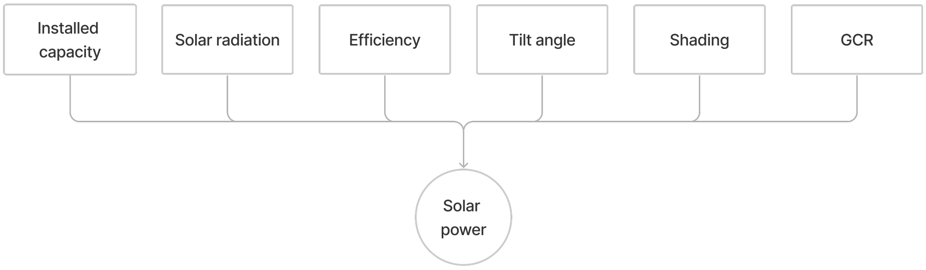


Figure 31: Block diagram of parameters and variables for simulation scenario 2.

Figure 32 displays the connection of the solar power plant to the grid, involving DC/AC inverters, internal transformers, switchgears, and a transformer at the grid connection point. Energy losses associated with each component are accounted for during simulation in PVsyst.

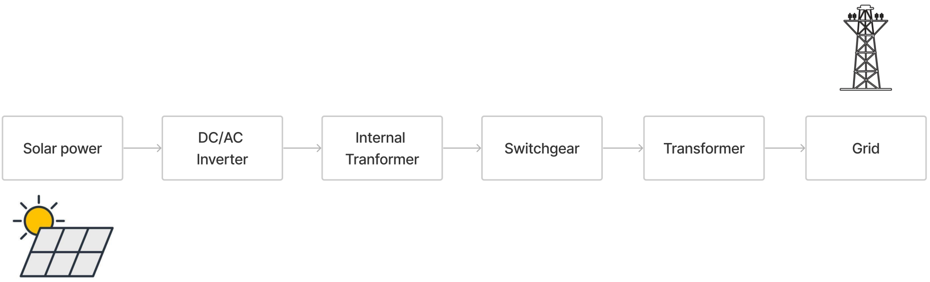


Figure 32: Connection diagram of scenario 1.

5.2.3 Scenario 2 - Hybrid solar-hydro power production - Without refinement

Scenario 2 involves the combined production of solar and hydro power plants without refining production through water storage in the hydro power plant reservoir. The two power plants share a common grid connection point at the hydro power plant. Therefore the financial calculations do not include the costs of building a new transformer, but instead the costs for connecting the solar power plant to the existing grid connection point in the transformer at the hydro power plant are included.

As mentioned, no refinement for storing water in the reservoir is performed when the combined production from the two power plants exceed the grid connection capacity. In such cases the production exceeding the grid connection capacity will be curtailed from the hydro power plant since that is the controllable power source in the scenario.

The production data for the solar power plant is obtained from simulation in PVsyst, while the production data provided by Statkraft AB, adjusted for a transformer efficiency of 97%, is used for the hydro power plant. The production data is then analysed in Microsoft Excel according to figure 33. Financial calculations are also made in Microsoft Excel. Using the production data together with the assumptions from section 4.3.1, Nord Pool day-ahead prices and the tariffs from Södra Hallands Kraft AB, which can be seen in figure 6, financial calculations are made. The tariffs are counted for the combined production of the solar-hydro hybrid system since they share a common grid connection.

Figure 33 illustrates the block diagram for solar-hydro hybrid production in scenario 2. As the hydro power plant and solar power plant produce power it will send as much as possible to the grid according to the grid connection capacity of 31,4 MW. All excess power will be wasted and thus not included in the total production or financial calculations.

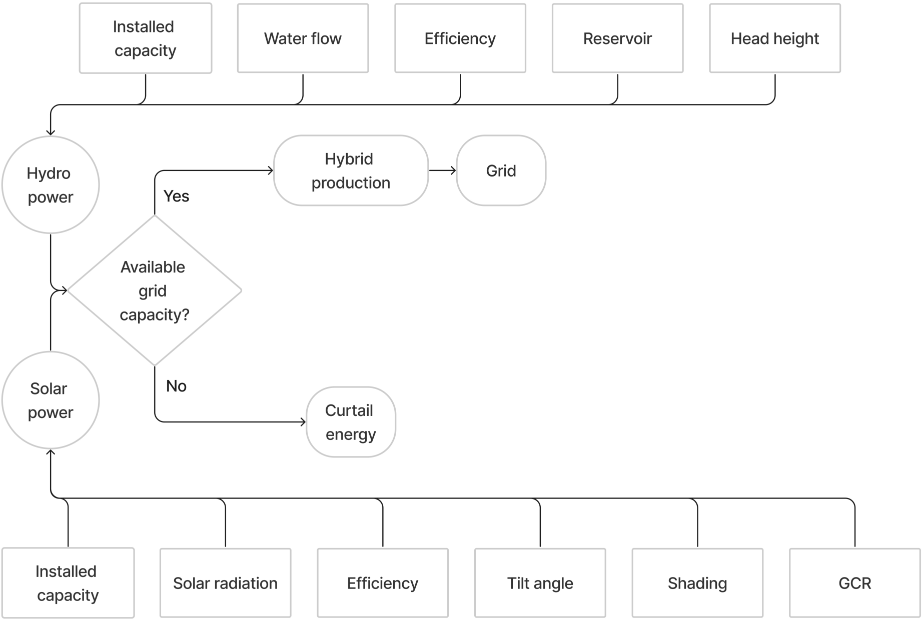


Figure 33: Block diagram of parameters and variables for simulation scenario 3.

The block diagram in figure 34 depicts how the hybrid system in scenario 2 is connected to the grid. The hydro power plant is connected to the grid connection transformer while the solar power plant goes through DC/AC inverters, internal transformers, switchgears before reaching the grid connection transformer. As mentioned, the losses occurring between the blocks are accounted for during simulation in PVsyst.

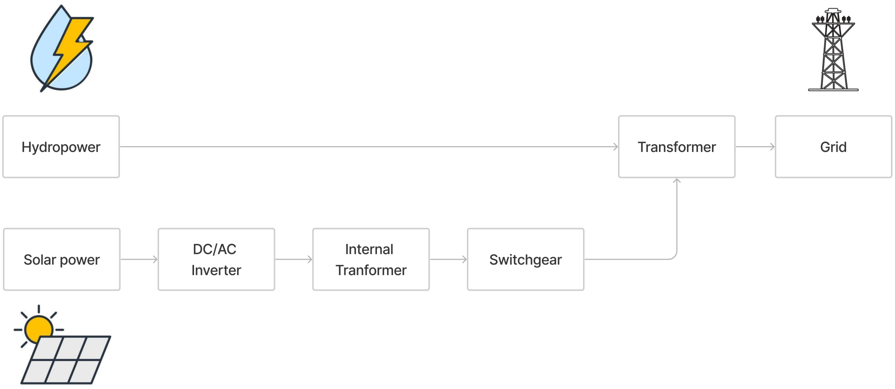


Figure 34: Connection diagram of scenario 2.

5.2.4 Scenario 3 - Hybrid solar-hydro power production - With refinement

In scenario 3, a refinement is performed for the hybrid power plant described in scenario 2. The refinement is performed in regards to the day-ahead prices on Nord Pool. Instead of curtailing or wasting power that exceeds the grid connection capacity, the excess power is saved in form of elevated water in the hydro power plant reservoir. The water is stored and utilised on a daily basis. This means that energy saved in form of reservoir water on day one will be utilised as much as possible on day two by prioritising the ten most profitable hours of the twenty four available hours in terms of electricity price and then making sure the capacity on the grid connection point is sufficient for this hour. If the grid connection capacity is insufficient to utilise the entire stored water supply from the previous day in one hour, the refinement method allocates as much energy as possible and then moves on to the second most profitable hour. This process will continue until the tenth most profitable hour or all stored water from the previous day has been utilised. Any remaining unallocated water will be wasted. The reason for focusing on ten hours is that during peak solar power production days, there are ten hours of minimal or non-existent solar power production, providing an opportunity to better utilise the stored energy. The stored and curtailed energy will at all times be energy from the hydro power plant as this is the controllable energy source in the scenario. The refinement method is fully implemented in Microsoft Excel and the block diagram for the refined hybrid power production can be seen in figure 35. Financial calculations are also made in Microsoft Excel.

As the two power plants share grid connection at the hydro power plant, the costs of building a new transformer are not included in the financial calculations. Instead, the costs for connecting the solar power plant to the existing grid connection point in the transformer at the hydro power plant are included. Using the production data together with the assumptions from section 4.3.1, Nord Pool day-ahead prices and the tariffs from Södra Hallands Kraft AB, which can be seen in figure 6, financial calculations are made. The tariffs are counted for the combined production of the solar-hydro hybrid system since they share grid connection.

The capacity of the grid connection is assumed to be dimensioned to the capacity of the hydro power plant of 31,4MW. Simulation in PVsyst provides the production data for the solar power plant and production data given by Statkraft Sverige AB in combination with the assumed efficiency of 97% of the transformer are used as the production data for the hydro power plant.

The water level will not be considered a criteria for production in this scenario as the hydro power production was provided as raw production data and no information regarding starting water levels at the beginning of the years were given. However, the variations will be calculated and presented to show its fluctuations during the years.

Figure 35 illustrates the block diagram for the hybrid power production in Scenario 3. The hydro power plant and solar power plant strive to deliver as much power as possible to the grid, up to the grid connection capacity of 31.4 MW. Excess power is not directly wasted or curtailed; instead, it is stored as elevated water in the hydro power plant reservoir for use on the following day. By considering the Nord Pool day-ahead prices and available grid connection capacity, the ten most profitable hours for utilising the stored energy are determined. The stored energy is then used as much as possible during these hours or until all stored energy has been utilised. Any remaining energy that cannot be utilised within these ten hours is wasted or curtailed.

As previously mentioned, figure 35 illustrates the block diagram for the hybrid power production in scenario 3. When the hydro power plant and solar power plant produce energy it will send as much as possible to the grid according to the grid connection capacity of 31,4 MW. All excess energy are, instead of being directly wasted or curtailed, stored as elevated water in the hydro power plant reservoir for use on the following day. By considering the

Nord Pool day-ahead prices and available grid connection capacity, the ten most profitable hours where the stored energy can be utilised for power production are determined. The stored energy is then utilised as much as possible during these ten hours or until all stored energy has been utilised. Any remaining stored energy that cannot be utilised within these ten hours it is wasted or curtailed.

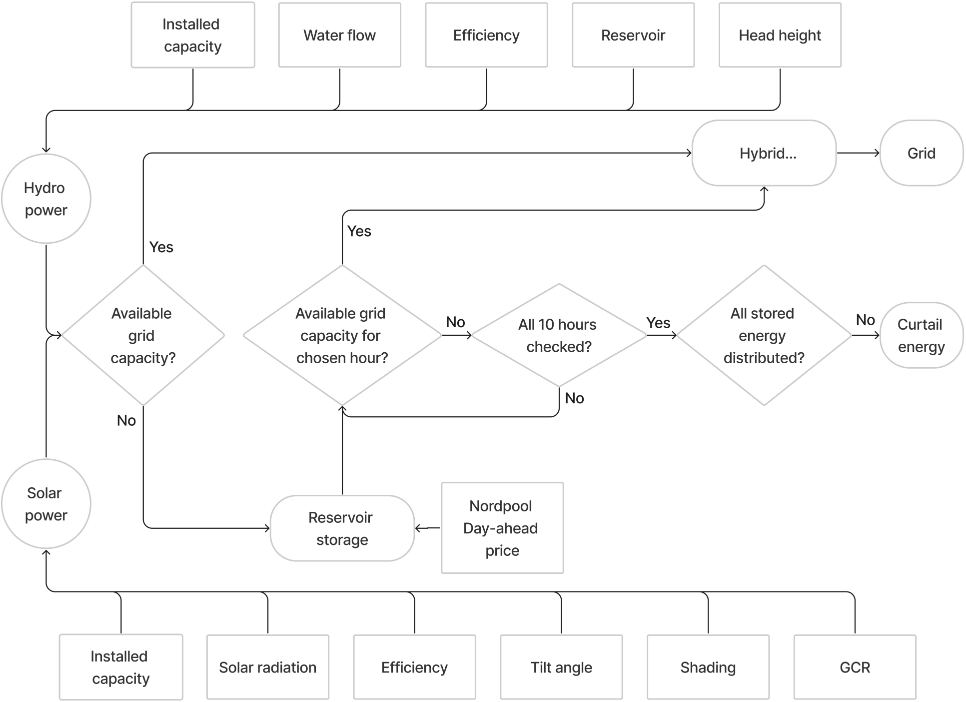


Figure 35: Refinement diagram for scenario 3.

Figure 36 depicts the block diagram illustrating the grid connection configuration for the hybrid system in Scenario 3. The hydro power plant is directly connected to the grid connection transformer while the solar power plant goes through DC/AC inverters, internal transformers and switchgears before reaching the grid connection transformer. The losses occurring between these components are taken into account during the simulation in PVsyst. The main difference from scenario 2 is that the reservoir of the hydro power plant is utilised for energy storage.

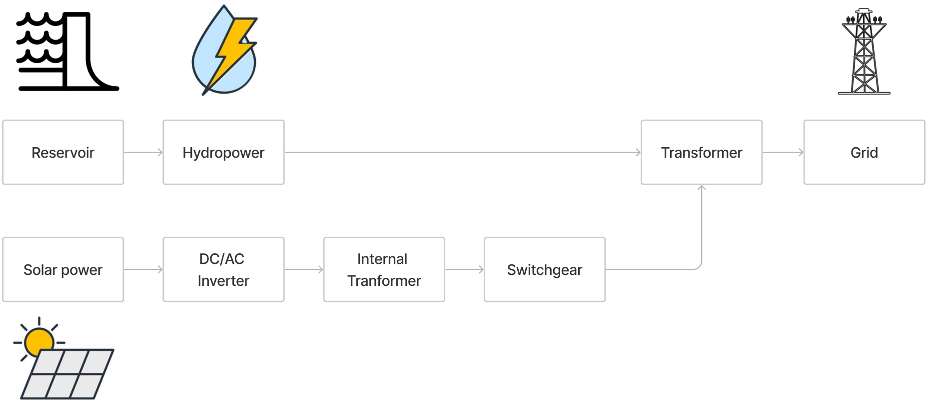


Figure 36: Connection diagram of scenario 3.

6 Simulation results

This section displays the results gathered through simulations and calculations for the different scenarios and ratios described in section 4 and 5. Firstly, power production results are introduced together with the fluctuation in the reservoir water levels for scenario 3. This is then followed by more in depth results for the refinement method implemented in scenario 3. After this economical results in form of NPV, IRR and payback time are presented and lastly a summary of some of the more interesting results are displayed.

6.1 Power production results

Below follows the results related to power production for the four different scenarios. The weekly average power production, total yearly power production, total yearly curtailed or wasted power, total yearly income and yearly average grid utilisation ratio will be displayed. Hourly power production is not showcased due to difficulties in displaying too many data points.

6.1.1 Scenario 0

Figure 37 displays the weekly average power production for scenario 0 for each week of 2018 and 2020. For the year 2020 the weekly maximum average power output is 31,4 MW to the grid and for 2018 the weekly maximum average is 31 MW. The seasonal differences in power production can be seen in the graph. The weekly average production for 2018 is for most part of the year lower than that of 2020.

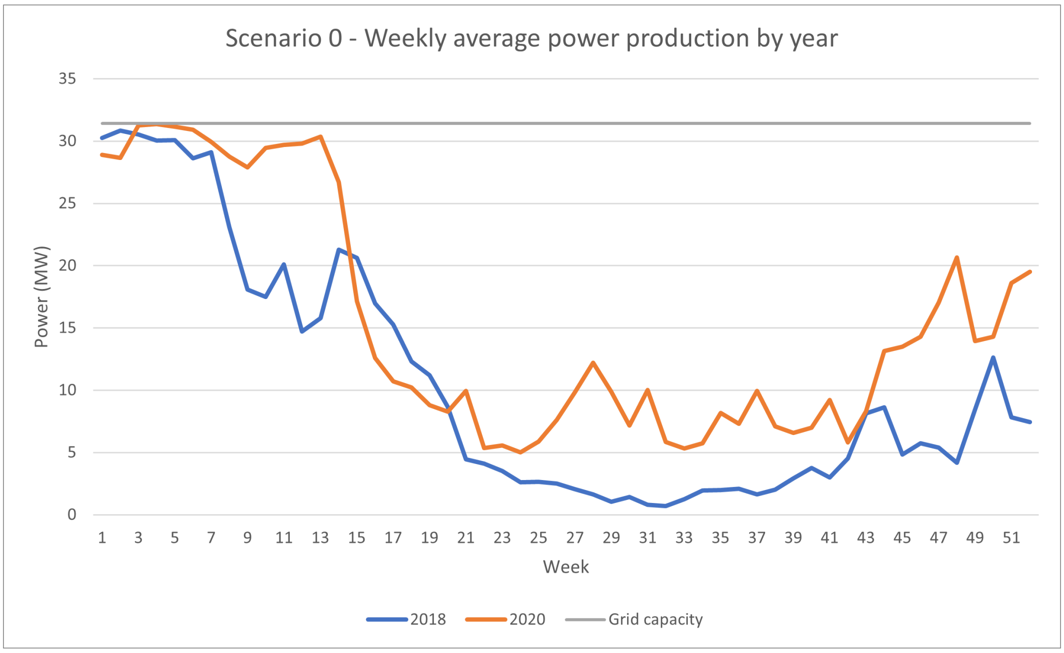


Figure 37: Scenario 0 - Weekly average hydro power production for 2018 and 2020

Table 8 display the yearly average grid utilisation ratio, the total yearly power production to the grid, total yearly excess or wasted power and the total yearly income for scenario 0 in 2018 and 2020. 2020 had overall higher power production and grid utilisation rate. However 2018 had higher total income. No energy is wasted in both cases.

Year	Average grid utilisation rate (%)	Energy to grid (GWh)	Excess energy (GWh)	Utilised excess energy (GWh)	Wasted excess energy (GWh)	Wasted energy of total production (%)	Total income (MSEK)	Missed income by curtailment (MSEK)
2018	34%	93	0	0	0	0%	36.7	0
2020	49%	135	0	0	0	0%	34.8	0

Table 8: Summary of results for scenario 0 for the years 2018 and 2020. Note that the values are rounded.

6.1.2 Scenario 1

In figure 38 the weekly average power production for scenario 1 for each week of 2018 and 2020 and for both solar power ratios can be observed. The two years follow a similar trend in weekly average power production where 2018 has a slightly higher production during the summer weeks compared to 2020 and higher average values for the 1.25:1 cases. The seasonal differences in power production can be seen in the graph.

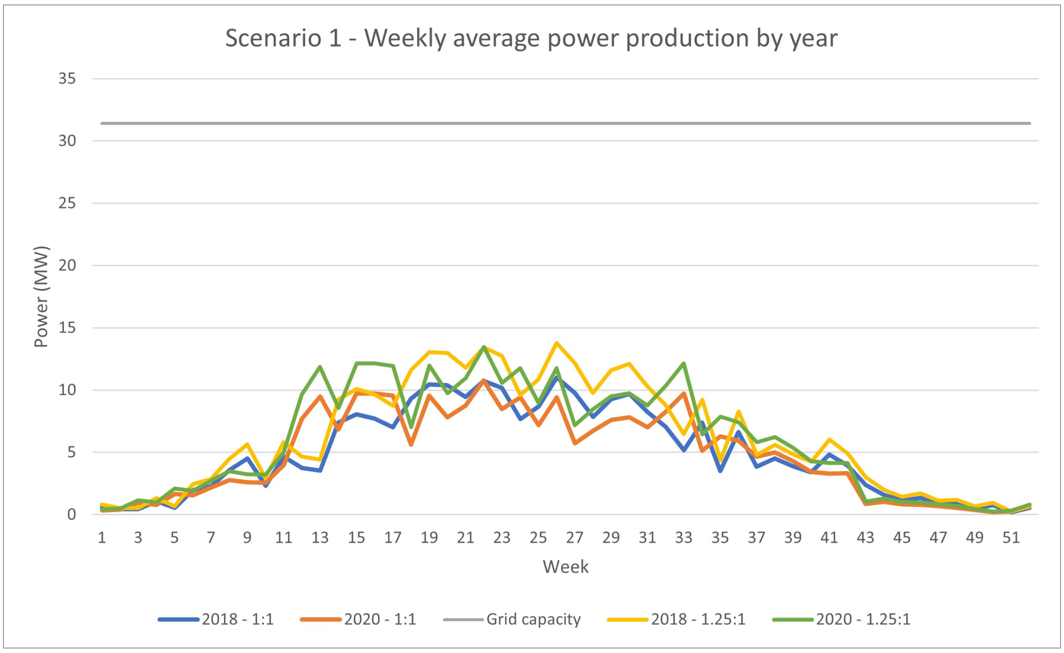


Figure 38: Scenario 1 - Weekly average solar power production for 2018 and 2020

Tables 9 and 10 indicate that the grid utilisation rate increases when a larger solar power plant is installed. When it comes to income, 2018 is more profitable than 2020 by more than 100%. Curtailment occurs for the larger solar plant which is expected as it is scaled larger than the available capacity at the grid connection point.

Year	**Average grid utilisation rate (%)**	**Energy to grid (GWh)**	**Excess energy (GWh)**	**Utilised excess energy (GWh)**	**Wasted excess energy (GWh)**	**Wasted energy of total production (%)**	**Total income (MSEK)**	**Missed income by curtailment (MSEK)**	**Increased income by refinement (MSEK)**
2018	16%	43	0	0	0	0%	17.7	0	0
2020	15%	42	0	0	0	0%	7.6	0	0

Table 9: Summary of results for scenario 1 for the years 2018 and 2020 at ratio 1:1. Note that the values are rounded.

Year	**Average grid utilisation rate (%)**	**Energy to grid (GWh)**	**Excess energy (GWh)**	**Utilised excess energy (GWh)**	**Wasted excess energy (GWh)**	**Wasted energy of total production (%)**	**Total income (MSEK)**	**Missed income by curtailment (MSEK)**	**Increased income by refinement (MSEK)**
2018	19%	54	2	0	2	4%	22	1.3	0
2020	18%	53	3	0	3	6%	10	0.7	0

Table 10: Summary of results for scenario 1 for the years 2018 and 2020 at ratio 1.25:1. Note that the values are rounded.

6.1.3 Scenario 2

Continuing to the hybrid systems, figure 39 depicts the weekly average power production for scenario 2 for each week of 2018 and 2020. For the year 2020 the weekly maximum average power output is 31,4 MW to the grid and for 2018 the weekly maximum average is 31 MW. The seasonal differences in power production and the effects of combining solar and hydro power can be seen in the graph. An increase in weekly average power production can be seen for both years compared to scenario 0. 2020 has a higher weekly average power production compared to 2018 but the difference in weekly average power production between the two years has also decreased compared to that for scenario 0. It is also visible that the difference between the two solar power ratios is minimal, mainly due to there being no implemented water storage method in this scenario

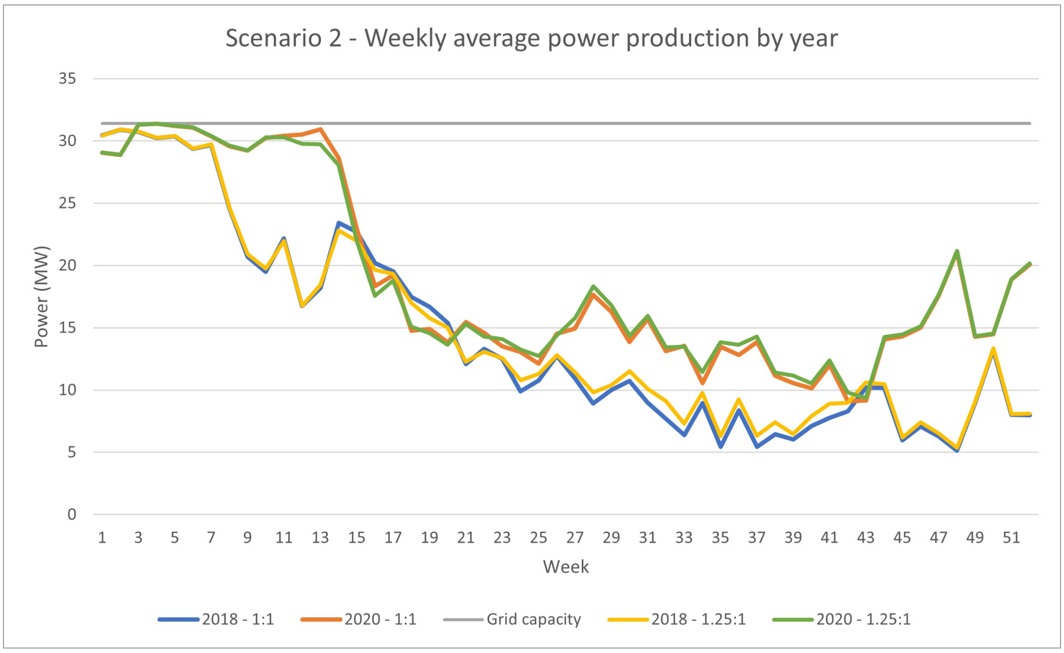


Figure 39: Scenario 2 - Weekly average hybrid system power production for 2018 and 2020

Similarly to scenario 1, tables 11 and 12 indicate that 2018 is more profitable than 2020. However, total power production and grid utilisation rate is fairly similar between the two ratios and the wasted energy is is almost doubled for the solar power plant of ratio 1.25:1. Total income follow the same pattern and is almost the same independent of the solar power plant size.

Year	**Average grid utilisation rate (%)**	**Energy to grid (GWh)**	**Excess energy (GWh)**	**Utilised excess energy (GWh)**	**Wasted excess energy (GWh)**	**Wasted energy of total production (%)**	**Total income (MSEK)**	**Missed income by curtailment (MSEK)**	**Increased income by refinement (MSEK)**
2018	46%	126	10	0	10	7%	54.5	4.4	0
2020	60%	164	13	0	13	7%	43.8	3.1	0

Table 11: Summary of results for scenario 2 for the years 2018 and 2020 at ratio 1:1. Note that the values are rounded.

Year	**Average grid utilisation rate (%)**	**Energy to grid (GWh)**	**Excess energy (GWh)**	**Utilised excess energy (GWh)**	**Wasted excess energy (GWh)**	**Wasted energy of total production (%)**	**Total income (MSEK)**	**Missed income by curtailment (MSEK)**	**Increased income by refinement (MSEK)**
2018	47%	129	18	0	18	14%	55.8	8.6	0
2020	60%	166	22	0	22	13%	44.2	5.7	0

Table 12: Summary of results for scenario 2 for the years 2018 and 2020 at ratio 1.25:1. Note that the values are rounded.

6.1.4 Scenario 3

Figure 40 displays the weekly average power production for scenario 3 for each week of 2018 and 2020. For the year 2020 the weekly maximum average power output is 31,4 MW to the grid and for 2018 the weekly maximum average is approximately 31 MW. The seasonal differences in power production and the effects of combining solar and hydro power can be seen in the graph. An increase in weekly average power production can be seen for both years compared to scenario 2 due to the implemented refinement method. 2020 has a higher weekly average power production compared to 2018 but the difference in weekly average power production between the two years has also decreased compared to that for scenario 2.

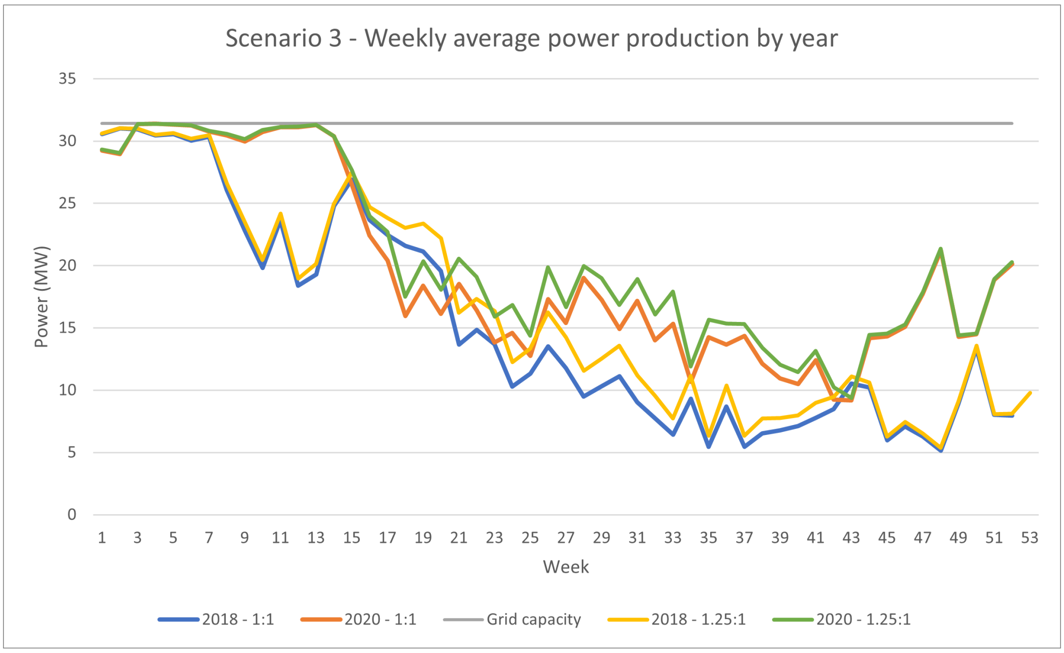


Figure 40: Scenario 3 - Weekly average hybrid system power production for 2018 and 2020

Tables 13 and 14 show that the grid utilisation rate increases when a larger solar power plant is installed and that 2018 is more profitable than 2020. The grid utilisation rate increases with 3%, as for scenario 1, when a larger solar power plant is increased. Energy to grid increases by approximately the same amount as for scenario 1 as well. Due to implemented refinement method the increase in wasted energy between the two ratios is decreased by approximately 0.5% compared to scenario 2. The income difference between the two ratios is larger than that for scenario 2 by 5.4 and 3.8 MSEK for the years 2018 and 2020 respectively.

Year	**Average grid utilisation rate (%)**	**Energy to grid (GWh)**	**Excess energy (GWh)**	**Utilised excess energy (GWh)**	**Wasted excess energy (GWh)**	**Wasted energy of total production (%)**	**Total income (MSEK)**	**Missed income by curtailment (MSEK)**	**Increased income by refinement (MSEK)**
2018	49%	134	10	8	2	1.5%	57.8	1.1	3.3
2020	63%	172	13	8	5	3%	46.2	0.7	2.4

Table 13: Summary of results for scenario 3 for the years 2018 and 2020 at ratio 1:1. Note that the values are rounded.

Year	Average grid utilisation rate (%)	Energy to grid (GWh)	Excess energy (GWh)	Utilised excess energy (GWh)	Wasted excess energy (GWh)	Wasted energy of total production (%)	Total income (MSEK)	Missed income by curtailment (MSEK)	Increased income by refinement (MSEK)
2018	52%	143	18	12	6	4%	62.5	3.2	5.4
2020	66%	181	22	12	10	5.5%	48.6	1.9	3.8

Table 14: Summary of results for scenario 3 for the years 2018 and 2020 at ratio 1.25:1. Note that the values are rounded.

Figures 41 and 42 illustrates the water level change for scenario 3 for the two different solar power plant ratios on a daily basis. They follow the same pattern with the difference being larger changes in water level for the ratio of 1.25:1 due to increased need for storage as the solar power plant produce more power.

The water level limit is exceeded for a few days and the specific water levels of these days for the two different simulated years and solar power ratio together with the amount of energy the exceeded water corresponds to can be seen in tables 15 - 18. 2020 stands for the most amount of days that exceed the allowed water level limits and does so during a period of eleven days in march. For 2018 the water level exceeds the water level limits for one day in April for the case with solar power ratio 1:1 and two days for solar power ratio 1.25:1.

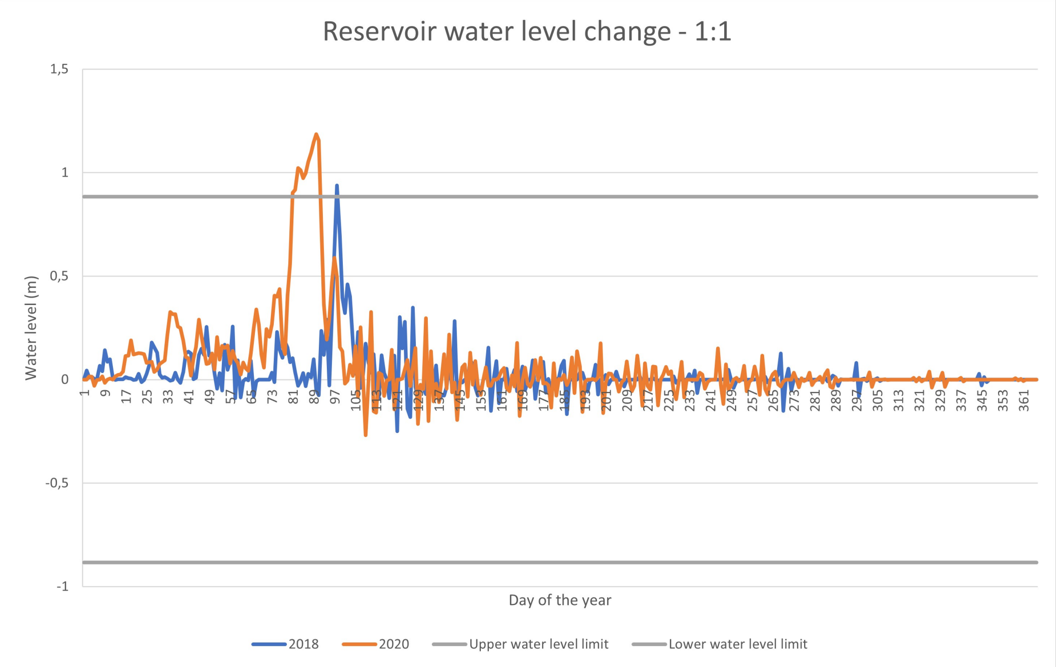


Figure 41: Scenario 3 - Daily fluctuation in reservoir water level for 2018 and 2020 with solar power ratio 1:1

Date	Water level limit (m)	Water level (m)	Difference (m)	Energy (MWh)
2018-04-08	±0.88	0.94	0.06	3

Table 15: Water levels exceeding water level limits and the potential energy it contains in scenario 3 for 2018 and solar power ratio 1:1. Note that the values are rounded

Date	Water level limit (m)	Water level (m)	Difference (m)	Energy (MWh)
2020-03-21	±0.88	0.90	0.02	1
2020-03-22	±0.88	0.92	0.04	2
2020-03-23	±0.88	1.02	0.14	8
2020-03-24	±0.88	1.01	0.13	7
2020-03-25	±0.88	0.97	0.09	5
2020-03-26	±0.88	1.00	0.12	6
2020-03-27	±0.88	1.05	0.17	9
2020-03-28	±0.88	1.09	0.21	12
2020-03-29	±0.88	1.15	0.27	15
2020-03-30	±0.88	1.18	0.30	17
2020-03-31	±0.88	1.16	0.28	15

Table 16: Water levels exceeding water level limits and the potential energy it contains in scenario 3 for 2020 and solar power ratio 1:1. Note that the values are rounded

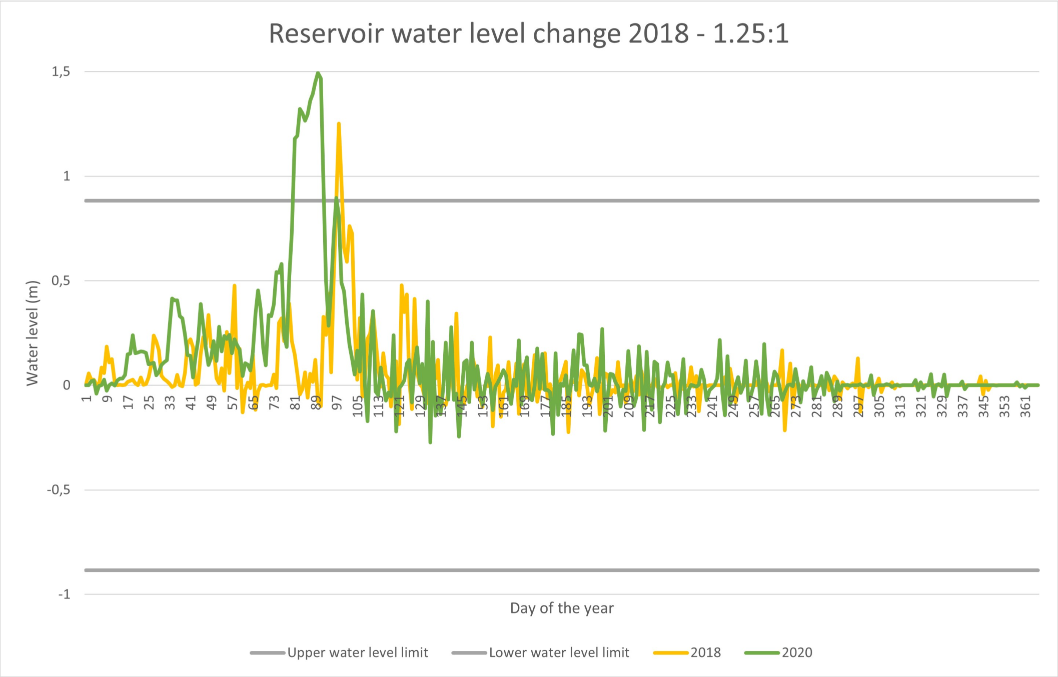


Figure 42: Scenario 3 - Daily fluctuation in reservoir water level for 2018 and 2020 with solar power ratio 1.25:1

Date	Water level limit (m)	Water level (m)	Difference (m)	Energy (MWh)
2018-04-08	±0.88	1.25	0.37	20
2018-04-09	±0.88	0.97	0.09	5

Table 17: Water levels exceeding water level limits and the potential energy it contains in scenario 3 for 2018 and solar power ratio 1.25:1. Note that the values are rounded

Date	Water level limit (m)	Water level (m)	Difference (m)	Energy (MWh)
2020-03-21	±0.88	1.18	0.30	16
2020-03-22	±0.88	1.19	0.31	17
2020-03-23	±0.88	1.32	0.44	24
2020-03-24	±0.88	1.30	0.42	23
2020-03-25	±0.88	1.27	0.38	21
2020-03-26	±0.88	1.29	0.41	23
2020-03-27	±0.88	1.36	0.48	26
2020-03-28	±0.88	1.39	0.51	28
2020-03-29	±0.88	1.45	0.57	31
2020-03-30	±0.88	1.49	0.61	34
2020-03-31	±0.88	1.47	0.59	33

Table 18: Water levels exceeding water level limits and the potential energy it contains in scenario 3 for 2020 and solar power ratio 1.25:1. Note that the values are rounded

6.2 Refinement results

The following graphs and tables display the power production for scenario 3 where a refinement method is implemented, as well as the change in water levels for 2018 and 2020 due to the implemented refinement method. First, the graphs and values for 2018 will be introduced and described, followed by the graphs and results for 2020.

Figure 43 - 53 and show the total hourly power production for the hybrid system as well as the water level in the reservoir for three days in January, April, July and October in 2018 and the same three days can be seen in figures 55 - 65. The blue bars in the power production graphs depict solar power production, while the orange bars represent hydro power production. The grey bars indicate power production that exceeds the grid connection capacity, as shown by the light blue line. The yellow bars represent hydro power production from stored water, which utilises otherwise curtailed power. Power production for scenario 2 is thus represented by the blue, orange, and grey bars, with the grey bars representing the curtailed energy for that scenario. In Scenario 3, all the bars are present, but the grey bars are not curtailed. Instead, they are stored as elevated water in the reservoir and utilised for electricity production the following day, shown as the yellow bars.

6.2.1 2018

Figures 43 and 44 showcase three days in January, representing a typical period in the winter season. The production for 2018 shows hydro power production at almost maximum capacity, with relatively low solar power production. The hydro power production is also active for all hours of the day. The water storage possibility is utilised as one can see slight shifts in power production. The difference between the two solar power ratios is minimal as solar power production is fairly low during this period of the year.

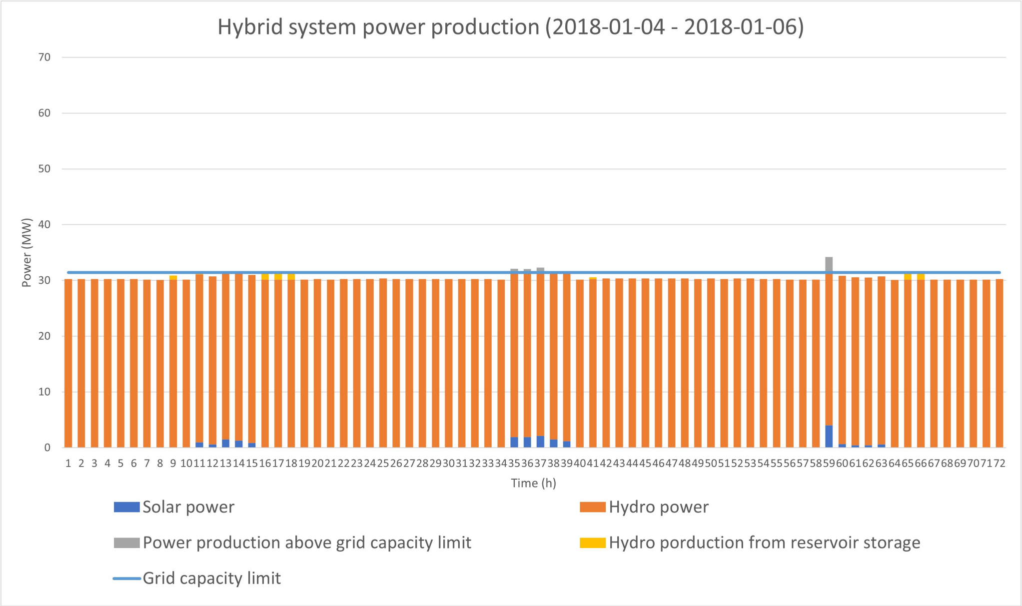


Figure 43: Scenario 3 - Three days of electricity production in an refined hybrid system with ratio 1:1, 2018/01/04 - 2018/01/06

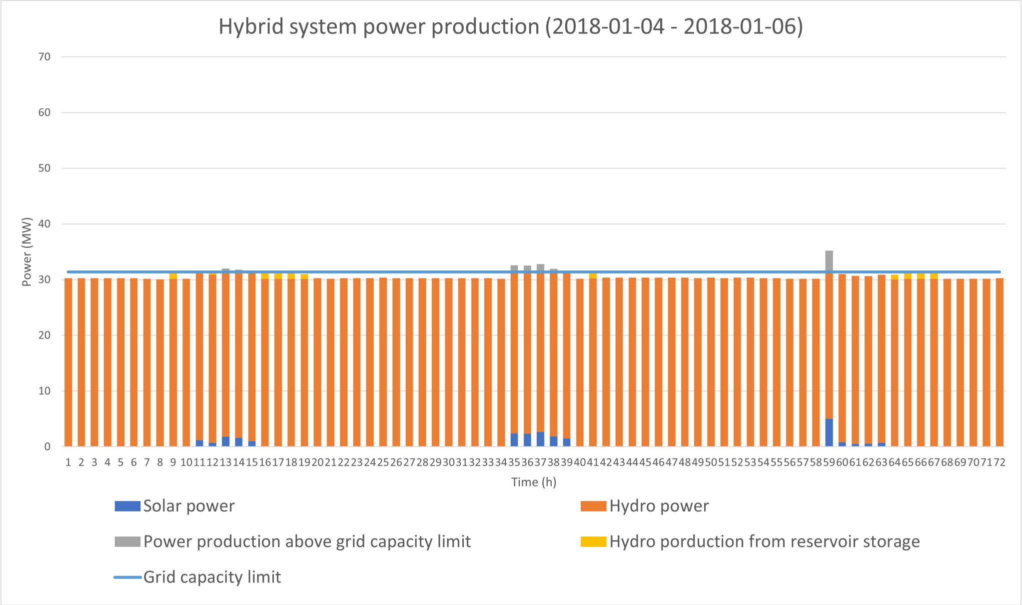


Figure 44: Scenario 3 - Three days of electricity production in a refined hybrid system with ratio 1.25:1, 2018/01/04 - 2018/01/06

Figure 45 illustrate the water level change during these three days for both simulated solar power ratios. It indicates that the possibility for energy storage during the period of these three days is viable as it never exceeds the allowed water level limits of approximately ±0.9m.

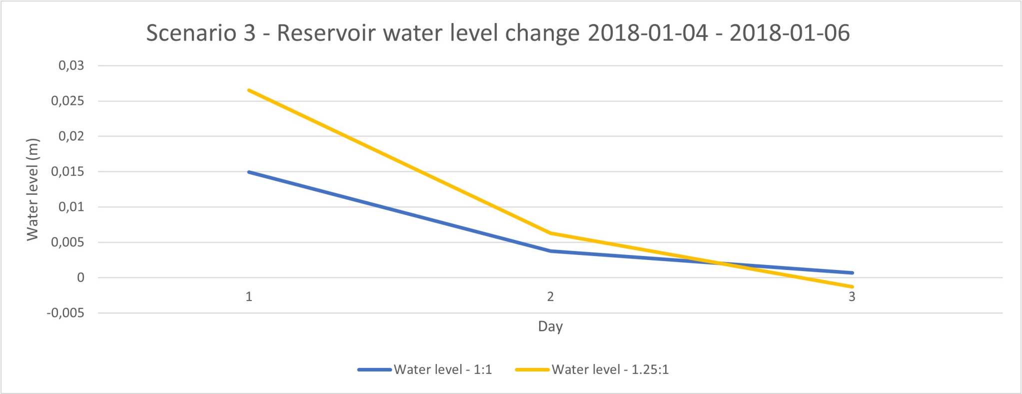


Figure 45: Scenario 3 - Water level deviation in a refined hybrid system with ratio 1:1 and 1.25:1, 2018/01/04 - 2018/01/06

Moving on to the three days in April, representing a typical period in spring season, both hydro and solar power production are high and the refinement is clearly visible, represented by the yellow bars as excess energy from one day is utilised on the next. It is also visible that the hydro power production is halted during the nights for this period. The difference between the two simulated solar power ratios can be seen in the two figures as more energy is stored and utilised.

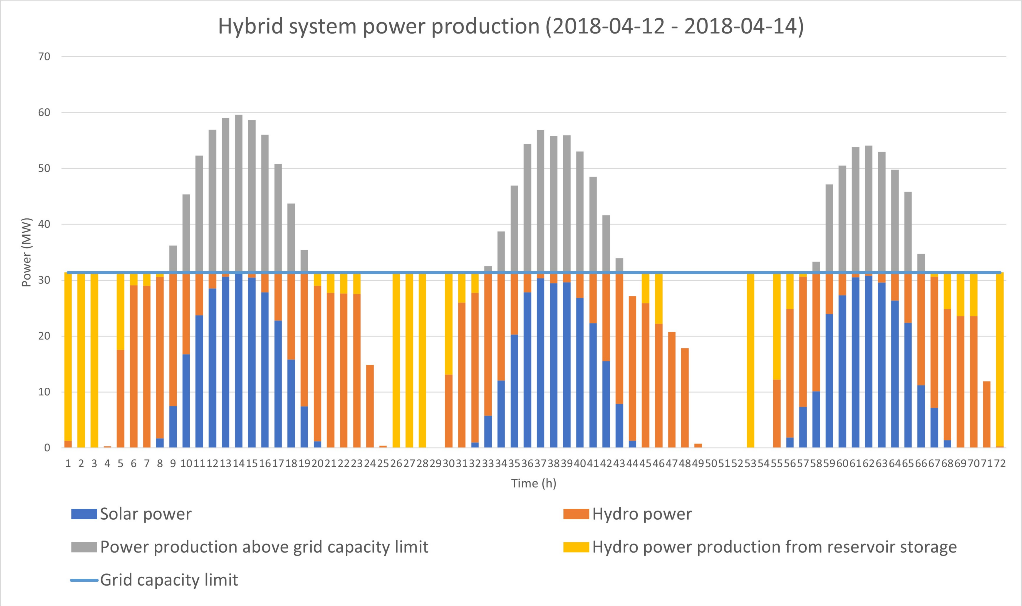


Figure 46: Scenario 3 - Three days of electricity production in a refined hybrid system with ratio 1:1, 2018/04/12 - 2018/04/14

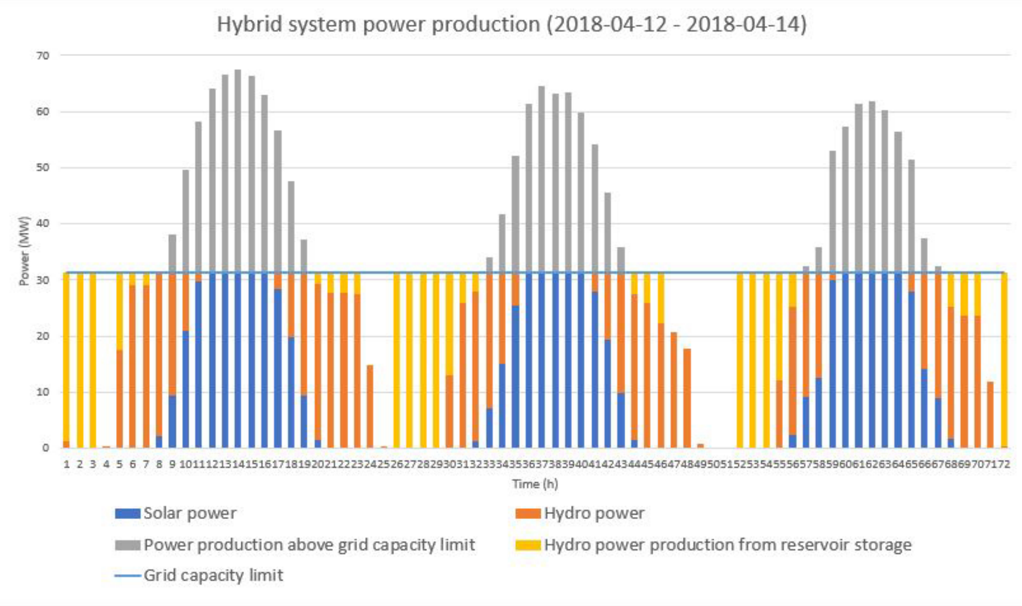


Figure 47: Scenario 3 - Three days of electricity production in a refined hybrid system with ratio 1.25:1, 2018/04/12 - 2018/04/14

Figure 48 illustrate the water level change during these three days for both simulated solar power ratios. It indicates that the possibility for energy storage during the period of these three days is practicable but for the case with solar power ratio 1.25:1 the water level is close to 0.8m and thus not far away from the allowed upper water level limit of 0.9m.

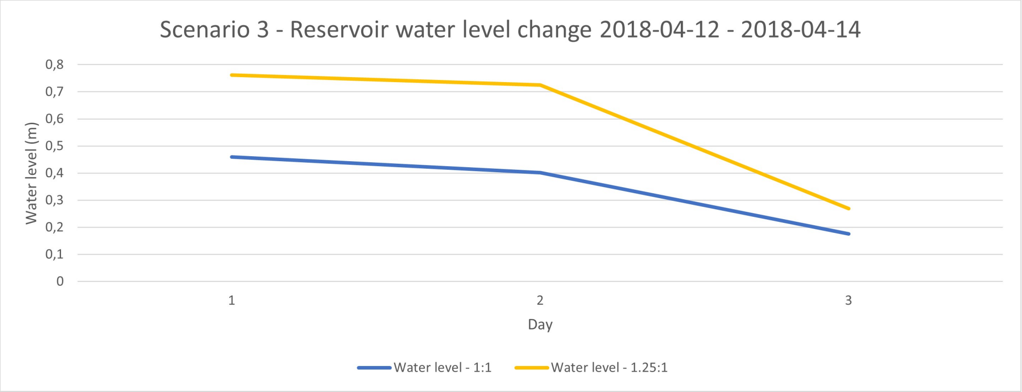


Figure 48: Scenario 3 - Water level deviation in a refined hybrid system with ratio 1:1 and 1.25:1, 2018/04/12 - 2018/04/14

During the the three days of the summer period, as shown in figures 49 and 50 , there is no hydro power production at all. Therefore no storing of energy occurs for the 1:1 ratio and the produced power from the solar power plant is directly sent to the grid. However, for the 1.25:1 case some utilisation of storage occurs as solar power production exceeds the grid capacity limits during day two and three.

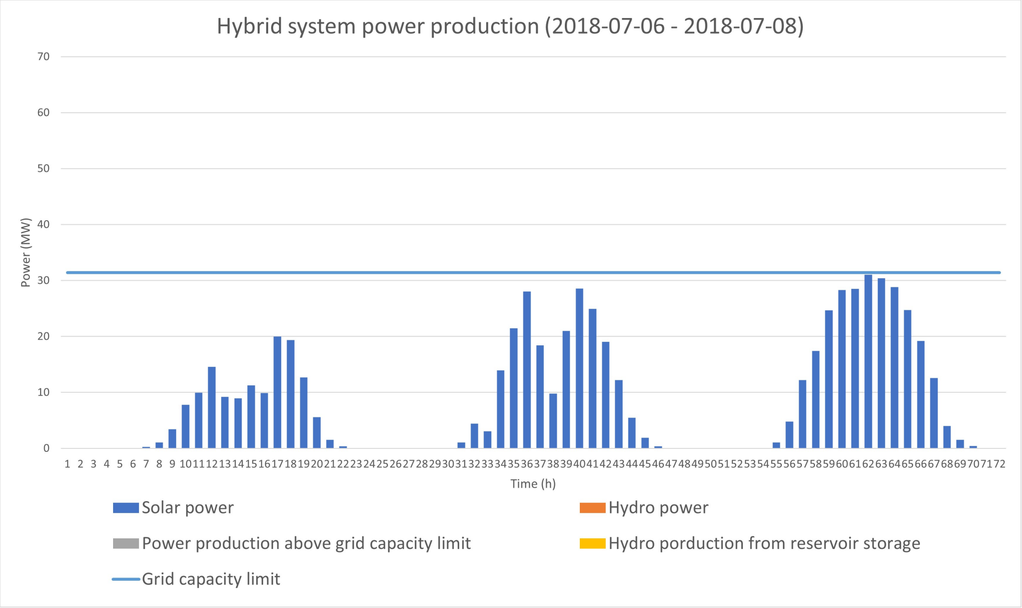


Figure 49: Scenario 3 - Three days of electricity production in a refined hybrid system with ratio 1:1, 2018/07/06 - 2018/07/08

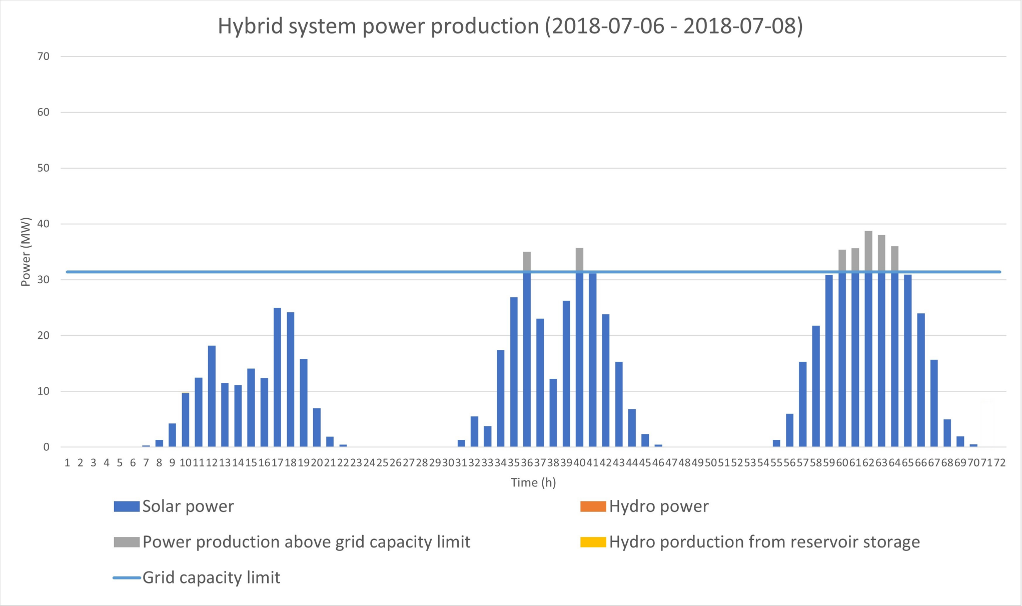


Figure 50: Scenario 3 - Three days of electricity production in a refined hybrid system with ratio 1.25:1, 2018/07/06 - 2018/07/08

Figure 51 illustrate the water level change during these three days for both simulated solar power ratios. The figure display that water levels never reach near the water level limits of ±0.9m and therefore the possibility for energy storage during the period of these three days is viable.

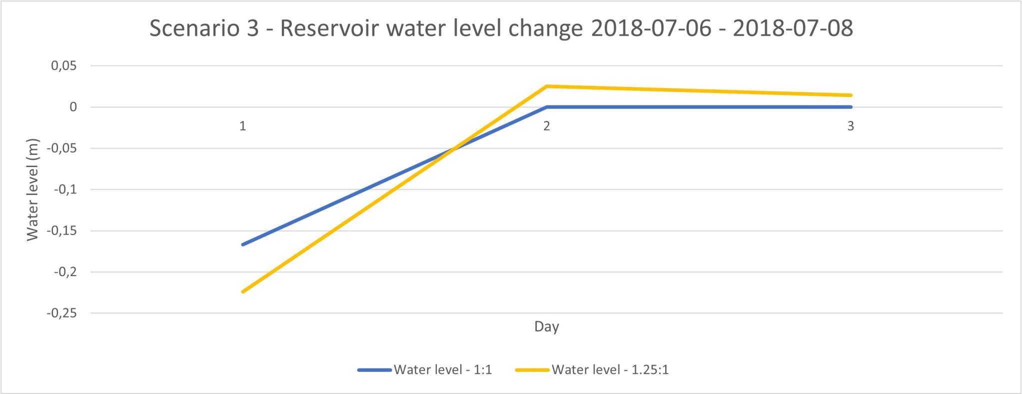


Figure 51: Scenario 3 - Water level deviation in a refined hybrid system with ratio 1:1 and 1.25:1, 2018/07/06 - 2018/07/08

Examining the three days in autumn, shown in figure 52 and 53, similarities with the three days during summer in figure 49 and 50 can be observed, as the hydro power production is minimal. However, some storage and utilisation of stored energy can be seen in the graph, represented by the yellow bar on the first day.

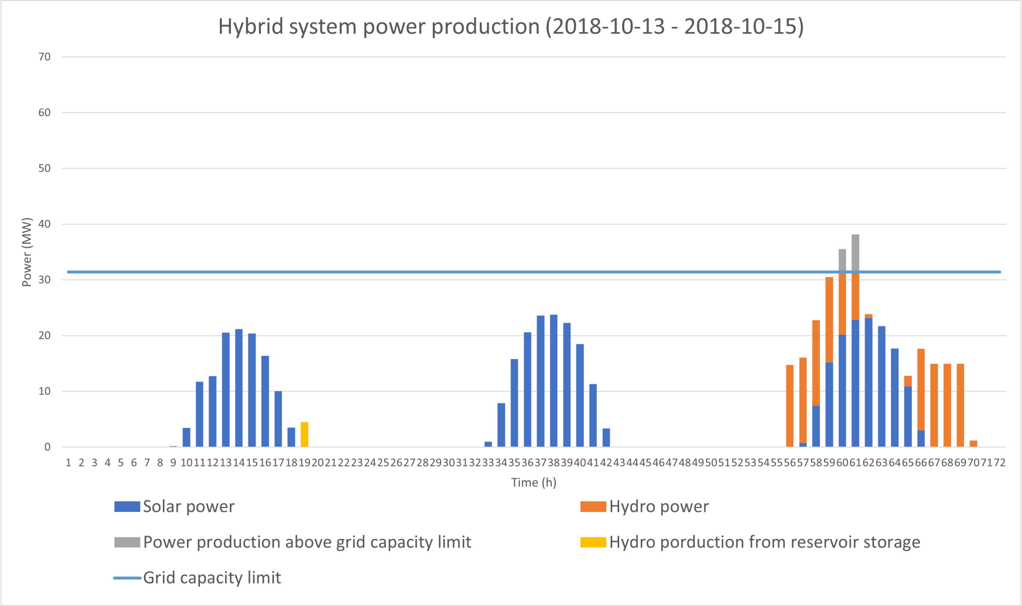


Figure 52: Scenario 3 - Three days of electricity production in a refined hybrid system with ratio 1:1, 2018/10/13 - 2018/10/15

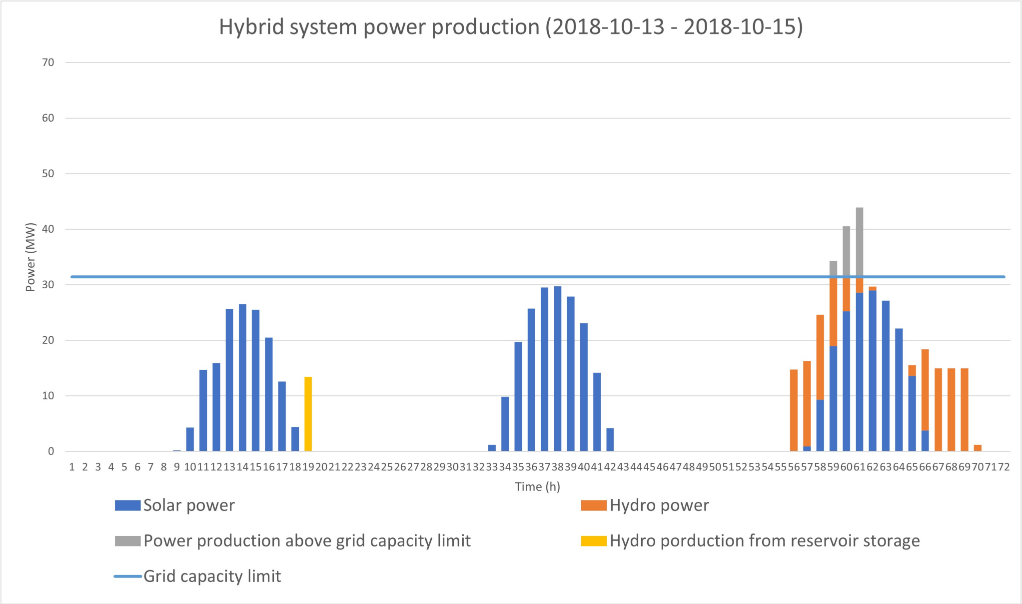


Figure 53: Scenario 3 - Three days of electricity production in a refined hybrid system with ratio 1.25:1, 2018/10/13 - 2018/10/15

The water levels in figure 54 shows that energy storage in the reservoir is possible during the period of these three days as it never reaches close or above the allowed limits of ±0.9m.

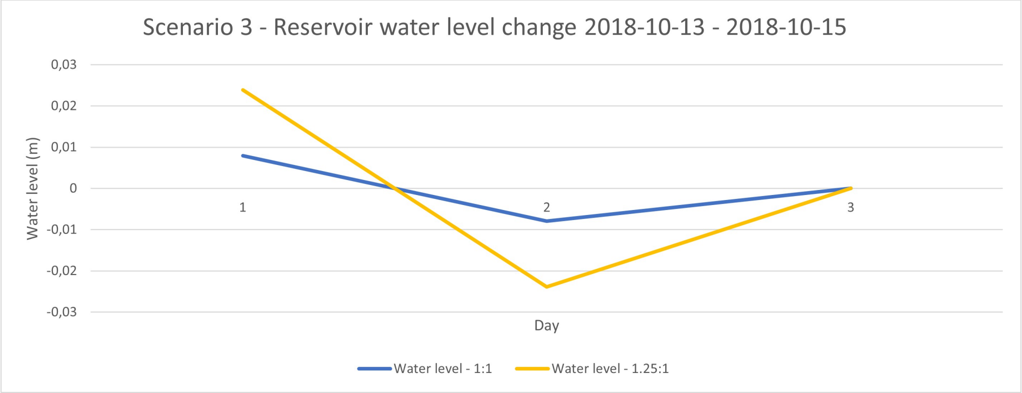


Figure 54: Scenario 3 - Water level deviation in a refined hybrid system with ratio 1:1 and 1.25:1, 2018/10/13 - 2018/10/15

6.2.2 2020

The three days in January 2020 can be observed in 55 and 56. It depicts the hydro power production at almost maximum capacity, with relatively low solar power production. The hydro power production is also active for all hours of the day. Slight shifts in energy production due to storage of water can be seen in the graphs.

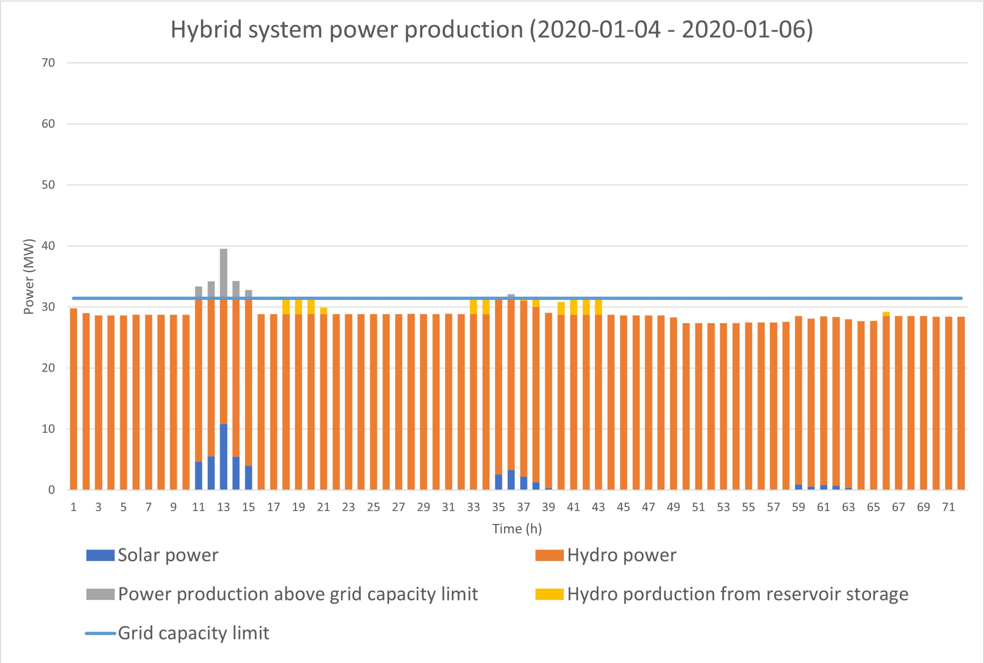


Figure 55: Scenario 3 - Three days of electricity production in a refined hybrid system with ratio 1:1, 2020/01/04 - 2020/01/06

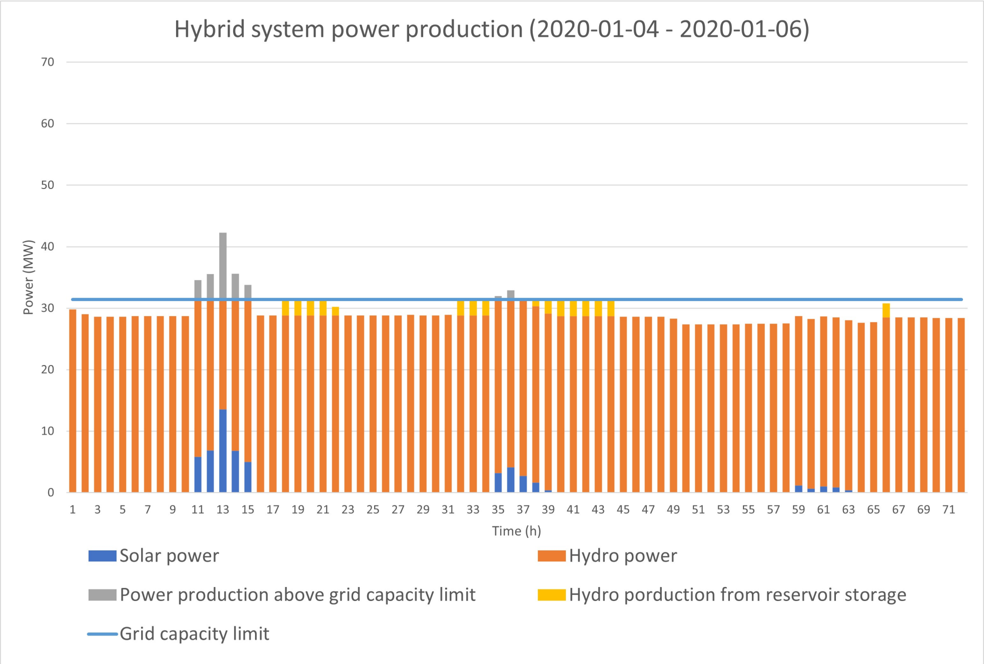


Figure 56: Scenario 3 - Three days of electricity production in a refined hybrid system with ratio 1.25:1, 2020/01/04 - 2020/01/06

The water levels in figure 57 are not near the limits of ±0.9m and storage is therefore possible for this period.

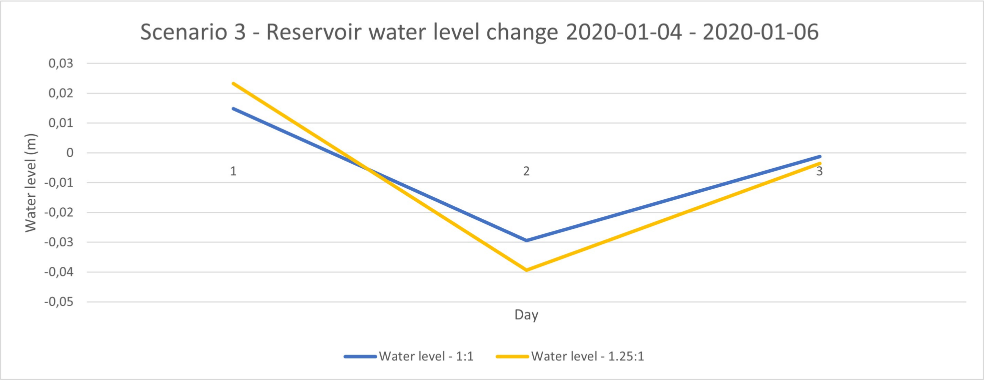


Figure 57: Scenario 3 - Water level deviation in a refined hybrid system with ratio 1:1 and 1.25:1, 2020/01/04 - 2020/01/06

Figure 58 and 59 depicts the three days in spring where both hydro and solar power production are high and the water storage possibility is clearly visible, as excess energy from the previous day is utilised on the next, represented by the yellow bars. The hydro power production remains continuous throughout the three days with no halts during the nights. Similarly as for 2018, more energy is stored and utilised for the case when a larger solar plant is installed.

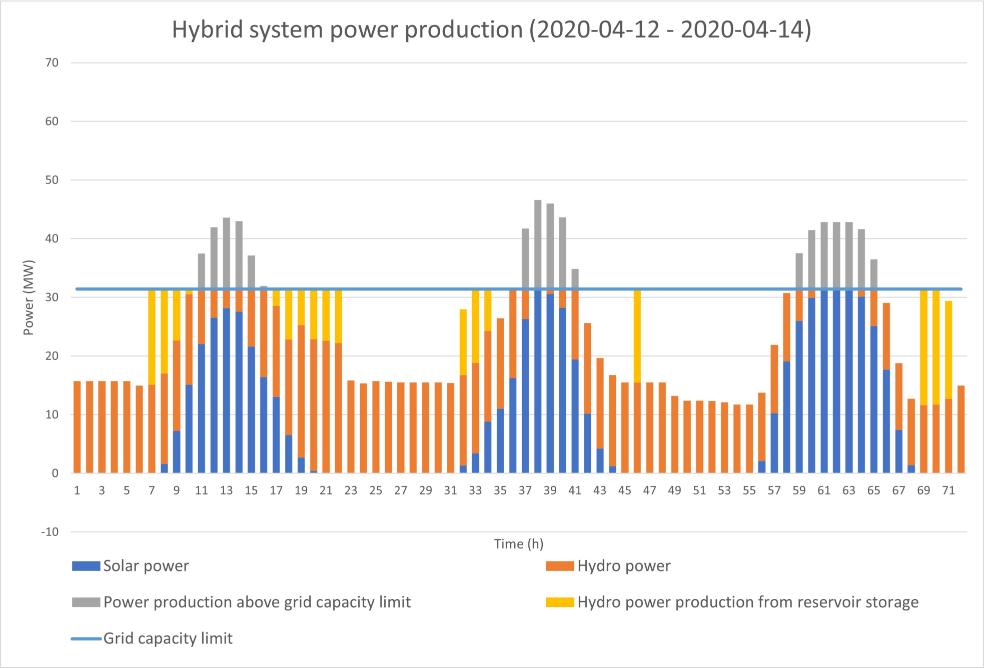


Figure 58: Scenario 3 - Three days of electricity production in a refined hybrid system with ratio 1:1, 2020/04/12 - 2020/04/14

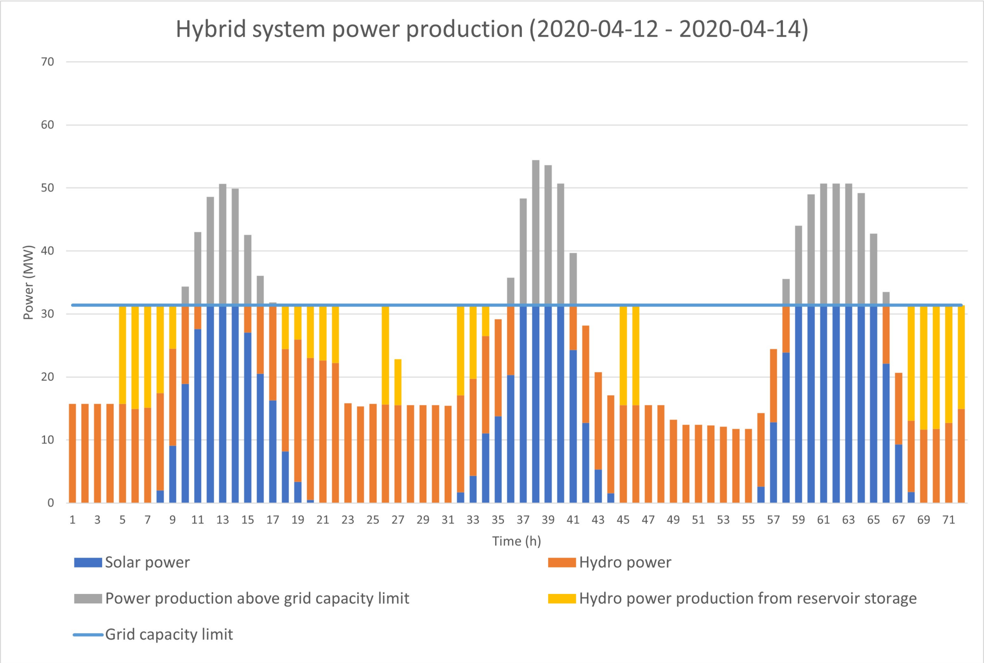


Figure 59: Scenario 3 - Three days of electricity production in a refined hybrid system with ratio 1.25:1, 2020/04/12 - 2020/04/14

Similarly to 2018, the water levels are slightly higher for this period of the year, however for 2020 it never reaches close to the water level limits, whihc can be seen in figure 60.

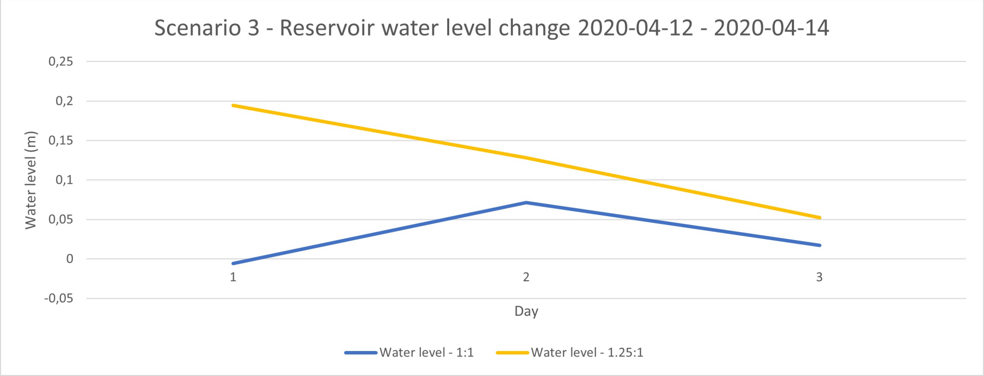


Figure 60: Scenario 3 - Water level deviation in a refined hybrid system with ratio 1:1 and 1.25:1, 2020/04/12 - 2020/04/14

Three days during the summer season in 2020 is shown in figures 61 and 62. Both solar and hydro power production is active during this period apart from a few hours on the first day. The utilisation of the storage capability of the hydro power plant can be observed to be active for the last two days as energy production is shifted from day two to day three, depicted by the yellow bars.

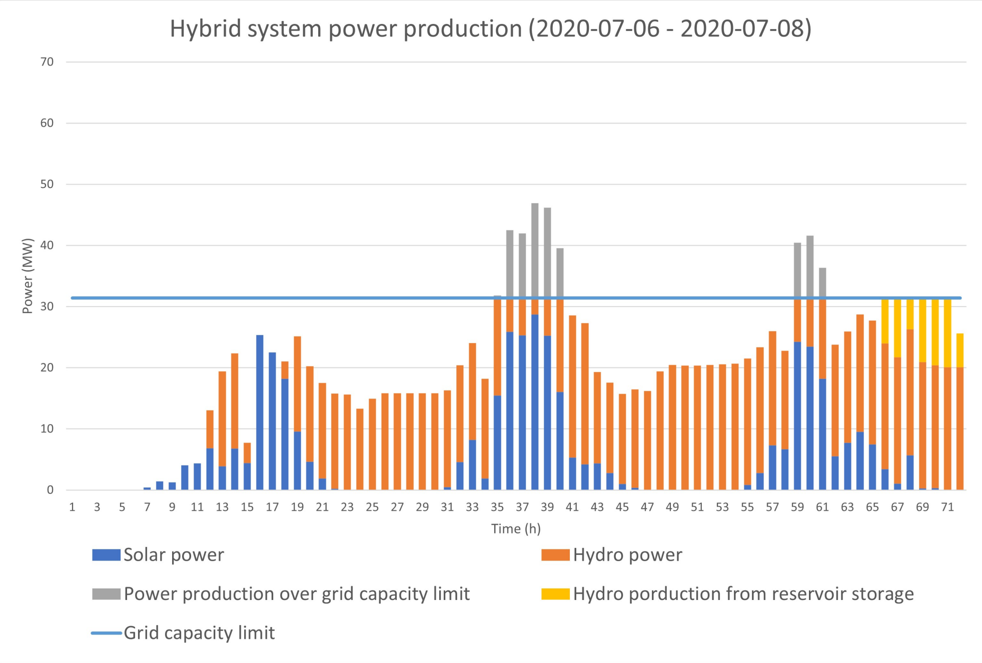


Figure 61: Scenario 3 - Three days of electricity production in a refined hybrid system with ratio 1:1, 2020/07/06 - 2020/07/08

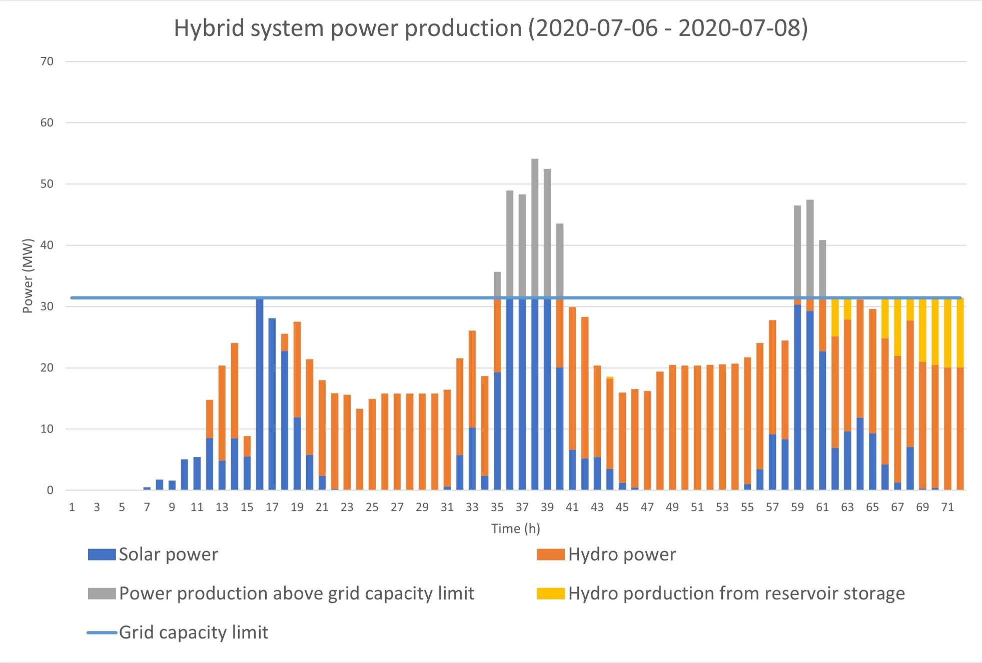


Figure 62: Scenario 3 - Three days of electricity production in a refined hybrid system with ratio 1.25:1, 2020/07/06 - 2020/07/08

Water levels during the summer period remains low for 2020 and never exceeds the water level limits of ±0.9m, which is shown in figure 63.

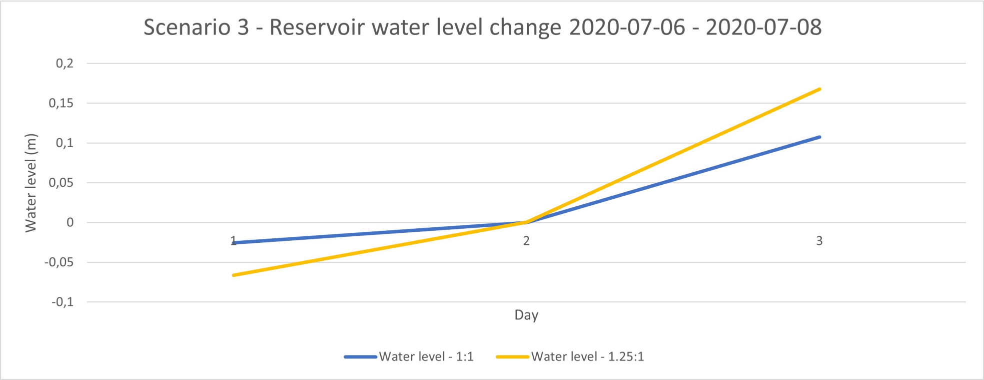


Figure 63: Scenario 3 - Water level deviation in a refined hybrid system with ratio 1:1 and 1.25:1, 2020/07/06 - 2020/07/08

Inspecting the three days in autumn, shown in figures 64 and 64, it can be seen that hydro power production is halted during the nights. The refinement method is also visible as excess energy, represented by the grey bars, is stored and utilised the next day, represented by the yellow bars.

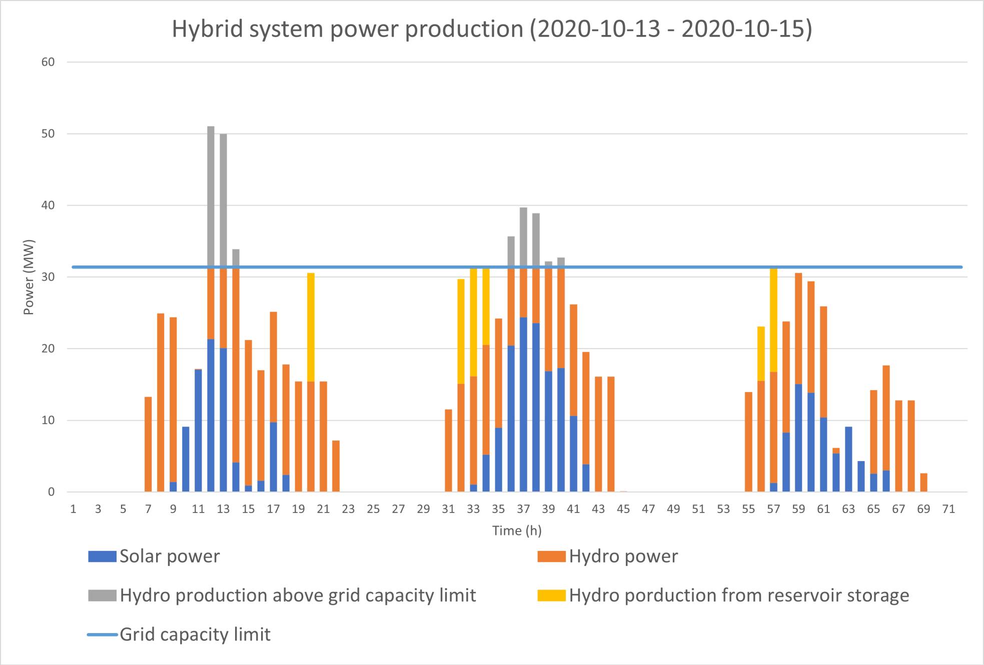


Figure 64: Scenario 3 - Three days of electricity production in a refined hybrid system with ratio 1:1, 2020/10/13 - 2020/10/15

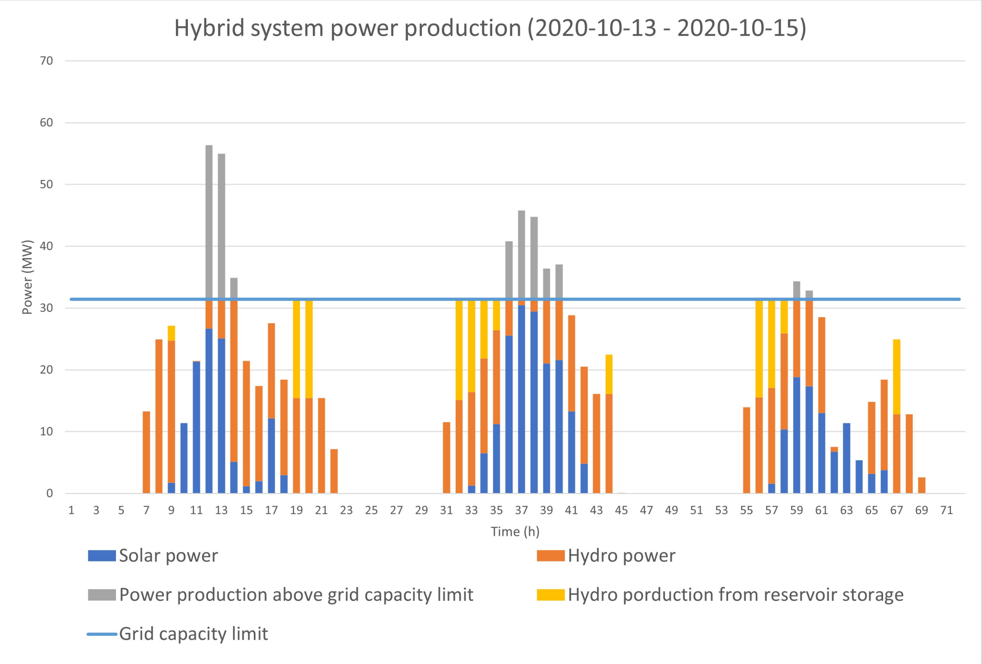


Figure 65: Scenario 3 - Three days of electricity production in a refined hybrid system with ratio 1.25:1, 2020/10/13 - 2020/10/15

Water levels remain low for the period in October in figure 66 and storage can therefore be utilised as intended.

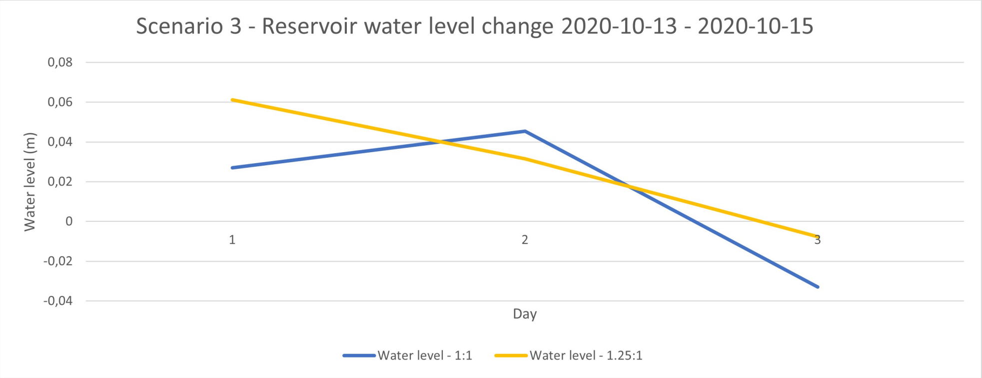


Figure 66: Scenario 3 - Water level deviation in a refined hybrid system with ratio 1:1 and 1.25:1, 2020/10/13 - 2020/10/15

6.3 Economical results

Table 19 and 20 shows the NPV, IRR and payback time for the three scenarios that include a solar power plant investment for the two years 2018 and 2020. Calculations are made for 30 years.

There are no scenario that result in positive values for NPV. The lowest value for NPV occurs for scenario 1 with the economical values of 2020 and solar power ratio 1.25:1, which gives an NPV of -285 MSEK, while the highest value occurs in 2018 for scenario 3 and solar power ratio 1.25:1, which has an NPV of -4 MSEK. This scenario also has the highest IRR of

7.8% and both the 1:1 and 1.25:1 ratios have 11 years payback time in 2018 for this scenario, which is the lowest of all scenarios and year. Scenario 1 in 2020 with solar power ratio 1:1 has the lowest IRR and highest payback time of -4.1% and 64 years.

Scenario	**NPV (MSEK)**	**IRR (%)**	**Payback time (years)**
0	-	-	-
1	-118	3,5	18
2	-46	6,3	13
3	-6	7,8	11

Table 19: Economical results based on 2018 prices with solar power ratio 1:1. Note that the values are rounded.

Scenario	**NPV (MSEK)**	**IRR (%)**	**Payback time (years)**
0	-	-	-
1	-240	-4,1	64
2	-167	0,5	28
3	-139	2,1	22

Table 20: Economical results based on 2020 prices with solar power ratio 1:1. Note that the values are rounded.

Scenario	**NPV (MSEK)**	**IRR (%)**	**Payback time (years)**
0	-	-	-
1	-141	3.6	18
2	-69	5.9	14
3	-4	7.9	11

Table 21: Economical results based on 2018 prices with solar power ratio 1.25:1. Note that the values are rounded.

Scenario	**NPV (MSEK)**	**IRR (%)**	**Payback time (years)**
0	-	-	-
1	-285	-3,6	57
2	-213	0,2	30
3	-168	2,3	22

Table 22: Economical results based on 2020 prices with solar power ratio 1.25:1. Note that the values are rounded.

6.4 Result summary

Tables 23 and 24 showcase some results from simulations and financial calculations for the four different scenarios for 2018 and 2020. It displays the average grid utilisation rates, energy sent to grid, curtailed energy and how the refinement method reduce it as well as financial results regarding total income and increased income due to the implemented refinement method.

It can observed that 2018 yields less total production but higher income than 2020. The storage refinement method, implemented in scenario 3, is also better utilised during 2018 as less energy is wasted and average grid utilisation rates reaches up to 60%. Excess energy is higher for 2020 in scenario 2 and 3 but utilisation of the excess energy in form of stored water in scenario 3 is the same for both years.

Scenario	Average grid utilisation rate (%)	Energy to grid (GWh)	Excess energy (GWh)	Utilised excess energy (GWh)	Wasted excess energy (GWh)	Wasted energy of total production (%)	Total income (MSEK)	Missed income by curtailment (MSEK)	Increased income by refinement (MSEK)
0	34%	93	0	0	0	0%	36.7	0	0
1	16%	43	0	0	0	0%	17.7	0	0
2	46%	126	10	0	10	7%	54.5	4.4	0
3	49%	134	10	8	2	1.5%	57.8	1.1	3.3

Table 23: Result summary for 2018 with solar power ratio 1:1. Note that the values are rounded.

Scenario	Average grid utilisation rate (%)	Energy to grid (GWh)	Excess energy (GWh)	Utilised excess energy (GWh)	Wasted excess energy (GWh)	Wasted energy of total production (%)	Total income (MSEK)	Missed income by curtailment (MSEK)	Increased income by refinement (MSEK)
0	49%	135	0	0	0	0%	34.8	0	0
1	15%	42	0	0	0	0%	7.6	0	0
2	60%	164	13	0	13	7%	43.8	3.1	0
3	63%	172	13	8	5	3%	46.2	0.7	2.4

Table 24: Result summary for 2020 with solar power ratio 1:1. Note that the values are rounded.

Scenario	Average grid utilisation rate (%)	Energy to grid (GWh)	Excess energy (GWh)	Utilised excess energy (GWh)	Wasted excess energy (GWh)	Wasted energy of total production (%)	Total income (MSEK)	Missed income by curtailment (MSEK)	Increased income by refinement (MSEK)
0	34%	93	0	0	0	0%	36,7	0	0
1	19%	54	2	0	2	4%	22.0	1.3	0
2	47%	129	18	0	18	14%	55.8	8.6	0
3	52%	143	18	12	6	4%	62.5	3.2	5.4

Table 25: Result summary for 2018 with solar power ratio 1.25:1. Note that the values are rounded.

Scenario	**Average grid utilisation rate (%)**	**Energy to grid (GWh)**	**Excess energy (GWh)**	**Utilised excess energy (GWh)**	**Wasted excess energy (GWh)**	**Wasted energy of total production (%)**	**Total income (MSEK)**	**Missed income by curtailment (MSEK)**	**Increased income by refinement (MSEK)**
0	49%	135	0	0	0	0%	34.8	0	0
1	18%	53	3	0	3	6%	10.0	0.7	0
2	60%	166	22	0	22	13%	44.2	5.7	0
3	66%	181	22	12	10	5.5%	48.6	1.9	3.8

Table 26: Result summary for 2020 with solar power ratio 1.25:1. Note that the values are rounded.

6.5 Result analysis

Inspecting figure 37, 38, 39 and 40, which displays the weekly average power production for each scenario, the trend line and how they compare to each other in terms of power production can be observed. When comparing the weekly average production for scenario 0 between the two years, it is evident that 2018 had lower power production compared to 2020. This can also be observed by comparing the total production for scenario 0 in table 23 and 24. The difference can be explained by the fact that 2018 was a dry year while 2020 was a wet year, resulting in higher water flow compared to the yearly average for the latter. This difference is particularly noticeable during the spring flood season (weeks 8-15) and the summer and early autumn weeks (weeks 21-41).

It is important to differentiate the weekly average power production from hourly power production as the maximum power output at a certain hour of the week will be higher than the weekly average maximum displayed in these figures. This is evident in figure 38, which shows the weekly average power production for scenario 1. The average maximum power output for the two years with ratio 1:1 reach about 11 MW and with ratio 1.25:1 approximately 14 MW, while in reality it reaches up to 31,4 MW and 40 MW respectively for certain hours during the year. The low weekly average production is due the intermittent nature of solar PV power generation, as the sun is not constantly shining throughout the day, resulting in a lower average value. During the summer months the longer daylight hours and higher solar irradiance increase the weekly average power production, as depicted in figure 38. The figure also shows that the solar power production follow similar curves for both years and is thus not affected by the dry and wet years in the same way as for scenario 0.

Analysing the weekly average power production for scenario 2 in figure 39 and scenario 3 in figure 40, slight differences in weekly average power production can be observed. The graphs follow a similar trends but the weekly average are slightly higher for scenario 3. This can be explained by the refinement method implemented for scenario 3 where less energy is wasted or curtailed through energy storage in the hydro power reservoir. The difference is also seen in tables 23, 24, 25 and 26 where scenario 3 has less curtailment due to utilisation of stored energy. During the periods of higher solar power production in spring, summer, and early autumn (weeks 15-37), when the solar power production is higher, the increase in weekly average power production is more visible, with an increase of approximately 4 MW for certain weeks. Since excess energy is stored as water in the reservoir and utilised on a daily basis rather than over longer periods of time, the differences in weekly average power production become more visible from week to week. If the water were stored for even longer periods of time and utilised during periods of generally lower hydro power production or when the electricity prices are higher, the graph would have shown larger changes in weekly average power production for some of the weeks and less change for other weeks.

Taking a closer look at figures 43, 44, 55 and 56 the production for scenario 3 can be observed for three days in January, representing a typical period during the winter season. Similarities between the two years can be seen as hydro power production is at almost maximum capacity with relatively low solar power production. Even though barely visible, some energy storage occurs for both scenarios.

Observing the three days in spring, depicted in figures 46, 47, 58 and 59 slight differences between the years can be seen. Both hydro and solar power production are high and the refinement is clearly visible. In 2020 however, hydro power production remains continuous, while in 2018 it is halted during the nights. This difference suggests that there might already be a refinement method in place in the data provided by Statkraft Sverige AB. This difference is most likely due to, as has been said before, the fact that 2018 was a dry year, requiring water conservation, while 2020 was a wet year, allowing for full utilisation of water resources.

During the summer period the two years differ in production, as shown in figures 49, 50, 61 and 62. The main difference is that for 2018 there is no hydro power production at all while during 2020 there is. The solar power production during 2020 is slightly lower than in 2018, indicating that the weather might have been more favorable for solar power during 2018. The difference here can as well be linked to 2018 being a dry year and 2020 a wet year. In the 2018 there might not have been enough water in the reservoir to support hydro power production during this period of the year or it might have been saved for other days to maximise the profits. This discrepancy also suggests that a refinement method for the hydro power plant may already be in place.

Lastly, examining the three days in autumn, shown in figures 52, 53, 64 and 65, hydro power production is minimal for 2018 while significantly higher in 2020. Again, this is likely due to 2018 being a dry year and 2020 a wet year. In 2020, hydro power production is not active during the night hours, once more indicating on an already implemented refinement method for the hydro power plant when water flow is insufficient for continuous production throughout the day.

It is important to note that the power production displayed in the above mentioned figures only showcase 3 days in each season. Therefore, the trends observed in the graphs may not accurately represent the entire season. However, they do provide a brief overview of the differences in power production between hydro power and solar power for different periods of the year, as well as a visualisation of how the implemented refinement method stores otherwise wasted energy.

Figures 41 and 42 depict the water levels in the reservoir for scenario 3 where a storage refinement method has been implemented. The reservoir maintain water levels within the allowed limits of approximately ± 0.9m except for a small period of time. This occurs during the spring flood for both years and solar power ratios and as 2020 was considered a wet year, storing water in combination with higher than usual floods cause the water level to rise above the allowed limits for a longer period than for 2018. It is important to note that the water level is assumed to start at a middle point between the upper and lower water level limits at the start of each year. This assumption is not necessarily accurate and a slight change in the starting value of the water level can impact the result for better or worse. This uncertainty is the reason it was not included as a defining parameter for the simulation in scenario 3.

Table 19, 20, 21 and 22 shows the results for NPV, IRR and payback time for the different scenarios and solar power ratios. Inspecting the results for NPV, negative values for all scenarios and both years can be observed. Scenario 1 has the least favorable NPV values, while scenario 3 has the most favorable values. One of the reasons for the better NPV, IRR and payback time in scenarios 2 and 3 compared to scenario 1 is the reduced investment costs when a new transformer with grid connection is not required. Interestingly, despite having lower total power production, which can be observed in tables 23, 24, 25 and 26, the best results are obtained in 2018, which can be linked to the higher electricity prices during that year, which can be seen in figure 28. The higher electricity price is likely due to the lower hydro power production in a dry year, as hydro power contributes to approximately 40% of the total electricity production in Sweden, thus having a large impact on the overall electricity market. With negative NPV values it is indicated that the present value of the cash inflows generated by the three scenarios is lower than the initial investment. This implies that the scenarios, as evaluated using the NPV method, do not yield positive net economic benefits throughout the 30 year span that was calculated for. The negative NPV could be, a part from the impact of electricity prices, attributed to various factors such as the chosen discount rate, cash flow estimations, or other relevant costs or benefits in the analysis. These uncertainties emphasise the importance of carefully considering the assumptions and variables used in the economic calculations as well as its sensitivity to changes in these parameters and variables.

The relatively low IRR values indicate that the internal rates of return for the projects are not sufficiently high to surpass the minimum required rate of return or the cost of capital. While the IRR metric provides insight into the profitability of an investment, it has its limitations. One such limitation is the assumption that cash flows are reinvested at the calculated IRR, which may not be realistic in practice. Moreover, the IRR can yield multiple solutions or be difficult to interpret when cash flows change sign multiple times. These uncertainties surrounding the IRR analysis highlight the need for caution when relying solely on this metric to make investment decisions. For scenario 3 during 2018 the IRR yields a close to positive result as the chosen discount rate was 8% and the result of IRR calculations for solar power ratio 1:1 gives a value of 7,8%, and 7.9% for solar power ratio 1.25:1. This indicates the influence and importance of assumed discount rate for the economical calculations as a slight change from 8% to less than 7.9% would yield a positive NPV in this specific scenario and year.

Inspecting the difference between the case of solar power plants with installed capacity ratio 1.25:1 and 1:1 for scenario 1 in 2018 and 2020, as well as for scenario 3 in 2020, the NPV can be seen to be worse for the larger solar power plant while the IRR is better. One reason for the lower NPV values is the higher investment costs associated with the increased installation capacity. These increased costs reduce the present value of future cash flows, resulting in a lower NPV. On the other hand, the IRR can be higher when the solar power plant is installed with 1.25:1 ratio. This is primarily because the project generates greater cash flows due to increased power production. The additional power production can result in higher revenues that could potentially outweigh the increased investment costs. Both years have worse results for the larger solar power plant in scenario 2. This is most likely due to the earlier mentioned increased investment costs associated with a larger solar power plant in combination with more wasted and curtailed energy as a larger occurrence of power production above grid capacity occurs and no refinement method to shift power production throughout the day is implemented.

Lastly, the payback time values indicate that the time required to recover the initial investment is long, specifically for 2020 as the payback times are well above or close to the lifespan of the solar power plant. Although payback time is a straightforward metric, it does not account for the time value of money or consider the cash flows beyond the payback period. An example of this is that when the solar power plant reach the end of its lifespan new investments must be made to upgrade the power plant. Due to this the payback time results that exceed the lifespan of 25-30 years for solar panels would be even longer as new investment costs would alter the result and prolong the payback time. These limitations underscore the need for comprehensive analysis and consideration of other financial metrics alongside the payback period.

Some interesting results can be observed for the two years in the result summary tables 23, 24, 25 and 26. The average grid utilisation rate, that indicates the amount of energy sent to the grid compared to the maximum possible amount that can be sent to the gird for each hour on a yearly average basis, implies that having a hybrid system significantly increase the utilisation rate. Comparing scenario 0 with scenario 3 the average utilisation rate never reaches above 50% for the two simulated years in scenario 0, whereas it reaches a maximum of 66% for scenario 3. This indicates that the grid capacity is utilised more in a hybrid system which, from an energy utilisation point of view, is positive since less capacity is wasted.

The utilisation rate results can be related to the amount of energy sent to the grid for the different scenarios, which can be observed in column 3 in the result summary tables. It can be observed that the impact of dry and wet years on total production is evident when comparing the dry year 2018 with the wet year 2020, particularly in scenario 0 where the difference is nearly 40 GWh. However, the result for scenario 1 demonstrates that dry and wet years have a minimal or no effect on solar power production, as the difference in total yearly production is only 1 GWh. Interestingly enough the total income for all scenarios is greater in 2018 despite having less total production. This can be attributed to the higher electricity prices during 2018, which has been stated before. However, electricity prices are not necessarily the only thing impacting the total income. By inspecting column 5 to 7 in the summary tables, which display the difference in wasted energy between the scenarios, it can be observed that scenario 3 has a lower percentage of energy wasted in 2018 compared to 2020. This reduction in wasted energy contributes to increased income as more electricity is sold to the grid. This suggests that 2018 was more favorable for refining the hybrid power production and thus increase sold electricity.

Another interesting result is that the total income for scenario 2 and 3 for both years, which can be seen in column 9 of the result summary tables, exceed the total income that would have been obtained if the two systems were operated separately. An explanation for this is that for scenario 2 and 3 the tariffs are only paid once since the hybrid system is connected at the same grid connection point and share owner. Another explanation, specifically for scenario 3, is that the implemented refinement method yields higher income due to stored energy being used for energy production during the ten most profitable hours of the day in regards to electricity price. This is especially noticeable in the results for solar power ratio 1.25:1 as more energy is stored and utilised due to the increased occurrence of power production above the grid connection capacity limit.

Generally, the increase in solar power ratio from 1:1 to 1.25:1 leads to more production over capacity and therefore more need for energy storage. This is clearly visible in the figures and tables displayed in the result section as water levels, utilisation of stored energy and wasted energy all increase. It does however also lead to higher power production and a larger grid utilisation rate.

7 Discussion

As mentioned in section 5.1, it is important to note that the refinement method used for the solar-hydro hybrid power plant does not consider shifting power production that does not exceed the grid capacity limit. Implementing a hybrid power plant that shift power throughout the day would most likely be more beneficial, ensuring a smoother and more balanced power output that potentially could reduce curtailment even further. It is important to acknowledge that there in all likelihood already exist a refinement method at the hydro power plant and that the existing refinement method employed for the hydro power plant potentially introduces some ambiguity in this thesis, as a fully hybrid system would cease hydro power production when the solar power plant operates at peak capacity. Another crucial aspect to consider is that if a solar power plant exceeds the maximum power production capacity allowed by the grid connection at peak power production, curtailment becomes inevitable unless a supplementary storage system, such as a battery, is integrated into the hybrid system.

The impact of increased electricity price has been evident in the results, showing distinct differences between the two simulated years. Specifically, 2018 exhibited significantly lower total power production compared to 2020 but despite this having a larger total income, primarily due to the increased electricity prices. The recent escalation in Swedish electricity prices has the potential to significantly influence the economic calculations in a positive way as income increases. However, the increase in Swedish electricity prices might not be a reality forever and it is not unreasonable to anticipate a potential decrease and eventual stabilisation of prices as more renewable energy production and storage possibilities are installed. This means that the calculations made in this report could be accurate for future projects, however it is crucial to consider the uncertainty surrounding costs associated with solar cells and the infrastructure required for constructing a solar power plant as prices might shift in the future. While solar cells have decreased in price since its introduction, the future progress is still uncertain. Prices could both rise or fall as new technology is developed, which influence the results of the economical calculations. Another significant aspect in the financial results is the lower investment costs in scenario 2 and 3, compared to scenario 1. Due to the absence of a new transformer installation at the grid connection point the investment costs notably decrease and have a significant impact on the economic outcomes. This highlights the value, from an investor perspective, of being able to connect to an existing transformer.

The grid utilisation rate is an interesting factor for both hybrid power plant owners and organisations interested in implementing such systems. Based on the conducted simulations in this report it is evident that the utilisation of the grid connection does not exceed 50% for scenario 0, even during a wet year when hydro power production surpasses the average annual production. This implies that connecting other systems to the grid connection point to create a hybrid system is feasible. However, it is important to note that there are certain periods throughout the year when the grid connection utilisation is capped, resulting in the need to curtail some of the excess energy. But, by using refinement methods, such as the one described in this master thesis, it is possible to reduce the occurrence of curtailment and reduce the time during which it takes place throughout the year. This gives further implications towards the feasibility of operating a hybrid system connected to a shared grid connection point.

The simulations conducted in this study have all been focused for conventional hydro power, where a flow of water upstream passes through the hydro power plant and continue downstream. An alternative hybrid solution could involve combining pumped hydro power with solar power. In such a scenario, excess energy generated by the solar power plant could be effectively utilised, either by pumping water from a lower reservoir to an upper reservoir or by storing it in the upper reservoir, introducing another dimension to the hybrid system. Incorporating this increase the potential value of a system with solar power ratio above 1:1 since the excess energy, which would otherwise be curtailed, can be used to pump water. Both closed loop and open loop pumped hydro power systems use an upper reservoir that is not directly connected to a flow of water, thus the limitations that could appear in regards of dependency of hydro power plants upstream are lost, and for closed loop systems the dependency on systems downstream. This implies that the storage possibilities could be greater than that of a conventional hydro power plant as the system could regulate the storage more freely. However, they must still operate within the water level limits of the reservoir. In open loop pumped hydro power, there may still be dependencies on systems downstream, thus limiting the freedom of storing energy somewhat. Finding suitable locations for implementing pumped hydro power might also be difficult as it requires both large reservoirs and high head heights. By implementing such a hybrid system the value of solar power could become more significant, as it can be utilised for both selling electricity to the grid and to pump water between the reservoirs. A refinement method for maximising profits in this scenario would differ from the one simulated in this report, as it would need to consider the trade off between using solar power energy for water pumping or for direct sale to the grid.

Floating PV is another interesting implementation that could very well be used in combination with hydro power, especially considering the availability of water areas within the reservoir suitable for installing floating PV systems. This implementation could offer several advantages, such as a reduction in land area requirements for the solar-hydro hybrid system and the potential elimination of long distances to the grid connection point that otherwise may occur. However, the cost of implementing floating PV is greater than that of land based PV, which has to be considered when doing the economical calculations of such system. Additionally, potential negative environmental impacts on the aquatic life in the reservoir due to reduced sunlight reaching the water surface could also occur. Nevertheless, due to reduced sunlight reaching the water surface water dissipation could also be decreased. Although floating PV do exist it is not at all as implemented as land based PV and could therefore require longer planing phases before installment as several factors such as the shifting water levels and the impact of streams and waves on the system has to be taken in to account.

8 Conclusion & Future studies

8.1 Conclusion

Addressing the technical and operational feasibility of a solar-hydro hybrid system it was found that integrating solar power with hydro power at a shared grid connection point is feasible. The results and analysis showed that the average grid utilisation rate of the hydro power plant did not exceed 50% even during a wet year. This suggests that connecting additional systems to the grid connection point to create a hybrid system is possible and the results for the hybrid system showed that it is viable. By employing refinement methods, such as the one used in this thesis, it is also possible to reduce curtailment and reduce the occurrence of grid capacity limitations. However, it is important to note that curtailment of power production may still be necessary during certain periods of the year, especially when a larger solar power plant is installed, and that the refinement method analysed in this thesis is not necessarily the most viable option for a hybrid system.

The economic performance analysis revealed mixed results for the hybrid system. The impact of increased electricity prices was evident, with significantly higher total income observed in 2018 despite lower total power production compared to 2020. However, it is important to acknowledge the uncertainty surrounding future electricity prices, as the recent escalation in Swedish electricity prices may not be sustainable in the long term. The economic calculations also considered factors such as the cost of solar cells and infrastructure, which may fluctuate in the future. While the hybrid system outperformed standalone solar power systems in terms of income and cost savings with the assumptions, the NPV, IRR and payback time were suboptimal for all scenarios and years. Therefore, it is crucial to consider the uncertainties in the economical results as they are based of assumption about various costs and rates. It is also important to understand that these calculations are made for a specific site in Sweden and that different sites located within Sweden or in other countries could yield different results.

Investigating alternative hybrid solutions, such as combining pumped hydro power with solar power, introduce additional dimensions to the hybrid system refinement, allowing for potentially greater storage possibilities and synergies between solar power generation and water pumping. However, it requires specific geographical features including significant elevation differences and access to large water reservoirs. Finding such locations can be a demanding task. Floating PV is another alternative solution for a solar-hydro hybrid system. Implementing floating PV offers advantages such as reduced land area requirements and shorter distances to the grid connection point. However, it is important to consider the higher implementation costs and potential environmental impacts on aquatic life. The economic calculations for scenarios including pumped hydro power and floating PV would differ from those presented in this study and in a scenario with pumped hydro power one would need to consider the trade-offs between using solar power production for water pumping or direct sale to the grid.

8.2 Future studies

While this study has provided valuable insights into the technical feasibility and economic performance of solar-hydro hybrid systems, there are several areas that could yield interesting results by further investigation and research. One of those are further research regarding refinement methods in a solar-hydro hybrid power plant. The refinement method implemented in this thesis offers a starting point for maximising the benefits of a hybrid system. However, there is room for exploring and developing more advanced refinement techniques that can effectively balance the power output of both solar and hydro components. Future studies could focus on refining and enhancing these methods to achieve even greater efficiency and reduce curtailment during different weather conditions and varying energy demand.

Another potential further investigation could be to improve the accuracy of assumptions by using different economical data, considering potential fluctuations in solar sell and infrastructure costs, and accounting for varying electricity price scenarios. This would provide a more realistic evaluation of the economic viability and profitability of solar-hydro hybrid systems. Further analysis of the relation between the capacity of solar and hydro power plants in a hybrid system would also be interesting as it would expand the research of this paper. Future studies could explore different power plant ratios, that are lower or higher than the ones analysed in this study, to identify the most efficient combination.

This study primarily focused on the integration of land based solar power with conventional hydro power plants. However, future research could dive deeper into the potential of combining solar power with pumped hydro storage systems, or integrating floating PV technologies. Investigating the feasibility, performance, and economic viability as well as the environmental impacts of hybrid solutions that incorporate pumped hydro power and floating PV would provide valuable insights for possible future projects.

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