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Hybrid park at Stokkfjellet

Bacheloroppgave

NTNU
Norges teknisk-naturvitenskapelige universitet
Fakultet for ingeniørvitenskap
Institutt for energi- og prosessteknikk

Combining solar and wind power in the same grid

Bacheloroppgave i Renewable Energy Engineering
Veileder: Jacob J. Lamb
Medveileder: Engin Söylemez
Mai 2023

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Kunnskap for en bedre verden

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Preface

This bachelor thesis is the final assignment of the bachelor's degree program Renewable Energy Engineering at NTNU in Trondheim. It is part of the course *FENT2900 - Bachelor Thesis Renewable Energy* and is valued at 20 credits. It is written for ANEO and NTNU by Elias Huse, Johanne Grindahl and Gro Nergård.

This thesis explores the viability of implementing solar panels in a pre-existing wind park, owned by ANEO. The goal is to find the most optimal operation and installation of a hybrid park. Through the project course the group has gained insight in the Norwegian energy market as well as the installation procedure of a power plant in Norway. There was also gained experience with a new simulation tool, PVsyst, and improved knowledge in MATLAB.

We would like to thank our external supervisors Beate Nesje and Anders Fjeldberg Teigmoen from ANEO. The valuable input and help in setup and limitation for this thesis has been most helpful and is very appreciated. Further we wishes to thank our internal supervisor Postdoctoral researcher Engin Söylemez for both insight and good advice on writing and structure, and also motivation throughout the process.

We also want to thank associate Professor for Department of Energy and Process Engineering Jacob J Lamb for help and clarifications. For technical advise and aid we thank Professor Steven Boles and Dosent Emeritus Trond Leiv Tuftevaag. Additionally we appreciate the clarification and guidance given by NVE and Statnett regarding their practices and data.

At last we would like to thank the Renewable Energy class of 2023 for support and motivation.

Trondheim, 21.05.2023

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Summary

This thesis analyses three options for operation of a proposed hybrid park at an already existing wind power plant situated at Stokkfjellet. This is done by simulating a PV-system and exploring three different scenarios.

The scope of this thesis involves technical and economical prospects around the proposed hybrid park. The main limitations were the transformer limit for Stokkfjellet at 90 MW, the already existing concession area and the existing available data used in the simulations and calculations. Additionally, risks or unforeseen events are not taken into account. Further, the three scenarios were explored. Scenario 1 inspects implementing solar panels into the already existing wind park without any storage possibility for overproduction. In scenario 2 a BESS is implemented to store the overproduction. In this scenario the energy stored is fed out on to the grid at the first possible time. The results do not present an economically optimal exploitation of the energy sent out on the grid, but rather optimizes to peak shave all overproduction. In scenario 3 all the power produced from the PV-system would be sold in the frequency market. However, the lack of detail in the frequency volume data, specifically the lack of dedicated up- or down-regulation prices and volumes, have influenced the results.

Scenario 1 resulted in an amount of energy being lost throughout the year, but a lower investment cost. It was demonstrated with NPV values that if the price per MW declines with 50% it would be economically viable to install solar panels on as little as 4% of the concession area. In scenario 2 all overproduction was stored and later fed out on the grid, but the increased investment cost resulted in only negative NPV values and therefore also not any economically viable options. In scenario 3 the profits were lower than for both scenario 1 and 2 because the volume power was sold at a lower price. With the increased investment cost from the battery, this resulted in negative NPV values for all cases.

This report finds that none of the scenarios are presently economically viable. The results indicate that scenario 1 is the best alternative for the proposed hybrid park at Stokkfjellet. This scenario have the potential to become economically viable due to the reduction in price for solar panels that is expected to happen in the coming years. However, by implementing some of the possible alternative methods, both scenario 2 and 3 could prove to be the more viable options. Specifically, a significant reduction in battery costs would lead to better NPV values.

Sammendrag

Denne oppgaven analyserer tre alternativer for drift av en foreslått hybridpark ved et allerede eksisterende vindkraftverk på Stokkfjellet. Dette gjøres ved å simulere et PV-system og utforske tre forskjellige scenarioer.

Omfanget for oppgaven inneholder tekniske og økonomiske prospekter rundt den foreslåtte hybridparken. Begrensningene var hovedsakelig transformatorgrensen for Stokkfjellet på 90 MW, det allerede eksisterende konsesjonsområdet, og eksisterende tilgjengelige data brukt i simuleringene og beregningene. I tillegg tas ikke risikovurdering eller uforutsette hendelser med i betraktning. Videre utforskes de tre scenarioene. Scenario 1 ser på implementering av solcellepaneler i den allerede eksisterende vindparken uten lagringsmuligheter for overproduksjonen. I scenario 2 implementeres det et BESS for å lagre overproduksjonen. I dette scenarioet føres den lagrede energien ut på nettet ved første mulighet. Resultatene gir ikke et økonomisk optimalt resultat, men optimerer med hensyn til å kunne ta opp all overproduksjon. I scenario 3 vil all produksjon fra PV-systemet bli solgt i frekvensmarkedet. Imidlertid har mangelen på detaljer i frekvensvolumdataene, spesielt mangelen på dedikerte opp- eller nedreguleringspriser og volumer hatt en påvirkning på resultatene.

Scenario 1 resulterte i at en mengde energi gikk tapt gjennom året, men en lavere investeringskostnad. Det ble påvist med NNV-verdier at dersom prisen per MW synker med 50% vil det være økonomisk lønnsomt å installere solcellepaneler på så lite som 4% av konsesjonsarealet. I scenario 2 ble all overproduksjon lagret og senere matet ut på nettet, men den økte investeringskostnaden resulterte i kun negative NNV-verdier og derfor heller ingen økonomiske forsvarlige alternativer. I scenario 3 var fortjenesten lavere enn for både scenario 1 og 2 fordi volumet energi ble solgt til en lavere pris. Med den økte investeringskostnaden fra batteriet, resulterte dette i negative NNV-verdier for alle tilfeller.

Denne rapporten finner at ingen av scenariene er økonomisk levedyktige per dags dato. Resultatene indikerer at scenario 1 er det beste alternativet for den foreslåtte hybridparken på Stokkfjellet. Dette scenarioet kan i fremtiden bli økonomisk levedyktig med en reduksjon i pris for solcellepaneler. Likevel kan scenario 2 og 3, ved å implementere mulige alternative metoder, vise seg å være mer levedyktige alternativer. Spesielt vil en betydelig reduksjon i batterikostnader føre til bedre NNV-verdier.

Contents

List of Abbriviations

AC	Alternating current
aFRR	Automatic frequency restoration reserve
AI	Artificial intelligence
DC	Direct current
EEA	European Economic Area
EMF	Electromotive force
FCR-N	Frequency containment reserve for normal operation
FCR-D	Frequency containment reserve for disturbances
FFR	Fast frequency reserve
GHI	Global Horizontal Irradiance
DHI	Diffuse Horizontal Irradiance
HV	High Voltage
HAWT	Horizontal axis wind turbine
IAM-losses	Incidence Angle Modifier
LIB	Lithium-ion battery
LID-losses	Light Induced Degradation
LV	Low Voltage
LFP	Lithium iron phosphate
mFRR	Manual frequency restoration reserve
MPPT	Maximum Power Point Tracking
NEK	The Norwegian Electrotechnical Committee
NMC	Nickle Magnesium Cobalt

NPV	Net Present Value
PERC	Passivated Emitter Rear Cell
PNom	Nominal Power
PV	Photovoltaic
SEI	Solid Electrolyte Interface
SoC	State of charge
STC	Standard Testing Conditions

List of Terms

Albedo	The value of how reflective a surface is from 0 to 1, where 0 is completely absorbent and 1 is completely reflective.
Bifacial	In correlation with solar power it means any photovoltaic solar cell that can produce electrical energy when illuminated on both its surfaces, front or rear.
Zenith	The perpendicular line straight up towards the atmosphere.

Unit

$	Dollar
€	Euro
GWh	Giga watt hours, 10^9
Hz	Hertz
kVA	Kilo volt amperes
kWh	Kilo watt hours, 10^3
MWh	Mega watt hours, 10^6
NOK	Norwegian kroner
V	Volts

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1 Introduction

Global warming has been presented as a crisis since the 1990s. For over 30 years it has been known that the earth is heating up at a too rapid pace. There has been periods during earths time with a warmer climate, but the rate in which the temperatures are rising today is alarming. A press release given by The Worlds Meteorological Institute states that 2021 was the 7th consecutive year (2015-2021) where global temperatures was more than $1°C$ above pre-industrial levels. They also stated that since the 1980s, each decade has been warmer than the previous one. This trend is expected to continue. [1]

Almost all scientists agree that humans are at fault for this rapid temperature increase. The use off fossil fuels to operate our society is the biggest cause of emission. Using transportation that depends on gas contributes considerably to emissions. However, the use of fossil fuels in energy production is one of the things that contributes the most to carbon emissions [2]. Coal-fired power plants especially contribute to global warming, ozone smog, acid rain, regional haze, and fine particle pollution [3].

In order for the emissions in each country to decrease, the share of power production from fossil fuels must be reduced and renewable energy sources be developed. Additionally, there has to be an increase in the electrification of society to reduce emissions. This will come with a need for increase in power production. Statnett states that, in Norway only, an increase of 30 to 50 terra-watt hours (TWh) is necessary to electrify the civilization. [4]

Simultaneously, Europe is facing an energy shortage following Russia's military aggression against Ukraine that started in February of 2022. Preliminary to the invasion Russian gas accounted for around 50% of the EU's gas supply. The weaponizing of energy by one of the main suppliers has destabilized the energy market and seen energy prices all over Europe rise significantly. [5]

To increase the delivery security and lessen the strain on the European grid, energy production companies need to look for new ways of increasing supply security. One way of increasing the delivery security is combining renewable energy sources in hybrid parks. Renewable energy sources are highly fluctuating, yet the peak of production can vary considerably from source to source which can produce a overlap that will increase delivery security. Solar power will have a higher production during summer while this is when both hydro- and wind-power will have lower production. Combining these energy sources into hybrid parks could therefore increase delivery security and positively affect the energy prices.

Stokkfjellet is a wind park owned by ANEO placed in Trøndelag county. The already existing wind park facilitates for a hybrid park. Installing a solar power plant within the already existing infrastructure would eliminate many costs. The connection to the high-voltage grid is eliminated as well as the cost for a high voltage transformer. This would decrease the installation cost of a new power source as well as increase ANEO's delivery security.

1.1 Literature study

Hybrid parks is an approach for power plants that have been implemented and proposed in other countries before. The most common combination used is wind and solar, and these parks are often geographically situated to accommodate for more wind and sun hours. The parks are usually built to see if they have a positive impact on the supply security of electric power and increase the contribution of renewable energy.

A study done by the Federal University of Itajubá in Brasil analyzed the economical aspects of hybrid parks. They specifically looked at installing PV panels in an already existing wind power plant. The conclusion for the study is that hybrid parks do decrease the probability of profit. However the probability of a profitable power plant is still as high as 89% with ideal wind to PV power ratio. [6]

A more specific case study considered the implementation of a hybrid park to power a factory in Al-Tafilah. They looked at a wind and solar power plant with lithium-ion batteries as an energy storing system. The findings showed that a hybrid park could be an effective solution, and that it is an economical better option to have batteries implemented in the park. [7]

In China there have been done similar studies to accommodate the country's increasing demand of new energy sources and supply security. One article published by Shanghai Jiao Tong University states that wind-solar hybrid generations could partially overcome the problems in the stand-alone wind and solar power generating system, which is mainly their unpredictable output of power. [8]

In Europe the first up-scale hybrid park was built at Haringvliet in the Netherlands. The park was finished in 2022 and an analysis done by Technical University of Denmark and Vattenfall AB shows promising results for both production and profits. The park uses battery storage as a way of peak shaving the surplus power produced and have found this effective.[9]

A study done by Gomes Et al. from 2023 looked at battery implementation in both solar- and wind-parks, and its possible economic benefits. It concluded that the implementation of a battery energy storage system (BESS) would provide a significant revenue increase. This study looked at the Italian and Iberian energy markets, not Scandinavian which could differ significantly. [10]

The increased implementation of renewable energy sources into the existing power grid has created a need for more frequency regulation. In 2020 Datta et al. did a study on implementing a energy storage system in a solar park to mitigate the parks incapability of producing inertia for under-frequency support to the grid. The study found that the introduction of a BESS helps the solar park with meeting the grid requirements for frequency regulation, while also being effective in planning for future changes in energy production. However, this study only focused on a PV penetration level of 1%, meaning the amount of solar power delivered to the system. [11]

1.2 Objective

The company Aneo has a wind power plant at Stokkfjellet. The concession granted has not been fully utilized and it could therefore be a possibility to expand production. To increase the delivery security, this thesis will examine if it is viable to turn Stokkfjellet wind power plant into a hybrid park with the installation of solar panels.

This thesis will explore through different types of data analysis how the production of wind power overlaps with solar power and if this combination is viable at Stokkfjellet. To find the most suitable option there will be explored three different scenarios and an economic evaluation will be made of each scenario.

Scenario 1 will explore the possibility of installing solar panels without the help of an energy storage system, and whether or not this solution is feasible economically and practically. Scenario 2 will investigate the effects of installing a energy storage system that will be used for peak shaving the solar production. Scenario 3 will explore the possible installation of a energy storage system that will be used for both peak shaving and frequency regulation. Researching different battery types will be the main focus when studying this scenario. The different areas of use have different demands, where peak shaving batteries demands larger capacity and batteries used for frequency regulation needs fast response times.

The theory behind these scenarios, the methodology behind the execution as well as their results will be presented and discussed in this thesis.

2 Theory of a Hybrid-Power Plant

In this section the theory behind this thesis will be presented. This will mainly consist of theory surrounding hybrid parks, specifically the a wind- and solar combination. There will also be presented certain economical aspects, that will detail different markets as well as the current price situation.

2.1 Wind turbines

The wind energy harnessed by humans was for a long time only used to perform mechanical work, such as pumping water. Today's modern wind turbines are based on the same principles that were used in the early windmills, but have been modified to produce electrical power. In August of 2022, there were 65 wind power plants with over 1.392 turbines in Norway. The installed power was 5.083 MW with an average annual production of 16.921 GWh. The map shown in Figure 2.1 shows all wind power parks built onshore the Norwegian mainland.

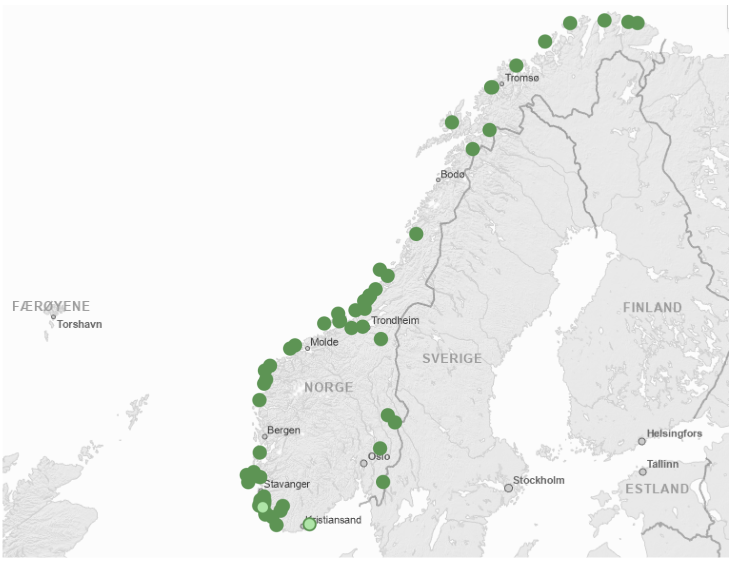


Figure 2.1: All onshore wind power plants in Norway (light dots are parks under development). [12]

A wind turbine works on the principle of making electric energy of the kinetic energy in the wind. The wind will turn the blades attached to a rotor which turns a shaft connected to a generator. The generator generates electric energy from the rotating mechanical energy from the shaft. There are mainly two types of wind turbines. The vertical axis wind turbine, called 'VAWT' for short, and the horizontal axis wind turbine, 'HAWT' for short. The standard turbine, and most frequently used, are the horizontal axis wind turbines. These turbines can be both offshore or land based. The biggest difference being the size, where the offshore turbines generally will be substantially larger.

The main components of a horizontal axis wind turbine, HAWT, are the foundation, tower, nacelle, the rotor and blades. The nacelle is placed on top of the tower and contains the generator, gear as well as necessary auxiliary units and control systems. The rotor usually consists of three blades, but other configurations are possible, which depends on what is appropriate for the project. The nacelle rotates with the wind direction, making sure the rotor plane is perpendicular to the wind direction. This will also aid in power output control [13].

Wind conditions can vary greatly between days, weeks and especially months. This will in turn affect the amount of wind power than can be produced. There will usually be more wind during fall and winter. This correlates well with the amount of power needed in Norway during these parts of the year since most of the power used in households is for heating. Figure 2.2 shows the typical effect curve for a wind turbine. This plot was plotted in MATLAB by using a theoretical equation for wind production [14]. In this case there has been assumed a cut-off wind speed of 26 m/s. However, this will vary from different generational turbines, manufacturer, or how much installed capacity the wind turbine has. It is most commonly between $25 - 30$ m/s [15].

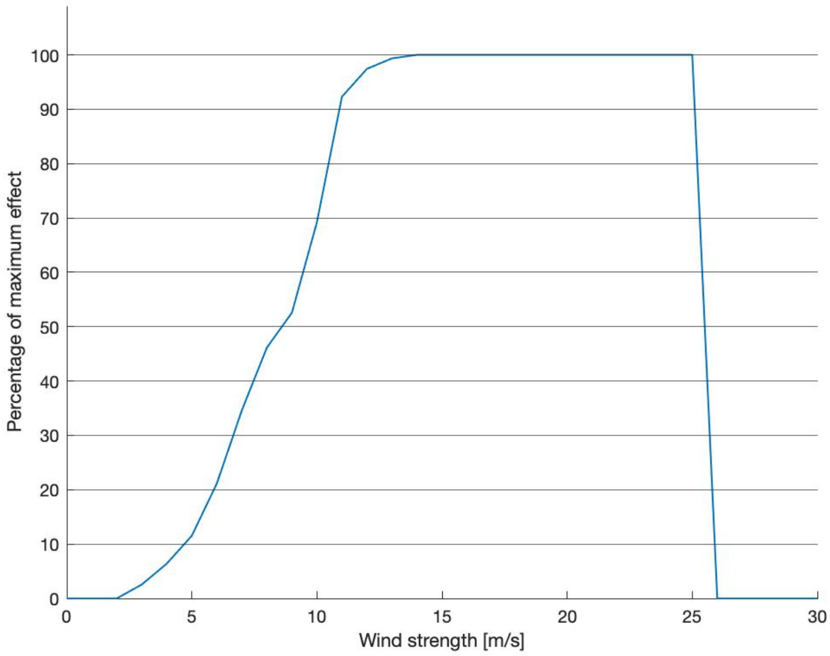


Figure 2.2: A typical effect curve for a wind turbine.

The lifetime of wind turbines are often assumed to be around 20 years with an unrecoverable loss in performance over time, just like all machinery experiences. This could be due to multiple factors, like less wind available, failing aerodynamic performance and conversion efficiency. It is difficult to specify how much each factor affects the lifetime of a turbine because of the highly variable availability of wind. However, one can expect a turbine to lose $1.6 \pm 0.2\%$ of their output every year, with average load factors declining from 28.5% when new to 21% at age 19 [16]. This level of degradation reduces a wind farm's output by 12% over a twenty year lifetime.

2.2 Solar panels

Solar energy is heat and light radiation from the sun. This energy can be utilized in many ways. In this section the technology behind solar cells will be explained and presented. The combination of solar cells is the main part of a solar panel, which can be combined in a large scale to create a solar power plant. The combination of multiple solar panels will have a higher production. Solar panels require a large area to be utilized, which can be problematic. The biggest solar park today is the Bhadla Solar Park in India with a capacity of 2245 MW on 57 km^2. In Europe the biggest built park is the Francisco Pizarro facility in Extremadura, which has a capacity of 590 MW.[17, 18, 19]

Solar cells are often called "Photovoltaic (PV) solar cells" and convert sunlight directly into electrical energy using photovoltaic effect. Photo emission takes place when light hits a material which makes electrodes detach [20]. Forcing these electrodes through a wire creates electric energy. The photo active material in a solar cell that makes this process possible consists of semiconductors, which is placed between two electrodes.[20]

In the solar cell industry silicon is the main semiconducting element [21]. Silicon is easily obtained and processed, is not toxic and because of the frequency of the material it is not environmentally harmful. Electronic components made of silicon are stable at temperatures up to 200°C. Semiconducting silicon is poly crystalline. This can also be turned into mono crystalline through different processes. Atoms of mono crystalline silicon are connected mutually by covalent bonds into surface centered crucible. Mono crystalline silicon is black, non-transparent, very shiny, hard and a weak conductor for electricity. It is therefore essential to add additional substances so that it becomes a good conductor for an electric current. [22]

The efficiency of silicon solar cells is theoretically around 28%, but in reality it is around 15-24%. Poly crystalline are 4-5% lower than mono crystalline. The efficiency is the relation between how much solar energy that will hit the surface of the solar cell, and how much will be converted into electrical energy [17].

Sun power production is very fluctuating. There will be no production during night time as well as being very dependent on weather conditions. In Norway the height of production will be during the summer time, since the sun is high in the sky and there are more daylight hours. This is the time of year when the consumption of energy is at its lowest and it is therefore expected a surplus in energy.

2.2.1 PV-systems

To make a functional PV-system there are many factors and options. How to optimize these factors for maximum production and profit is usually very dependent on geographical location.

There are many different types of solar panels on the market and the choice of model will heavily impact how the system functions. The main choice is between mono crystalline and poly crystalline, there are also both monofacial and bifacial models. Monofacial is the most common with the solar cells only on one side and bifacial being able to generate energy from both the front and rear side.

The ratio between modules and inverters is also an important factor, especially in bigger systems. This ratio is normally decided by the PNom ratio, which is the ratio between the nominal power of the inverter and the PV array power at standard test conditions (STC). A PNom of 1 yields optimal power output, but due to economical factors this is commonly set higher. This way some production is lost, but the installation cost is lower. [23, 24]

The inclination of the solar panels is of great importance for how much light is captured by the panel. Optimal inclination of the solar modules is approximately 90 degrees minus the latitude. This is because the intensity of the solar radiation is gradually reduced as it passes through the Earth's atmosphere. This means that the further north the facility is located, the more vertically the panels should be mounted. A facility in Oslo is optimally angled at about 30 degrees from the vertical, while in Tromsø it is best with an angle of about 20 degrees in relation to zenith. [25]

There are many ways of mounting solar panels. The different ways can affect the efficiency substantially. If the solar panels are mounted on metal frames, open free mounting, there will be a higher airflow around the solar panel which will cool it down more and heighten the efficiency. Semi-integrated solar panels with an air duct behind have a partial closed back but still one air duct which increases the air flow. Fully installed back mounting will decrease the efficiency by 5-10% since there is no air flow to cool the solar panel down. When installing the panels there also has to be a pitch distance, this describes the distance from the front of a panel to the front of the panel in the next row. This distance varies from system to system based on climate and tilt, but usually ranges from $4 - 12m$ [26, 27]

For all sizes of PV installations the development of degradation is inevitable. An overall failure to control production quality, faulty PV plant design as well as faulty operation will decline the efficiency of the panels. Degradation rate is formulated as a reduction of maximum power over time and predicting it is still a challenging task, especially since different PV technologies are subject to different degrees of degradation. The fact that the degree of degradation of the PV modules is linear during long-term operation is widely accepted. [28]

2.2.2 Bifacial solar panels

One of the promising developments in solar technology's are bifacial panels. These panels generate electrical energy from both sides of the panel and so also yields more production in total. This is becoming more and more common feature for solar panels and are predicted to be the most common type in the future. The reason they have become this popular are the advancement for passivated emitter rear cell (PERC) which have made bifacial models more efficient and cheaper to manufacture. The design of the panels is usually without a frame with either a reflective back or encapsulated in glass. This exposes both the front and rear side to sunlight. Bifacial panels are also usually made with mono crystalline cells. This is more expensive but has a higher efficiency, and the highest selling point for these panels are their high efficiency. [29, 30]

A depiction of how the light reflects of the ground to hit the panels on the rear and front side is shown in Figure 2.3. The reflection of the ground varies very from different surface grounds and the ratio of reflected sunlight is calculated by the albedo factor. The albedo factor is a number from $0 - 1$ depicting how much of the light is reflected. Light colored ground reflect more, and snow is regarded as one of the best natural surfaces for bifacial solar panels due to the high albedo factor.[31]

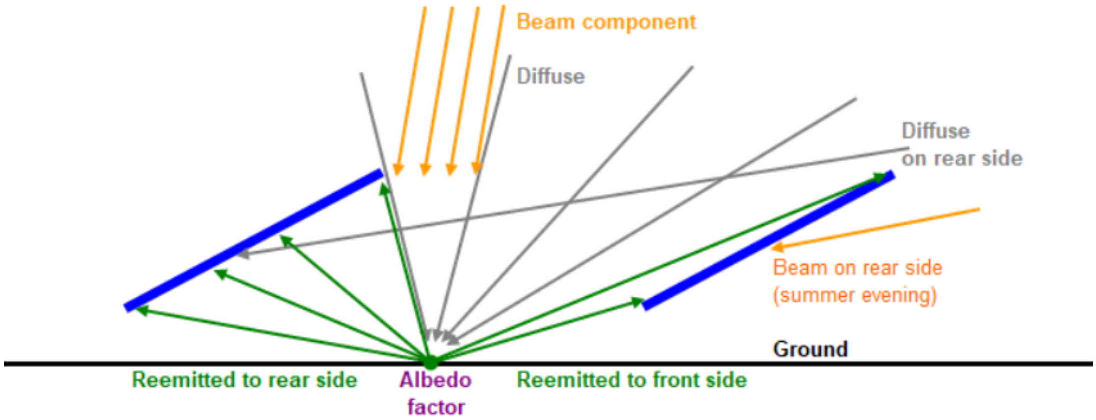


Figure 2.3: Depiction of how the sunlight reflects of the ground [32].

2.2.3 Market price solar panels

Solar panels have often been regarded as expensive and therefore not a viable option for industrial power production [33, 34]. This perception has changed over the years, and with new technologies and optimizations of systems there are many industrial solar power plants being built today. These power plants are mostly around the equator and other regions where there are a large number of days with sun. The expansion of industrial solar power plants to colder climates has been slow but with the increased demand for renewable energy and the steady decreasing cost of investment, solar panels have become a more common source of energy.

Many studies that have looked at the cost of solar panels over time have seen a drastic decrease over the years [33, 34]. An analysis on the investments of different power sources from Lazard shows that since 2009 to 2021, the investment cost measured in $\$/MWh$ for solar PV-crystalline have decreased by 90%. This is significantly more than any of the other energy sources analyzed. One of the graphs showing this progress from the analysis is shown in Figure 2.4, and is taken from the Lazard analysis from 2021.

Figure 2.4: Historical utility scale comparison from Lazard [35].

The reason for this progress is mainly new technology that increase the efficiency. When the price became cost efficient and the parks started to be built, the panels also became mass-produced which drove the price down even further. The investment cost is still predicted to decrease in the future, but possibly not at the same rate as the last years. In Figure 2.4 there is indications on a stagnation in price reduction for the last 3 years that also suggest this. Some forecast's are more optimistic and predict a continuing reduction in cost at almost the same rate [36].

2.3 Lithium Ion batteries

Storing energy in rechargeable batteries has been a known technology for many decades. A battery converts chemical energy directly into electrical energy via an electrochemical reduction-oxidation (redox) reaction. There are many different lithium-ion batteries depending on which electrode materials are used. An example is the lithium-ion battery where lithium cobalt oxide (LCO) is used as cathode. An LCO battery can withstand many cycles at high voltage. However, given its low capacity and power, a LCO is not well-suited for grid-scale applications. Given the large number of different Lithium Ion Batteries (LIBs), in this section the different characteristics for different LIBs will be presented. Three main chemistries for grid scaled battery charging will therefore be examined further.

However the chemistry differs, the main principle of how a lithium-ion battery is the same. A battery cells key components are positive and negative electrodes, electrolyte, separator and an enclosure. The cathode is the positive electrode when discharging and negative when charging and the anode is the opposite. When discharging lithium-ions move through the electrolyte from the anode to the cathode and the electrons get picked up by the current collector and passed through a wire [37]. This process is shown in Figure 2.5.

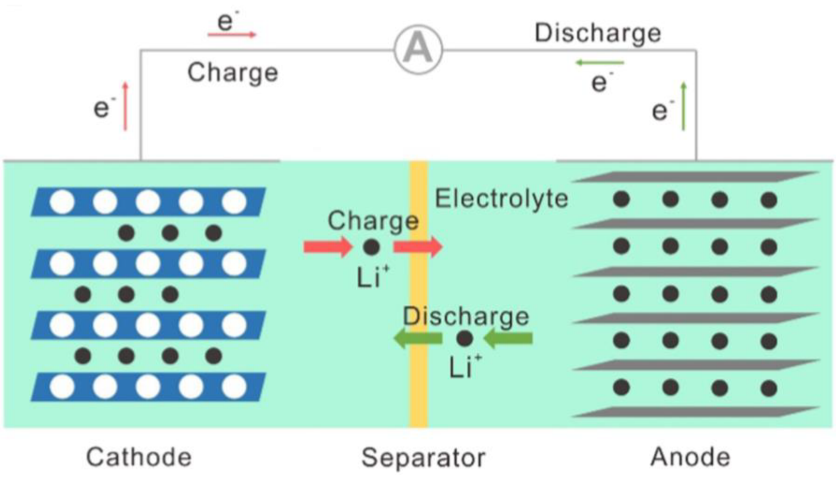


Figure 2.5: Basic working principle of a LIB in a charging- and discharging state [38].

Battery aging can be dissociated into two components: calendar aging and cycle aging. Calendar aging happens when the battery is not in use, while cycle aging happens when the battery is either being charged or discharged. The main calendar aging mechanism is the formation and growth of the Solid Electrolyte Interface (SEI) layer on the negative electrode. At high levels of temperature and State of Charge (SoC) SEI formation is accelerated. The main cycling aging mechanism is the lithium plating of the negative electrode. This is increased at high charge rates and at low temperatures. [39]

As well as being one of the most commonly used rechargeable battery chemistries, lithium-ion batteries will also be produced locally. Currently there are multiple battery producing companies starting up in Norway. There´s FREYR [40], Morrow [41] and Beyonder [42]. They all vary in chemistry and production process, however they are all making rechargeable lithium-ion batteries. Weather or not these companies will continue to build their factories will vary in the near future, due to the Inflation Reduction Act newly passed in the US. This act will give more support to clean energy producers than the Norwegian government can, so the possibility of the previously named companies building in the US instead is considerable.

Nickle magnesium cobalt (NMC) battery is a type of li-ion chemistry that is commonly used. NMC-batteries have a slightly lower performance than other batteries, however they operate better at lower temperatures. This battery type has a higher energy density than other li-ion batteries, so their physical size will be smaller at the same capacity. Nickle cobalt (NCA) batteries have a similar chemistry as NMC batteries, just without the manganese. These batteries are expensive in addition to having a shorter life cycle than other batteries. Both nickle based batteries have a generally shorter life cycle than other lithium-ion chemistries.

The last couple of years multiple news articles about the environmental impact of mining nickle has emerged. The Guardian, Euronews and Reuters, among others, has released news articles about how nickle mining both affects the environment as well as the miners [43, 44, 45]. All these articles point out that as we are trying to electrify our society, while pushing prices down, another part of the resource chain is starting to suffer.

In Norway today there is one nickle mine active, yet there are six possible locations for new mines [46]. Mining nickle in Norway, making it locally produced, will affect how sustainable the nickle batteries will be. However, it is not clear weather there are future plans for staring up these nickle mines.

Lithium iron phosphate (LFP) is another type of lithium-ion chemistry. LFP-batteries have a slightly higher efficiency and can operate better when the state of charge (SoC) is low. Degradation happens slower with LFP batteries, so they're able to store and release more electricity. One of the biggest benefits of choosing an LFP battery is its safety. The combination of lithium iron phosphate is more stable than other chemistry's at higher temperatures. LFP batteries can also better handle larger draws of power. Because of this, LFP batteries are less likely to experience thermal runaway.

There is also the social aspect of what material to use in LFP batteries. The global and regional phosphorous systems are plagued by concerns and issues of supply constraints coupled together with increased demand of phosphorous since it is a main component in both battery chemistry and food production [37].

2.3.1 Battery prices

The price of batteries has reduced drastically since the early nineties to today [47]. This is due to better technology and a higher demand. The marked prices and costs of installation on an industrial scale is hard to find. This is because of market secrets and a general withhold of information in an increasingly profitable marked.

In the available studies and forecasts the prices and cost of batteries vary a lot. This is expected when comparing specific markets for countries, and also for different types of batteries. They all still have a reduction in price, but for varying rates. For lithium-ion batteries this reduction is steep and is today regarded as the cheapest option on the marked. An analysis of lithium-ion battery cost and marked show a reduction of 73% from 2010 to 2016 and expected this trend to continue, but also stabilize due to a strain on the supply chain [48]. Other studies predict that the prices will have a lower limit and proposes that new technology is essential to drive the prices down further [49]. Many have tried to forecast the price and demand progress towards 2030. Almost all expect a stagnation in price reduction and a higher demand, some are optimistic on technology advancements and others try to make a more conservative estimate. [50, 51, 52, 53]

In Europe the EU have proposed new regulations for battery production and manufacturing, they want more transparency and more responsibility to the manufacturers. This is only proposed and might change, but the probability of some new regulations is high. The proposal will expect a more sustainable battery lifetime, from mining of the raw materials to making batteries easier to recycle. This might make it more expensive and labor intensive to produce batteries for the

European marked. Norway is not a member of the EU, but the government have stated, in context of the proposal, that this will have an impact on all countries in the EEA. [54, 55]

2.4 Transformer

Transformers are electromagnetic components that transfer electrical energy from one voltage level to another. They are essentially constructed with a core of metal, usually iron, and windings in pairs around the core. The difference in the number of windings in the pairs determines the step in voltage the transformer operates at. It is normal to distinguish between the windings as the primary side and the secondary side, or the high voltage side (HV) and low voltage side (LV). [56]

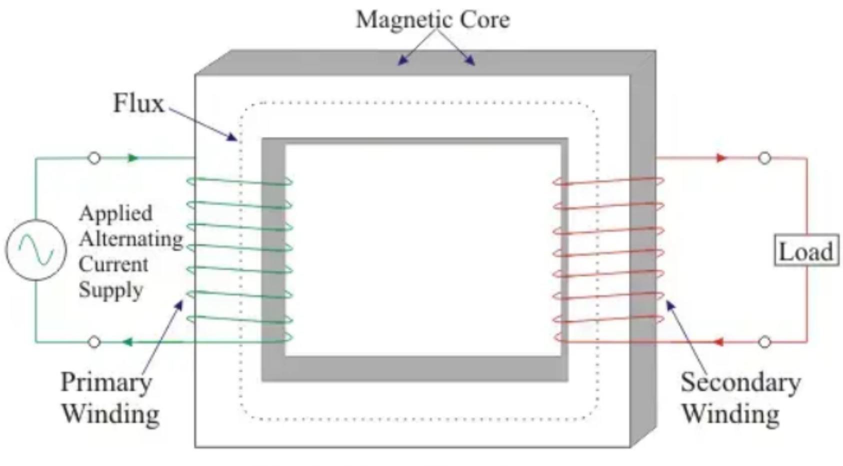


Figure 2.6: Illustration of a simple transformer.

The principle of mutual induction is the base of the operation in a transformer. An AC voltage source is connected on the primary side and sends in its current in the primary winding. This generates an alternating electromagnetic field, ideally sinusoidal. This up-building of the magnetic field is called mutual induction. The field lines will move through the core and generate a flux stream, which is the measure of an electric field on a given surface. This will in turn lead the secondary side to induce a voltage, also called electromagnetic induced force (EMF). The structure is visualized in Figure 2.6.

2.4.1 Three-phase transformers

Industrial transformers designed for high voltage are generally three phase transformers, meaning they have three winding couples and transmits three phase voltages and currents. All three lines have the same amplitude and frequency but are 120° phase shifted in relation to each other. This is ideal for industry, and it has both economic and technical advantages. It is the most used system for industry operating on bigger grids and over longer distances. [57, 58]

With a three-phase system it is possible to have either a star, delta or zigzag connection between the phases, with star and delta being the most common. A star configuration resembles a Y with all the lines connected in a middle point, in contrast to a delta configuration which resembles a triangle like the Greek letter Δ with all lines connected in series. For the transformer both the LV side and HV side can separately have either one of these configurations leading to many possible options for the coupling. The most used configuration is a delta-star with a phase shift of 30°, but the delta-delta connection have become more and more common due to economical benefits. The notation for these configurations are specified in the NEK standard IRC 60076-1. [59, 58]

2.4.2 Lifespan and losses

The lifespan of a transformer is mostly determined by its insulation material and avoidance of technical failure leading to breakdown [60, 61]. A problem causing damage to the insulation material is the transformer operating over the nominal current rate over time. The losses in a transformer can be split into four categories: dielectric-loss which affect the insulation material and therefore causes faster aging, load/stray-loss that generate heat, copper-loss and core-loss, of which the last can be separated in hysteresis and eddy-current losses. The major losses are by far the copper and core losses, and these are the biggest factor in determening the efficensy of a transformer. [62]. The core-loss is constant for a transformer with constant voltage and frequency, and differs only with the materials used for the core. The copper losses is determined by the current and ohmic resistance of the transformers and is proportional to the square of the current. This makes the current crucial to keep these losses at a minimum.

It is important for industrial transformers to be integrated in a control system. This is to ensure that the transformer runs optimal and is not damaged. The cost of a new transformer at an industrial site can be very expensive and therefore it is ideal to utilize all of the transformers potential lifespan. A control system can include voltage regulators, sensors and more. The transformer itself can sometimes include a tap changer on either the HV or LV side. A tap changer is a form for voltage control and can be used for example to keep the HV terminal constant or within prescribed limits. It dose this by changing the ratio between the windings by applying a type of switch. [63, 64, 58]

2.5 Hybrid park

As mentioned in the introduction, the energy sector has witnessed a shift towards renewable energy sources as countries worldwide strive to meet their energy demands in a sustainable manner. As mentioned earlier, one promising approach to achieving this goal is the implementation of hybrid energy parks. These parks integrate multiple renewable and non-renewable energy sources into a single system, aiming to leverage the strengths of each source while mitigating their limitations [65].

By capitalizing on the unique advantages of each energy source, hybrid energy parks offer a potential solution to the challenges associated with a single-source energy system, and reduce the dependence on non-renewable energy sources. This approach also aims to create a more robust and resilient energy infrastructure that can adapt to changing environmental and economical conditions. [65]

One type of hybrid energy park is the combination of solar and wind technologies. As outlined in Section 2.2 on solar power production, the solar parks primary energy output occurs during the summer months when the intensity and frequency of solar radiation are the most abundant. Conversely, as explained in the Section 2.1 on wind power, the most significant power production for wind turbines happens during winter and nighttime periods. By integrating these two energy sources within a single park, their respective advantages are expected to offset their limitations, ultimately resulting in a more efficient and reliable energy system. [8]

Currently there are several hybrid parks around the world, where the majority are solar- and wind-based. As mentioned in Section 1.1, the Haringvliet park is currently the largest in Europe, with an expected annual energy production of $140GWh$. It combines a 22 MW wind park, a 38 MW solar park and a battery with a capacity of $12MWh$, giving it a maximum output of 60 MW. [9]

The creation of hybrid parks by implementing energy sources into already existing power systems is an alternative to creating a power plant from the ground up. Given that hybrid parks are relatively new to the energy market, the regulations surrounding them are currently in development. This is also the case for solar parks, especially in Norway, because of the limited amount of parks built. In Norway, when installing a new power plant there has to be granted a concession, and these are applied for at NVE. [66]

While the implementation of different energy sources is supposed to make the production steadier, overlapping production hours can still result in overproduction. A way of mitigating this is to use peak shaving, which is the process of storing energy produced by a power source in order to limit production spikes. This is done by using energy storage to store the production spikes, and deliver at times of low production instead. Instead of losing the overproduction, peak shaving can be implemented to exploit the excess energy.[67].

2.6 The Norwegian energy market

The energy market is not only there to determine the spot price of the power every hour. The most important task of the energy market is to ensure that there is a balance between power production and consumption. In addition, the market ensures that the resources are used as efficiently as possible. Renewable power production in Norway is currently relatively localized. The reason for this is the restricted access to renewable resources throughout the country due to different geographical landscapes. Thus, production capacity in Norway is unevenly distributed regionally. This means that the transmission network is crucial for the power to be distributed to consumers in different parts of the country.

There are power exchange cables connecting Norway to the European transmission grid, which in turn gives the country the opportunity to trade on the European power market. Today there are 17 cables connecting Norway to Sweden, Denmark, Finland, Russia, Britain and Germany [68]. Figure 2.7 shows the cables, the direction of the power flow, as well as the volume. This gives Norway an increased security of supply and the possibility of withholding hydropower in times where there is a larger production on the rest of the European grid.

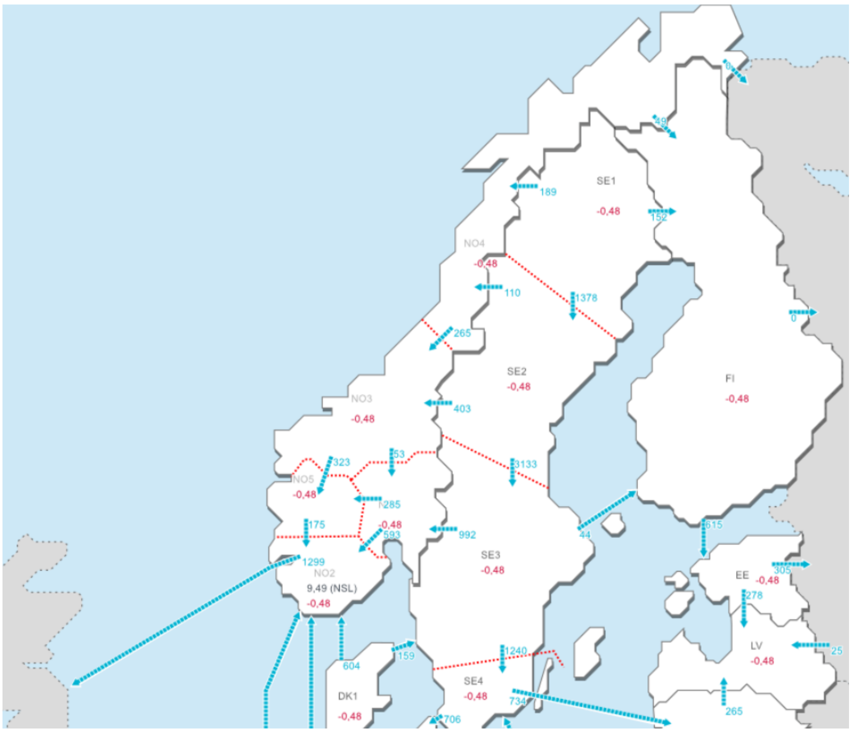


Figure 2.7: Norwegian power marked [69].

The spot price of an area is determined through several smaller markets. The 24-hour market sets the following days spot prices. Power is traded in that market for every hour of the day. As the 24-hour market closes, a spot price is set per bid area, which is the same as power regions, for all power sold for that hour in question. After the 24-hour market closes and up to one hour before the time of use, power is traded in the intraday market. In this market, suppliers and producers can adjust the volume to be sold or bought. The current is traded continuously. In the last hour before the power is used, and throughout operation, the balance market applies. Through this market, they can adjust production at power stations and consumption in industry so that the same amount of electricity is always produced as is used. [70]

2.6.1 Frequency regulation

For all electric power systems, the two most important parameters to control is the voltage and the frequency. The quality of these two factors are what determines the quality of the power system in question. There are predefined limits that these two need to be kept within, and any fluctuation will have an effect on the number of disturbances or outages that the system experiences. The frequency of the power grid is dependent on load demand and power supply. If the load demand becomes higher than the amount of power supplied, the grid frequency decreases. Similarly, if the power supply becomes higher than the demand, the frequency will increase. A high enough increase in frequency can cause electrical equipment to fail, and have a negative influence on the power quality. A decrease can cause generators to either trip or shut down, causing power outages and blackouts. [71]

With the increasing implementation of renewable energy systems into the existing power grid, the need for frequency regulation is becoming more important. With the large amount of hydro power plants in Norway, the need for regulation has been reduced because of their kinetic energy contribution through existing turbines. The inertia provided by the turbines in the system keeps the frequency stable. However, if the system inertia where to decrease, the grid would need a supply of power in order to keep the frequency at a normal level. [72]

The European and Asian frequency standard is $50Hz$, while the American is $60Hz$. The current standard condition is at 0.1% over or under the frequency standard, with any fluctuation from this limit being regarded as an emergency condition [71]. When the power system reaches this condition, four different frequency control reserves are tapped into, the fast frequency reserve (FFR), the frequency containment reserve (FCR), the automatic frequency restoration reserve (aFFR), and the manual frequency restoration reserve (mFRR). The whole process of regulating a disturbance in the grid can be thought of as a step-by-step operation, where each consecutive reserve regulates the impact of the one prior [72]. The timeline of reserve activation is illustrated in Figure 2.8, which was collected from a article written by Statnett [73].

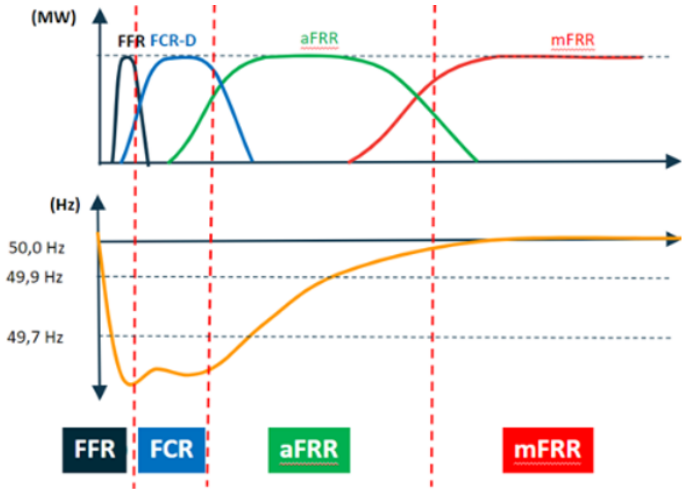


Figure 2.8: Timeline of reserve activation [73].

The first reserve to kick in is the FFR, which has a response time of between 0.7-1.3 seconds, and lasts for between 5-30 seconds. The main purpose is to slow down the change in frequency, so that it doesn't reach a dangerous limit. The FCR is then introduced, which has a response time of 30 seconds, and lasts for a minimum of 15 minutes. Its purpose is to stop the change and stabilize it. The aFFR, with a response time of 2 minutes, pushes the frequency back to the normal level. The mFRR, response time of 12.5 minutes, keeps the frequency at the nominal range until complete stability has been reached. [72]

2.6.2 Frequency market

The energy markets are always focused on balancing the frequency before the operating hours. However, there will always be some discrepancies between the estimates and the reality. It is therefore Statnetts role to have regulation reserves available in order to combat these divergences. The way they collect these are by purchasing them from energy producers. What they are essentially buying is energy availability, meaning that if Statnett were to purchase 5 MW of reserves from an energy company, they would be obligated to either deliver this to the grid when needed, or withhold it, in order to balance the frequency. This market is called the capacity market, and it represents availability in a certain time frame. This means that the producers will be paid regardless of whether the power is used or not. [72]

In addition to the capacity market, there is also an activation market. In the activation market the power is purchased right before the regulating hours, and is meant to be used to regulate smaller disturbances. Here, the manufacturers are only paid if the power is used. The type of reserves that are sold are either mFFR or aFFR. [72]

As previously mentioned, the reserve that activates after the FFR is the FCR. The market for FCR is divided into the D2 and the D1 markets, which represents the spot-market and the residual market respectively. Inside both of these are FCR-N and FCR-D. The former is the designed to kick in between the normal frequency range, which is 49.9 Hz to 50.1 Hz, and the latter activates in the event of larger disturbances on the grid frequency. Because of the grids tendency to normally stay between the normal frequency range, the FCR-N reserves are used more frequently than the FCR-D or the FFR. Additionally, as a result of the constant regulation provided, the volumes of power required for each are lower than that of the FFR. [72]

The different volumes for each hour are handed out based on which supplier gives the lowest bid. Because of this, there will sometimes be certain periods were a certain volume won't be sold because of lower bid coming from another supplier. Instead of losing the potential revenue that volume represents, energy arbitrage can be used to maximize the value of the volume that wasn't sold. Energy arbitrage is a strategy that involves buying and selling energy at times when it is most profitable. In a hybrid park that uses a battery energy storage system, energy arbitrage can be used to generate revenue by charging the battery when energy prices are low and discharging it when prices are high. This can be done by storing excess energy from the wind and solar power sources during periods of low demand or low prices, and then selling it back to the grid during periods of high demand or high prices. [74]

2.7 Financial Calculations

In order to calculate the economic viability of a project, a method of investment analysis must be used. One such method is to calculate the net present value of the project (NPV). NPV is used to determine the value of an investment. This is done by comparing the present value of cash flows to the initial cost over a set period of time. A key advantage of using this method is that it takes into account the changing value of money over time. In order to calculate the NPV of a project, equation 2.1 is used. [75, 76]

$$NPV = -C_0 + \sum_{t=0}^{n} \frac{C_n}{(1+r)^n} \tag{2.1}$$

n is the lifetime of project

C_0 is the intitial cost

C_n is the cash flow

r is the internal rate

The initial investment cost of the project is a key factor in this calculation. The initial investment costs can consist of things such as installation, land acquisition and material costs [75, 76]. Another key factor in the NPV calculation is the internal rate (IR), which has a significant influence on the resulting value.

The internal policy rate can be used as a default IR if it is not possible to acquire the IR of the market. This is because the IR is often information that is withheld from the general public by private companies [75]. The internal policy rate is set by Norges Bank, and it is the rate at which banks loan money to each other. It is used to control a countries overall economic condition, and is set by assessing the countries economy, inflation and other similar factors. This is a rate that is reviewed regularly and will be adjusted up or down depending on the economic condition of the country. [77]

Another method of investment analysis is the payback method. The main point of this is to show how long it takes for a project to break even, which is when the revenue gained equals the investment costs. Unlike the NPV method, the payback method does not take the time value of money into account. It is often used when clear budget constrains are set. [78, 76]

3 Methods and Project specifications

Exploring the possibility of turning a wind park to a hybrid park is a complex endeavor. In this section the methodology of this process will be presented. First the already exciting wind park, its infrastructure and the overall changes to a hybrid park is presented. Then the scope and limitations of the analyses. At last the approach for the simulation and calculations for the different scenarios will be presented.

3.1 Stokkfjellet wind-power plant

Stokkfjellet wind-power plant is situated in Selbu municipality in Trøndelag county. Figure 3.1 shows the power plant in its present condition. The concession for the plant was granted in 2014 and final permit was granted by the Ministry of Petroleum and Energy in 2017. The concession grants a plant for 90$megawatts$ (MW) for an area of $5,8\ km^2$. The plant only covers part of the original area of the concession due to the development of wind turbines with better efficiency leading to the need of fewer turbines than originally planned. The park was finalized in 2021. Today, the installed capacity at Stokkfjellet is $88,2\ MW$ with a yearly production of 311 GWh. There are 21 turbines of the model Vestas V136 with a capacity of $4,2\ MW$ each. They have a hub height of 112$meters$ (m) and a rotor diameter of 136 m.Figure 3.1 shows part of the park and is taken by one of the group members. [79, 80]

Figure 3.1: Stokkfjellet wind power plant.

The grid structure of the park was built in conjunction with the installation of the plant and was therefore dimensioned after the concession of 90 MW. All the turbines have a cable connecting them to the transformer station, these cables are buried and carry 33 kV. The transformer of 100 MVA converts this up to high voltage of 132 kV. From there a 132 kV cable goes to the transformer station at Nea and connects the plant to the national grid. [79, 80]

3.2 Scope and limitations

This thesis analyzes a proposed hybrid park and three different scenarios of how to operate this park. It then analyzes if these scenarios are profitable options. This is a substantial task, and the scope will help define the focus and exclusions of the thesis. The scope will geographically be within the concession area at Stokkfjellet. The main focus is production and profit and how this changes for the different scenarios. The production calculations have a time frame of one year, while the economical calculations take a thirty year time frame. A visual representation of the scope is shown in Figure 3.2.

All the calculations take an assumption of a limit of 90 MW of power sent to the grid. This was done because of the current concession of 90 MW for the wind park. After a conversation with NVE it was made clear that all new installations has to apply for a new concession. This means that even though there are 1.8 MW unused power installed according to the current concession, this cannot be complemented with solar power without a new concession granted from NVE. This however, makes the only limiting factor for installing solar power the transformer which is also set to a limit of 90 MW. It was also understood from the conversation with NVE that since part of the area for the previous concession was not used, it had a higher likelihood that this could be used for a new installation. Because of this, the areas looked upon for installing solar power will be within the unused area from the concession to the wind park.

The system drawn in Figure 3.2 show the system set up for the proposed hybrid park. The PV-system is simulated and the wind production with the needed data for this is collected form nearby weather stations. The wind park production is AI generated data, but based on real data form the transformer at Nea marked by the red dot.The reason for this and a comparison of the data-sets will be presented in Section 3.4. The calculations combining the wind and solar parks takes inn the simulation data and the AI-production, and for scenario 2 and 3 it also includes the battery. The battery includes a transformer, but calculations for this was deemed outside of the scope because it realistically would be placed inside the PV-system to reduce the losses and investment cost. The simulation however did not allow this in a way that made it possible to do all the calculations wanted.

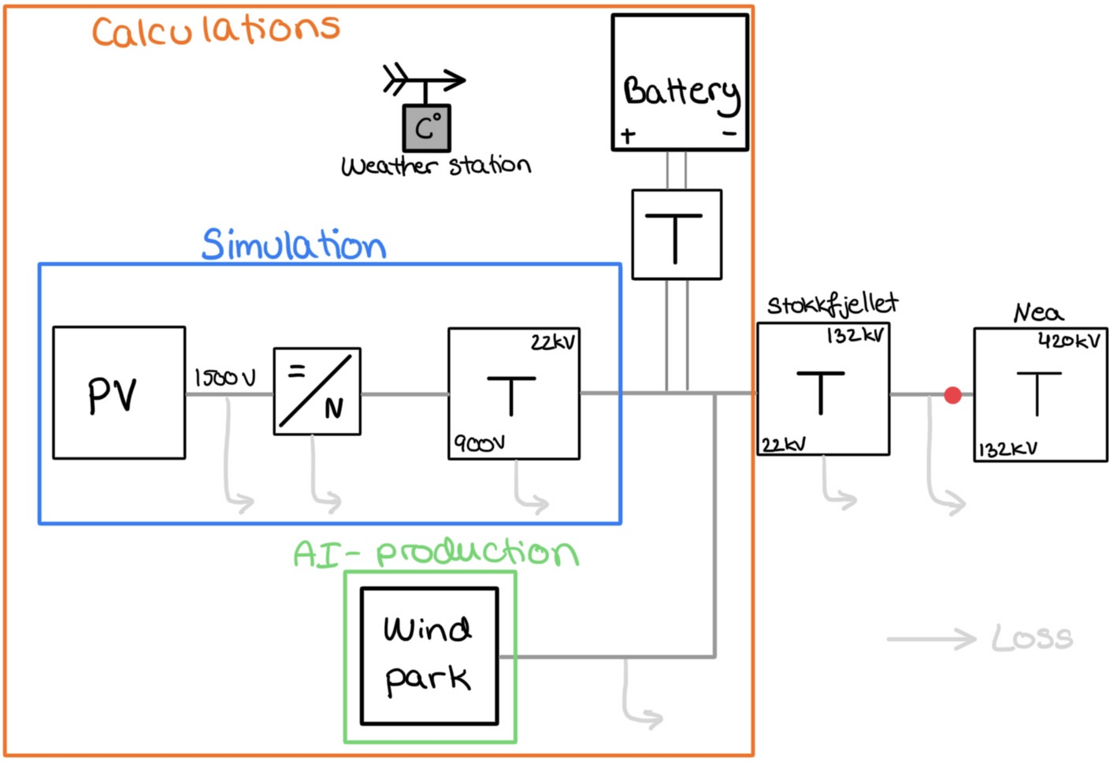


Figure 3.2: System layout for the hybrid park.

To simplify the simulations and calculations further this report does not take into account the possibility and risk of any unforeseen events like technical breakdown, failure or other events that will lead to a shut down or greatly affect the production and profit of the hybrid park. This may reduce the accuracy of the results, but they will still give a good picture of the system and an estimate of the three scenarios.

The aging and degradation of the system is not been part of the calculations. This would have the an impact on the economical analyzes as this looks at a longer time frame. How wind turbines and solar panels degrade over time is explained in the Sections 2.1 and 2.2.1.

At the current state max production from the plant does not negatively impact the transformer. With the installation of solar panels, this might change and the most important factor in this will be the current exceeding the nominal rated value as stated in the theory Section 2.4.2. This falls outside of the defined scope, but is a notable remark.

3.2.1 Equipment

To look at Stokkfjellet as a hybrid park and the different options in the three scenarios, a combination of programming calculations and simulations will be used. MATLAB R2020b and R2023a was the programming tools used to do all numerical calculations and the plotting of the results. This program was chosen because of the groups familiarity with the programming language and the easily displayed outputs as well as tables and plots. It also features a Live

Editor for creating scripts that combine code, output, and formatted text in an executable notebook. [81]

For the simulation of the PV system the program PVsyst 7.3 was used. The use of this program was a request by ANEO, and a student license was funded by them. It is a commonly used program in the industry, and gives realistic results with many custom options. The program also have an internally robust database for meteorological data and also gives the opportunity to import measured data. PVsyst takes in the PV module type and inverter. In this thesis they are the JA Solar 550W bifacial panels and the Huawei technologies 160kW inverter included in the Table 3.1 [82, 83]. Both were requested by ANEO to use in the simulation and is therefor the only components looked at in this study.

The transformer in the park has a capacity of 100 MVA and in this study there is an assumption that there is a max power output of 90 MW and this will further be referred to as the transformer limit. Anything above this will not go through the transformer and will either have to be considered as lost production or stored in batteries. This assumption is done to simplify the system and calculations. Realistically the limitations of the transformer is not as clear-cut since it can run over nominal limits as explained in the theory 2.4.2. This transformer also have a tap changer and is able to regulate the voltage between 17 levels, and can therefore regulate some aspects of its running condition. The limit was set to accommodate for loss and was regarded a necessary assumption to make good comparable results and to narrow down the focus.

The wind power is AI-generated based on the 21 Vestas turbines 3.1 in the park. For scenario 2 and 3 there is the inclusion of a battery, which is a lithium-ion NMC battery. This was the option chosen because of the combination of costs and scalability.

Table 3.1: List of all key equipment used in the project

Equipment	Function
PVsyst 7.3	Simulation tool used to simulate the PV-system.
MATLAB R2023a and R2020b	Programming tool used for calculations.
JA Solar 550W	Solar panel used in calculations and simulation.
Huawei technologies 160 kW	Inverter used in the simulation of the PV-system.
ABB transformer 90 MW	Transformer connecting the park to the grid with a voltage step from 33 kV to 132 kV.
LFP battery	The battery pack used in the energy storage system.
Vestas V136 4.2 MW and used in generated wind data.	Wind turbines located at the current wind park,

3.3 PVsyst simulation

There were done 20 simulations in this thesis, all for one year with different sized areas. They are representations of 20 solar power plants for increasingly lager areas. The areas range from 58000$m2$ to 1160000$m2$ which respectively represent 1% up to 20% of the total concession on the current wind power plant. The southern part of the concession area is currently not in use, and is therefore the section where the installation of solar panels is most relevant. The terrain is mostly mountain and marshland with no extreme altitude differences. There are three small lakes that are considered as exclusion areas and will be avoided for the installation of the solar panels. The rest is assumed to be flat and usable for the installation without major difficulties. Figure 3.3 shows the total concession area with the 20% section drawn inn and the three lakes.

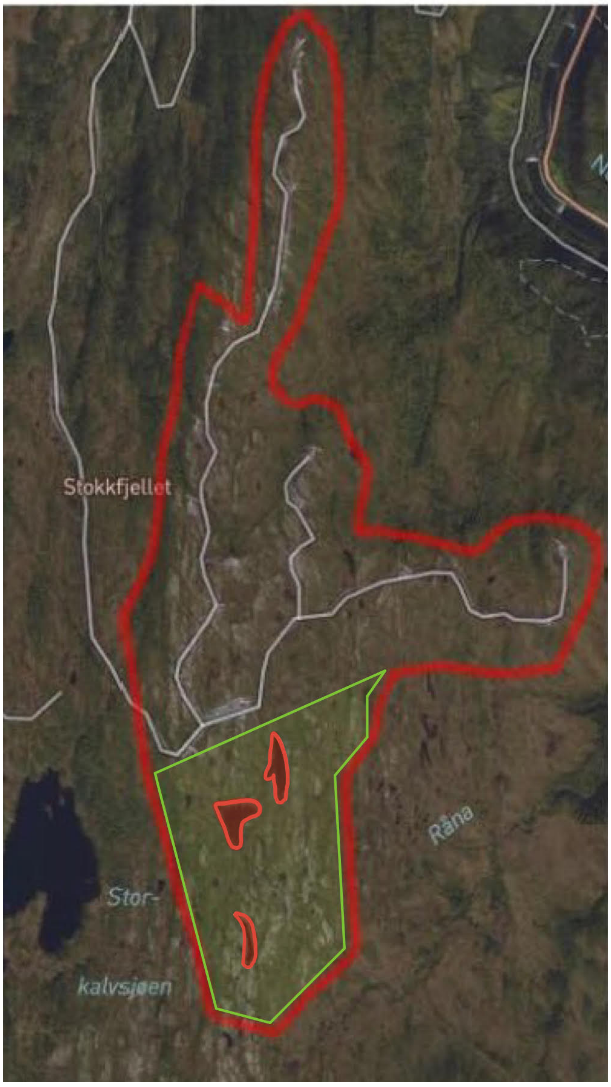
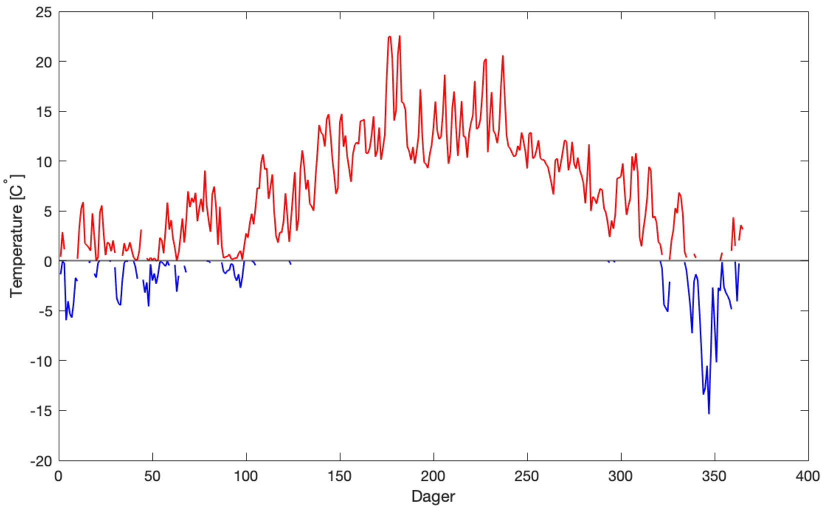


Figure 3.3: The concession area with the southern part highlighted green and the three lakes marked in red, aerial photo from [84].

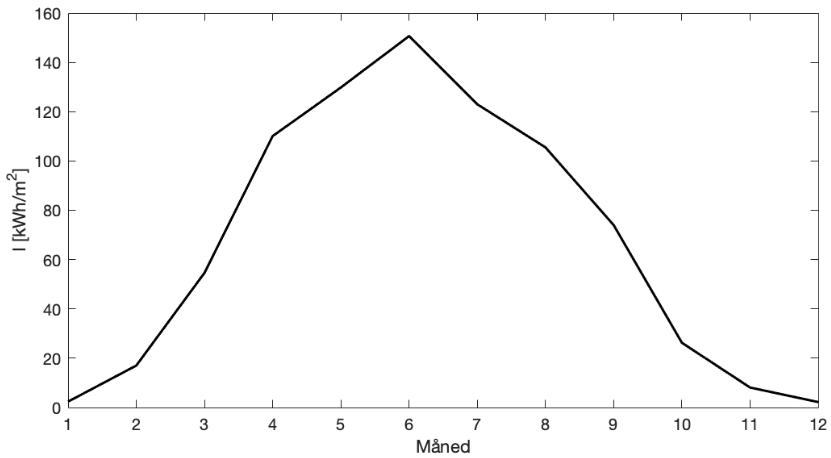
3.3.1 Metrological data basis

PVsyst bases it simulation on meteorological data input. The input data PVsyst can provide is based on geographical sites which contains values for GHI, DHI, ambiant temperature, wind velocity, linke turbidity, relative humidity and sun paths. The data is given as monthly values and PVsyst then generates a synthetic hourly table using stochastic models. This method of generating meteorological profiles for specific geographical sites has been thoroughly tested for the European climates, but can be misleading for extreme climates. [85, 86]

The geographical site used in these simulations is called *Selbu-stubbe/Kråkstad* and was found in PVsyst public databases. In addition, the file was modified to include the specific GHI data measured in the park seen in Figure 3.4b and the ambient temperature measured at the nearest meteorological station seen in Figure 3.4a. The ambient temperature data set is imported from the Norwegian Centre for Climate Services (NCCS) and is graphed in the Figure by Yr. Both data sets are from the year 2022, which is selected to correlate with the production data from the wind power plant. This approach by having both PVsyst data and real measured data was considered the best and most realistic to give representational output data. The horizon line and data used in the simulation is imported from the geographical site files.



(a) Temperature for 2022 [87].



(b) Total sun irradiation at Stokkfjellet each month.

Figure 3.4: Weather data of GHI and ambient temperature

3.3.2 System overview

To make a fully functioning PV system PVsyst needs information about many of the perimeters and components that are going to be used. The system orientation is one of the key factors to determine the system layout. This mainly includes the tilt and azimuth of the panels. These parameters are respectively set to 27° and 0°. The tilt is calculated by taking a 90° angle and subtracting the latitude of 63° as described in the theory Section 2.2.1. The azimuth is set to zero to catch the most sunlight as the sun rise in the east and sets in the vest.

The chosen PV module is bifacial. This will give additional production form the backside of the panel. PVsyst has a setting to estimate the bifacial features of the module. For this setting mostly default values have been used, but the albedo values for the ground were altered to represent the site more realistically. This was done because albedo values are extremely varying between different places and has a big impact on the loss off the bifacial system. The values were chosen by compering the table within PVsyst for different ground surfaces with the snow downfall through the year taken from Yr [87]. Snow is the most important factor for the albedo value since it changes the reflection off the ground and increases the albedo values drastically. This comparison resulted in the Table 3.2. It snows during the months of January, February, March and in April and December is some downfall but a bigger portion of consists of rain than the other months. The correlation between the albedo values and the amount of snow is shown by placing the Table 3.2 for the chosen albedo values and the Figure 3.5 for snow depth right above one another.

Table 3.2: Monthly albedo values.

January	February	March	April	May	June	July	August	September	October	November	December
0.82	0.82	0.82	0.70	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.5

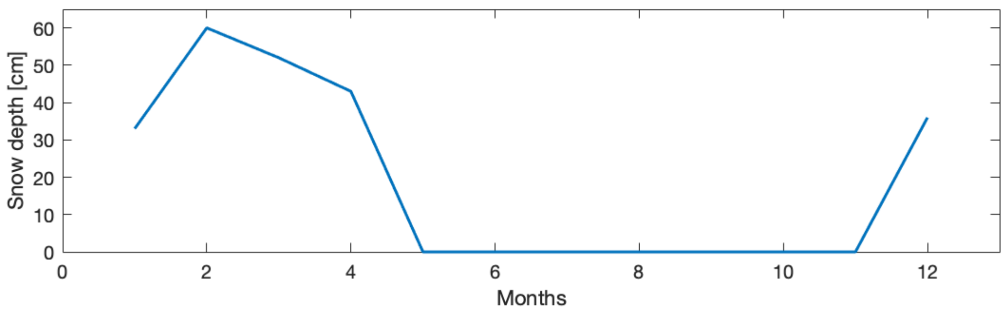


Figure 3.5: Snow depth measured for 2022

The system setup for the modules and the inverter were done to achieve a realistic and viable structure that is similar to what could actually be implemented at Stokkfjellet. The number of modules in series is set to 27 and number of strings to the inverter is always chosen to attain a PNom ratio of 1.44, where the multi-MPPT feature is used. The PNom ratio is the ratio between array nominal power at STC and the inverters nominal power as explained in theory Section 2.2.1. For optimal performance this should be 1, but that is unrealistic in the industry due to economical factors. Having more inverters to optimize production does not yield enough production to justify the purchase. All these parameter assumptions were made in cooperation with ANEO to be as realistic as possible. The values are therefore not specifically optimized for the project but are all in a reasonable realistic scope.

The pitch and elevation of the panels are chosen to $10m$ and $1.5m$. Normal ranges for the pitch are between $8m - 12m$ for bifacial modules and the optimal pitch can be found by empirically tests. This was not done in this study, the value was chosen based on the assumption of the bifacial module benefiting from the distance and reducing the possibility of snowdrifts. This is the phenomenon when blowing snow reduces the visibility, this can also create piles of snow between the panels. A lager pitch gives the snow more space and reduces the chance of this happening. The elevation is also chosen to accommodate the snow in the winter and is to avoid the panels being buried. [26, 88]

3.3.3 Detailed losses

For the detailed losses most perimeters are set to the default value. This includes the terminal loss value for "free" mounted modules with air circulation as stated in the theory 2.2.1, module quality, light induced degradation (LID), module mismatch losses, sting voltage mismatch losses, soiling loss and incidence angle modifier (IAM) losses. The aging of the components is not accounted for due to the simulation runs one year of production and the lifetime for the panels are 30 years [82].

The ohmic loss deals with all losses attributed to the cables and transformers in the system. To decide how many transformers and meters with cable one has to take into account a system boundary was decided upon. The PV-system as well as its boundary is presented in Figure 3.6. This boundary is the same in all simulations making more comparable results. The boundary is modeled after the 20% area and is therefore the most conservative estimate. The first assumption is that there will always be $600m$ from the inverters to the transformer and these cables have a wire section of $70mm$. The second assumption is that the distance from the transformer to the injection point is $1270m$ with a wire section of $50mm$. The distances are roughly measured from the concession area form Figure 3.3 and the wire sections are the ones proposed by PVsyst.

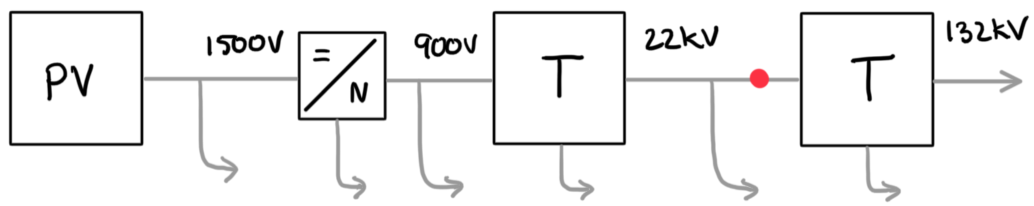


Figure 3.6: System boundary for the PV system.

For 20% of the concession area 39 transformers are needed. This would change with a decreasing area and production, however, this was not altered due to time limitations. If this had been done the number of transformers would have been reduced until they all achieved a rated power of 5 MW. This is a common transformer for industry use and therefore relatively cheap and easily accessible. As mentioned in the theory Section 2.4.2 the efficiency of the transformer is one of the highest for electrical components and for this reason it is expected that the losses from these are negligible in comparison with other factors of the system.

Since the system doesn't have production at night the feature "disconnect nighttime" was turned on. This prevents the system to draw power the hours it does not produce any energy. For a real installation this can only be done if the owner of the transformers agrees to this practice. Since the proposed park would be fully owned by ANEO, this is a reasonable assumption.

3.3.4 Output data

PVsyst gives output data mainly in the form of a report that is created for every simulation. This report consist of a system overview and a summery of the results. These results are all shown in monthly values and the total for the year. The report for the 10% area is attached in the appendix. Hourly production data is obtained by running an advanced simulation and enabling the output file for hourly data. This allows for many options of outputs, including all the table data given monthly in the report. The hourly data for the production is the one used in further calculations in MATLAB.

3.4 Scenario 1

The first calculation made in MATLAB was calculating the size of the area being used in PVsyst. There was first explored an option of finding how much production would be ideal, and what area does this production need using a theoretical approach. However, this approach did not correspond well with using PVsyst as a simulation tool. Instead, there was calculated a production for a percentage of the concession area where all calculations were done for all areas to see if one was more beneficial than another.

To be able to calculate how the transformer would limit the solar production, ANEO provided data from the wind production from 2022. However, this last year there was a cutoff period during the summer and no power was produced. To be able to calculate as tho there was production, ANEO sent us AI generated data that simulated what a regular year would look like. This was done since the park was finished in 2021 and they did not have a full years worth of wind data without the cutoff period. The measured data and AI generated wind data is presented in Figure 3.7. These data sets are presented in the appendix. The output effect of a turbine correlated to the wind speed, as was presented in 2.1. Figure 2.2 show the general correlation between output power and wind speed, which correlates well with the power plot, Figure 3.7, since there is more and higher wind speeds during winter and fall.

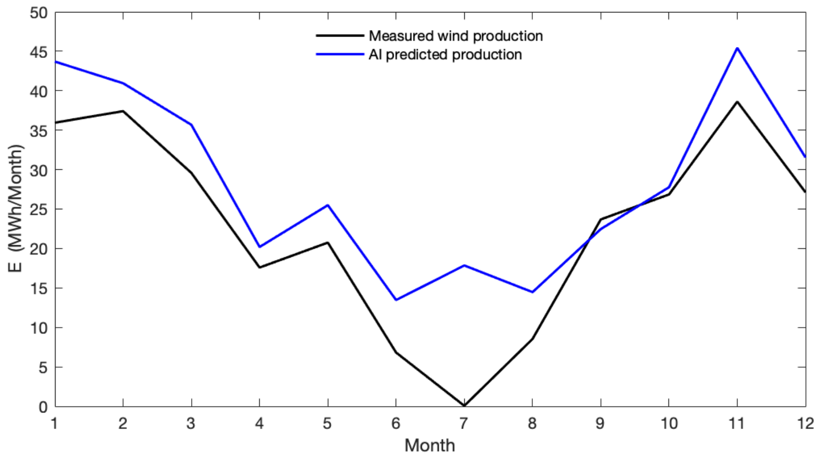


Figure 3.7: Wind production from Stokkfjellet.

To show how the solar production would add to the wind production at Stokkfjellet all 20 matrices with hourly production for a year was imported into MATLAB. Then the solar production was added to the wind production. This was done to see how much of the combined production would go over the 90 MW limit of the transformer. All power above the limit of the transformer was then peak shaved, since this power would get lost in reality and would therefore not contribute to the power that would be sent out on the grid. Since there is only solar power that would exceed the limitations of the transformer, if one subtracts the overproduction from the solar production the matrix left contains all solar power that's sent out to the grid. These calculations are presented in the attached files from MATLAB.

Here there was made an assumption that all energy produced can be sent out on the grid whenever its produced and room in the transformer. This was assumed since there was no data available as to what volume was needed each hour of the year. There was also made a decision that including this variable would be too large a task, and take away from the scope not contribute to it.

3.4.1 Financial Calculations Scenario 1

The possible economic benefit when creating a hybrid park will be calculated by using the NPV method. In order to do so, each scenarios different aspects has to be taken into consideration. Finding the initial costs related to each system, as well as using the different production matrices in order to calculate profit will therefore be key.

Each of the three scenarios will use euro(€) as the chosen currency. The most important reason for this is the prices given by ANEO are given in euro. The installation and maintenance costs are both given in euro, as well as the NO3-table in the Appendix which has €/MW as its unit of measurement. This table shows the price of energy for the NO3-area i Norway, which is the area that Stokkfjellet resides in, and was given to the group by ANEO. Another thing to take into consideration is the general volatility of currencies, which is a factor that will become more sensitive when converting between different currencies. After the group used the conversion rate from the Norwegian Bank to convert euro to Norwegian krones, it was concluded that the effect this had on the results were to significant to justify keeping. It was therefore decided to stick with a single currency during the calculations.

The assumed installation cost, as well as the operational costs of the park were also given by ANEO. They are presented in Table 3.3. These numbers are important to calculate the net revenue to the park. These costs will be added as initial investment costs when calculating the NPV of the different areas, and will also be used in the other two scenarios.

Table 3.3: Initial investment costs for PV-system.

Equipment	Amount	Unit
Capital cost (PV-system inc. inverter)	600,000	€/ MW
Development costs	100,000	€
Energy management	100,000	€/ year
Operation cost (Land lease)	3% of profit	-

The matrix created in the previous section showing the power sent to the grid from solar production is then multiplied by the NO3-prices for each hour.This results in a matrix that shows the profit made every hour for a year for every area. The total profits are then calculated by summing up the profits for each area.

The NPV will be calculated by using equation 2.1, presented in Section 2.7. The time period chosen for each scenario is 30 years, which is the remaining concession time for Stokkfjellet, as well as being the time frame given by ANEO. The internal rate was set to be 3%, which was the national policy rate during the data collection for this project. The land lease is calculated by multiplying the profits by 0.03, in order to show the percentage of profits added every year. This is then added to the maintenance costs, and multiplied by the time frame of 30 years in order to present the steady yearly costs. When all the investment costs have been inserted into the equation, as well as the total profits, the NPV is calculated by summing up the present value for each of the 30 years and subtracting the initial investment cost in order to get the NPV. All the financial calculations are presented in the attached files, which shows the MATLAB script for each scenario.

3.5 Scenario 2

In scenario 2 the overproduction will be peak shaved and stored in a battery. The same simulated solar production and wind production was used in this scenario as was in scenario 1. The code for scenario 2 is presented in the attached files.

To find the dimensions of the battery to peak shave the overproduction a for loop was created. This for loop takes in the matrix with overproduction and sums up all values each day. The battery was then dimensioned after the max value in this matrix for all the twenty different areas. This would ensure that the battery would be able to peak shave all values each day without reaching 100% state of charge while doing so. As mentioned in Section 3.3.4, the PV system will be shut off during the night as to not consume energy while no power is produced, therefore it will be possible to empty the battery each night to peak shave again the day after.

The battery decided upon is a NMC battery pack from Northvolt, specifically designed for delivering sustainable power and rapid deployment. The specifications of the battery is presented in Table 3.4. This battery was decided upon since it is easily scalable as well as having the right frequency. There was explored the possibility of using two battery systems for the different operations, however, the investment cost of this was so large it was decided against.

Table 3.4: Battery specifications [89].

Product name	Volthub Grid
Connection frequency	50 Hz
Operating voltage	360-400 VAC
Max supply power	225 kVA
Max load power (peak shave)	275 kW
Dimensions	1600mm x2000mm x1200mm
Weight	2300kg

Using the ISO standard for containers, the batteries were dimensioned to fit as many battery packs as possible in one container and add together the max load power for all battery packs to find how much capacity one container had. As the ISO standard for the largest container is 19.4 ft x 7.8 ft x 7.8 ft, this will fit 16 battery packs. This results in each container having a max load power of 4.4 MW.

Considering the main goal is to have a viable park at 10% area, it was decided that the batteries would be dimensioned to cover max day production up until 10%. The amount of containers needed for each percentage was determined by dividing the max day production by the container capacity and then rounding those numbers up, making sure all all energy would have room.

A for loop was created to determine how much energy every percentage of area would lose. This summed up all consecutive numbers in the matrix with all values where the battery was charged. This was done by first creating a matrix with ones where the charge and discharge matrix had a positive value and zeros where there were no charging or that battery was discharging. After this a function was made to give out a matrix that determined which place in the first matrix the value went from zero to one and then from one to zero. This matrix as well as the original matrix with charging values was then put through a for loop that summed up all values from where zero became one until one became zero.

The capacity for each container was then subtracted from the matrix with all consecutive values summed up. All values above the containers capacity was then presented in a matrix each hour of the year. This was then subtracted from the matrix with the overproduction since this would not be able to be stored in the battery.

To find how much power would be sent out on the grid from the battery another for loop was created. The for loop takes in a matrix with the charge, without the amount lost due to the lack of space in the container, as well as a matrix with the amount available in the transformer. The for loop then creates a matrix with how much power will be sent out on the grid every hour after charging the battery. In this scenario as well there was made an assumption that all energy stored can be sent out on the grid whenever there is room in the transformer.

3.5.1 Financial Calculations Scenario 2

In this scenario the overproduced power that was lost in scenario 1 will be stored in a battery and sent out on the grid at a later time. As mentioned in Section 3.5, it is assumed that all electricity stored can be fed out on the grid whenever there's room in the transformer.

The matrix created in Section 3.5, showing the power sent out by the battery for each hour of the year, was added to the matrix showing the hourly production under the transformer limit. This was then multiplied by the NO3-prices, and subsequently summed up. The result is then the total profits gained from both selling the produced power under the limit, as well as the power delivered by the battery.

After the total profits from scenario 2 have been calculated, the costs associated will have to be determined in order to calculate the NPV. The costs coming from the installation of solar panels are the same as in scenario 1, and it is therefore the implementation of the BESS that will make the most significant impact on the initial investment cost.

Finding an estimate for the cost of the BESS proved to be difficult. While there existed some theoretical estimates, they varied widely. After a conversation with several suppliers, the final estimate became from 500 000 €$/MW$ to 800 000 €$/MW$, depending on the size of the installation. An assumption is made that an increase in the volume of batteries purchased means that the euro per MW decrease. The battery prices for each percentage of production area has therefore been calculated using a linear price regulation method, where the euro per MW decreases with an increase in capacity needed. This is done by setting the price for the starting volume of 1 MW to 800 000 €, and the maximum volume to 500 000 €. The maximum volume set is at 300 MW. A formula for linear regression was then used to calculate the change in price for each increase in volume. The price for each of the area volumes was then multiplied by the number of battery containers needed for each area. The result is a matrix showing the battery costs associated with each production area. This will then be added to the initial investment cost of the scenario. The NPV will then be calculated by using the investment cost and the total profits made from both the BESS and the solar production under the transformer limit. The method for calculating the NPV will then be the same as in scenario 1.

3.6 Scenario 3

In this scenario the solar production will first and foremost be used to sell in the frequency market. The same solar production that was simulated in scenario 1, and used in scenario 2, will also be used in this scenario. The code for scenario 3 is presented in the attached files. The code overlaps with scenario 2 so all calculations for the frequency market is presented in Scenario 3, while the battery dimensioning is presented in the same script as scenario 2.

Statnetts has the control and data over the secondary frequency reserves. There were four different markets to chose from, D-1 and D-2 and FCR-N and FCR-D. These markets were explained in Section 2.6.2. Considering that the PV system, together with the battery, will stand for most of the production the FCR-N D-2 marked was decided upon since the volume requirement was slightly lower than the other markets. Figure 3.8 shows the hourly demand for the FCR-N D-2 market for 2022.

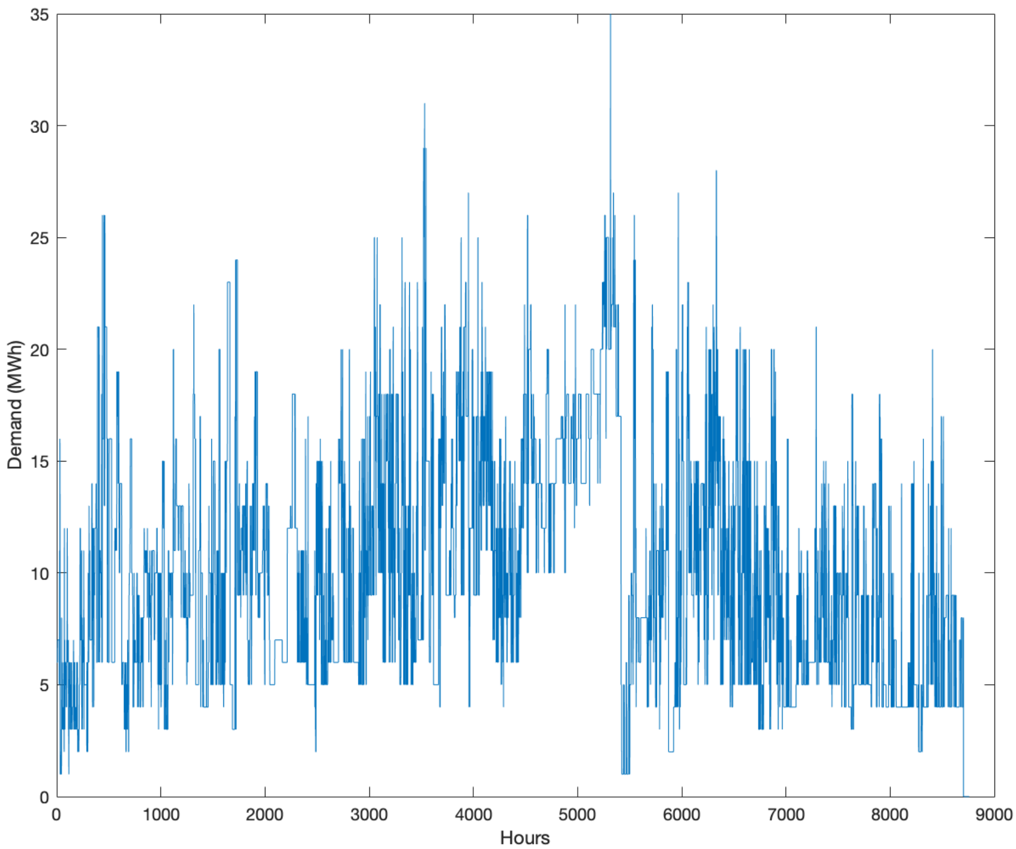


Figure 3.8: FCR-N Demand for 2022. [90]

There was first explored selling in the frequency market with just the overproduction, however this proved to be quite few hours of the year. Therefore it is assumed that all solar production that meets the market demand will be sold in the FCR-N market instead of the regular market.

With this assumption it is also assumed that every time there is enough power it will be sold.

The data on the FCR-N volume and price was then imported to MATLAB. This data set does not distinguish between the different market areas. By this it is meant that for 00:00 on 01.01.22 all values are listed for NO1 to NO5, and then for 01:00 and so on. Therefore the first thing that was determined in MATLAB were all places for NO3 and after this the data for NO3 were extracted from the imported file.

In the data set from Statnett there is not listed any value if the volume for an hour equals 0. Because of this, when the values for NO3 are extracted there is only 8704 values instead of 8760, which are the amount of hours in a year. The attempts to figure out how to place where the zero values should go had no results, therefore they were all added to the end of the year. These hours would not have resulted in any profit, and it is assumed that the price difference would not differ too much if they were placed correctly.

The data set from Statnett does also not have any signs indicating if the volume need that hour is to withdraw or add to the grid. This is because the company has to have the capacity of that volume that hour. This is here assumed that to any given time the volume has to be able to either be added or withdrawn. This has to be taken under consideration when calculating the dimensions of the battery and the profits.

It was explored to use two battery systems for the two operations, one for frequency regulation and one for peak shaving. This was dismissed due to a report written by Elian Pusceddu et al. exploring the use of two battery system for peak shaving and arbitrage contrary one. The report concluded that it was more beneficial having the low investment cost of one battery for both applications. [91]

Calculating the dimensions for the battery in this scenario was very similar to scenario 2 which was explained in Section 3.5. In this case the battery was dimensioned to store both the overproduction and all volumes for the frequency market. This way, the battery would be able to take up both the overproduction and scale down the production for the FCR-N market. Considering the benefits and disadvantages of using either a single- or two-battery system, which is presented above, a single-battery system was chosen for this scenario.

The battery was still dimensioned to store the max day production, only this time with both the overproduction and frequency market volume. In this scenario as well it was decided that the batteries would be dimensioned to cover max day production up until 10% of the area. Using the same size and capacity for containers as scenario 2, the amount of containers needed to store the value of power was then calculated for all percentages of area up until 10%. After this, the new variable with power needed to be stored was sent through the same function and for loop as was made in scenario 2 to sum up all consecutive values. The capacity for each container was then subtracted from that matrix finding all power that would exceed the battery dimentions. This was then subtracted from the overproduction and frequency market volume matrix creating a matrix showing how much the battery would be charged every hour of the year.

The charge matrix was then sent through the second for loop made in scenario 2 finding how much power would be sent out on the grid every hour after charging the battery. In this scenario as well there was made an assumption that all energy stored can be sent out on the grid whenever there is room in the transformer.

3.6.1 Financial Calculations Scenario 3

As previously mentioned, scenario 3 introduces a new revenue stream in the form of the frequency market. When calculating the revenue gained from this scenario, the FCR-N prices have to be used as well as the NO3 prices for the volumes sold.

In order to calculate the profits gained from participation in the FCR-N market, the volume sold throughout the year needs to be found. The matrix showing the volume sold in the freqency market for each hour is multiplied by the FCR-N-price matrix to calculate the revenue gained from frequency regulation [90].

However, as mentioned in the previous section, for certain periods the amount of energy stored in the battery will surpass the volume needed in the frequency regulation, or it will be too small. The excess energy will therefore be sold to the energy market at the normal NO3-price. The script that was created to calculate this in MATLAB is shown in the attached files. The matrix that shows the overproduction for each hour will be multiplied by the NO3-price in order to calculate revenue gained from selling in the energy market. This additional revenue is then added to the revenue gained from FCR-N, showing the total revenue.

The cost of each BESS is calculated using the same method used in Section 3.5.1. When the BESS cost for each area has been determined, it will then be added to the initial investment costs. The NPV calculation will therefore take into consideration the increasing costs associated with expanding area.

4 Results

All of the results from the simulation in PVsyst and calculations in Matlab will be presented in this section. The calculations will build on the results of the simulations. When displaying specific results where the data is only graphed for one area, this will be the 10% area.

4.1 PVsyst

The simulation result from PVsyst were the first to be produced. This is because all further calculations are based on these simulation. These results will mainly include the hourly production data for all twenty areas. There will also be produced reports for all the simulations, the report for 10% is shown in the attached files. The other reports are equivalent to this and the same information is represented.

The hourly production for all the simulations are shown in Figure 4.1, here all production is summed up for each month. There is a clear correlation between more production and increased area size, and it also seems to be a linear relationship. The exception is area 17 which has quite a smaller leap from area 16 than the other leaps, as both shown in the Table 4.1 and shown in Figure 4.1. This is because this is where the largest lake within the concession area, see Figure 3.3, is placed included. This leads to some of the production area being lost. This will influence the further results.

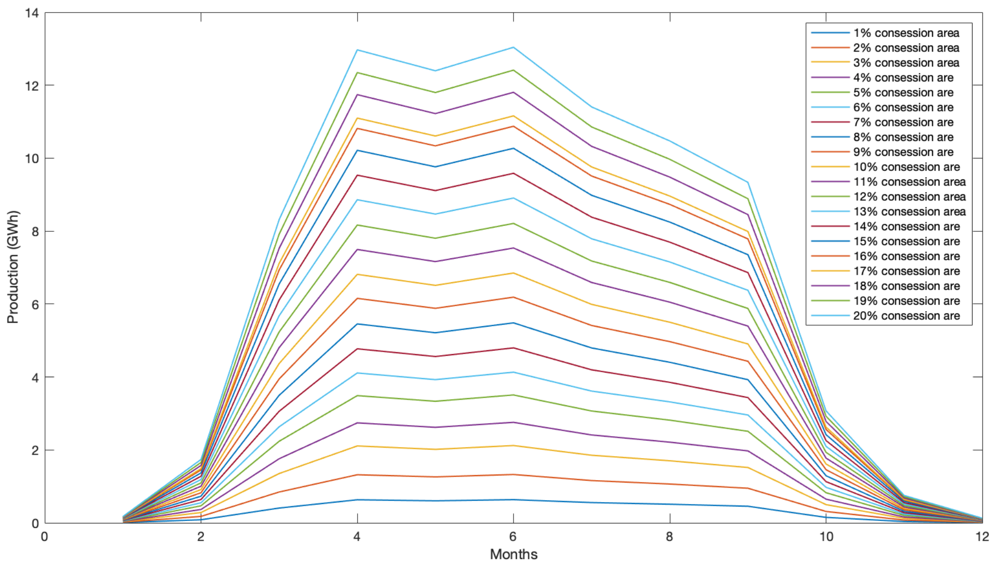


Figure 4.1: Production from all areas.

In Table 4.1 the yearly results for the PVsyst simulation are presented. All of this information is collected form the generated reports that follow the simulations, where the 10% area report is in the attached files. The different areas are presented as both percentages of the original concession area, as well as in square meters. Since the areas are hand drawn in to the simulation program, the precise areas used in PVsyst is also represented. The difference between the actual and simulated areas never exceeds 1 m^2. The corresponding yearly production and number of modules are also shown. All of these results follow the same linear progression and plotting the modules for the corresponding areas would give a figure very similar to Figure 4.1.

Table 4.1: Overall results from PVsyst

Percentage	Area $[m^2]$	Area measured in PVsyst $[m^2]$	Yearly production $[MWh]$	Number of modules [-]
1%	58,000	58,000.68	4,094	8,910
2%	116,000	116,000.31	8,528	18,576
3%	174,000	174,000.13	13,629	29,700
4%	232,000	232,000.82	17,715	38,610
5%	290,000	290,000.91	22,544	49,140
6%	348,000	348,000.30	26,554	57,888
7%	406,000	406,000.71	30,836	67,230
8%	464,000	464,000.06	35,241	76,842
9%	522,000	522,000.16	39,769	86,724
10%	580,000	580,000.43	44,024	96,012
11%	638,000	638,000.56	48,430	10,5624
12%	696,000	696,000.43	52,760	115,074
13%	754,000	754,000.97	57,237	124,848
14%	812,000	812,000.72	61,589	134,352
15%	870,000	870,000.23	65,995	143,964
16%	928,000	928,000.72	69,879	152,442
17%	986,000	986,000.45	71,706	156,438
18%	1,044,000	1,044,000.37	75,860	165,510
19%	1,102,000	1,102,000.31	79,766	174,042
20%	1,160,000	1,160,000.93	83,795	182,844

The loss diagram is presented in the report in the attached files, and in Figure 4.2. It gives a look at the system and where it looses potential production. This is important information for anyone that want to study the system.

The contributors to production is primarily divided in two. It is the regular GHI radiation, with some contribution from the global incident in collective plane which is the transposition of the irradiance from horizontal to the plane of the array, and the bifacial additional production. The biggest losses for the regular production is the far and near shading, the soiling loss and the IAM factor. The shading is dependent on the horizon and physical parameters like the pitch of the system.

The biggest impact on the bifacial production input is the albedo values which takes away almost 70% of the potential. The view factor for the rear end also takes out a significant part of the production and it leaves the input from the bifacial at around 20% of its potential.

At the mid point of the diagram the figure is cut in two, this marks the combination of the regular production and the bifacial contribution, and it also shows the efficiency of the system at STC. In the lower half of the figure all the other small losses are listed. This includes the losses from the chosen module and inverter, and the ohmic losses linked to the cables and components. Finally the energy injected in to the grid is shown at the bottom of the figure. A more thorough explanation on the loss diagram can be found on the PVsyst website and in their tutorial videos [92].

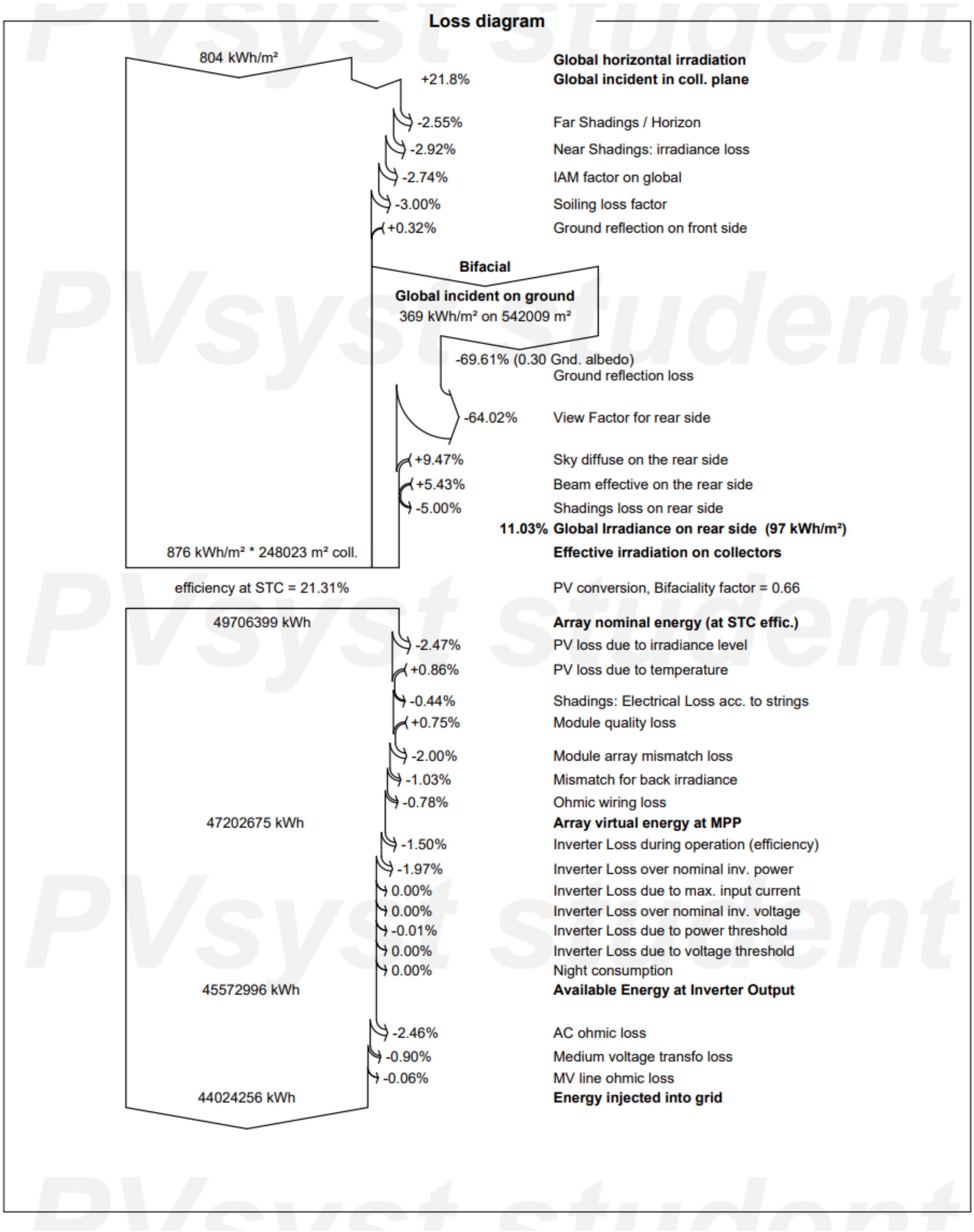
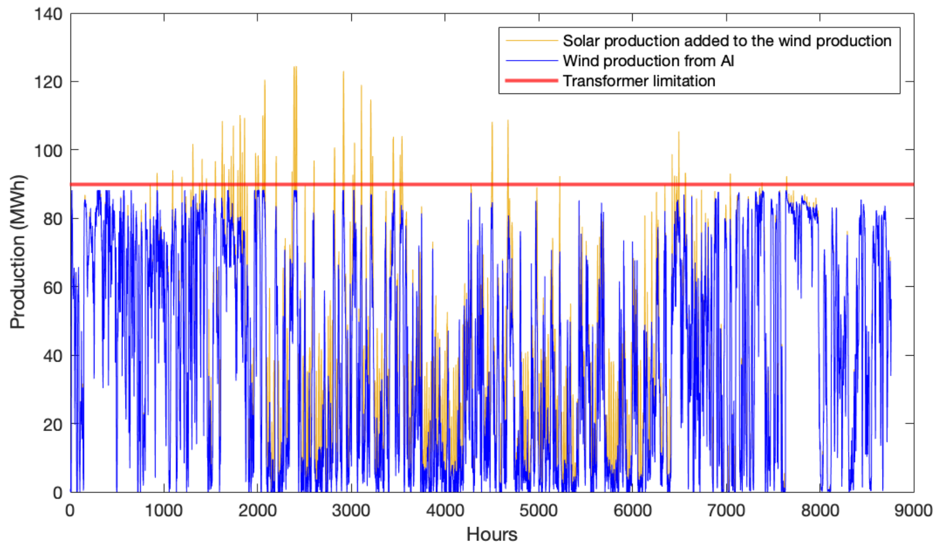


Figure 4.2: The loss diagram from the simulation of the 10% area.

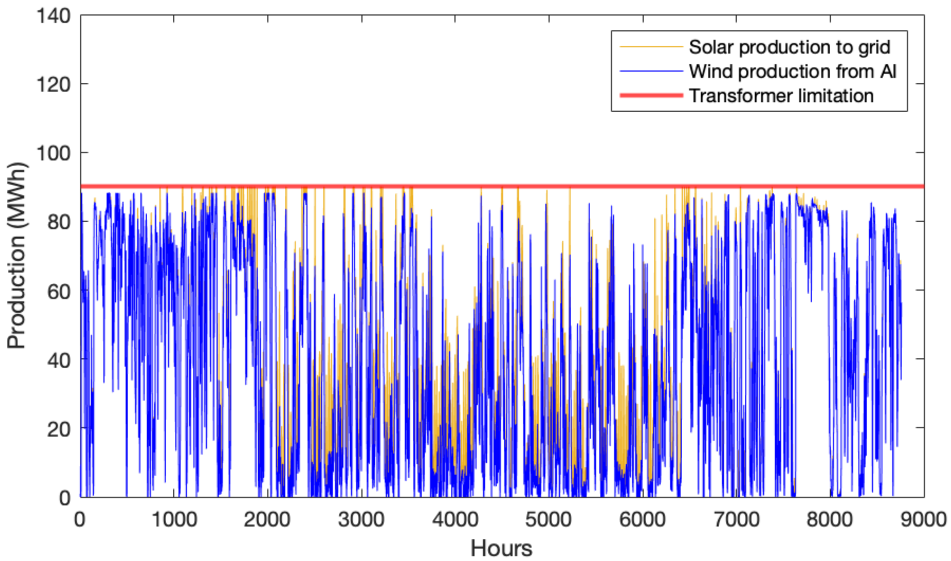
AS mentioned these results will be used in the calculations for all the scenarios. Primarily the hourly production data is used as the distribution of solar power over one year and makes basis to create the hybrid park.

4.2 Scenario 1

Scenario 1 explores the viability of implementing solar power alone in the wind park. As explained in Section 3.4 the solar power was added to the wind power to see how much power could be sold under the transformer limit. Figure 4.3a shows wind and solar production plotted together. Since there is no storage, all production above the transformer limit will be lost. Therefore all energy sent out on the grid, and contributing to the profit, is presented in Figure 4.3b. This is shown for 10% of the concession area. There is more power that is lost during spring considering there is also a relatively high wind production at the same time.



(a) Solar and wind production plotted together.



(b) Solar and wind production plotted together with no overproduction.

Figure 4.3: Production for 10% of the concession area.

The yearly solar energy production for each area for scenario 1 is presented in Table 4.2. This is after all overproduction is peak shaved as shown in Figure 4.3b, but for all the different percentage areas. With a higher yearly production there is a bigger loss of energy, but also more profitable production.

Table 4.2: Yearly energy sent out on the grid for scenario 1

Percentage of area	Energy [MWh]
1%	4,079.5347
2%	8,438.0330
3%	13,398.3146
4%	17,340.8026
5%	21,955.7962
6%	25,737.9706
7%	29,734.6549
8%	33,800.6418
9%	37,926.0961
10%	41,737.3263
11%	45,620.3335
12%	49,393.6354
13%	53,249.5728
14%	56,950.4033
15%	60,651.0143
16%	63,876.8864
17%	65,376.5645
18%	68,747.4616
19%	71,868.9082
20%	75,049.9017

In total for this scenario there are no notable oddities in results and they follow the same pattern as the simulated results with higher production on lager areas, also after the losses. The hourly data sets form all the areas is used as a base for the economical calculations in the next section.

4.2.1 Financial results scenario 1

The financial results from scenario 1 will be presented in this section, which includes both the yearly profit and NPV values. As explained in Section 3.4.1, the yearly profit is calculated by multiplying the hourly production values found and the spot prices for the energy market for NO3 given from ANEO. These profits are presented in Table 4.3, along with the corresponding NPV. The results show that the profits positively increases with a bigger area, while also showing a negative correlation between the NPV and the area size.

Table 4.3: Yearly profits and NPV for scenario 1

Percentage of area	Yearly profit (EUR [€])	NPV [-]
1%	120,261.0558	-3,683,130
2%	249,438.5142	-4,340,975
3%	397,356.3312	-5,112,641
4%	515,439.5816	-5,738,457
5%	654,493.7523	-6,487,834
6%	769,340.8156	-7,123,620
7%	891,317.9990	-7,815,674
8%	1,015,820.3912	-8,547,332
9%	1,142,132.7233	-9,332,615
10%	1,259,092.8300	-1,010,5185
11%	1,378,706.7456	-1,093,2659
12%	1,495,329.1024	-1,176,5310
13%	1,614,863.2599	-1,264,7807
14%	1,729,425.6182	-1,353,8655
15%	1,844,032.6728	-1,446,4266
16%	1,944,183.2788	-15,299,010
17%	1,990,858.7712	-15,702,829
18%	2,096,070.6058	-16,634,391
19%	2,193,843.7195	-17,533,555
20%	2,293,640.0155	-18,482,163

The correlation between area size and NPV is visualized in Figure 4.4, which is a plot of the area percentage and NPV. Similarly to Table 4.3, the plot shows a change in the linearity of the graph between 16% and 17%, with the change in profits not having the same trend as the other percentages. This result is consistent with the findings found in Section 4.1.

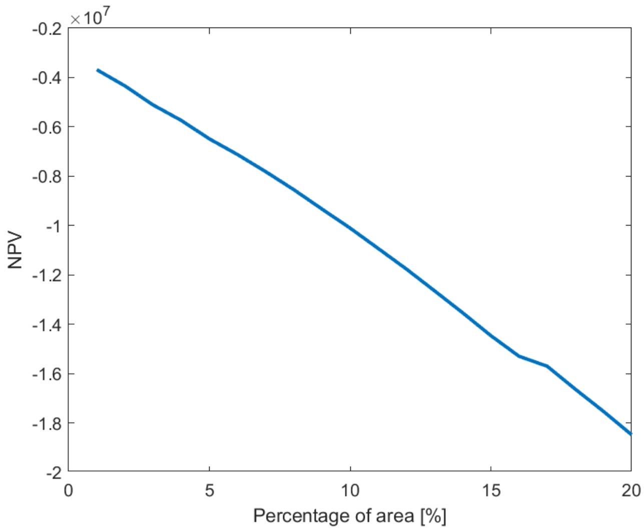


Figure 4.4: NPV for the different areas in Scenario 1.

The change in NPV at different cost reductions related to the solar panels are displayed in Table 4.4. For each percentage of area, the corresponding NPV is shown at different percentages of the original cost.

Table 4.4: NPV for all areas with cost adjustment for scenario 1

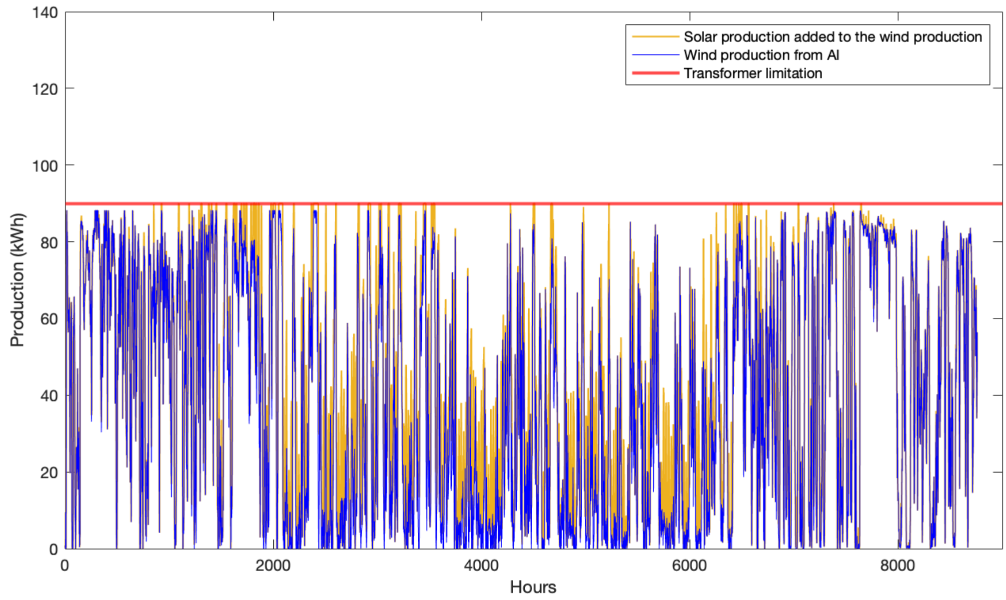
	NPV at percentage of original cost				
Percentage of area	90%	70%	50%	30%	10%
1%	-3,389,100	-2,801,040	-2,212,980	-1,624,920	-1,036,860
2%	-3,727,967	-2,501,951	-1,275,935	-49,919	1,176,097
3%	-4,132,541	-2,172,341	-212,141	1,748,059	3,708,259
4%	-4,464,327	-1,916,067	632,193	3,180,453	5,728,713
5%	-4,866,214	-1,622,974	1,620,266	4,863,506	8,106,746
6%	-5,213,316	-1,392,708	2,427,900	6,248,508	10,069,116
7%	-5,597,084	-1,159,904	3,277,276	7,714,456	12,151,636
8%	-6,011,546	-939,974	4,131,598	9,203,170	14,274,742
9%	-6,470,723	-746,939	4,976,845	10,700,629	16,424,413
10%	-6,936,789	-599,997	5,736,795	12,073,587	18,410,379
11%	-7,447,067	-475,883	6,495,301	13,466,485	20,437,669
12%	-7,967,868	-372,984	7,221,900	14,816,784	22,411,668
13%	-8,527,823	-287,855	7,952,113	16,192,081	24,432,049
14%	-9,105,039	-237,807	8,629,425	17,496,657	26,363,889
15%	-9,713,454	-211,830	9,289,794	18,791,418	28,293,042
16%	-10,268,424	-207,252	9,853,920	19,915,092	29,976,264
17%	-10,540375	-215,467	10,109,441	20,434,349	30,759,257
18%	-11,172,561	-248,901	10,674,759	21,598,419	32,522,079
19%	-11,790,169	-303,397	11,183,375	22,670,147	34,156,919
20%	-12,448,311	-380,607	11,687,097	23,754,801	35,822,505

The results show that at a reduction of 10% to 30%, the NPV still remains negative. However, NPV still increases by a significant amount. At a 50% cost reduction, the NPV becomes positive for every area over 3%, meaning that the investment is profitable for these areas. For a 70% decrease in costs, the NPV becomes positive at an area of 3%. The trend continues for the last two reductions, with the area percentage needed for a positive NPV reaching 3% for a cost reduction of 70%, and 2% for a reduction of 90%.

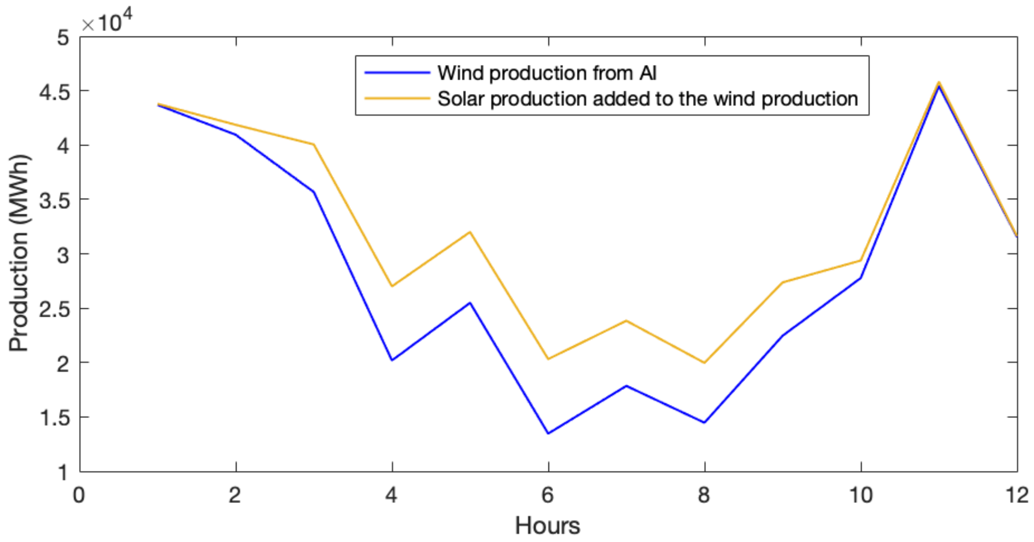
4.3 Scenario 2

In scenario 2 all overproduction is stored in a battery and then delivered out on to the grid at the first possible opportunity. The PV-system is turned off at night but the battery can still operate independently, which often means most discharges happens at night. Figure 4.5a show the solar power on top of the wind production. The solar power includes the power sent out on the grid from the battery for 10% of the concession area. This is almost indistinguishable from Figure 4.3b. This is because the amount of solar energy stored by the battery is relatively inconsequential compared to the rest of the solar production.

Figure 4.5b show the summed up monthly data from Figure 4.5a. This shows how much in total every month the PV- and battery- system contributes to increased power production. All production is within



(a) Hourly production with power from battery peak shaving.



(b) Monthly production with power from battery peak shaving.

Figure 4.5: Production with power from battery peak shaving for 10% of the concession area.

In Figure 4.6 the charge and discharge of the battery through the year is presented for 10% of the concession area. The positive numbers are the charge and the negative are the discharge. All this is done within the transformers limit. Just as shown in Figure 4.3a, there is much more overproduction during the spring months than the rest of the year.

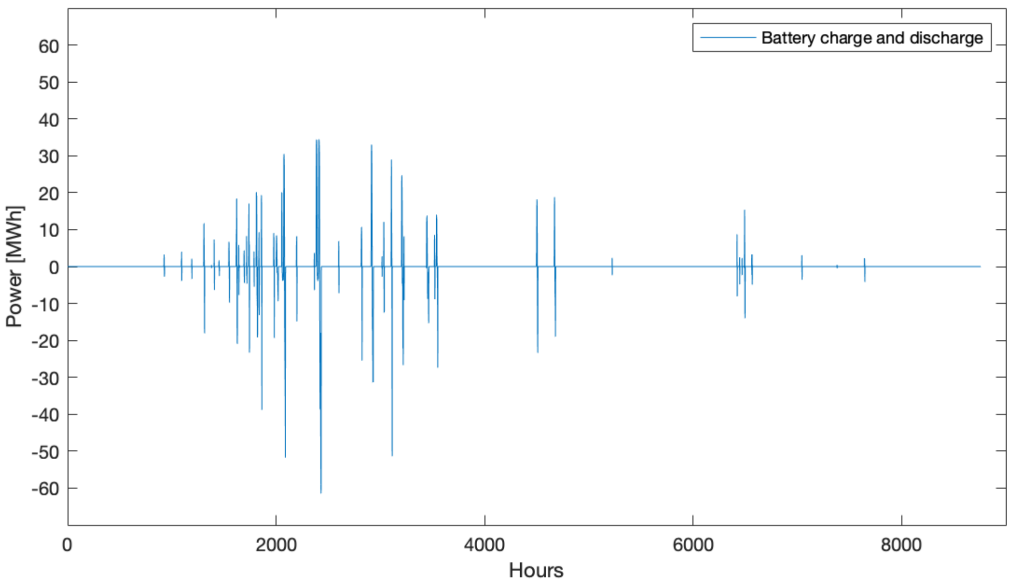


Figure 4.6: Battery peak shaving and output.

The batteries are dimensioned to cover the max day production up until the 10% area, as explained in Section 3.5. The results from the battery dimensioning are shown in Table 4.5. This includes the amount of energy stored, battery containers needed and how many hours and volume will be lost due to lack of battery capacity. As expected, as long as the battery containers are dimensioned to cover a whole day of production no power will be lost. The amount lost when the battery is not dimensioned for is quite unsubstantial.

Table 4.5: Yearly results battery scenario 2

Procentage of area	Energy stored [MWh/year]	Containers with battery	Energy lost [MWh/year]	Hours with lost energy
1%	14.6048	2	0	0
2%	89.5369	8	0	0
3%	231.1533	15	0	0
4%	374.5034	21	0	0
5%	587.7062	29	0	0
6%	816.2656	35	0	0
7%	1101.0585	42	0	0
8%	1440.2844	49	0	0
9%	1842.9385	56	0	0
10%	2286.9243	63	0	0
11%	2755.3984	63	54.6546	2
12%	3242.2816	63	124.0935	3
13%	3765.9669	63	221.8095	4
14%	4298.0946	63	340.7461	4
15%	4882.8917	63	461.0883	4
16%	5435.4211	63	567.1766	4
17%	5712.4388	63	617.1466	4
18%	6355.3501	63	756.8526	6
19%	6976.0163	63	920.7868	7
20%	7617.1755	63	1128.2712	9

The yearly energy sent out on the grid from the PV-system for scenario two for each area is presented in Table 4.6. This includes all power that was stored in the battery and sent out on the grid at a later time.

Table 4.6: Yearly energy sent out on the grid

Percentage of area	Energy [MWh]
1%	4,094.1395
2%	8,527.5700
3%	13,629.4679
4%	17,715.3060
5%	22,543.5024
6%	26,554.2362
7%	30,835.7134
8%	35,240.9262
9%	39,769.0346
10%	44,024.2506
11%	48,430.3336
12%	52,759.8864
13%	57,237.1274
14%	61,588.9033
15%	65,994.5332
16%	69,878.9169
17%	71,705.5327
18%	75,858.9074
19%	79,764.7905
20%	83,794.2201

In summary the production is slightly higher, but not significantly. The loss in overproduction is 0 up until the 11% area and from there the losses increases linearly. The battery is most active in the spring and early summer when there is a substantial amount of energy produced for both wind and solar. The discharge happens mostly at night when the PV system is inactive. As in the previous scenario, all the hourly results for the areas is used in the economical calculations.

4.3.1 Financial results scenario 2

As explained in Section 3.5.1 the profit in scenario two is calculated fairly similar as scenario 1. In this case however, the power sent from the battery to the grid was added to the solar production under transformer limit and then profits were determined from these production numbers. In Table 4.7 the yearly profits for each area are presented along with the corresponding NPV.

Table 4.7: Yearly profits and NPV for Scenario 2

Percentage of area	Yearly profit (EUR [€])	NPV
1%	120,523.4310	-10,649,118
2%	251,230.8183	-31,257,979
3%	402,279.6039	-53,511,794
4%	523,097.4075	-71,034,754
5%	666,063.4485	-92,132,875
6%	785,083.6897	-106,374,250
7%	912,251.3422	-121,165,531
8%	1,043,207.5467	-134,068,029
9%	1,177,853.6133	-145,083,679
10%	1,304,948.5000	-154,147,690
11%	1,437,827.4880	-154,715,163
12%	1,569,493.8407	-155,252,944
13%	1,705,085.8852	-155,820,700
14%	1,836,490.2951	-156,381,436
15%	1,971,233.4574	-156,912,370
16%	2,097,297.5855	-157,239,198
17%	2,156,573.5575	-157,396,043
18%	2,291,635.8998	-157,742,521
19%	2,417,291.5439	-158,095,175
20%	2,541,179.7671	-158,571,571

The results show that all the NPV values are negative for every area, and that it becomes more negative for each increase in percentage. As explained in Section 3.5.1, the initial investment cost of scenario 2 will increase because of the added installation cost associated with the BESS. The negative correlation between NPV and area size is presented in Figure 4.7, with the NPV on the y-axis and the area percentage on the x-axis.

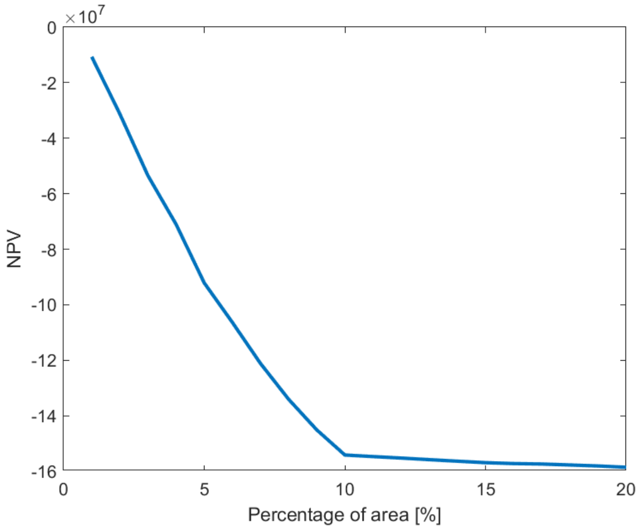


Figure 4.7: NPV for the different areas.

The graph shows that the NPV will decrease quite dramatically up to 10%, at which the graph normalizes for the last area percentages. The NPV value associated with the reduction in initial investment cost is presented in Table 4.8. Here the different reductions are shown as percentages of original cost, going from 90% to 10%.

Table 4.8: NPV for all areas with cost adjustment for scenario 2

	NPV at percentage of original cost				
Percentage of area	90%	70%	50%	30%	10%
1%	-10,355,088	-9,767,028	-9,178,968	-8,590,908	-8,002,848
2%	-30,644,971	-29,418,955	-28,192,939	-26,966,923	-25,740,907
3%	-52,531,694	-50,571,494	-48,611,294	-46,651,094	-44,690,894
4%	-69,760,624	-67,212,364	-64,664,104	-62,115,844	-59,567,584
5%	-90,511,255	-87,268,015	-84,024,775	-80,781,535	-77,538,295
6%	-104,463,946	-100,643,338	-96,822,730	-93,002,122	-89,181,514
7%	-118,946,941	-114,509,761	-110,072,581	-105,635,401	-101,198,221
8%	-131,532,243	-126,460,671	-121,389,099	-116,317,527	-111,245,955
9%	-142,221,787	-136,498,003	-130,774,219	-125,050,435	-119,326,651
10%	-150,979,294	-144,642,502	-138,305,710	-131,968,918	-125,632,126
11%	-151,229,571	-144,258,387	-137,287,203	-130,316,019	-123,344,835
12%	-151,455,502	-143,860,618	-136,265,734	-128,670,850	-121,075,966
13%	-151,700,716	-143,460,748	-135,220,780	-126,980,812	-118,740,844
14%	-151,947,820	-143,080,588	-134,213,356	-125,346,124	-116,478,892
15%	-152,161,558	-142,659,934	-133,158,310	-123,656,686	-114,155,062
16%	-152,208,612	-142,147,440	-132,086,268	-122,025,096	-111,963,924
17%	-152,233,589	-141,908,681	-131,583,773	-121,258,865	-110,933,957
18%	-152,280,691	-141,357,031	-130,433,371	-119,509,711	-108,586,051
19%	-152,351,789	-140,865,017	-129,378,245	-117,891,473	-106,404,701
20%	-152,537,719	-140,470,015	-128,402,311	-116,334,607	-104,266,903

The decrease in costs can be seen to have a positive effect on the NPV for each area. Still, while the NPV does increase, it never reaches a positive value. This means that even if the initial investment costs of the project where to decrease by 90 percent, the project would still not be a profitable investment.

4.4 Scenario 3

As explained in Section 3.6 all solar production as well as power from the battery would take part in selling volumes in the frequency market. Figure 4.8 shows how much volume every hour of the year the PV-system produces, yellow, and how much can be sold in the frequency market, blue. The yellow is all energy from solar and battery fed out to the grid. This plot shows that while one can sell in the frequency market, there would still be a notable amount of energy to sell in the regular market.

As well as showing which volume is needed in the frequency market, Figure 4.8 show how the transformer limit affects the amount of solar energy sent out on the grid. The clear line in the plot comes from this. This also shows that during spring there are times where the battery has charged so much that when wind does not produce the solar power can fill this gap which creates the peaks.

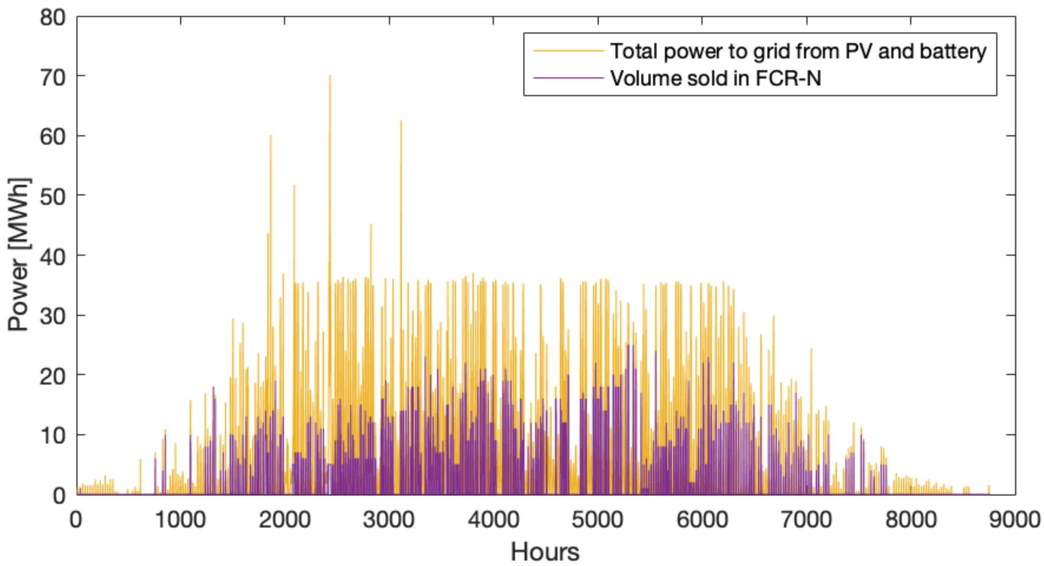


Figure 4.8: Volume sold in FCR-N and regular NO3.

To visualize how many hours in a year there would be enough power from the PV-system to be able to sell in the frequency market, a bar diagram, Figure 4.9, was made. This shows that even at 20% of the concession area, there would only be produced enough energy to compete in the frequency market for about 1/4 of the hours in a year. This bar diagram also envisions that as the production increases, the rate of increase stagnates with the increased area size.

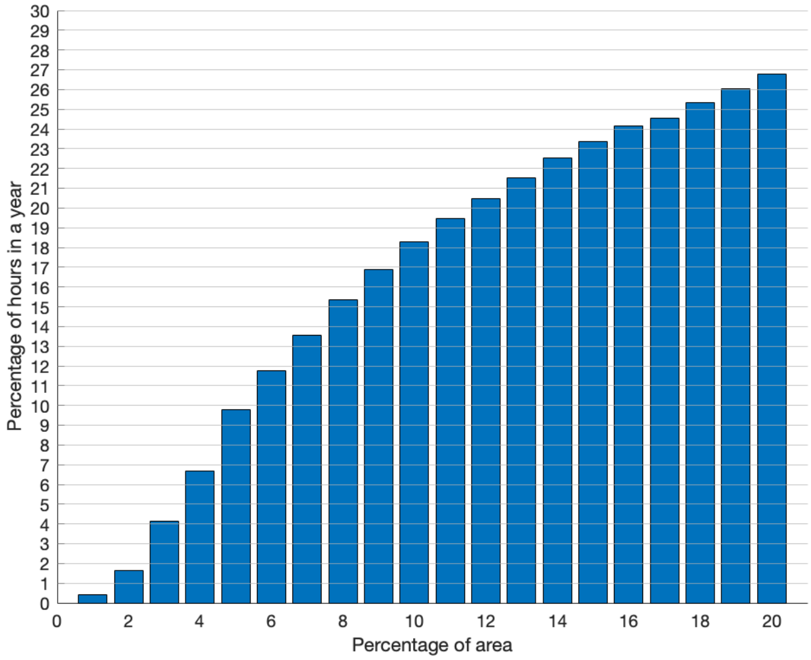


Figure 4.9: Hours in the year sold at the frequency market.

In Figure 4.10 the charge and discharge of the battery through the year is presented for 10% of the concession area. The positive numbers is the value charged and the negative are the values discharged. This is done for as much overproduction as possible for the battery capacity, but without considering the frequency market.

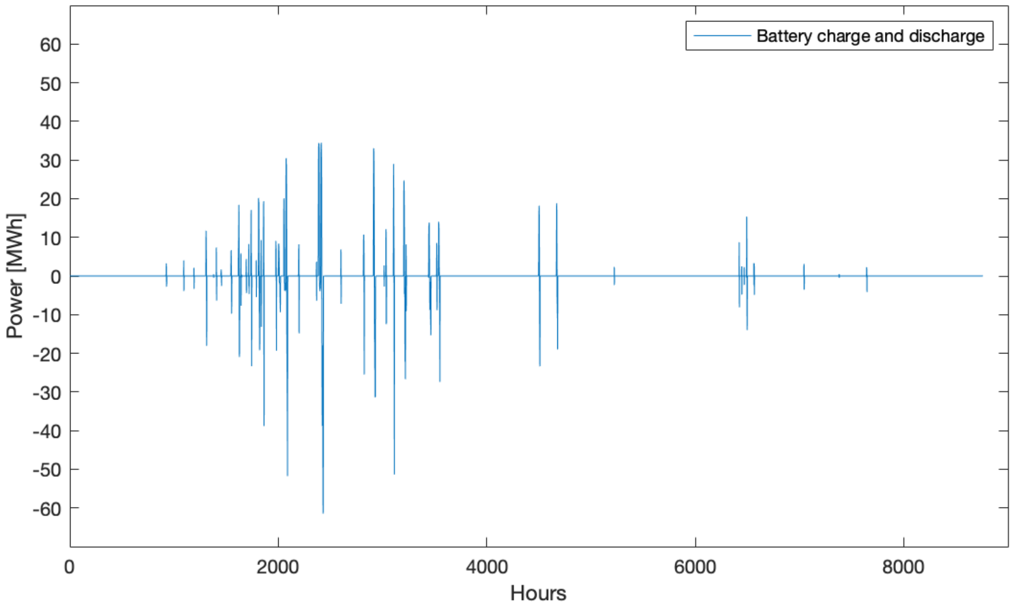


Figure 4.10: Battery charge and discharge scenario 3.

Table 4.9 show the dimensions and possible energy stored for scenario 3. The energy stored here includes the volumes for the frequency market, so the numbers represent the stored overproduction and the possibility of stored production for the frequency market. There are times during the year where there is produced enough energy during the day to sell in the frequency market during all hours of the night. This means that adding up all consecutive numbers, as explained in Section 3.6, would exceed one days worth of production. This means that the battery that is dimensioned after a max days overproduction would, during some days, not cover all energy being needed to be stored. This happens as early as 5% of area, however there are not many hours during a year where this is a problem as is shown in the table.

The energy lost in Table 4.9 includes the loss of possible stored volume for the frequency market. Production lost is only the overproduction from solar power that the BESS will not store due to the limit in the batteries capacity. This shows that dimensioning the battery the same way in this scenario as for scenario 2 generates not only loss in the possible volume stored for the frequency market, but also generates a loss for the actual solar production.

Table 4.9: Yearly results battery scenario 3

Percentage of area	Energy stored [MWh/year]	Containers with battery	Energy lost [MWh/year]	Production lost [MWh/year]	Hours lost
1%	62.6048	4	0	0	0
2%	658.5369	11	0	0	0
3%	2263.1533	21	0	0	0
4%	4334.5034	30	0	0	0
5%	7325.3669	38	11.3393	6.3393	1
6%	9505.0679	44	23.1977	18.1977	1
7%	11443.4808	51	27.5777	22.5777	1
8%	13565.4603	58	87.8241	82.8241	1
9%	15526.2196	65	100.71890	90.7189	2
10%	17546.5118	72	97.41250	87.4125	2
11%	19284.2454	72	162.8076	152.8076	2
12%	20601.3246	72	371.0505	345.0505	4
13%	22237.6769	72	528.0995	488.0995	5
14%	23762.2286	72	715.6121	674.6121	6
15%	25196.0507	72	925.9293	870.9293	7
16%	26426.1531	72	1140.4446	1087.4446	8
17%	27049.6258	72	1265.9596	1205.9596	9
18%	28364.9881	72	1541.2146	1463.9846	11
19%	29527.8110	72	1876.9921	1780.9921	13
20%	30714.9523	72	2273.4944	2154.4614	16

Since the battery is dimensioned for a max days worth of overproduction, including the frequency market, the battery will be bigger and be able to peak shave more when there is not enough for the frequency market anyway. This power available was summed up and is presented in Table 4.10.

Table 4.10: Total volume available scenario 3

Percentage of area	Energy [MWh]
1%	4,094.1395
2%	8,527.5699
3%	13,629.4679
4%	17,715.3060
5%	22,543.5024
6%	26,554.2362
7%	30,835.7134
8%	35,240.9262
9%	39,769.0346
10%	44,024.2506
11%	48,430.3865
12%	52,759.9877
13%	57,237.2948
14%	61,589.1452
15%	65,994.8330
16%	69,879.2676
17%	71,705.9072
18%	75,859.3620
19%	79,765.3516
20%	83,794.9086

In this scenario the production is almost the same as in the previous scenario, but the charge and discharge of the battery is controlled by the frequency market. This gives a slightly different profile for the battery, but overall no big changes. With a differently scaled battery the starting point for loss of volume is for the 5% area. This means that scaling the battery for max days production limits the possibility of always having enough battery capacity for both overproduction as well as volume to take up what the frequency market needs. All of the hourly results for all areas give the basis for the economical calculations in the next section.

4.4.1 Financial results scenario 3

Figure 4.11 show the total possible volume sold for each month in the FCR-N market for 10% of the concession area alongside the mean price each month for the FCR-N market in the NO3 sector. This presents which times in a year it is more profitable to sell as well as which hours in the year the volume is being sold for this scenario.

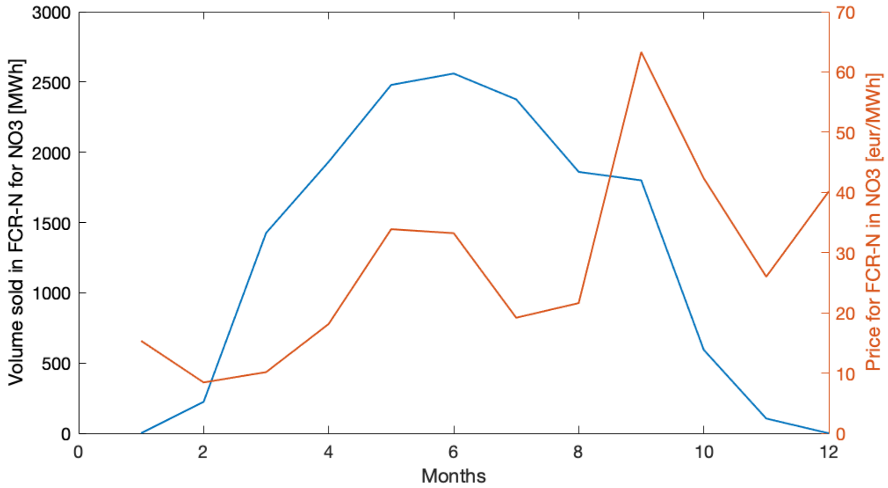


Figure 4.11: Volume sold and price for FCR-N NO3.

Figure 4.12 shows the total volume sold for each month in the regular market for 10% of the concession area alongside the mean spot price every month for the NO3 sector. The spot price for the regular market vary largely. The volume sold in the regular market are times when there is not enough volume with solar power to sell in the frequency market, or there is more power produced than the volume the frequency market is demanding.

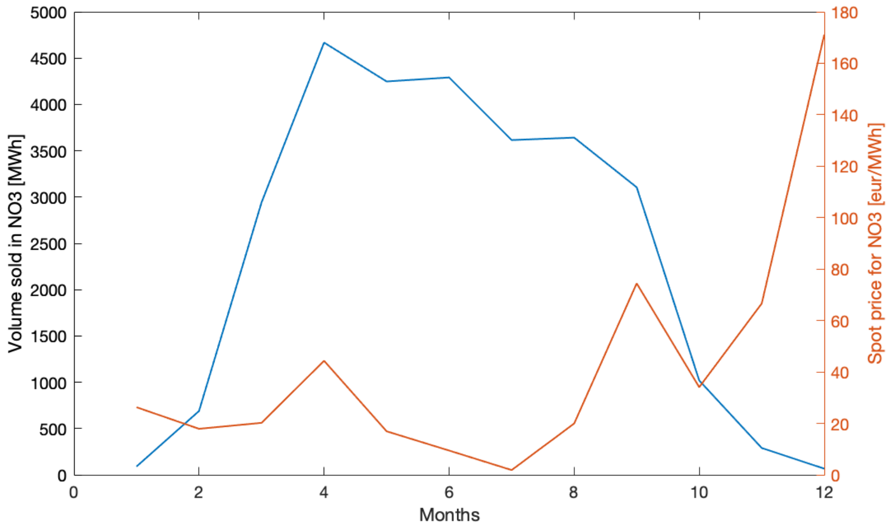


Figure 4.12: Volume sold and price for regular market NO3.

Below in Table 4.11 the yearly profits and corresponding NPV for scenario 3 is presented. The table shows the yearly profit while selling energy both in the frequency market as well as in the regular energy market.

Table 4.11: Yearly profit and NPV for scenario 3

Percentage of area	Yearly profit (EUR [€])	NPV
1%	117,562.8010	-17,522,880
2%	239,578.8683	-40,952,396
3%	376,164.0339	-70,974,413
4%	491,320.4275	-94,461,370
5%	638,123.2185	-112,687,124
6%	762,489.4597	-124,725,842
7%	891,091.0522	-137,041,499
8%	1,030,278.426	-147,335,144
9%	1,169,613.3433	-155,811,372
10%	1,309,534.6000	-162,176,462
11%	1,451,333.7680	-162,569,096
12%	1,587,404.1007	-163,020,557
13%	1,731,064.8752	-163,430,162
14%	1,868,350.6051	-163,875,622
15%	2,006,506.6874	-164,339,661
16%	2,138,976.7755	-164,540,929
17%	2,200,186.7675	-164,659,866
18%	2,336,731.5598	-164,977,288
19%	2,465,510.9139	-165,268,716
20%	2,591,618.6771	-165,701,608

The results shows a positive correlation between area size and yearly profits, and a negative correlation between NPV and area size. In order to more clearly show the the change of NPV, Figure 4.13 was made. The x-axis is the area percentage, and the y-axis is the NPV.

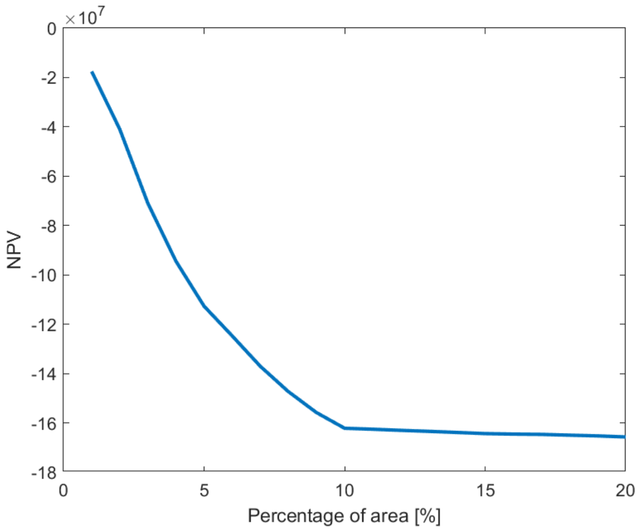


Figure 4.13: NPV for the different areas in scenario 3.

The graph shows that at 10% the NPV will start to flatten out, and become more stable. This corresponds well with the results presented in Table 4.11, which shows the NPV stabilizing at 10% and outwards. Still, the NPV never becomes positive, suggesting that the investment does not become profitable for any area. Too see if this has to do with the initial cost of the project, a new table is made showing the NPV with different cost reductions. The results are presented below in Table 4.12.

Table 4.12: NPV for all areas with cost adjustment for scenario 3

	NPV at Percentage of original cost				
Percentage of area	90%	70%	50%	30%	10%
1%	-17,228,850	-16,640,790	-16,052,730	-15,464,670	-14,876,610
2%	-40,339,388	-39,113,372	-37,887,356	-36,661,340	-35,435,324
3%	-69,994,313	-68,034,113	-66,073,913	-64,113,713	-62,153,513
4%	-93,187,240	-90,638,980	-88,090,720	-85,542,460	-82,994,200
5%	-111,065,504	-107,822,264	-104,579,024	-101,335,784	-98,092,544
6%	-122,815,538	-118,994,930	-115,174,322	-111,353,714	-107,533,106
7%	-134,822,909	-130,385,729	-125,948,549	-121,511,369	-117,074,189
8%	-144,799,358	-139,727,786	-134,656,214	-129,584,642	-124,513,070
9%	-152,949,480	-147,225,696	-141,501,912	-135,778,128	-130,054,344
10%	-159,008,066	-152,671,274	-146,334,482	-139,997,690	-133,660,898
11%	-159,083,504	-152,112,320	-145,141,136	-138,169,952	-131,198,768
12%	-159,223,115	-151,628,231	-144,033,347	-136,438,463	-128,843,579
13%	-159,310,178	-151,070,210	-142,830,242	-134,590,274	-126,350,306
14%	-159,442,006	-150,574,774	-141,707,542	-132,840,310	-123,973,078
15%	-159,588,849	-150,087,225	-140,585,601	-131,083,977	-121,582,353
16%	-159,510,343	-149,449,171	-139,387,999	-129,326,827	-119,265,655
17%	-159,497,412	-149,172,504	-138,847,596	-128,522,688	-118,197,780
18%	-159,515,458	-148,591,798	-137,668,138	-126,744,478	-115,820,818
19%	-159,525,330	-148,038,558	-136,551,786	-125,065,014	-113,578,242
20%	-159,667,756	-147,600,052	-135,532,348	-123,464,644	-111,396,940

While the NPV of the different areas increase with the different cost reductions, the value still does not become positive. The rate of the NPV decline is also reduced after the 10%-mark, which is consistent with the graph presented in Figure 4.13.

5 Discussion

This section focuses on the uncertainties and potential short comings of the results as well as the findings in this thesis. Both in the scope, methodology and in the data analysis there have been made assumptions that affect the results. This may lead to the results not realistically showing the reality of the situation and give less accurate output in the simulations and calculations done.

Throughout the assumptions were often made because the system needed the simplification to be less complicated and to keep the focus on the goals of the thesis. They are also often chosen to be conservative. Specifically for the financial calculations the biggest challenge have been secrecy in the industry and little available data on costs and marked prices.

A lot of the thesis also revolve around relatively new concepts and the exploration of these. There is only one big hybrid park in Europe, as mentioned in the literature study 1.1. The frequency market is also relatively new and is a quickly developing marked with little data and study's done on it. This makes assumptions very important in order to create a good representation of the different scenarios.

5.1 PVsyst simulation

Simulations will always be a simplification of reality even when done to most accurately represent it. The simulations done in this thesis include many assumptions, all of which are mentioned in the methodology Section 3.3, that impact the results. Therefore, the results may not be totally realistic and that should be considered when making conclusions based on these simulations. This does not mean that valid conclusions can't be made, but the accuracy in small details of the results are limited.

5.1.1 System setup

There are many options and approaches too choose from when simulating an industrial power plant. These simulations were done with both theoretical knowledge and the assistance of the company that have proposed the solar park at the site. This combination makes a system that includes realistic parameters and a plausible setup. This however dose not give the most optimal setup where all parameters and choices have been thoroughly researched and economically considered to give the most production for the least money. If this is done the production would undoubtedly be higher which would in turn increase the profits. This makes the profit results in this report lower than they probably would be if the solar power plant was realized.

The area, in square meters, of the park is manually drawn into the simulation program and consists of a slight difference between the actual percentages and the areas simulated. This is shown in Table 4.1 and the differences are so small that it probably does not influence the results noticeable. There is however another matter, that is also a result of the manually drawing, that might have an impact. The optimal shape for the area would be a rectangle, and for the smaller areas this is easier to obtain. When a rectangle was not longer possible the drawings where defined by the borders of the original concession area and the exclusion areas. This which gives less optimal spacing for the panels even doe PVsyst maximizes the area given. At the same time there would probably be more obstacles in the terrain that is not accounted for in the simulation that would reduce the number of modules. It is hard to estimate how big of an impact this has on the results, but it adds to the uncertainties and make it hard to draw conclusions on exactly how many modules could fit inside the area.

From the Figure 4.1 the 17% production area stands out by not following the same progression as the others. This is because this is the area where the largest lake is included, and therefore not as many modules could be installed. This is something to be aware of in the further calculations. It is also a further reminder that with a bigger area it will also be harder to find optimal placements and the terrain will have a bigger influence since it becomes harder to avoid.

5.1.2 Losses

From the results the loss diagram shown in Figure 4.2 is interesting because it gives a very good picture of where the system loses production and therefore also a good starting point to optimize it.

The albedo values have a big impact on how much production the system gains from the bifacial PV-modules. These values were assumed by a comparison of weather data and the PVsyst table for albedo values based on different surfaces [93]. The assumption is that the biggest impact would be the snow precipitation on the site and the albedo values were altered accordingly. This is probably a good assumption and gives more representative results than the default settings of 0.2 the whole year. A even more realistic set of values would probably need further research and inspection of the site and areas where the solar panels would be placed.

The soiling loss which is set to the default takes out 3% of the regular production for the 10% area which is a substantial amount. Soiling loss is the accumulation of dust and dirt and how that affects the system. This depends largely on the weather conditions and especially rainfall. Therefore, due to the amount of rainfall in Trøndelag county this is probably a conservative assumption.

The transformer and ohmic losses are simplified as explained in the methodology Section 3.3.3 and are also therefore a less realistic picture of how the real losses would look like. Since these assumptions are based on the biggest area it is the most conservatively estimated losses.

5.1.3 Overall credibility of the simulations

The simulations are overall a good representation of a possible solar power plant at Stokkfjellet. There are weaknesses in the assumptions done and is therefore not suited to conclude on very specific details, but gives a good picture of trends and overall perspectives. Most of the assumptions give conservative estimates, and lowering the probability of the simulations giving false positive results are very low. The simulation gives a further solid basis for the scenarios to build on and to do calculations around the financial aspects.

5.2 Scenario 1

The biggest assumption for this scenario is the production limit set to $90W$ to accommodate for the capacity of the transformer. As mentioned in the methodology section this was an assumption made to simplify the calculations. However, if the real limitations and losses of the transformer would have been part of the scope it would probably have yielded less losses in the sun production. This is because the transformer can both run over nominal current to a certain level and regulate via the tap changer, making it able to take on more power than the set limit in this report. This would again lead to a bigger profit, but since the losses already are relatively small it wouldn't lead to a substantial impact.

The wind data used as a base in this scenario is AI-generated data. This data was assumed after a conversation with ANEO to not include any losses. If this is correct, the real production would be lower and also allow more of the solar production under the transformer limit. This would give more profit with less overproduction. The overproduction is already small and mostly only a substantial amount during the spring as seen in Figure 4.3. Therefore this probably dose not impact the results heavily. This would also mean less overproduction in scenario 2 and 3.

All production over the 90 MW limit is lost and the rest is always sold on the regular energy market. Here the assumption of always being able to sell the produced energy could have a negative impact on the results. In reality there would be a loss attributed to load varying and a possibly of not always being able to sell to the grid. This assumption is also done in the other scenarios, increasing the possible profits.

From the financial results in Section 4.2.1 the NPV values shows a negative almost linear correlation with increased area size. This shows that a big scale solar park in combination with the wind park at Stokkfjellet probably isn't a economical viable option. This is the same trend found in one of the studies in the literature study 1.1 [6], with the biggest difference being that they found a profitable outcome for smaller areas of solar installation. The areas looked at in this thesis are relatively big compared to other solar parks, and a selection of smaller areas could have given different results with smaller installation costs.

When reducing the installation costs of the system the NPV values improve, but are only positive for a 50% reduction and up. The 1% area never have a positive NPV. Weather or not it is realistic to expect the installation costs for solar power to decline by this much in the foreseeable future, will be discussed further in Section 5.5.

The simulations that the production is based on is done for one year. This is because of the available data. Since degradation of the system is outside of the scope it results in all production and profits staying the same over the lifetime of the hybrid park. The effect this has on the results will also be discussed in Section 5.5

5.3 Scenario 2

Choosing which battery chemistry to use was a intricate endeavor. The most common battery chemistries presented in Section 2.3, LFP and NMC, have many positive and negative characteristics. Even though the chemistry in the LFP batteries seem more suitable for the hybrid park, there are many downfalls with the chemistry as well. As explained in Section 2.3 the LFP batteries does not work as well in colder conditions, which is expected at Stokkfjellet. Another problem was fining a LFP pack that was easily scalable to fit the amount of volume the hybrid park produces.

The NMC pack from Northvolt, with parameters presented in Section 3.5, was decided upon mostly because it was easily scalable as well as having a local battery producer. One of the benefits of choosing NMC over LFP is the better performance at lower temperatures which will be crucial for the colder parts of the year. The proposed new regulations from the EU, explained in Section 2.3.1, tackles the problems with the non-sustainability of today's nickle mining as the regulation might make all battery production more sustainable.

For the combination of battery and renewable energy cycle aging, explained in Section 2.3, is the largest obstacle. Since renewable energy sources are so fluctuating in production, the battery will be charged and discharged at a rapid pace. However, as the area decreases so does the amount of energy stored throughout the year, as presented in the resulting Table 4.5. This will mean the calendaring aging will increase as less area is used for the park, and the battery will not be in use for considerable amounts of time during the year.

When dimensioning the battery it is only scaled to peak shave all overproduction up until 10% of the area as explained in Section 3.5. This is however not the most optimal solution. For the percentages up until 10% of the concession this way of dimensioning the battery shows how economically viable it is if the battery peak shaves all over production. While for 10% and up, it shows how economically it is if the battery only takes partial of the overproduction. This shows a trend that is best presented in Figure 4.7 and demonstrates that it might be better economically to dimension the battery to not take all overproduction. However, this is a very general strategy to show this trend and has a substantial margin of error. The most optimal correlation between amount of profit from the stored energy and the cost of the BESS is not explored and this could have a substantial impact on the results.

The assumption that the energy stored will be sent out on the grid is another acute assumption. This maximized the possible amount of energy to get peak shaved for the battery capacity. However, this might not be the most optimal solution. During some days through the year, mostly during the summer months when the spot prices are very low, there is overproduction every hour of the daytime. During night, when then the PV system is then turned off, the battery discharges completely, when the spot prices are even lower. This will make sure the battery is fully empty in the morning, but will mean that the energy will be sold at a lower price than what could have been if a smart system was used. Because of this the profits calculated are relatively conservative compared to a more realistic result.

Since there will be maximum power delivered through the transformer more often in this scenario, because of the battery and fluctuation will happen vastly fast. The transformer would probably need a more precise control system. This could be implemented at the battery to insure optimal running condition for both components. However the assumptions made for the transformer limit is conservative, and therefore this might not be a concern. The transformer already have some options for regulations as presented in Section 3.2.1 which also make a intricate control system less of a priority.

For both scenario 2 and 3, the proposed battery system has only sold the stored power whenever possible, selling both at times when the price is low and when the price is high. In order to make the energy sales from the BESS more efficient, an arbitrage technique could be implemented. This is done by storing the produced energy from the solar park during low-price hours, and selling the stored energy during high-price hours. This would take advantage of the price difference and increase the overall revenue obtained. Creating a code that is able to accurately calculate this is quite challenging, so the choice was therefore made to rather stick by the assumption that the energy would be sold immediately.

In comparison to scenario 1 there is less production lost, but a higher investment cost. The added production do not make up for this investment cost, and therefore results in only negative NPV values. The implementation of BESS dose however give more freedom and control over the production and another form of operation might give more profitable system.

5.4 Scenario 3

As mentioned in Section 3.6, the FCR-N market does not specify weather the volume set for regulating the frequency is up or down. While the dimensioning of the battery tries to mitigate this by having a capacity that takes into consideration the possibility of one volume having to be delivered or withdrawn and peak shave all overproduction, the accuracy of this dimensioning is not favorable. One thing that is not taken under consideration in these assumptions are that if the volume is taken up in the battery it would be available to sell at a later time. This would possibly create a larger volume to be sold either later in the frequency market or in the regular market and would create a higher profit. Still, the method chosen is probably one of the most accurate methods considering the lack of information regarding the regulating volumes.

The Tables 4.7 and 4.11 show that the profit when entering the frequency market drops substantially. As is also shown in Section 4.4.1 the volumes are sold to different prices. By comparing the spot prices for the regular marked and the frequency marked, which separately is shown in Figures 4.11 and 4.12, the regular marked generally have higher prices. This could have been an exception in 2022, however the trend shown in the energy market, Section 2.6 the last couple of years imply that the energy prices might stay high. An other noteworthy observation of the price comparison is that the highest prices in the regular marked occur in the later half of the year. In the summer season the frequency market tends to have the highest prices. An optimization of when to attend which marked could potentially show a seasonally based approach.

The assumption that whenever there is produced enough energy to sell in the frequency market there will be space to sell is an improbable one. This was an acute assumption to show what participation in the FCR-N market does with the profit and the battery dimensions. In reality, as explained in Section 2.6.2, it is the lowest bidder that will sell that volume. This in turn makes it hard to predict how many times during a year one will be able to sell. Seeing the trend mentioned earlier entering the frequency market creates a drop in the profits. This could however improve since a higher volume would realistically be sold in the regular market, and possibly at a higher price.

Another factor mentioned in Section 3.6 is the fault in the table for FCR-N, which results in 56 hours of the year not being included in the profit calculations. While this means that the economic results are not completely accurate, the volume would be lost in these 56 hours anyway. This could, to a small degree, affect the dimensioning of the battery since it is dimensioned after the max daily need and this could be lower if the times with no volume needed was distributed correctly. However, since it is such a small portion of the whole year this happens the margin of error is practically negligible.

The decision to use a single battery for both peak shaving and frequency control can create some potential problems due to conflicting requirements for battery operation. Peak shaving requires the battery to be charged during low demand periods when energy is cheaper and discharged during high demand periods when energy is more expensive. A larger capacity is therefore preferred. The frequency control requires the battery to be available to quickly respond to changes in the grid frequency, placing a greater emphasis on the batteries charge- and discharge-rate. This conflict between the two applications can reduce the overall revenue potential of the battery system.

As explained in Section 3.5, the use of two battery systems was explored to eliminate conflict of interest that emerges while using on battery. Using two separate batteries has the advantage of being more easily dimensioned and controlled. This is because the need to take the other use-case into consideration is removed. Because of this, the control systems do not have to be as sophisticated. On the other hand, this would increase the investment cost by a substantial amount which would again defeat the benefit of using two battery systems.

The difficulty of using a battery for frequency regulation is that the required characteristics are different from a system that is to be used for peak shaving. Because of the relatively short intervals of the frequency regulation, the overall capacity of the battery could be smaller than that of the peak-shaving battery. However, given that a very short reaction time is required, especially for the FFR as mentioned in Section 2.6.1, the battery must be able to quickly charge and discharge. This could potentially put a strain on the lifetime of a BESS.

In the same fashion as in scenario 2 the transformer would need a more accurate control system than compared to scenario 1. This could be implemented either at the battery site or at the transformer, but would in this case also need to involve a smart system to include an interaction with the frequency market. As mentioned in 3.5 there might not be a problem for the transformer to handle this without a complex control system, due to its own regulative components like the tap changer.

In this scenario there is more production loss than in scenario 1, but still less than scenario 2. This is due to the dimensioning of the BESS. This leads to the highest investment cost of all the scenarios. The profit from the inclusion in the frequency market does not justify this cost. There is also probably a more optimal way of sizing the battery and a better way of distributing the production between the markets to optimize profit.

5.5 Financial

The method of NPV has been chosen on the basis of its use in similar projects, as well as its simplicity while also taking the changing value of money into account. While its viability has been proven to be strong, there still exists some issues surrounding this method. One such issue is that it doesn't account for the inherent insecurity of project planning. Being able to quantify the risks associated with investments would make the calculations more accurate, especially in terms of probable investment value.

An alternative to using NPV would be to use the payback method, as mentioned in 2.7. The problem with this however, is that it does not take into account the time value of money. Overall it is difficult to find a method of economic analysis that takes everything into account, and therefore choosing the method most relevant for the type of project is key. Considering its downsides, the NPV-method was concluded to be the most suitable alternative for this project.

As mentioned in Section 2.7, the internal rate chosen for this thesis was the internal policy rate in Norway. In the NPV calculations, the chosen internal rate is highly influential on the resulting value. If the actual internal rate where to be higher than the one used in this thesis, it would negatively affect the NPV value. However, because of the secrecy surrounding the internal rate in this industry, inquiring a realistic rate was proven to be difficult. It is also important to point out that while a higher internal rate would result in more negative NPV values, it would still not have an impact on the trend shown in Figure 4.7 and 4.13. Using the rate set by the central bank is therefore considered to be appropriate in this instance, but for a more accurate economic analysis a more realistic rate should be implemented.

The calculations regarding the price adjustment for solar cells have tried to find the price at which the project becomes a worthwhile investment. Still, the accuracy of these predictions are based on the decline in recent years which was mentioned in Section 2.2.3. Using an economic analysis to predict the future reduction in prices would result in a more accurate prediction of when this scenario would become financially viable. However, because of the limitations set regarding this thesis, creating an economic model in order to accurately predict this would be too large of an undertaking. The present assumption is therefore considered to be necessary and appropriate.

The financial calculations that have been done has used the euro as the currency when calculating both profits and cost. As explained in Section 3.4.1,the sensitivity of currency value was the main reasoning behind this choice. By only using a single currency for all calculations without any conversions, the results became less vulnerable to fluctuations in currency value. Still, while a lack of conversion inside the calculations themselves make the results more solid, the euro itself is still able to vary significantly. The financial calculations will always be very sensitive to outside influence. This is however hard to take into account when calculating the results.

While the NPV calculations take both the varying cost related to the battery and the varying profits generated by the different scenarios into consideration. It does not consider that the profit for each area will vary widely in a 30 year period. Both because of fluctuation in prices and the degradation of the system. All of the production presented has used data from 2022 as its basis, and therefore the resulting NPV calculations have also only used this one production year as its basis. The influence this could have on the results could both be positive and negative depending on the variation in solar radiation and wind in the future. A more accurate way to do this could be to use production data over a period of 10 years in order to get a more precise view of the varying production and resulting profits over a longer lifespan. However, since the wind park at Stokkfjellet was finished in 2019, the production data available does not allow for this.

A more accurate calculation could be done by also factoring in that for projects of this magnitude deals made with suppliers would probably lead to a reduction in costs. This is similar to the assumptions made about battery costs in Section 3.5.1, which explained that the costs would go down with an increase in needed capacity. However, the costs would have to be researched by working closer with suppliers and manufacturers, which can be difficult given the abundance of industry secrets which are rarely revealed to the public. Therefore, while having this information would result in a more accurate NPV and investment cost prediction, the data would be difficult to collect.

The results presented in Section 4.4.1 showed that the costs associated with the implementation of a BESS had a significant impact on the NPV of the different areas. While the price adjustment for solar cells showed that scenario 1 became profitable with a decrease of around 40%, a similar adjustment could have been made for the last two scenarios regarding the cost of the BESS. As mentioned in Section 2.3.1, the current prices for BESS have been steadily decreasing the last few years. However this is not necessarily the case.

In contrast to the price change in solar power, which is predicted to be reduced over the coming years, the proposed regulations by the EU regarding BESS could result in a price increase instead of decrease for batteries, as mentioned in Section 2.3.1. Given the uncertainty around the cost reduction of BESS, the choice was made to disregard this in the NPV calculations.

The spot prices for the energy market have risen substantially the last years and will have a substantial affect on the profits from the solar production. The evolution of the spot prices are however hard to predict. As mentioned in the introduction 1 many nations have signed to close down many fossil fueled energy plants, so there will be a larger incentive to produce renewable energy. A change like that would mean many nations would go from a stable, yet not renewable, energy source to a renewable yet somewhat unstable energy source. This will in turn affect the spot price. Since renewable sources are more fluctuating, there can be times with considerable lower spot prices due to overproduction as well as times with higher spot prices due to lack of energy production. This can change just during the day since renewable sources are weather dependent.

6 Further work

While the previous discussions has focused on the assumptions made and the problems surrounding some of the calculations, this section will present possible further work that can be investigated.

As was discussed earlier, the use of a battery for frequency regulation can potentially shorten the lifetime of the battery significantly. The introduction of a supercapacitor could help mitigate this however. A supercapacitor can tolerate substantially more charge- and discharge-cycles than a normal battery, and is also capable of delivering power at a much faster rate. Using a system that utilizes both the storage capability of a traditional battery, and the enhanced power delivery of the supercapacitor, could help lengthen the lifetime of the storage system [94]. Additionally, the increased discharge-rate that comes with a supercapacitor could make it possible to participate in the FFR-market, which demands a faster response than the FCR-N, as mentioned in Section 2.6.1.

While this thesis has looked at hybrid parks as a solution to replace fossil fuels and decrease global emissions, the detailed impact the construction of this proposed hybrid park has on emissions has not been a focus. The emissions resulting from the production of the renewable energy sources have already been studied in several reports, but a comprehensive life cycle analysis of hybrid parks has not yet been thoroughly investigated. While the introduction of hybrid parks will reduce the need for fossil fuels, a more comprehensive study should be done on the long term impacts of these power systems. Further, a similiar analysis could be done around the different scenarios explored, finding out which of the three would have the least environmental impact.

The Norwegian frequency market is currently being reworked, and as a result the prices will see a change in the coming years. Other categories will also be introduced, with an example being the introduction of a dedicated market for down-regulating FCR-N [72]. This change in market behavior could make it more profitable to participate in the frequency market in the years to come, especially considering the growth in renewable energy sources in today's energy infrastructure. As mentioned in Section 2.6.1, the current implementation of renewable energy sources creates a need for more frequency regulation in the power grid, which will likely lead to this market becoming larger in the future.

7 Conclusion

The goals of this thesis is to look at three different ways of operating a proposed hybrid park at Stokkfjellet and to see if these are viable options and analyze the possible potential.

Scenario 1 inspects implementing solar panels into the already existing wind park without any storage possibility for the overproduction. This resulted in an amount of energy being lost throughout the year, but a lower investment cost than the two other scenarios. It was demonstrated that if the price of the PV system declines with 50% it would be economically viable to install solar panels on as little as 4% of the concession area.

In scenario 2 a BESS is implemented to store the overproduction. In this case the energy stored is fed out on the grid at the first possible time. These results are not an optimal for the possible economical revenue, but rather optimized to peak shave all overproduction. Because of this, and the increased investment cost, the NPV values are never positive and therefore not economically viable. However, if the battery usage was more optimal it might prove to be more feasible.

In scenario 3 all the power produced from the PV system would be used to sell in the frequency market. This was done on incomplete data sets, hence the assumptions that shaped the scenario were improbable. Because of this the profits for scenario 3 were lower than for both scenario 1 and 2. With the increased investment cost from the battery, this resulted in negative NPV values for all cases.

While this thesis has presented results that show how a hybrid park can be a viable alternative at Stokkfjellet, additional further work could be done in order to more accurately predict both the profits and the production. Among other things, a regulation system that could optimize the amount sold to different markets could be explored. Further, a comprehensive look on the effects a hybrid park will have on global emissions could also be studied. Lastly, optimizing the economic benefit of a hybrid park should be investigated, as the NPV method which has been used in this project has multiple flaws.

This report finds that none of the scenarios are presently economically viable. The results indicate that scenario 1 is the best alternative for the proposed hybrid park at Stokkfjellet. This scenario could become economically viable due to the reduction in price for solar panels that is expected to happen in the coming years. However, by implementing some of the possible alternative methods, both scenario 2 and 3 could prove to be the more viable options. Specifically, a significant reduction in battery costs would make the NPV results more positive.

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Version 7.3.3

PVsyst - Simulation report

Grid-Connected System

Project: Stokkfjellet_hybridpark

Variant: Scenario_10%

Tables on a building

System power: 52.81 MWp

Selbu-Stubbe/Kråkstad - Norway

Author

Johanne Grindahl (Norway)

Project summary

Geographical Site
Selbu-Stubbe/Kråkstad
Norway

Situation
Latitude 63.20 °N
Longitude 11.12 °E
Altitude 176 m
Time zone UTC+1

Meteo data
Selbu-Stubbe/Kråkstad
MeteoNorm 8.1 station (Egne_GHI_Temp) - Synthetic

Monthly albedo values

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
Albedo	0.82	0.82	0.82	0.70	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.50

System summary

Grid-Connected System
Tables on a building

PV Field Orientation
Fixed plane
Tilt/Azimuth 27 / 0 °

Near Shadings
According to strings
Electrical effect 100 %

User's needs
Unlimited load (grid)

System information

PV Array
Nb. of modules 96012 units
Pnom total 52.81 MWp

Inverters
Nb. of units 229.2 units
Pnom total 36.68 MWac
Pnom ratio 1.440

Results summary

Produced Energy 44024256 kWh/year
Specific production 834 kWh/kWp/year
Perf. Ratio PR 85.17 %

Table of contents

General parameters

Grid-Connected System — **Tables on a building**

PV Field Orientation

Orientation
Fixed plane
Tilt/Azimuth 27 / 0 °

Sheds configuration
Nb. of sheds 1778 units

Sizes
Sheds spacing 10.00 m
Collector width 4.58 m
Ground Cov. Ratio (GCR) 45.8 %

Shading limit angle
Limit profile angle 19.3 °

Models used
Transposition Perez
Diffuse Perez, Meteonorm
Circumsolar separate

Horizon
Average Height 3.9 °

Near Shadings
According to strings
Electrical effect 100 %

User's needs
Unlimited load (grid)

Bifacial system
Model 2D Calculation
unlimited sheds

Bifacial model geometry

Sheds spacing	10.00 m
Sheds width	4.58 m
Limit profile angle	19.3 °
GCR	45.8 %
Height above ground	1.50 m

Bifacial model definitions

Ground albedo average	0.42
Bifaciality factor	66 %
Rear shading factor	5.0 %
Rear mismatch loss	10.0 %
Shed transparent fraction	0.0 %

Monthly ground albedo values

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Year
0.82	0.82	0.82	0.70	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.50	0.42

PV Array Characteristics

PV module
Manufacturer Generic
Model JAM72-D30-550-MB
(Original PVsyst database)
Unit Nom. Power 550 Wp
Number of PV modules 96012 units
Nominal (STC) 52.81 MWp
Modules 3556 Strings x 27 In series

At operating cond. (50°C)
Pmpp 48.47 MWp
U mpp 1027 V
I mpp 47217 A

Inverter
Manufacturer Generic
Model SUN2000-185KTL-INH0-50C
(Original PVsyst database)
Unit Nom. Power 160 kWac
Number of inverters 2063 * MPPT 11% 229.2 units
Total power 36676 kWac
Operating voltage 600-1500 V
Max. power (=>30°C) 185 kWac
Pnom ratio (DC:AC) 1.44
No power sharing between MPPTs

Total PV power
Nominal (STC) 52807 kWp
Total 96012 modules
Module area 248023 m²

Total inverter power
Total power 36676 kWac
Nb. of inverters 230 units
0.8 unused
Pnom ratio 1.44

Array losses

Array Soiling Losses
Loss Fraction 3.0 %

Thermal Loss factor
Module temperature according to irradiance
Uc (const) 29.0 W/m²K
Uv (wind) 0.0 W/m²K/m/s

DC wiring losses
Global array res. 0.36 mΩ
Loss Fraction 1.5 % at STC

Serie Diode Loss
Voltage drop 0.7 V
Loss Fraction 0.1 % at STC

Module Quality Loss
Loss Fraction -0.8 %

Module mismatch losses
Loss Fraction 2.0 % at MPP

IAM loss factor
Incidence effect (IAM): User defined profile

0°	30°	50°	65°	70°	75°	80°	85°	90°
1.000	1.000	0.989	0.945	0.890	0.821	0.681	0.439	0.000

AC wiring losses

Inv. output line up to MV transfo
Inverter voltage 800 Vac tri
Loss Fraction 5.70 % at STC
Inverter: SUN2000-185KTL-INH0-50C
Wire section (229 Inv.) Copper 229 x 3 x 70 mm²
Average wires length 600 m

MV line up to Injection
MV Voltage 22 kV
Average each inverter
Wires Copper 3 x 50 mm²
Length 1270 m
Loss Fraction 0.13 % at STC

AC losses in transformers

MV transfo
Medium voltage 22 kV
One transfo parameters
Nominal power at STC 1.33 MVA
Iron Loss (night disconnect) 1.37 kVA
Iron loss fraction 0.10 % at STC
Copper loss 12.88 kVA
Copper loss fraction 0.97 % at STC
Coils equivalent resistance 3 x 4.65 mΩ

Operating losses at STC (full system)
Nb. identical MV transfos 39
Nominal power at STC 51.92 MVA
Iron loss (night disconnect) 53.47 kVA
Copper loss 502.14 kVA

Horizon definition

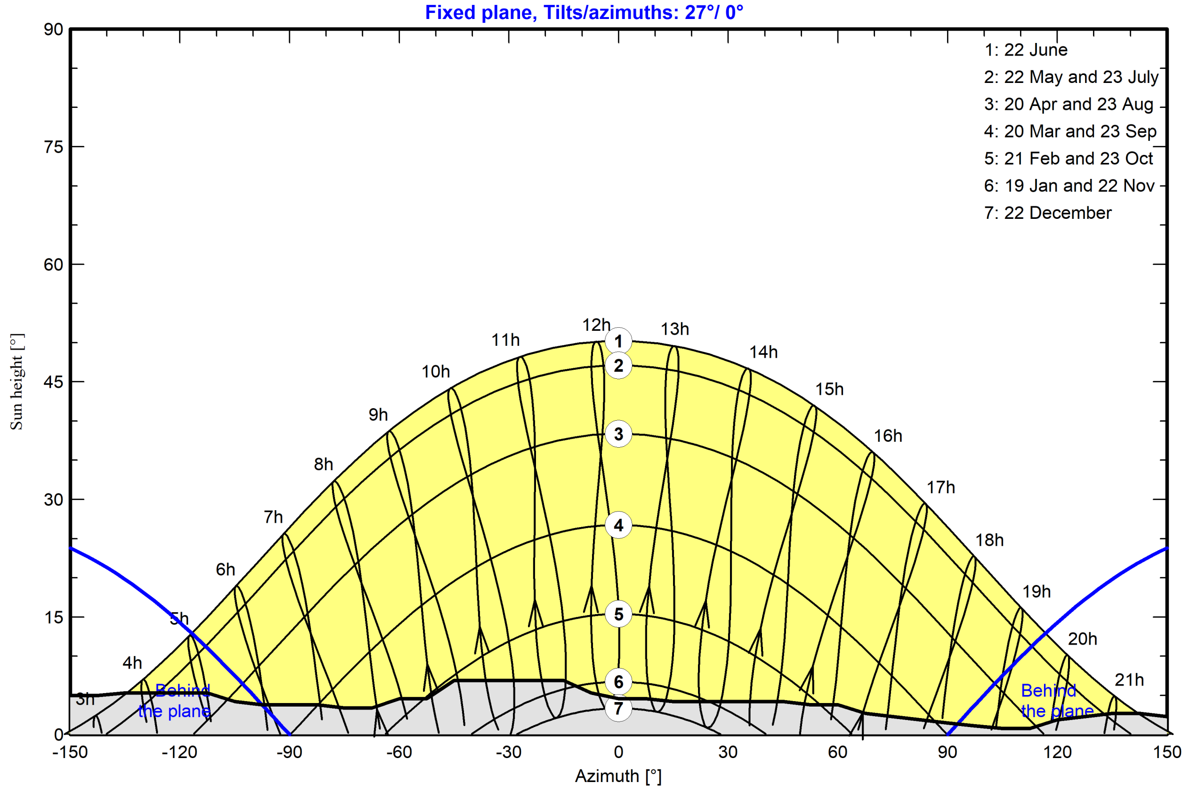
Horizon from PVGIS website API, Lat=63°12"0', Long=11°7"12', Alt=176m

Average Height	3.9 °	Albedo Factor	0.74
Diffuse Factor	0.97	Albedo Fraction	100 %

Horizon profile

Azimuth [°]	-180	-173	-165	-158	-150	-143	-135	-113	-105	-98	-83	-75	-68
Height [°]	3.4	4.2	4.6	4.6	5.0	5.0	5.3	5.3	4.2	3.8	3.8	3.4	3.4
Azimuth [°]	-60	-53	-45	-15	-8	0	8	15	45	53	60	68	75
Height [°]	4.6	4.6	6.9	6.9	5.3	4.6	4.6	4.2	4.2	3.8	3.8	2.7	2.3
Azimuth [°]	83	90	98	105	113	120	128	135	143	150	158	173	180
Height [°]	1.9	1.5	1.1	0.8	0.8	1.9	2.3	2.7	2.7	2.3	3.1	3.1	3.4

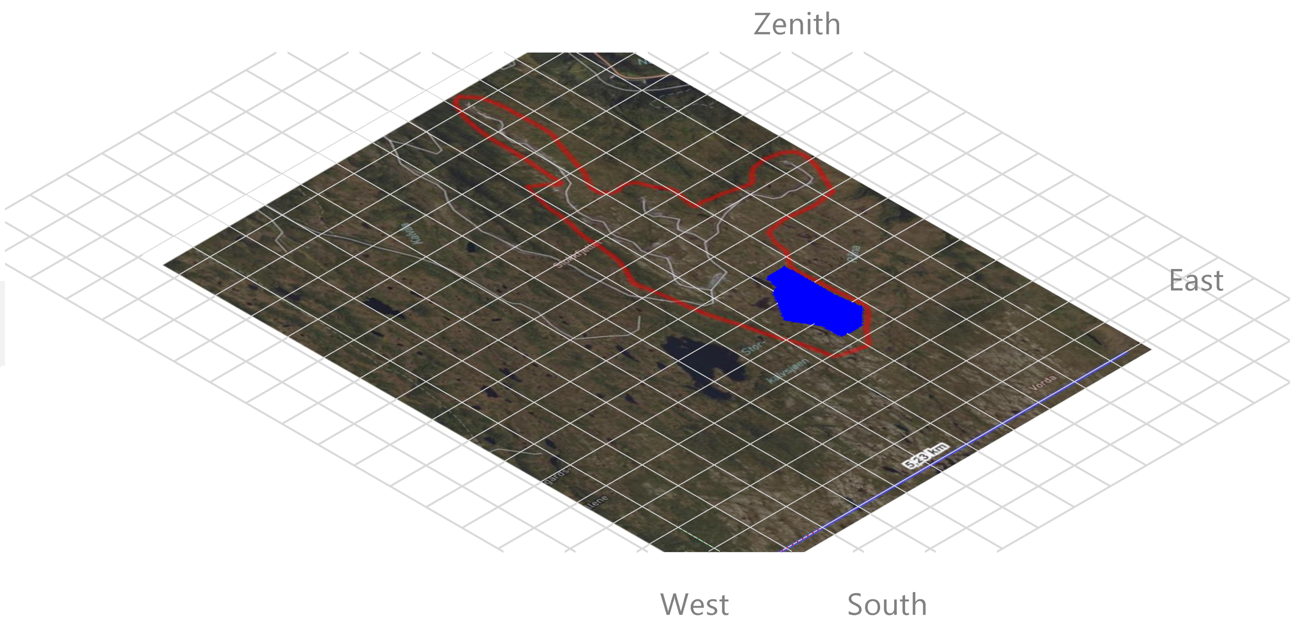
Sun Paths (Height / Azimuth diagram)



PVsyst V7.3.3
VC9, Simulation date:
23/04/23 21:56
with v7.3.3

Near shadings parameter

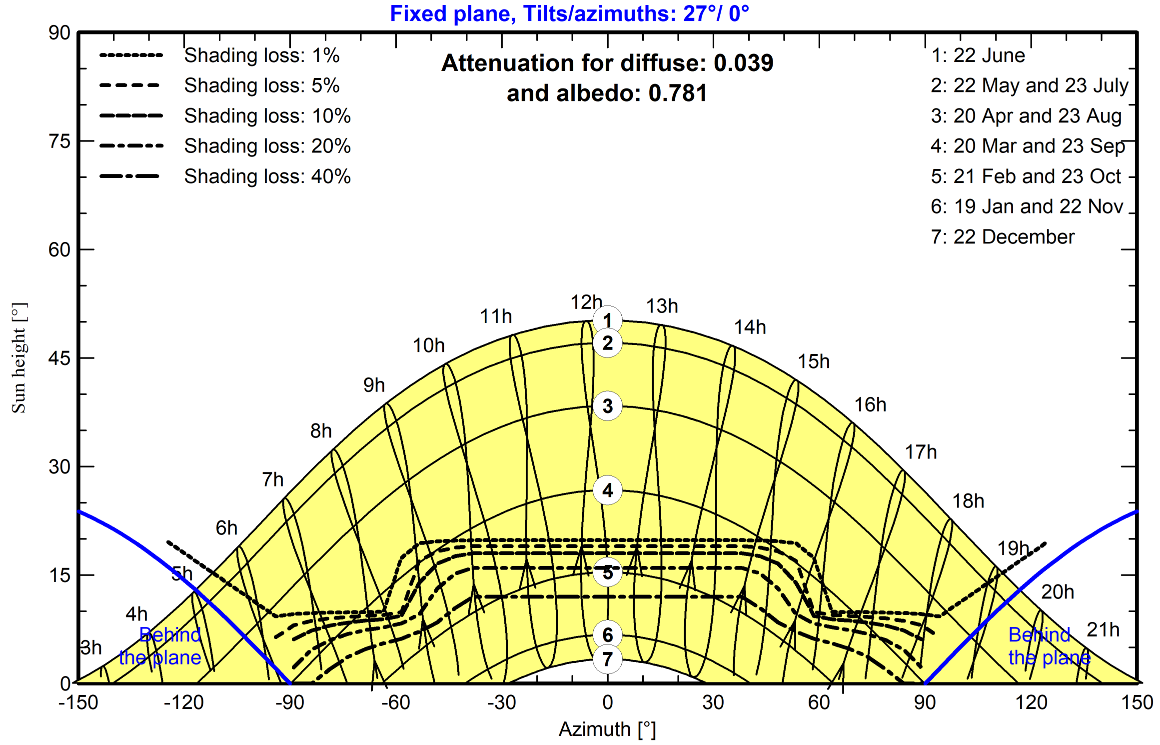
Perspective of the PV-field and surrounding shading scene



Iso-shadings diagram

Orientation #1

Fixed plane, Tilts/azimuths: 27°/ 0°

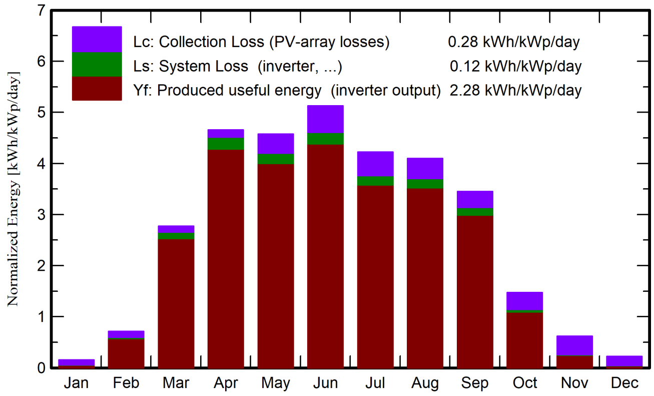


Main results

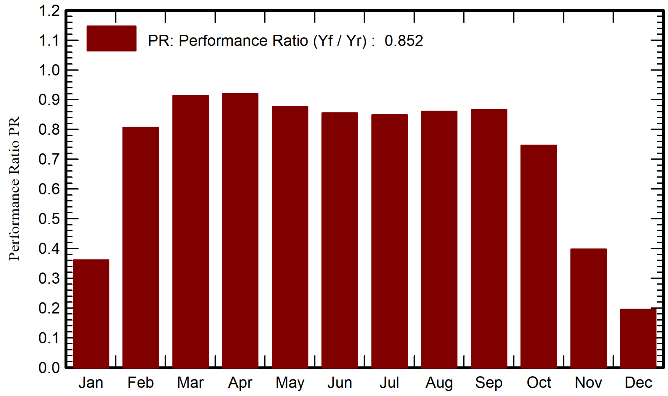
System Production

Produced Energy	44024256 kWh/year	Specific production	834 kWh/kWp/year
		Perf. Ratio PR	85.17 %

Normalized productions (per installed kWp)



Performance Ratio PR



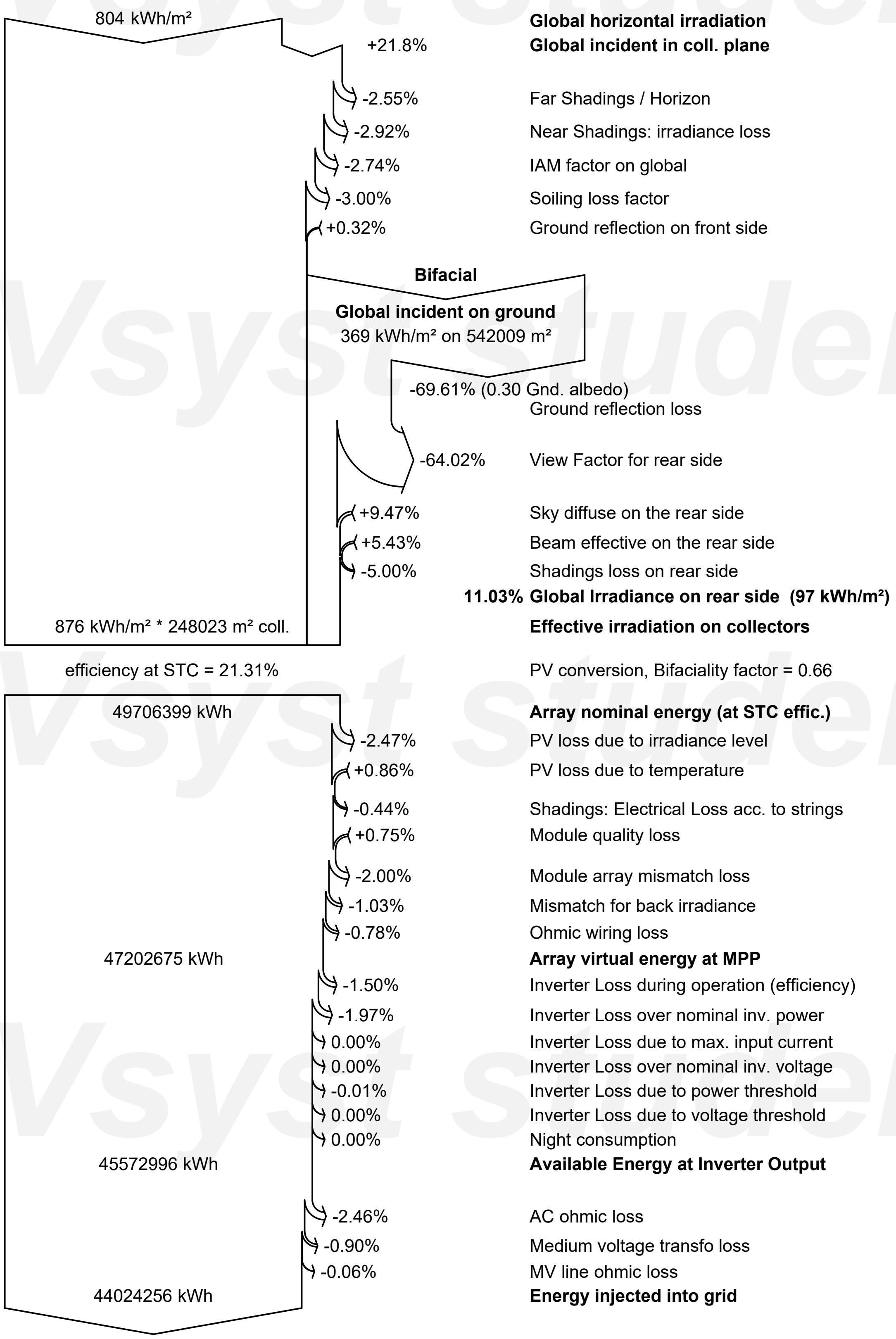
Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	E_Grid kWh	PR ratio
January	2.7	2.40	-1.00	4.8	1.9	101339	91405	0.362
February	14.3	12.30	-1.10	20.0	15.7	888931	851409	0.807
March	54.9	25.70	1.90	86.0	77.3	4351829	4148302	0.913
April	107.8	44.40	2.50	139.8	127.9	7161065	6790388	0.920
May	131.0	72.10	8.30	141.9	130.6	6887475	6557347	0.875
June	149.2	77.90	13.30	153.9	141.8	7308067	6947834	0.855
July	125.0	69.60	13.40	130.9	120.3	6167599	5862840	0.848
August	108.2	58.10	14.20	127.0	117.3	6067717	5775127	0.861
September	73.5	33.80	10.10	103.5	95.6	4983508	4739633	0.867
October	26.9	16.10	5.60	45.6	37.6	1876018	1797644	0.747
November	7.9	5.60	2.70	18.6	8.8	412057	390878	0.398
December	2.4	1.90	-7.00	6.9	1.6	79401	71449	0.195
Year	803.8	419.90	5.27	978.9	876.5	46285007	44024256	0.852

Legends

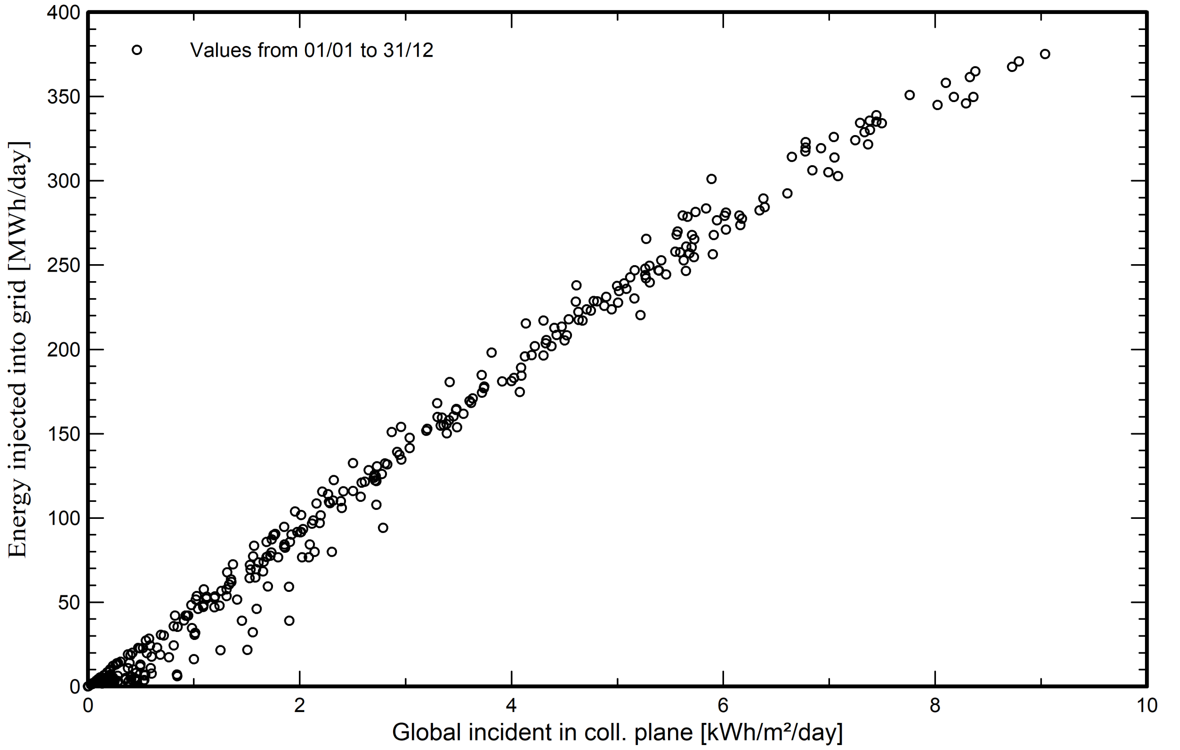
GlobHor	Global horizontal irradiation	EArray	Effective energy at the output of the array
DiffHor	Horizontal diffuse irradiation	E_Grid	Energy injected into grid
T_Amb	Ambient Temperature	PR	Performance Ratio
GlobInc	Global incident in coll. plane		
GlobEff	Effective Global, corr. for IAM and shadings		

Loss diagram

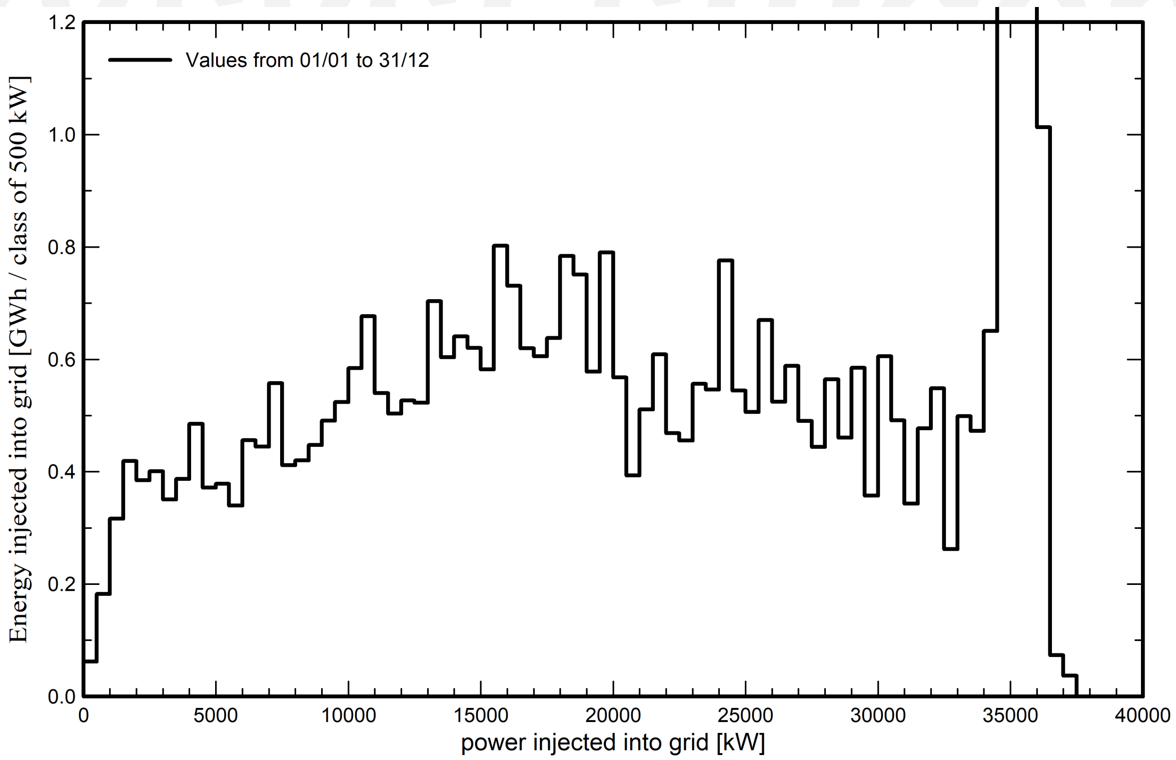


Predef. graphs

Daily Input/Output diagram



System Output Power Distribution



```
close all; clear all; clc
```

Scenario 1

Installere solcelle park uten bruk av batteri

```
% Importere alle kolonner fra CSV-fil
I          = readtable('Stokkfjellet_solinnstråling.csv','Delimiter',';',
'PreserveVariableNames',1);
I           = I.insolation;
I           = I(744:(743+8760))./1000; %kW

save("Sol_innstraling","I")

Tu           = readtable('utetemp.csv','Delimiter',';',
'PreserveVariableNames',1);
Tu           = Tu.Lufttemperatur;    % Hente ut kun kolonne for utetemperatur
Tu           = replace(Tu,',','.');  % Bytte ut komma med punktum
Tu           = char(Tu);             % Endre format til string
Tu           = str2num(Tu);          % Endre format fra string til tallverdi
Tu           = Tu(1:8760);

save("Temperature","Tu")

P_cutoff           =
readtable('Stokkfjellet_produksjon_2787.csv','Delimiter',';',
'PreserveVariableNames',1);
P_cutoff           = P_cutoff.Produksjon;
P_cutoff           = replace(P_cutoff,',','.');
P_cutoff           = char(P_cutoff);
P_cutoff           = str2num(P_cutoff);
P_cutoff           = P_cutoff(2787:11546);       % Hent ut 8760 verdier fra
2022 (tilsvarer 1 år) [MW]

save("Production_cutoff","P_cutoff")

P_AI           = readtable('production.csv','Delimiter',';',
'PreserveVariableNames',1);
P_AI           = P_AI.AI_Prediction;
P_AI           = replace(P_AI,',','.');
P_AI           = char(P_AI);
P_AI           = str2num(P_AI);
P_AI           = P_AI(1:8760);           % Hent ut kun 8760 verdier
(tilsvarer 1 år) [MW]

save("Production_AI","P_AI")

NO3           = readtable('production.csv','Delimiter',';',
'PreserveVariableNames',1);
NO3           = NO3.EUR_MWh;
```

```
NO3           = replace(NO3,',','.');
NO3           = char(NO3);
NO3           = str2num(NO3);
NO3           = NO3(1:8760).*10^(-3);           % EUR/kWh

save("EUR_per_MWh","NO3")


areal1 = [Productionarea('areal produksjon/areal_1.CSV')];
areal2 = [Productionarea('areal produksjon/areal_2.CSV')];
areal3 = [Productionarea('areal produksjon/areal_3.CSV')];
areal4 = [Productionarea('areal produksjon/areal_4.CSV')];
areal5 = [Productionarea('areal produksjon/areal_5.CSV')];
areal6 = [Productionarea('areal produksjon/areal_6.CSV')];
areal7 = [Productionarea('areal produksjon/areal_7.CSV')];
areal8 = [Productionarea('areal produksjon/areal_8.CSV')];
areal9 = [Productionarea('areal produksjon/areal_9.CSV')];
areal10 = Productionarea('areal produksjon/areal_10.CSV');
areal11 = Productionarea('areal produksjon/areal_11.CSV');
areal12 = Productionarea('areal produksjon/areal_12.CSV');
areal13 = Productionarea('areal produksjon/areal_13.CSV');
areal14 = Productionarea('areal produksjon/areal_14.CSV');
areal15 = Productionarea('areal produksjon/areal_15.CSV');
areal16 = Productionarea('areal produksjon/areal_16.CSV');
areal17 = Productionarea('areal produksjon/areal_17.CSV');
areal18 = Productionarea('areal produksjon/areal_18.CSV');
areal19 = Productionarea('areal produksjon/areal_19.CSV');
areal20 = Productionarea('areal produksjon/areal_20.CSV');


production = [areal1 areal2 areal3 areal4 areal5 areal6 areal7 areal8
areal9 areal10 areal11 areal12 areal13 areal14 areal15 areal16 areal17
areal18 areal19 areal20];

sum(production);

save("Areal production","production")

tot_prod = bsxfun(@plus, P_AI, production.*10^(-3)); %MW
over_prod = ((tot_prod)-90).*(((tot_prod)-90)>0); %MW
sol_prod_trafo1 = bsxfun(@minus, production.*10^(-3), over_prod); %MW
sol_prod_trafo = sol_prod_trafo1.*10^(3); %kW

save("Total production with wind", "tot_prod")
save("Over prod", "over_prod");
save("Sol prod trafo", "sol_prod_trafo1")

x = sum(sol_prod_trafo);
x = x';
save("Tot sol prod", "x")
```

```
y = sum(sol_prod_trafo1);
y = y';
save("Lost sol prod year", "y")

save("Total production","tot_prod")
```

Økonomi analyse

```
ant_panel =
readtable('arlig_oversikt.csv','Delimiter',';','PreserveVariableNames',1);

ant_panel = ant_panel.Antall_moduler;

profit_eur = sol_prod_trafo1.*NO3;
profit_eur_year = sum(profit_eur);
profit_eur_year = round(profit_eur_year',4);

save("Profit from solar under trafo","profit_eur_year");

profit1 = tot_prod.*NO3; %EUR
profit_year1 = sum(profit1);

euro = 10.5;
ar = 30;

kost1 = 600000.*ant_panel.*550.*10^(-6)+100000+100000*ar+
profit_eur_year.*0.03;
%This was altered manually to represent the kost reduction in solar
%production

ko=kost1';
r=1.03;

syms n
NNV=round(-ko+symsum(profit_eur_year./(r^n),n,1,30))'
NNV = double(NNV)
```

```
function areal = Productionarea(filename)

areal = readtable(filename,'Delimiter',';','PreserveVariableNames',1);
areal = areal.E_Grid;
areal = areal(2:8761);

end
```

```
close all; clear all; clc
```

Scenario 2

Installing solar panels with battery, dimentioning of battery for scenario 3 as well.

```
load("Areal production.mat")
load("Production_AI.mat")
load("EUR_per_MWh")
load("Total production with wind")
load("Over prod")
load("Sol prod trafo")

capacity_remaining = -((tot_prod)-90*10^3).*(((tot_prod)-90*10^3)<0);
hours = (1:8760);

%For loop that calculates how much and when the battery feeds out on the
grid

% length is equal to hours in the year plus one
battery_charge = zeros(8761,20); %sets initial value to zero
for i = 1:8760
    battery_charge(i+1,:) = (battery_charge(i,:) + over_prod(i,:)
- capacity_remaining(i,:)).*((battery_charge(i,:) + over_prod(i,:) -
capacity_remaining(i,:))>0);

    battery_diff = battery_charge(2:8761,:) - battery_charge(1:8761-1,:); %
calculate the change in battery charge for for each hour
end


save("Battery", "battery_diff")

charge = (battery_diff.*10^(-3)).*(battery_diff>0); %MWh
grid = -battery_diff.*(battery_diff<0); %kWh

save("Energy to grid","grid")

%Total production thatis sent out on the grid from solar and battery
sol_prod_trafo = bsxfun(@plus,sol_prod_trafo1,grid.*10^(-3));
tot_prod = bsxfun(@plus,sol_prod_trafo.*10^3,P_AI.*10^3);

x = sum(sol_prod_trafo); %MWh
x = x';

y = sol_prod_trafo.*NO3.*10^(3);
y = sum(y)';
```

Battery dimentioning for scen 2 and 3

```
load("FCR N solgt volum") % "solgt_volum" i MW
battery_size = charge + solgt_volum;%MW

year = sum(battery_size);
year = year';

for i = 1:365
    p = (i-1)*8760/365 + 1;
    b = i*8760/365;
    DagliData1 = over_prod(p:b,:);
    over_prod_dag(i,:) = sum(DagliData1);

    DagliData2 = sol_prod_trafo1(p:b,:);
    sol_dag(i,:) = sum(DagliData2);

    DagliData3 = sol_prod_trafo(p:b,:);
    sol_grid_dag(i,:) = sum(DagliData3);

    DagliData4 = battery_size(p:b,:);
    battery_size_day3(i,:) = sum(DagliData4);
end

%%%%% batt = batteri og kont = konteiner %%%%%

kont = 12.04*2.28*2.26; %m^3
dim_batt = 1.6*2*1.2; %m^3
batt = round(kont/dim_batt,0); %batterier per kontainer

batt_capacity = batt*275*10^(-3); %MW/per kontainer


%stopper dimensjoneringen på batteri str 10 %%%%%%%%%%
batt2 = max(over_prod_dag).*10^(-3);%MWh
batt2 = batt2(:,1:10);
batt3 = max(battery_size_day3); %MWh
batt3 = batt3(:,1:10);

for i = 1:10
    batt2(:,end+1) = batt2(:,10);
    batt3(:,end+1) = batt3(:,10);
end
%%%%%%%%%%


%ceil runder alltid tallene oppover til nærmeste hele slik at alt av
%overproduksjon vil tas med
```

```
kont2 = ceil(batt2./batt_capacity);
kont3 = ceil(batt3./batt_capacity);

save("battery scenario 2","kont2")
save("battery scenario 3","kont3")

kont_cap2 = kont2.*batt_capacity;
kont_cap3 = kont3.*batt_capacity;
```

Calculating how much production will get lost when dimentioning the battery for a days production

```
%Scenario 3

tot_grid_opplad = zeros(size(battery_size));

id_nonzero = (battery_size>eps);
[begin,ends] = find_start_end_group(id_nonzero); % find start and end
indexes of groups of zeroes

for k = 1:numel(begin)
    start = begin(k);  % start index of k th groups of non zero values
    stop = ends(k);  % end index of k th groups of non zero values
    tot_grid_opplad(stop) = sum(battery_size(start:stop));
end

batt_cutoff = bsxfun(@minus,tot_grid_opplad,kont_cap3);
batt_cutoff = batt_cutoff.*(batt_cutoff>0); %Inneholder alt batteriet ikke
tar med

lost_production = bsxfun(@minus,batt_cutoff,solgt_volum);
lost_production = lost_production.*(lost_production>0);
lost_production = sum(lost_production)';

max(batt_cutoff);
b = sum(batt_cutoff);
b=b';

batt_scen3 = bsxfun(@minus,battery_diff,batt_cutoff);
batt_scen3 = batt_scen3.*(batt_scen3>0);
c = sum(batt_scen3);
c = c';


%Scenario 2
over_prod = over_prod*10^(-3);
d = round(sum(over_prod),4);
d = d';
```

```
tot_grid_opplad2 = zeros(size(over_prod));
id_nonzero2 = (over_prod>eps);
[begin,ends] = find_start_end_group(id_nonzero2);

% loop over this groupes
for j = 1:numel(begin)
    start = begin(j);  % start index of k th groups of non zero values
    stop = ends(j);  % end index of k th groups of non zero values
    tot_grid_opplad2(stop) = sum(over_prod(start:stop));
end

batt_cutoff2 = bsxfun(@minus,tot_grid_opplad2,kont_cap2);
batt_cutoff2 = batt_cutoff2.*(batt_cutoff2>0); %Inneholder alt batteriet
ikke tar med

lost_production2 = bsxfun(@minus,batt_cutoff2,solgt_volum);
lost_production2 = lost_production2.*(lost_production2>0);
lost_production2 = sum(lost_production2)';

max(batt_cutoff2);
e = sum(batt_cutoff2);
e = e';

batt_scen2 = bsxfun(@minus,battery_diff,batt_cutoff2);
batt_scen2 = batt_scen2.*(batt_scen2>0);
f = sum(batt_scen2);
f = f';
```

Energy from PV system and battery for scenario 2 and 3

```
sol_prod_trafo2 = bsxfun(@plus,sol_prod_trafo1,batt_scen2.*10^(-3));

sol_prod_trafo3 = bsxfun(@plus,sol_prod_trafo1,batt_scen3.*10^(-3));
sol_prod_trafo3 = sum(sol_prod_trafo3)';

tot_energy2 = bsxfun(@minus,f,e);
tot_energy3 = bsxfun(@minus,year,b);
save("Battery to grid3", "batt_scen3")
save("Battery to grid2", "batt_scen2")
```

NPV Calculations Scenario 2 and 3

```
load("Original cost")
load("Profit total scenario 3")
load("Profit from solar under trafo")
```

```
x2 = 4.4.*kont2;
x3 = 4.4.*kont3;
kost2 = -(1003.3445).*x2 + 801003.3445; %Eur per MW
kost3 = -(1003.3445).*x3 + 801003.3445; %Eur per MW

batteri_kost2 = kost2.*x2
batteri_kost3 = kost3.*x3

kost2=bsxfun(@plus, kost1', batteri_kost2);
kost3=bsxfun(@plus, kost1', batteri_kost3)

ko2=kost2';
ko3=kost3';
r=1.03;

profit_2=grid.*NO3; % NO3 er i EUR/kW
profit_2_year=sum(profit_2);

tot_profit=bsxfun(@plus, profit_2_year, profit_eur_year);
tot_profit=tot_profit';

syms n
NNV2=round(-ko2+symsum(tot_profit./(r^n),n,1,30))'
NNV2 = double(NNV2)

NNV3=round(-ko3+symsum(Profit_tot_year./(r^n),n,1,30))'
NNV3 = double(NNV3)
```

```
function [begin,ends] = find_start_end_group(ind)
    % This locates the beginning /ending points of data groups
    % Important : ind must be a LOGICAL array
    D = diff([0;ind(:);0]);
    begin = find(D == 1);
    ends = find(D == -1) - 1;
end
```

```
close all; clear all; clc
```

Scenario 3

Med batteri i frekvens markedet

```
load("Production_AI.mat")
load("Areal production.mat")
load("Energy to grid.mat")
load("EUR_per_MWh")
% max(grid)
% max(production)

FCR = readtable('PrimaryReserves_D2_2022','Delimiter',';',
'PreserveVariableNames',1);
FCR = FCR.FCR_N_Volume;

FCR_price = readtable('FCRN_price.csv','Delimiter',';',
'PreserveVariableNames',1);
FCR_price = FCR_price.FCR_N_Price;

ant = readtable('PrimaryReserves_D2_2022','Delimiter',';',
'PreserveVariableNames',1);
ant = ant.Area;
ant = string(ant);

x = strcmp(ant,"NO3");
x = string(x);
y = zeros(size(x));
y(strcmp(x,"true")) = 1;

FCR_NO3 = FCR .* y;
FCR_NO3 = nonzeros(FCR_NO3);

FCR_N_price = FCR_price.* y;
FCR_N_price = nonzeros(FCR_N_price);

for i  = 1:56
    FCR_NO3( end+1, : ) = 0;

    FCR_N_price( end+1, : ) = 0;
end

tot_prod = bsxfun(@plus, P_AI, production.*10^(-3));
sol_prod_trafo = bsxfun(@minus, production.*10^(-3),
((tot_prod)-90).*(((tot_prod)-90)>0));
sol_prod_trafo = bsxfun(@plus,sol_prod_trafo,grid.*10^(-3));

selling_frec = bsxfun(@minus,sol_prod_trafo,FCR_NO3);
selling_frec = selling_frec.*(selling_frec>0);
```

```
% Her er det lengden på matrisene som har noe å si: hvor mange timer i året
man får solgt på frekvens markedet.

    selling_frec1 = nonzeros(selling_frec(:,1));
    selling_frec2 = nonzeros(selling_frec(:,2));
    selling_frec3 = nonzeros(selling_frec(:,3));
    selling_frec4 = nonzeros(selling_frec(:,4));
    selling_frec5 = nonzeros(selling_frec(:,5));
    selling_frec6 = nonzeros(selling_frec(:,6));
    selling_frec7 = nonzeros(selling_frec(:,7));
    selling_frec8 = nonzeros(selling_frec(:,8));
    selling_frec9 = nonzeros(selling_frec(:,9));
    selling_frec10 = nonzeros(selling_frec(:,10));
    selling_frec11 = nonzeros(selling_frec(:,11));
    selling_frec12 = nonzeros(selling_frec(:,12));
    selling_frec13 = nonzeros(selling_frec(:,13));
    selling_frec14 = nonzeros(selling_frec(:,14));
    selling_frec15 = nonzeros(selling_frec(:,15));
    selling_frec16 = nonzeros(selling_frec(:,16));
    selling_frec17 = nonzeros(selling_frec(:,17));
    selling_frec18 = nonzeros(selling_frec(:,18));
    selling_frec19 = nonzeros(selling_frec(:,19));
    selling_frec20 = nonzeros(selling_frec(:,20));

hours = [length(selling_frec1)
    length(selling_frec2)
    length(selling_frec3)
    length(selling_frec4)
    length(selling_frec5)
    length(selling_frec6 )
    length(selling_frec7 )
    length(selling_frec8 )
    length(selling_frec9 )
    length(selling_frec10 )
    length(selling_frec11 )
    length(selling_frec12 )
    length(selling_frec13 )
    length(selling_frec14 )
    length(selling_frec15 )
    length(selling_frec16 )
    length(selling_frec17 )
    length(selling_frec18 )
    length(selling_frec19 )
    length(selling_frec20 )]./8760.*10^2;

solgt_volum = FCR_NO3 .* (selling_frec>0);

save("FCR N solgt volum", "solgt_volum")
```

```
Profit_frec = FCR_NO3 .* (selling_frec>0).* FCR_N_price;
Profit_frec_year = sum(Profit_frec);

Profit_usual = (sol_prod_trafo .* (~selling_frec)+selling_frec).*NO3.*10^3;
%Bytter 0 og 1
Profit_usual_year = sum(Profit_usual);

Profit_tot = Profit_frec + Profit_usual;
Profit_tot_year = sum(Profit_tot);
Profit_tot_year = Profit_tot_year';

save("Profit total scenario 3", "Profit_tot_year")
```

NTNU
Kunnskap for en bedre verden