Marte Hoff Hvamstad
Ravn Adrian Ravndal
Yulia Vagapova

Design of an energy storage solution for a hybrid wind/solar power plant in South Africa

Bachelor's thesis in Engineering, Renewable Energy
Supervisor: Bruno G. Pollet
Co-supervisor: John Amund Lund
May 2022

Bachelor's thesis

NTNU
Norwegian University of Science and Technology
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Department of Energy and Process Engineering

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Bacheloroppgave

Oppgavens tittel: Design av et energilagringssystem for et hybrid vind/sol kraftanlegg i Sør Afrika **Project title (ENG):** Design of an energy storage solution for a hybrid wind/solar power plant in South Africa	**Gitt dato:** 29.11.2021 **Innleveringsdato:** 20.05.2022 **Antall sider rapport / sider vedlagt:** 100/10
Gruppedeltakere: Ravn Adrian Ravndal Marte Hoff Hvamstad Yulia Vagapova	**Veileder:** Bruno G. Pollet Professor, NTNU **Prosjektnummer:** 22BIFOREN-008
Oppdragsgiver: Norsk Vind	**Kontaktperson hos oppdragsgiver:** John Amund Lund

Fritt tilgjengelig: X

Tilgjengelig etter avtale med oppdragsgiver: ☐

Rapporten frigitt etter:

Gruppedeltakere signaturer:

Ravn A. Ravndal   Yulia Vagapova   Marte H. Hvamstad

Ravn A. Ravndal   Yulia Vagapova   Marte H. Hvamstad

Preface

This bachelor thesis is written by three engineering students of the Renewable Energy study program at the Department of Energy and Process Engineering, Norwegian University of Science and Technology (NTNU) in Trondheim, Norway. The thesis is the finishing part of the study program and is equal to 20 credits of the total of 180 credits.

The thesis topic was suggested by the Norwegian company within wind power - Norsk Vind. This project is a feasibility study of storage system optimization for a hybrid plant in the Republic of South Africa.

Our words of appreciation go to our internal supervisor, Professor Bruno G. Pollet at NTNU, who provided us with guidance and essential knowledge throughout the entire process. We would also like to thank our external supervisor John Amund Lund, at Norsk Vind, for providing us with the thesis topic, necessary data and help with further implementation. The group also thanks the students at the Statistics Help (Statistikkhjelpen) at NTNU, for helping with the data processing.

Trondheim 19.05.2022

Ravn A. Ravndal **Yulia Vagapova** **Marte H. Hvamstad**

Abstract

74% of the energy sector in South Africa consists of coal. The sector is unable to meet the energy demand of the country. As a result, the country experiences planned daily power outages. Coal is an unsustainable and environmentally harmful energy source. Change is needed in order to better the energy situation. Investments are done in renewable projects to make the country less dependent on coal. The company Norsk Vind is developing various wind projects in Norway, but has also an ongoing project in Tanzania. They wish to expand on the African continent with a hybrid wind/solar plant in South Africa, to contribute and help the country to utilise their rich solar and wind resources.

The planned hybrid plant consists of three 70 MW solar plants and two 140 MW wind plants. The goal of the thesis was to investigate the profitability of including a battery energy storage system for storage arbitrage purposes. Initially five different battery technologies were researched, with the lithium iron phosphate battery and the vanadium redox flow battery being chosen for further investigation.

Data series for energy production from solar and wind plants were provided by Norsk Vind. These were scaled to match the given system, then analyzed with the help of Python and Excel. Income from the plant and battery system was found by using time of use tariffs and simulating charging and discharging cycles for the battery technologies over a year. Based on a system lifetime of 30 years, the calculated incomes were used in net present value, internal rate of return and levelized cost of storage calculations with the help of MATLAB and Excel. This was done in order to find the most profitable systems.

It was found that several LFP-systems with 4-5 hr duration discharge and 10-75 MW power capacities would be profitable. The 50 MW/5 hr system resulted in the largest NPV and IRR, in addition to the lowest LCOS. It was also discovered that none of the VRB-systems were profitable in this case. The group would recommend Norsk Vind to further look into a LFP battery energy storage system.

Sammendrag

74% av energisektoren i Sør-Afrika består av kull. Sektoren klarer ikke å møte energibehovet til landet. Dette fører til at landet opplever daglige planlagte strømbrudd. Kull er en ikke-fornybar og forurensende energikilde. Forandring er nødvendig for at landets energisituasjon skal bli forbedret. For å gjøre landet mindre avhengig av kull, investeres det i fornybarsektoren. Bedriften Norsk Vind utvikler flere ulike vindprosjekter i Norge, men har også et pågående prosjekt i Tanzania. De ønsker å ekspandere videre i Afrika med et hybrid vind/sol kraftverk i Sør-Afrika. Dette skal bidra til at landet tar i bruk sine rike sol- og vindressurser.

Den planlagte hybrid kraftstasjonen består av tre 70 MW solkraftverk og to 140 MW vindkraftverk. Målet for denne avhandlingen er å undersøke om det ville ha vært økonomisk gunstig å inkludere et batteri energilagringssystem i hybridsystemet ved lagringsarbitrasje. Fem ulike batteriteknologier ble undersøkt i utgangspunktet. Det ble bestemt å analysere batteriteknologiene litium jernfosfat og vanadium redox flow batteri.

Dataserier for energiproduksjon fra et solkraftverk og et vindkraftverk ble gitt av Norsk Vind. Disse dataene ble oppskalert for å passe den gitte størrelsen for kraftverket, og deretter analysert med Python og Excel. Inntekten til kraftverket og energilagringssystemet ble funnet ved å bruke forbrukstariffer og simulering av opp- og utladning av batteriene over ett år. Basert på at systemet har en 30 års levetid ble denne inntekten brukt videre for å kalkulere netto nåverdi, intern avkastning og utjevnet lagringskostnad ved hjelp av MATLAB og Excel. Dette ble gjort for å finne det mest økonomisk lønnsomme systemet.

Det ble funnet at det var flere LFP-systemer med 4 til 5 timer i utladningstid og 10-75 MW effektkapasitet som ville ha vært lønnsomme. Systemet med 50 MW/5 timer ble fastsatt som det mest lønnsomme med størst netto nåverdi og intern avkastning, samt lavest utjevnet langringskostnad. Det ble også oppdaget at ingen av de analyserte VRB-systemene var lønnsomme. Gruppen vil anbefale at Norsk Vind ser nærmere på muligheten for å ta i bruk et LFP-batteri energilagringssystem.

List of Abbreviations

α-SI	Amorphus Silicon
ABL	Atmospheric Boundary Layer
AC	Alternating Current
AGM	Absorbed Glass Mat
AM	Air Mass
B-TMS	Battery Thermal Management System
BESS	Battery Energy Storage System
BMS	Battery Management System
BRICS	Brazil, Russia, India, China and South Africa
c-SI	Crystalline Silicone
CAPEX	Capital Expenditure
CSP	Concentrated Solar Power
DC	Direct Current
DIF	Diffuce Horizontal Irradiation
DNI	Direct Normal Irradiation
DoD	Depth of Discharge
EFB	Enhanced Flooded Battery
EMS	Energy Management System
ESS	Energy Storage System
EV	Electric Vehicle
GDP	Gross Domestic Product
GHI	Global Horizontal Irradiation
HAWT	Horizontal Axis Wind Turbine
IDE	Integrated Development Environment
IPP	Independent Power Producers
IRR	Internal Rate of Return
LAB	Lead-acid Battery
LCOS	Levelized Cost Of Storage
LCO	Lithium Cobalt Oxide
LFP	Lithium Iron Phosphate
LIB	Lithium-ion Battery
LMO	Lithium Manganese Oxide
LNO	Lithium Nickel Oxide
LTO	Lithium Titanate
MUSD	Million American Dollar
NAS	Sodium Sulfur
NCA	Lithium Nickel Cobalt Aluminium Oxide

NMC	Lithium Nickel Manganese Cobalt Oxide
NOCT	Nominal Operating Cell Temperature
NPV	Net Present Value
O&M	Operations and Maintenance
OPEX	Operating Expenditure
PNNL	Pacific Northwest National Laboratory
PV	Photovoltaic
REIPPPP	The Renewable Energy Independent Power Producers Procurement Programme
RFB	Redox Flow Battery
RTE	Round Trip Efficiency
S-TMS	System Thermal Management System
SCADA	Supervisory Control and Data Acquisition
SE	Solid Electrolyte
SHC	Solar Heating and Cooling
SoC	State of Charge
SSB	Solid-State Battery
STC	Standard Test Conditions
TFSC	Thin-Film Solar Cells
TOU	Time Of Use
USD	American Dollar
VAWT	Vertical Axis Wind Turbine
VRB	Vanadium Redox Battery
VRLA	Valve Regulated Lead-Acid
WACC	Weighted Average Cost of Capital
ZAR	South African Rand

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1 Introduction

In this section the background, project problem, scope and methodology of the thesis will be presented.

1.1 Background

South Africa is among the largest economies in Africa, having the third highest Gross Domestic Product (GDP) on the continent in 2021 at 329.53 billion USD [5]. However, the country faces major challenges in the energy sector. Only 85% of the population has access to electricity [36]. The population is experiencing load shedding due to lack in energy production. Municipalities are scheduled to have daily blackouts for several hours [91]. Electricity prices are high in the morning and afternoon, where the biggest consumption occurs. In addition, the energy sector is affected by a poor and badly maintained infrastructure after apartheid.

The annual electricity consumption in South Africa is over 220 TWh [88]. The country's energy supply stems mostly from coal, which constituted 74% of the primary energy supply in 2018 [36]. Coal is cheap, and there are big coal reservoirs in the country. However, it is also dirty with a carbon intensity of approximately 1 000 g/kWh [65]. Investments in renewable energy have been made in recent years. South Africa has potential for green energy, with good conditions for renewable sources such as solar and wind, especially in the north-western area of the Northern Cape. The country was in 2019 rated as the 12th most attractive investment for renewable energy worldwide [122].

With the increase in renewable energy production, there is a growing demand of energy storage systems. Solar irradiation and wind resources vary over time, making the production vary as well. Storing the energy produced can be a useful tool when producing and selling renewable energy, as it increases the system's flexibility. Battery energy storage systems are a viable option as they are low-cost compared to other types of energy storage systems. Energy can easily be charged and discharged from the battery system with little loss. Prices of batteries are also decreasing and the technology is being developed further. Such storage systems can have many application areas, one of them being storage arbitrage.

1.2 Project problem

As the energy crisis in South Africa continues to grow, a solution to produce more energy is needed. Power plants need to be constructed in order to increase the energy production. With an energy storage system (ESS) installed, the energy can be stored and sold when needed.

The purpose of this bachelor thesis is to make a conceptual design of a battery storage solution for a hybrid wind/solar power plant in South Africa. The design will be based on estimating income from charging/discharging the battery system and evaluation of different battery energy storage technologies. Through economic optimisation of the battery energy storage system (BESS), considering such things as net present value (NPV), internal rate of return (IRR) and levelized cost of storage (LCOS), the most profitable solutions will be found. Is adding a BESS to the system economically feasible? If so, which BESS technology and size is most optimal?

1.3 Scope and methodology

Scope

- Research the energy landscape in South Africa.
- Research different battery technologies.
- Obtain information about cost and performance parameters of the different batteries for grid-scale systems.
- An overview of the power production from the hybrid plant through estimations.
- Estimate the income from the BESS based on electricity tariff.
- Do an economical optimisation and evaluation of the BESS.

Methodology

The thesis is based on information gathered by the group members through literature review, online sources and mail correspondences. With the gathered information, a battery storage solution for the hybrid plant will be presented. Through weekly meetings with the internal supervisor, and meetings when needed with the external supervisor, the group received guidance throughout the project.

Literature review

The figures in the following sections are produced/reproduced by the group, unless cited.

2 The Republic of South Africa

South Africa is the southernmost country on the African continent. The nation has a population of 59.3 million (per 2020) and a total area of 1 213 090 km^2 [97]. The country has three capitals, one for each governmental power; Pretoria - administrative capital, Cape Town - legislative capital and Bloemfontein - judicial capital. The nation shares borders with Namibia, Botswana, Zimbabwe, Mozambique, Eswatini and surrounds the landlocked country of Lesotho [115, 124]. Figure 2.1 depicts the map of the country.

Figure 2.1: Map of South Africa, showing the borders to the neighboring countries [116].

2.1 Demography

South Africa is considered an economical, military and political great power on the African continent, but it still has its problems which stems from the apartheid period [124]. The three largest cities are Cape Town, Durban and Johannesburg. The largest province is Gauteng, home to both Pretoria and Johannesburg. The country is also the 26th largest in the world by population and area [115].

The population consists of black African (81% of the total population), colored (9%), white (8%) and Indian/Asian (2%). Note that colored is a term used in South Africa, for people of mixed race ancestry who have developed their own defined cultural identity over several hundred years. South Africa has eleven official languages, with the most prominent ones being isiZulu, isiXhosa, English and Afrikaans [115, 124].

In Table 2.1, one can observe South Africa's average in median age, fertility rate, life expectancy and GDP per capita compared to Norway and the World .

Table 2.1: South Africa compared to Norway and the World average [46, 50, 76, 86]

	South Africa	***Norway***	***World Average***
Median age	28	39.5	30
Fertility rate	2.36	1.68	2.41
Life expectancy	64.38	82.51	72.91
GDP per capita [USD]	5 656	67 330	10 919

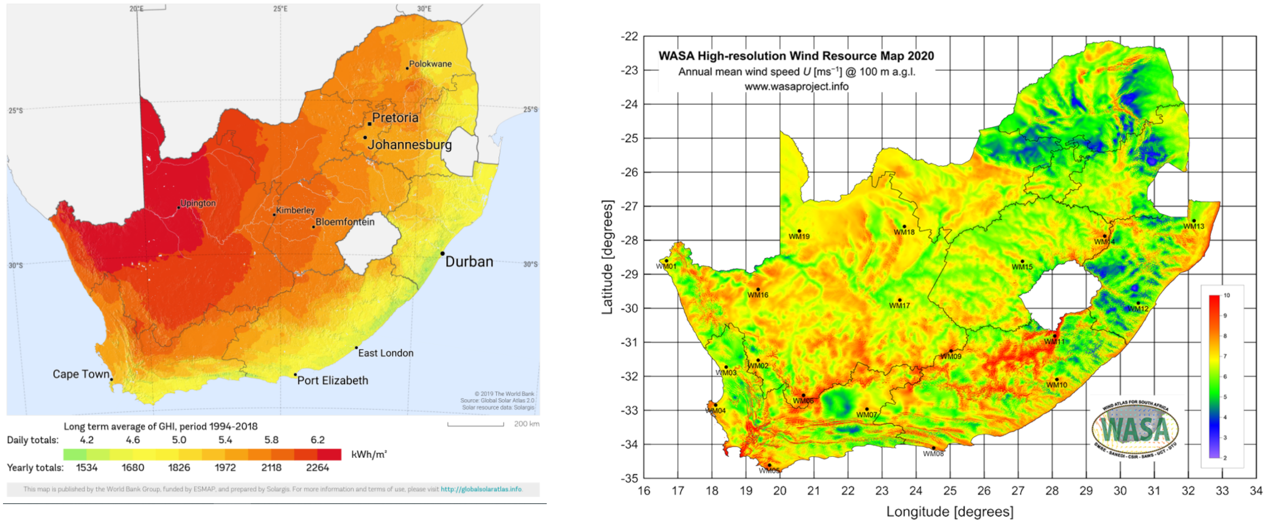
It is estimated that 96.7% has access to a clean water source and 93.2% has access to a sanitation facility. South Africa is the country in the world with the highest number of people living with HIV (7.5-7.8 million) [70, 115].

2.2 Geography and climate

With a total land area of over 1.2 million km^2, South Africa has both a varied geography and climate. South Africa has a long coastline stretching 3000 km from Namibia on the Atlantic coast in the northwest, around the tip of Africa to the northeast, with Mozambique on the Indian ocean's coastline. The country has a diverse wildlife, vegetation and various types of biomes ranging from forests to deserts and savannas [11].

The climate in South Africa is mostly subtropical, but with large regional variations. In the Western Cape province in the southwest, there is a Mediterranean climate with rainfall in the winter. The rest of the country generally has its rainfall in the summer. The northwest is dry and consists largely of deserts. In the northeast by Mozambique, there is a subtropical climate. Summer temperatures range from 21-30°C and during winter one can experience below freezing temperatures. South Africa is quite a dry country, which has affected the country earlier with drought periods, which lead to heavy water restrictions for the population [80, 82].

South Africa has great opportunities for renewable energy with rich resources in especially solar energy, but also in wind. The solar irradiance is high, especially in the Northern Cape. Figure 2.2a illustrates the global horizontal irradiation (GHI) of the country. With these high amounts of GHI and around 2500 hours of sun every year, South Africa is primed for usage of solar power [105]. In addition does South Africa has the potential to utilise its wind resources, with both the Northern and Eastern cape having great annual mean wind speeds as observed in Figure 2.2b.



(a) Global Horizontal Irradiation in South Africa [52].

(b) Mean wind speed in South Africa [119].

Figure 2.2: South African solar and wind resources.

2.3 Economy

South Africa is one of the largest economies on the African continent. The economy experienced a significant boost in the years after abolishing apartheid in 1990-1993. The post-apartheid South Africa was still facing problems of integrating the previously oppressed majority of the population into the economy. In 1996 the state created a five-year plan - GEAR (Growth, Employment and Redistribution), and various new laws to solve the problem. The plan was only partly successful, but it served as an important foundation to even the differences. However, there are still traces of apartheid to be found in the population to this day. Unemployment, poverty and inequality are some of the issues that are still dominating the economy. Since the financial crisis in 2008, unemployment in the country has been at 25-30% [53, 123].

The economic growth had been on a steady decline since 2011, and as a result of the pandemic, the growth took a heavy hit with a negative GDP growth of -6.4 in 2020. The GDP of South Africa has also declined in correspondence to this. The GDP was on an all time high with 458 billion USD in 2011, which stands in stark contrast to the around 335 billion USD in 2020. The department of statistics declared in March 2020 that South Africa is entering its third recession since 1994 [49].

South Africa is dependent on its mining industry with various precious metals as some of its most important resources. Figure 2.3 illustrates the great importance of the mining industry to the South African export and economy. The highest singular exports are the precious metals gold and platinum with 12.8% and 11.7% of the total export respectively [117].

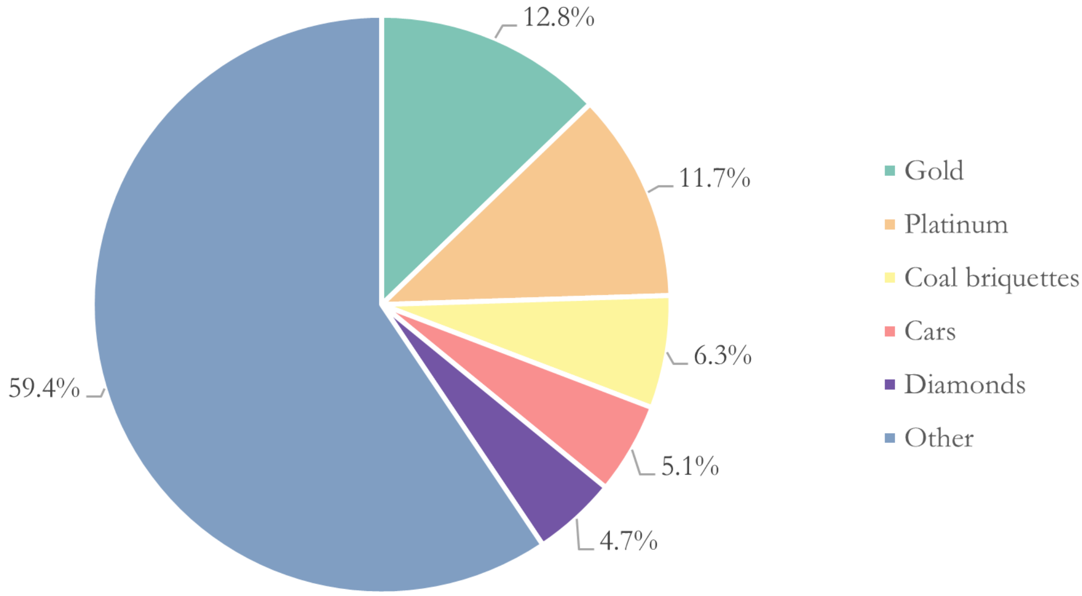


Figure 2.3: South African export (2020).

South Africa has been part of the BRICS (Brazil, Russia, India, China, South Africa) since 2011. The group consists of countries that are predicted to be challengers to "the West". It is meant to serve as an easier way for cooperation among the members. But, as BRICS is not a binding alliance, its possibility for solidarity often gets overshadowed by internal affairs and problems [109]. South Africa is also the only African member of G20, which is an economic union between 19 countries and the EU [71].

2.4 Energy landscape

The current energy situation is characterized by energy shortages and blackouts. Approximately 85% of the population has access to electricity, meaning millions of people live without electricity. Electricity production has to increase in order to cover the demand, possibly by increasing the renewable energy production, where South Africa has a lot of potential. In 2019, only 12% of hydro, 16% of solar and 2% of wind capacity was utilised, as seen in Figure 2.4. Capacity utilised is annual generation divided by year-end capacity times 8 760 hr/year [36].

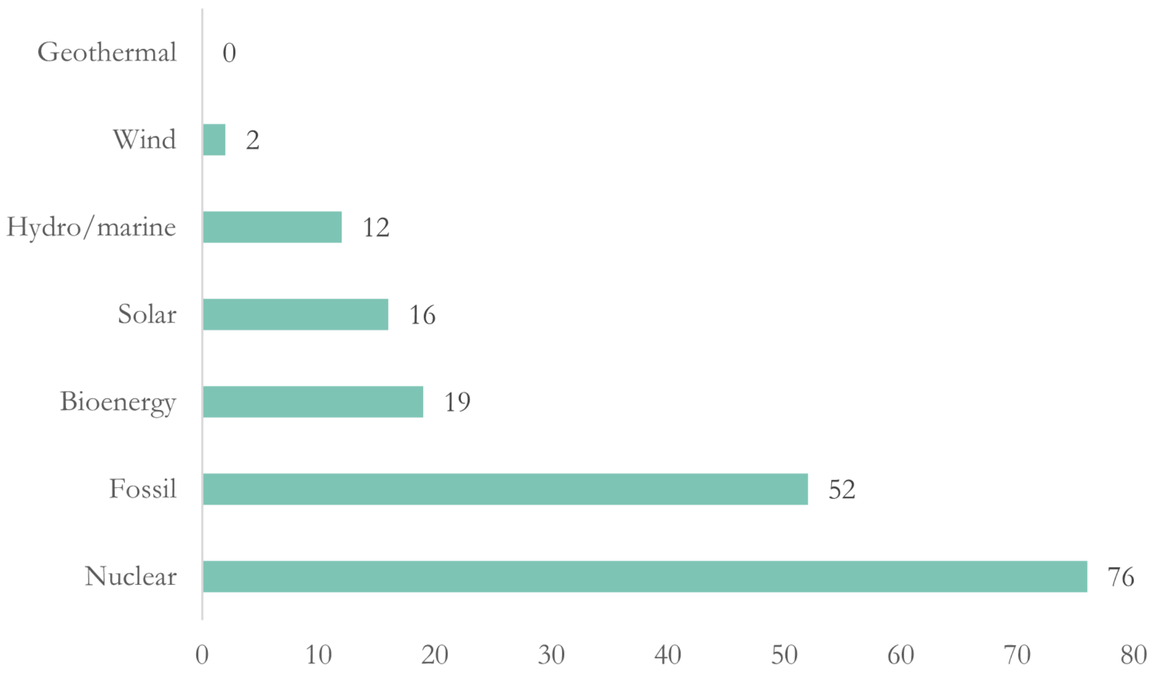


Figure 2.4: Capacity utilisation in 2019 (%), reproduced [36].

South Africa's energy sector consists mostly of coal, with it being 74% of the total primary energy supply in 2018 [36]. Coal is plentiful and cheap, and the country has the 5th largest coal reserves in the world, at approximately 66.7 billion tons. Most of South Africa's greenhouse gas emissions stem from coal, and therefore renewable energy projects have been a priority. However, coal is likely to remain the main source of electricity production in the following decades, as other energy sources cannot yet replace the big coal supply [122].

2.4.1 Electricity situation

South Africa faces major challenges within the energy sector. Large parts of the population do not have access to electricity, in addition to the country experiencing power outages due to shortages in the energy production. As the energy demand increases in the country, the energy production has not been able to keep up. Especially after apartheid, the energy demand grew rapidly, leading to rapid industrialization to meet the demand. Poor infrastructure and maintenance, outdated power plants and politicization of the power market are some of the factors that has led to the energy crisis [4].

Infrastructure

The electricity sector can be divided into three sub-sectors: generation, transmission and distribution. In terms of generation, Eskom is the primary electricity supplier in South Africa. Eskom is a state-owned company, and generates about 90% of the electricity in the country. The utility owns and operates several power plants, including coal-fired, gas-fired, hydro and pumped storage power stations, and one nuclear power station. Eskom generates, transmits and distributes electricity to industrial, residential and other customers, as well as municipalities who then distributes the electricity among the residents. The net maximum generating capacity in 2018 was 48 GW, according to Eskom's Integrated Results 2018. Coal-fired power stations make up most of the capacity [122].

In 2003 it was decided that there would be a private sector in the electricity industry. Future power generation capacity would be divided between Eskom (70%) and Independent Power Producers (IPPs) (30%). The Renewable Energy Independent Power Producers Procurement Programme (REIPPPP) was established as a result, and aimed to bring additional power into the energy sector through private investments in renewable energy. This is a competitive bidding mechanism, and works as an auction of renewable energy projects in South Africa. Eskom purchases electricity from IPPs through various agreements [122].

Electricity grid

The electricity grid in South Africa is marked by poor infrastructure, especially in the Northern Cape province. The area is underdeveloped in terms of large-scale grid infrastructure [88]. The transmission of the energy sector consists of high voltage lines that transport electricity to cities and towns. From there, it branches out to 325 000 km of lower-voltage lines that distribute electricity to customers. The transmission and distribution lines connect the generation plants and users in a network that form the grid [103]. Figure 2.5 shows the national electricity grid in the country.

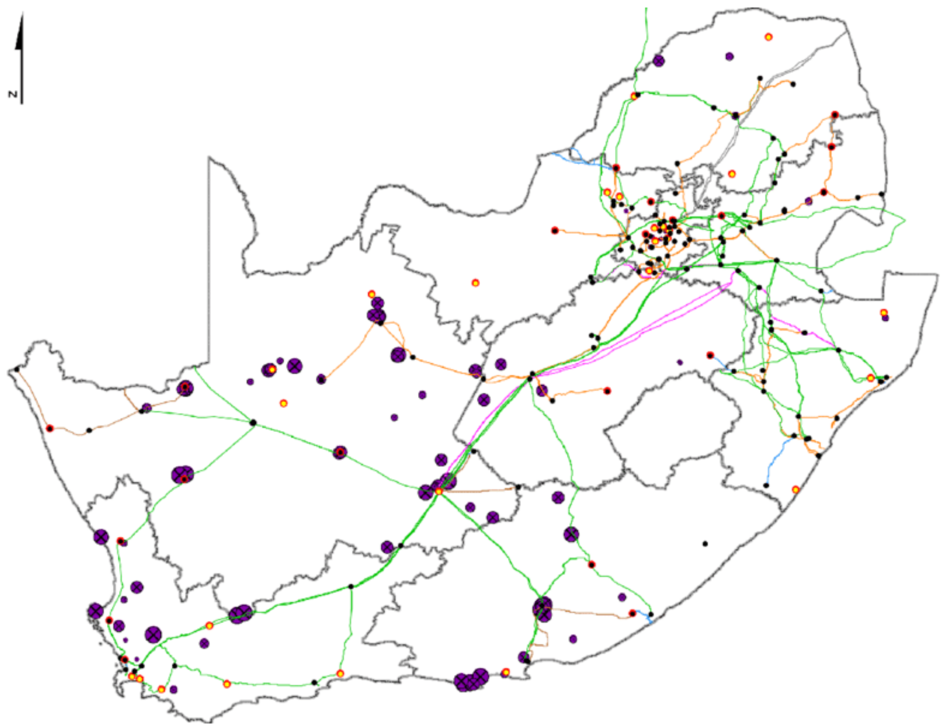


Figure 2.5: The national electricity grid in South Africa. Solid lines show transmission lines. Black, red and yellow dots show current Eskom infrastructure (sub-stations) and purple dots around crosshairs show REIPPPP projects [88].

Blackouts

Because of the energy shortages, the population is experiencing blackouts. Eskom has developed load shedding schedules for the different municipalities, where there is no electricity being supplied for several hours a day. The load is rationed between the municipalities when the power demand cannot be met. The municipalities are scheduled to have blackouts at different times, and the blackouts are evenly distributed, so that the energy distribution is fair [91]. Figure 2.6 shows the annual power outages in hours. The data includes all the blackouts throughout the country. Despite several attempts in bettering the electricity situation, the power outages are increasing. In 2021 the power was out at a total of 1240 hours, compared to 127 hours in 2018 [41].

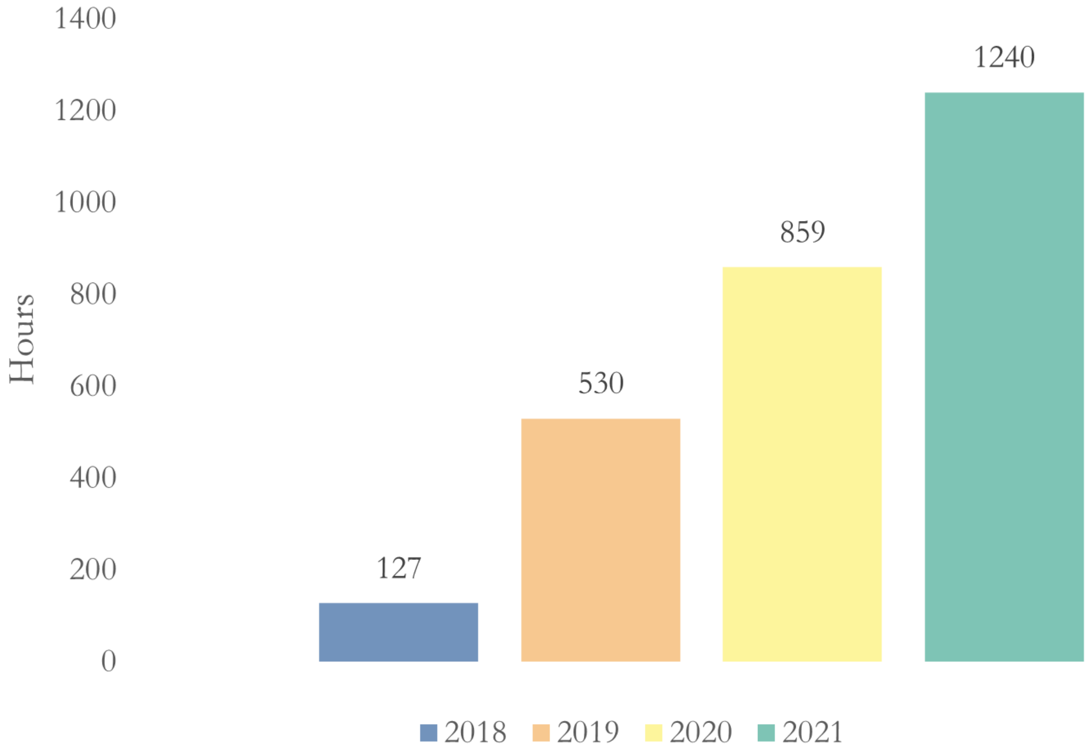


Figure 2.6: Annual hours of power outage in South Africa, reproduced [41].

Load shedding is important, as the grid could suffer catastrophic failure if overloaded. In that case, the areas affected could be in a blackout for several days as the reconnection of the generators would take time [103].

Load profile

A load profile shows daily consumer electricity demand. The load profile has an energy peak in the morning and larger peak in the evening. Figure 2.7 shows an estimated load profile for South Africa. The shape of this load profile is typical, where electricity is mainly used when the residents are at home during the morning and evening [108]. As seen in Appendix A, the electricity tariff is high when the demand is high, meaning in the morning and the evening.

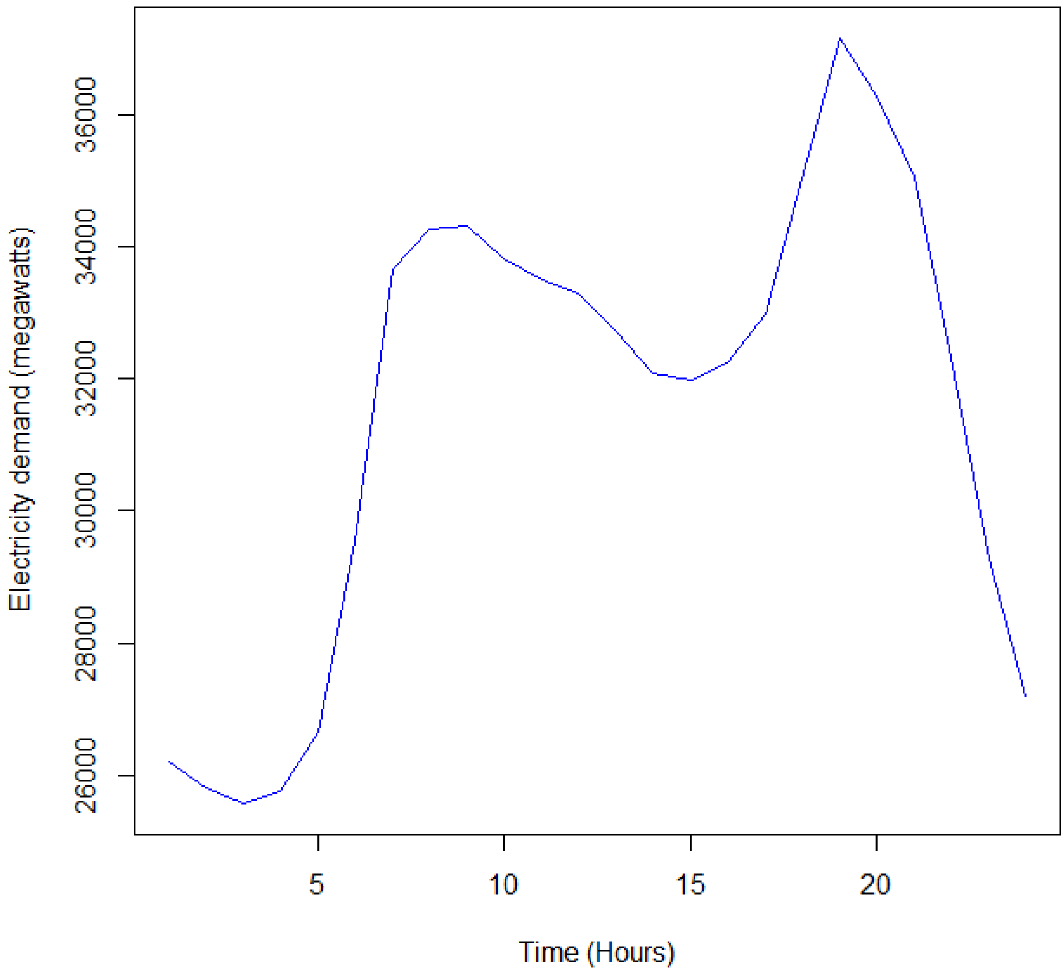
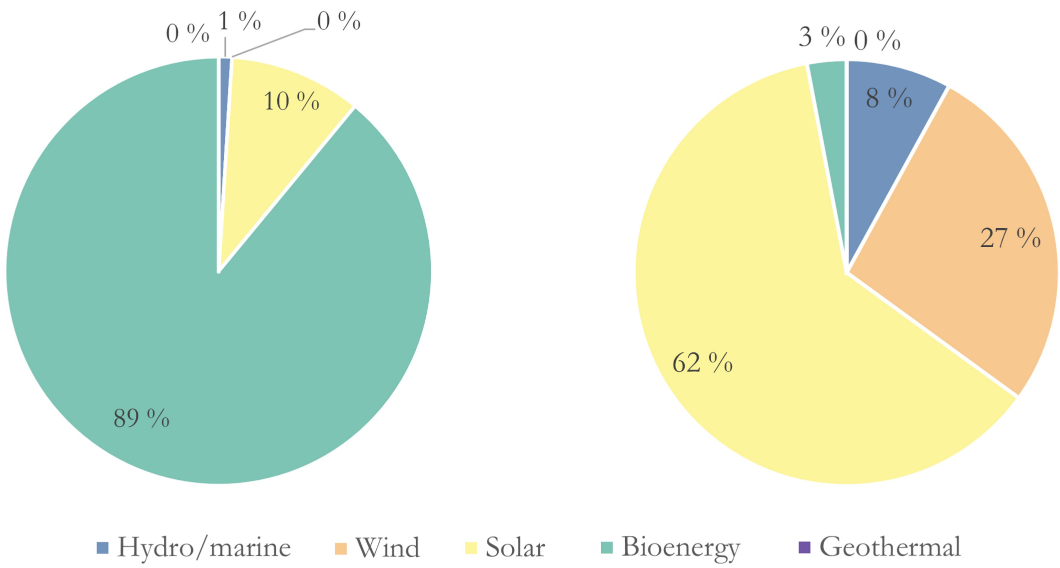


Figure 2.7: Typical daily load profile for South Africa [108].

2.4.2 Renewable energy

South Africa's natural resources of wind and solar show a great potential for production of renewable energy. The country is dependant on coal, but it does have some small-scale hydroelectric plants and one nuclear power station. Biomass, such as wood and dung, solar power and wind also contribute to the energy supply [122]. Figure 2.8a shows the renewable energy supply in South Africa. 89% of the renewable energy supply was provided by bioenergy, 10% was solar and 1% was hydropower. The wind and geothermal energy supplies are such small percentages of the total energy supply that they appear to be zero [36].

Although most of the renewable energy supply stems from bioenergy, the other types of renewable energy have a higher capacity, as shown in Figure 2.8b. Solar energy has the biggest percentage of capacity of the renewables with 62%, while wind makes up 27%. The renewable capacity is presented in Figure 2.8b [36].



(a) (b)

Figure 2.8: (a) Renewable energy supply in 2018 . (b) Renewable energy capacity in 2020 [36].

Renewable energy has become a viable option, as the costs of fossil fuels are increasing while costs for renewables are decreasing. More investments have been made in the country, many through REIPPPP. Because of the programme, large scale projects are being planned and built in South Africa. The country has received international acclaim for fairness, transparency and certainty of REIPPPP [122].

3 Wind energy

This section will cover relevant theory on wind energy, starting with wind resources and characteristics, then different wind technologies and working principles of a wind turbine.

3.1 Wind resources

As with all of the energy on Earth, wind as an energy resource originates from the sun. The wind occurs in the troposphere - the lowest layer of the planet's atmosphere. Wind flows are affected by pressure differences which are affected by solar irradiation. Irradiation is absorbed differently in different parts of the world, where most gets absorbed around the equator and the least around the poles of the planet. Thus the air rises at the equator, creating low-pressure, and sinks at the poles, creating high-pressure area. This allows the winds to circulate globally. Another force that creates winds is the Coriolis force which is caused by the Earth's rotation. Other forces affecting the winds are inertial and friction surface forces. The winds also vary depending on seasons when it either gets colder or warmer [84].

3.1.1 Atmospheric Boundary Layer (ABL)

The troposphere is also known as the atmospheric boundary layer (ABL) and is largely affected by the Earth's surface as it is the lowest layer of the atmosphere. Such factors as the temperature, velocity and humidity change quickly and thus affect such phenomena as wind. In the neutral atmosphere, the boundary layer is mainly affected by the Coriolis effect and the surface roughness. The latter varies depending on the surface obstacles [84]. Some typical values of the surface roughness length z_0 are given in Table 3.1.

Table 3.1: Typical surface roughness length $z_0[m]$ [20]

Type of terrain	$\boldsymbol{z_0[m]}$
Cities, forests	0.7
Open farmland, few trees and buildings	0.03
Flat desert, rough sea	0.001

The wind speed variation can be calculated by two different models - the log law or the power law. Without going into detail on the models, both describe the velocity variation based on height, reference height and speed and surface roughness (inputs depend on the model type)[84]. Figure 3.1 illustrates a typical logarithmic wind profile based on the models. The wind velocities are greater at greater heights, and thus lower near the ground.

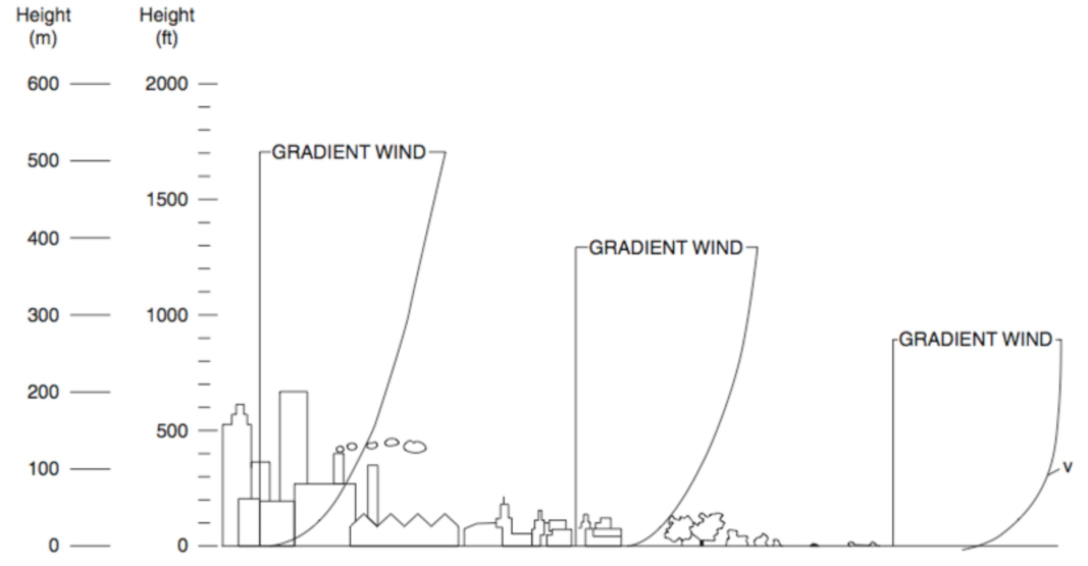


Figure 3.1: Wind profile for different terrains [48].

3.2 Wind technologies

Wind has historically been used as a resource for many purposes, such as seafaring and windmills. However, modern wind turbines have become a revolutionary technology only recently in the late 20th century. With an increased interest in renewables the development increased in the beginning of 21st century with European nations leading the research. The total installed wind energy capacity had reached 733 276 GW in 2020, with China as the nation with largest wind capacity in the world. Most of the wind energy is located onshore, while the offshore technologies have also has been gaining traction over the past years [101].

(a) HAWT [142]

(b) VAWT [133]

Figure 3.2: Differently axis oriented wind turbines.

A wind turbine is a machine that extracts the mechanical energy of the wind and converts it into electrical energy through a generator. A more detailed explanation on the working principle is described in the next subsection. A wind turbine can be oriented in two different ways - horizontal axis (HAWT, Figure 3.2a) and vertical axis (VAWT, Figure 3.2b). For a HAWT, the axis of rotation is parallel to the ground while for a VAWT the axis of rotation is perpendicular to the ground, as seen in Figure 3.2. There is a number of other turbine designs that have been researched, but HAWT remains the most commonly used wind turbine due to its reliability, costs and efficiency. More blades can potentially result in achieving a higher energy extraction, however a three-bladed turbine has been proven to be the most profitable and efficient, thus it is more common [84].

3.2.1 Turbine components

A HAWT roughly consists of a rotor, a nacelle and a tower as shown in Figure 3.3. The rotor includes the rotating parts such as the blades and the hub. The blades can be pitched depending on the incoming wind velocity and the production needs, which can be for maximum power extraction or power production control. The nacelle includes the other rotating parts which convert the mechanical energy into electrical. The shafts, gearbox, coupling, mechanical brake and generator are some of the components usually found in the nacelle. The transmission cable is found inside the tower, which leads to other electrical components such as switchgear, transformers and other power electronics [84]. Turbine performance depends on the different components, especially the blade and the generator. There are therefore different designs and configurations that can be considered when designing a wind turbine.

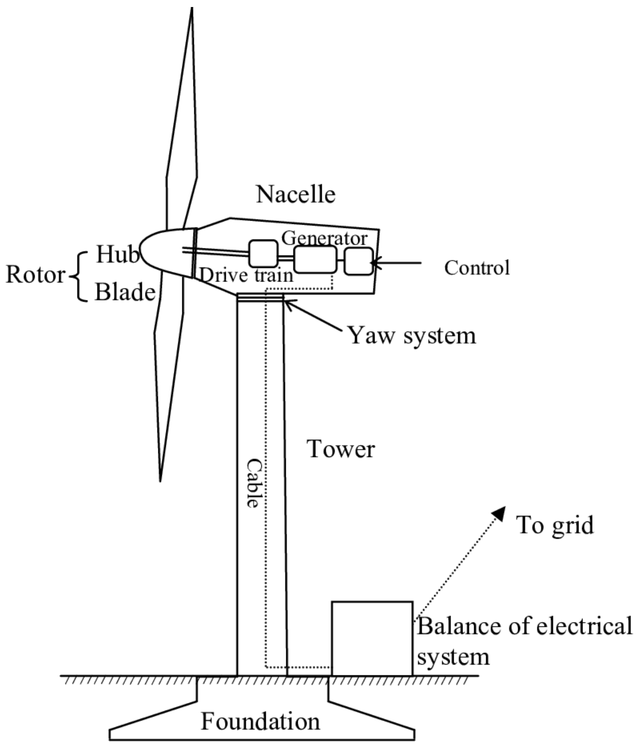


Figure 3.3: Machine components in a HAWT [8].

3.3 Working principles

The rotor of a wind turbine extracts mechanical energy out of the wind which then gets converted to electrical power through a generator. The overall turbine performance is a combination of rotor and generator efficiencies. The theory can therefore be divided into aerodynamics and electrical machinery. While the actual working principles are more complicated, the following theory will give a simplified description of how a wind turbine operates.

3.3.1 Lift and drag forces

The cross-sectional area of a blade is called an airfoil. An airfoil makes mechanical forces occur when the wind meets its surface. It can have different geometries that will determine the turbine's performance, as of why there have been developed a plethora of airfoil shapes. As the fluid flows over the airfoil, pressure and friction forces will result in so called drag and lift forces. These forces can be observed in Figure 3.4. Chord indicates the length of the airfoil, while the angle of attack is the angle between the incoming wind and the chord. The lift force is the one generating the necessary power. The forces have characteristic coefficients called drag and lift coefficients, which will essentially determine the total rotor performance [84]. The greater the relationship is between the coefficients, the better the performance.

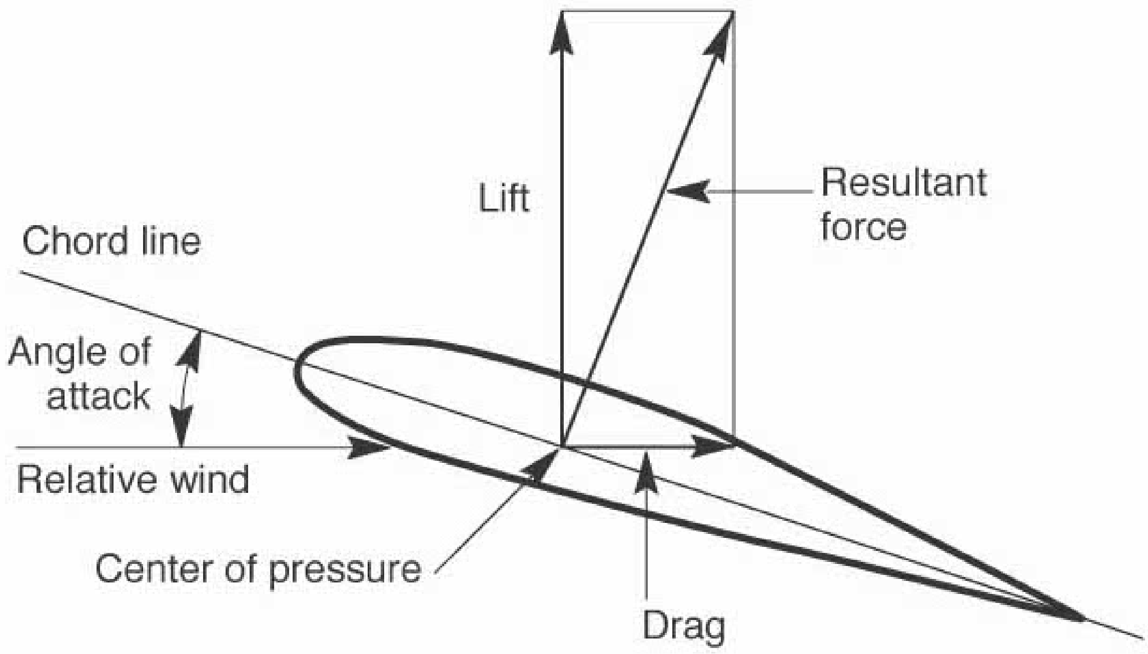


Figure 3.4: Lift and drag forces acting on an airfoil [22].

3.3.2 Actuator disc

It is not possible to extract all the power from the wind due to the energy losses that will occur when the wind passes the rotor. The actual power extraction can be explained by the actuator disc theory, where the turbine rotor is essentially presented by a disc of the same area. Figure 3.5 depicts that the wind flow expands as it passes the disc and undergoes a velocity drop where the energy exchange happens. A power coefficient can be developed as a relationship between the amount of energy extracted and the available amount of energy. The coefficient indicates the rotor performance and has a theoretical maximum value of $\frac{16}{27} = 59.3\%$ known as the Betz limit [20].

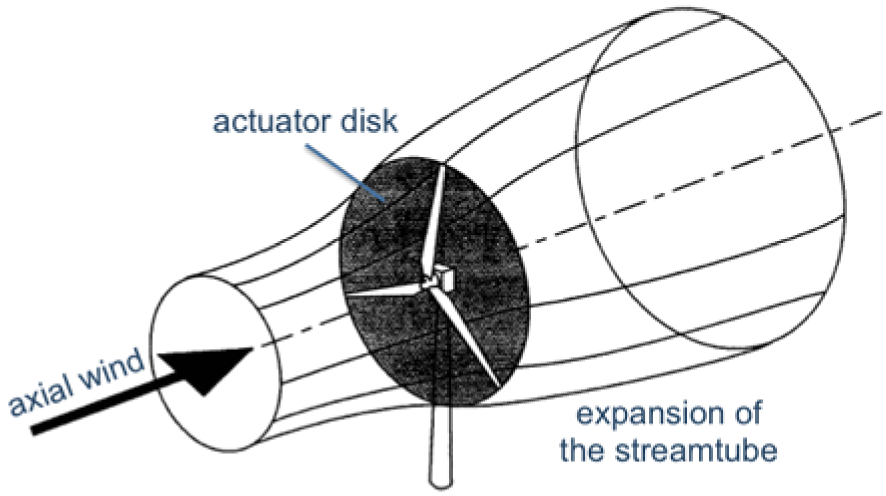


Figure 3.5: Wind stream passing the actuator disc [1].

3.3.3 Generator

A generator is an electric machine that works by the phenomena called magnetic induction. A flux that fluctuates with time generates a voltage and an electric force that allows the electrons in a conductor move, thus creating a current. The turbine rotor is attached to a shaft that is also attached to the generator. As the blades rotate, the mechanical energy will convert into electrical energy through the induction phenomena. The generator will have some energy losses in the form of heat and rotational losses. The generator efficiency is therefore determined by the relationship between the electrical energy output and the mechanical energy input. The combined rotor efficiency, or the rotor's power coefficient and generator efficiency make the total wind turbine efficiency [84].

3.3.4 Power curve

The power output can be predicted with a power curve that is specific for every wind turbine, meaning that it depends on the turbine design. The curve gives the electrical power output as a function of the wind speed at the blades, as one can see in Figure 3.6. There are three speeds that indicate important operation areas for the turbine. The cut-in speed v_c is the minimal speed where the blades start to rotate and deliver useful power. v_r is the rated speed is the speed where the turbine produces the rated (usually maximum) power. The cut-off speed v_f is the maximum speed of the turbine, meaning that the power at higher wind speeds will not be useful [84]. The region between v_c and v_r is the non-rated region where the power output is not constant, while the rated region between the rated and the cut-off speeds is where the wind turbine operates and produces the most power.

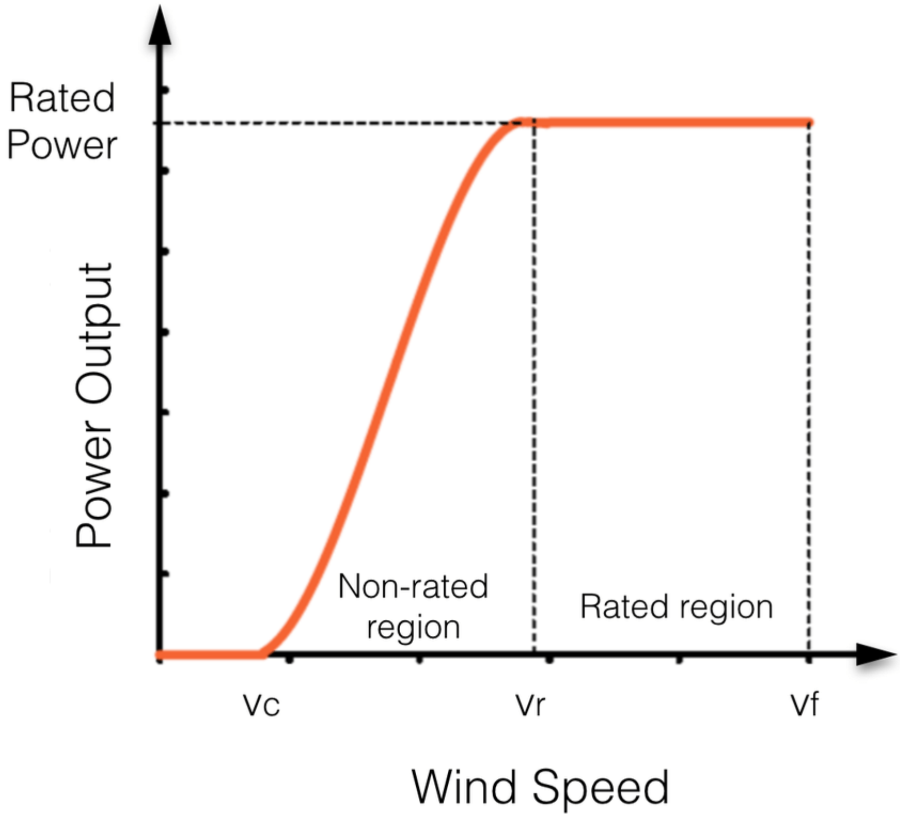


Figure 3.6: Typical power curve for a wind turbine where v_c is the cut-in speed, v_r is the rated speed and v_f is the cut-off speed [32].

4 Solar energy

Solar energy is an almost limitless form of energy, and has great potential as a form of renewable energy. The yearly solar radiation to the earth corresponds to approximately 15 000 times the whole world's annual energy consumption. The world's energy needs can be met by covering about 0.1% of the world's desert areas with solar cells [57].

The sun emits electromagnetic radiation, which can be harnessed and used to produce electricity or heat. In a photovoltaic cell, the energy emitted from the sun is converted to electrical energy through the photovoltaic effect.

4.1 Solar irradiation

The annual average solar irradiance which reaches the outside of the atmosphere is $1,367 \pm 2\ W/m^2$. Ozon, water vapor, carbon dioxide and other gases absorb some of the radiation in the atmosphere, meaning the solar irradiation is lower on the earth's surface [57]. The solar irradiation varies, depending on the geographical location, as the distance and angle from the sun will vary. Season and time of day will also have an impact. This can be seen in Figure 4.1, which shows the GHI.

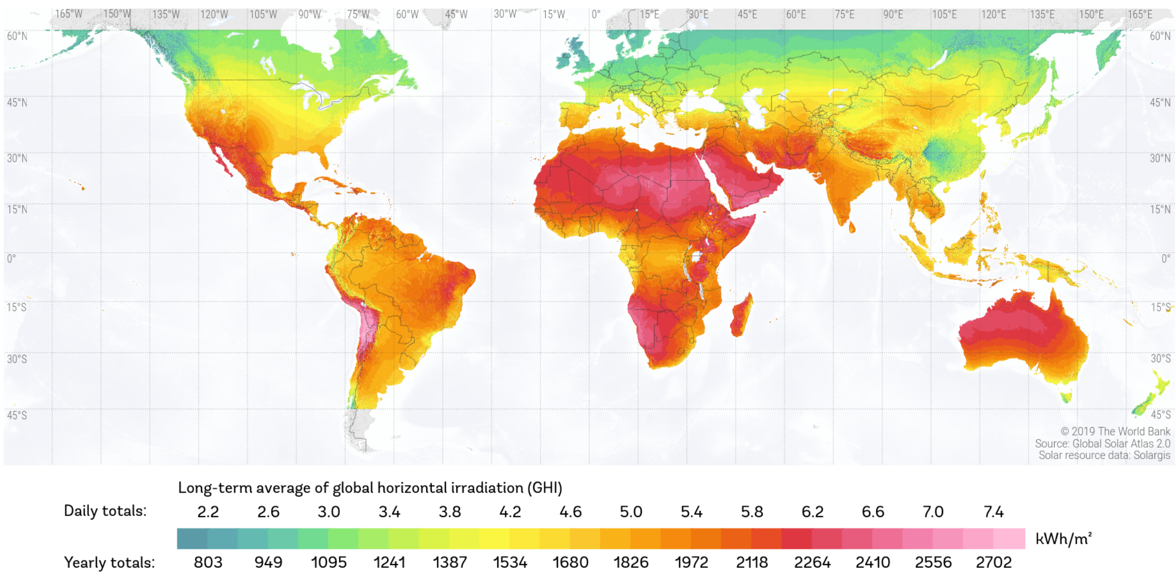


Figure 4.1: Solar resource map of GHI [51].

GHI is the total amount of radiation received by a horizontal surface. This value includes Direct Normal Irradiation (DNI) and Diffuce Horizontal Irradiation (DIF). DNI is the radiation that hits the surface in a straight line, while DIF is the radiation that does not have a direct path to the surface [138]. This can be due to factors such as the local weather conditions and landscape [113].

To get the most optimal production from the solar panels, they need to be tilted in the direction that captures the most solar irradiation. The production is the highest when the sun is perpendicular to the panels. The optimal tilt angle will vary, as the sun's position varies throughout the day and with the seasons [139]. When the panel is tilted, sun irradiation reflected from the ground will also hit the panel. The tilt angle is illustrated in Figure 4.2.

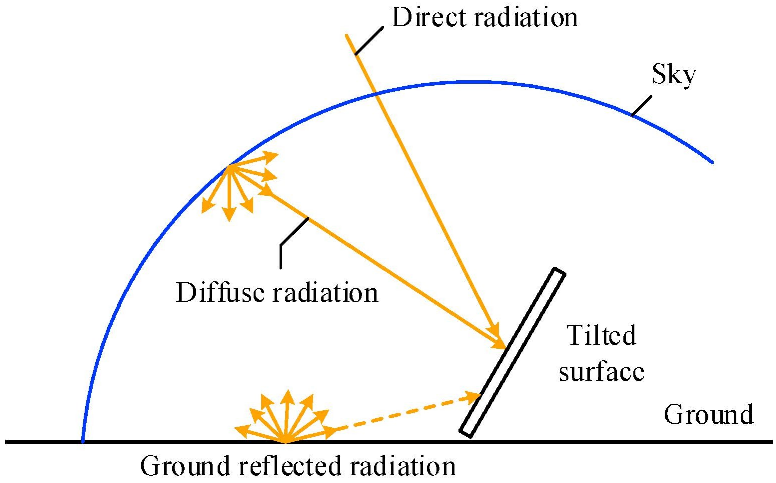


Figure 4.2: Three solar radiation components; direct, diffuse and ground reflected radiation [144].

4.2 Photovoltaic (PV) working principles

Photovoltaic cells convert sunlight into electrical energy. The cells consists of two layers of semiconducting material, where silicon is mostly used. A PV cell is a p-n diode. The diode consists of a n-type layer (negatively charged) and a p-type layer (positively charged), where the space in between is called the p-n junction. Photons hit the electrons, and they absorb the energy which causes a potential difference. The potential difference between the layers causes the electrons to move to the n-side, and electron holes will be formed on the p-side. The excited electrons will move through an outer circuit and come back to the p-side. The current of electrons in the outer circuit generate electrical current [57]. Figure 4.3 illustrates this circuit.

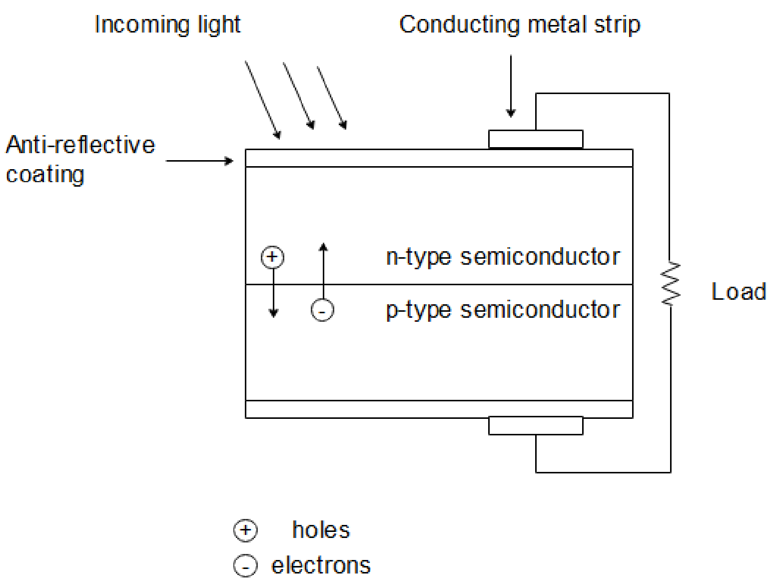


Figure 4.3: Sketch of the working principle of a photovoltaic cell [2].

A PV module consists of multiple PV cells connected in a system. PV cells are connected in series to increase voltage and in parallel to increase the current. The efficiency of most photovoltaic cells is at 15-22%, meaning a large number of cells are required to produce moderate amounts of power.

The rated power is the product of the short-circuit current density and the open-circuit voltage. To get a reliable measurement of the nominal power, it is determined at standard test conditions (STC). At these conditions, the temperature is set at 25°C, the solar irradiance to 1000 W/m^2, air mass AM1.5 and zero wind speed. However, since the temperature in reality varies, an expected temperature is needed to get a realistic power output. The Nominal Operating Cell Temperature (NOCT) is the temperature reached by open circuited cells in a module with irradiance being 800 W/m^2, air temperature at 20°C and wind velocity at 1 m/s [120]. A typical NOCT value for a solar panel is approximately 45°C [61].

The solar panel performance decreases as the temperature increases. The temperature coefficient of the rated power, y_{Pmax}, is how much the solar panel's efficiency is reduced by for each degree increase in the panel's temperature. A typical y_{Pmax}-value is around -0.4%/°C, and it is always negative [61].

4.2.1 Inverter

One of the main components in a solar panel system is the inverter. Inverters convert direct current (DC) electricity generated by the PV modules into alternating current (AC) electricity, which is used for local transmission of electricity. PV-system can either have one inverter that is connected to all of the PV-modules or microinverters that are connected to the modules individually. Inverters have to be replaced at least once throughout the lifetime of about 25-30 years of the PV-modules [112].

4.2.2 PV-technologies

The two most common PV-technologies that are used today are crystalline silicone (c-SI) and thin-film solar cells (TFSC).

Crystalline Silicone (c-SI)

Crystalline silicone has been dominating the PV-market for the last 30 years, being used for both off-grid and on-grid system applications. Silicone is the leading material used in the photovoltaic cells. There are different kinds of crystalline silicone, where the difference is the degree of purity they obtain when producing them. The better purity the silicon has, the better efficiency the photovoltaic will have. Crystalline silicone is mostly divided into monocrystalline- and polycrystalline wafers [31].

Monocrystalline cells are made out of single crystal silicon ingots which are cut into thin wafers with the help of the Czochralski process. Monocrystalline cells are expensive to manufacture, but it is the most efficient solar panel type with an efficiency range of 17-22%. This type of PV-cell has the highest efficiency because it is a singular crystal, thus making it easy for the electrons to flow through [99, 128].

Polycrystalline cells are made from slice cutting a block of silicon. The polycrystalline cell contains multiple silicon crystals, hence making it easier to produce the wafers, and thus they are less expensive than the monocrystalline. However, because of the slightly lower efficiency range of 15-17%, one would have to install a larger module to produce the same amount of energy as a monocrystalline module would [99, 128].

Thin-film solar cells (TFSC)
Thin-film solar cells are another common PV-technology. Its benefits include the material being lightweight, minimal material usage and increasing efficiencies. The three main TFSC-technologies are amorphus silicon ($\alpha - SI$), copper indium galium selenide (CIGS) and cadmium telluride (CdTe). TFSC has a lower efficiency than crystalline silicon-based PV-technologies, as commercially available TFCS has an efficiency range of around 10-13%. One would have to install more TFCS-panels to match the output of crystalline panels. Currently it is mainly used for small-scale production [74, 128].

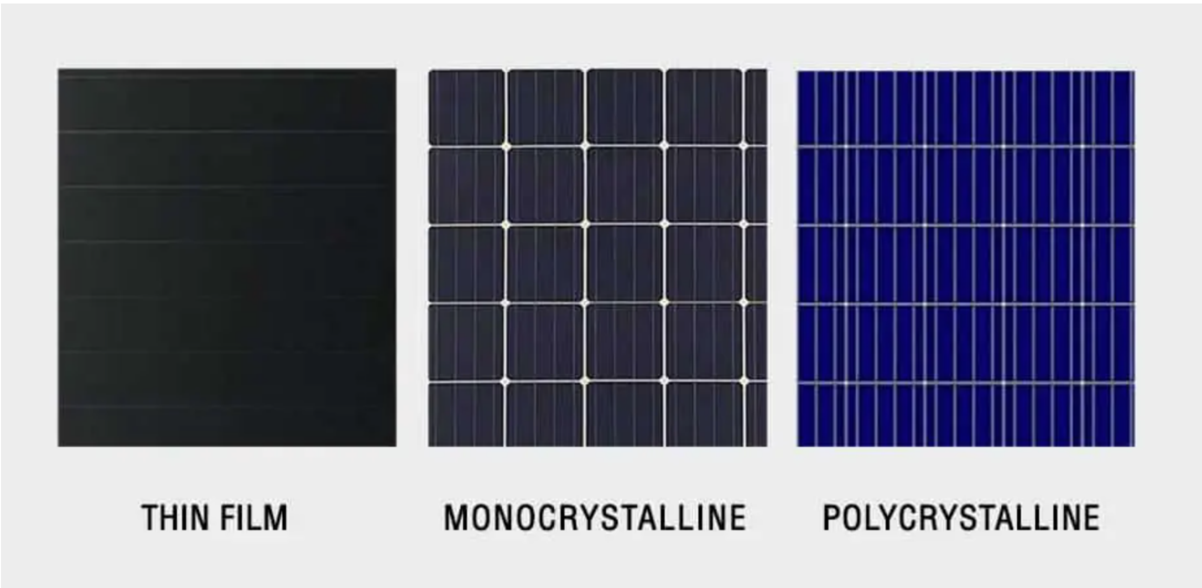


Figure 4.4: Different PV-technologies and their appearance [90].

4.3 Other solar technologies

Another type of solar technology is solar thermal collectors, which can be divided into concentrated solar power and solar heating and cooling, pictured in Figure 4.5. These are described below.

Concentrated Solar Power (CSP)
Concentrated Solar Power is one of the two major solar technologies that utilises thermal energy. CSP-technologies use mirrors or other sorts of reflectors to reflect and concentrate sunlight on a receiver. Energy from concentrated sunlight heats up a fluid in the receiver with high temperature properties. CSP-plants can range from solar power towers, where sunlight is reflected up on a massive tower, as seen in Figure 4.5a, to more linear systems where the receiver

is placed right above the mirrors. [27]

Solar Heating and Cooling (SHC)

Another solar technology that relies on thermal energy is the SHC-technologies. SHC-technologies collect thermal energy from solar radiation and transfers this thermal energy as heat to a portable medium like water, then the heated water can flow where it is needed. This technology is used for water and space heating, additionally it can be used for cooling [60, 68]. Solar tube collectors are shown in Figure 4.5b.

(a) Mirrors reflecting the light to a solar power tower in a CSP-plant [126].

(b) The tube collectors for hot water in a SHC-system [111].

Figure 4.5: Examples of CSP and SHC-systems

5 Hybrid solar/wind plant

A hybrid power plant is a combination of several energy producing technologies. The complementary energy sources can give advantages, such as when one of them is unavailable to produce energy. This leads to a more efficient, flexible and stable energy production. This is especially beneficial for renewable technologies, such as wind and solar power, which are highly dependable on the weather conditions and location [62]. It is preferable for the sources to anti-correlate as much as possible, in order to get the best output of the hybrid plant [67]. There are different possible combinations for such a plant, for example wind-hydro, wind-diesel, PV-thermal and wind-PV. Since the latter type is the most relevant for the scope of the thesis, it will be described further.

5.1 Working principles

The system consists of the power supplies - wind and solar plants, connected in parallel. In addition there has to be a DC/AC inverter that will convert DC-supply to AC-supply which is required for the consumers. The inverter has to be sized correctly in order to be able to deliver the required power. If undersized it will not deliver enough power, if oversized the inverter will be less efficient in addition to be more costly [67]. The system components and connections are shown in Figure 5.1.

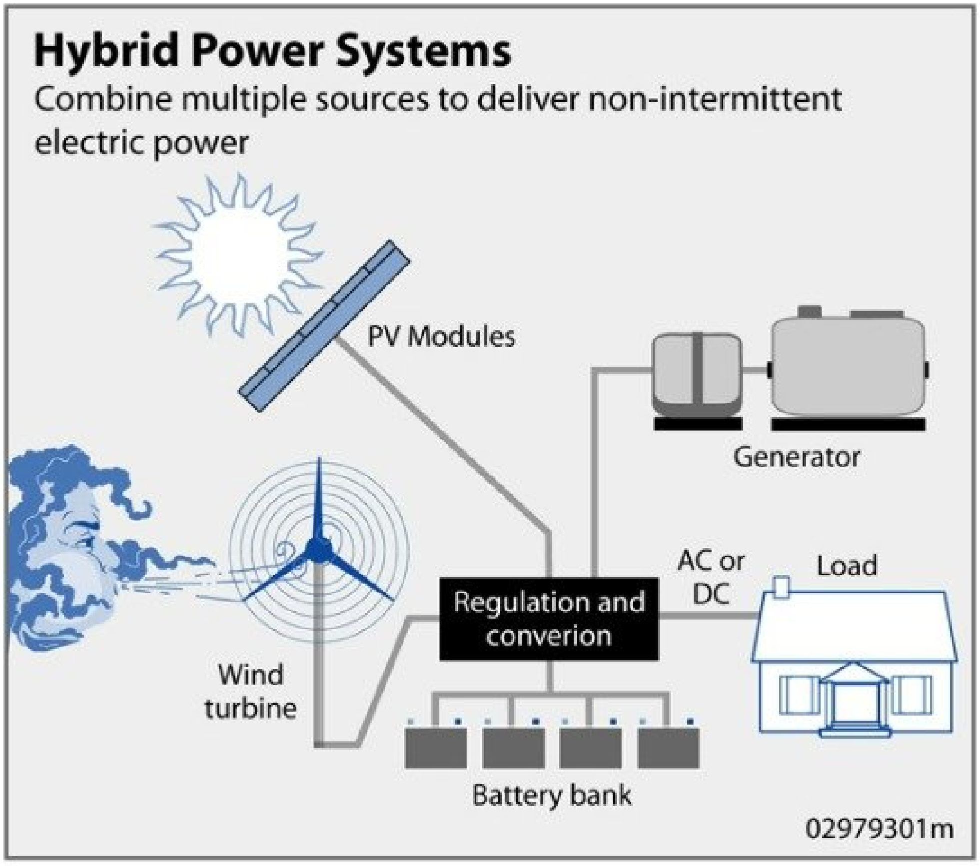


Figure 5.1: Schematics of a hybrid wind/solar plant. Here the generator provides the backup supply. It is not the case for this specific thesis [63].

Often such systems are preferable with an energy storage. There can be four possible operating scenarios. One of them is that the energy production from the plant is larger than load demand. In that case, the overproduced energy will be stored with help of an ESS, for example batteries. If the storage is full, the energy goes to low priority loads. The second scenario is when the load demand is larger than the energy production from one of the supplies, but less than the other. One of the energy sources will then cover that demand. The next scenario is when both of the energy producers are in deficit compared to the load demand. Here the energy storage will help supply the consumers with the missing needed power. The last case is when there is no production from either of the sources. Again the energy storage will cover the load demand, but this time fully [67].

6 Battery Energy Storage System (BESS)

This section will give an overview on battery energy storage systems, the general BESS terminology, application areas and system components.

Total capacity of battery storage worldwide was around 17 GW by the end of 2020, where about two-thirds of the capacity consist of utility-scale systems. The investments in BESS are also increasing with the rise of the renewable technologies, with China and the USA leading the capacity additions [37]. A well designed BESS needs to consider high efficiency and long cycle life. Other important qualities are low cost and safety in order to provide the system with good performance [24]. Grid-scale battery systems usually consist of battery packs, inverters, power electronics and can either be connected to low voltage-level or high voltage-level through a transformer [10]. More on the system components in the following sections.

6.1 BESS terminology

Below are some key metrics that are important when considering a BESS.

Power capacity
The greatest rate of discharge (in kW or MW) the BESS can achieve, when starting from fully charged condition, also known as rated power capacity [16].

Power density
Power density, given in watt (W) per unit volume (L) or mass (kg), describes how quickly a battery can discharge its energy. The larger the density, the quicker it discharges [121].

Discharge duration
The amount of time the BESS can discharge at full power capability, usually given in hours (h) [16].

Energy capacity
The maximum quantity of stored energy (in kWh or MWh) [16].

Energy density
The amount of energy in watt-hours (Wh) stored per unit volume (L) or mass (kg) of the battery. The larger the energy density, the more energy a battery can store [6].

Self-discharge
When the stored charge or energy of the battery is decreased by internal chemical reactions, or without being purposely discharged to perform a task. Self-discharge is expressed as percentage of charge lost over a period of time. It decreases the quantity of energy available for discharge [16].

State of charge and Depth of discharge
State of charge (SoC), is the ratio between the amount of energy stored and the maximum

amount of energy that is possible to be stored in the battery. Depth of discharge (DoD), indicates the part of the energy discharged from the storage relative to the amount extractable stored energy [6]. The two parameters have a relation of $SoC + DoD = 1$

Cycle life and calendar life

A cycle is one round of charging and discharging of a battery, while a cycle life means the amount of cycles a battery can undergo throughout its lifetime before becoming inefficient for application [6]. This usually happens when the capacity reaches 80%. Calendar life is the amount of time a battery can be stored, with minimal use, while the capacity remains above 80%. It is highly dependant on SoC [15].

Round-trip efficiency (RTE)

The ratio of the energy put into the battery storage and the energy discharged afterwards. The better the efficiency, the less energy loss during the discharging [6].

C-rate

Charge rate is the energy storage capacity divided by 1 hour. For example 1C is the charge rate for the battery to charge in 1 hour [6].

6.2 Grid-scale energy storage

A grid-scale, also called utility-scale, energy storage system is a large-scale storage of energy production. Several storage technologies can be applied, such as pumped hydro, flywheel, compressed air and battery storage. For grid-scale, several BESS-technologies are being exploited. More on these in the later sections. An example of a grid-scale storage is shown in Figure 6.1.

Figure 6.1: 31.5 MW Grand Ridge Storage Facility located in Illinois, USA [78].

6.2.1 Application areas

A utility-scale storage system can be used for different needs. The system design is thus often based on the application type, as the applications require specific technical considerations. The applications can be divided into five main groups - ancillary service, behind-the-meter, energy trade, grid support and investment deferral, and combined applications [58].

Ancillary service

This group includes frequency regulation. Frequency imbalance can be caused by differences in the power supply and the power demand [58]. Grid-scale energy storage can help with regulating the frequency by responding much faster than conventional systems that already exist [64]. The rise and fall over/below the nominal grid frequencies can lead to power outages or damage to the connected load [10]. For frequency regulation, the preferable power capacity is 10 - 40 MW, discharge duration of less than 1 hr, and 250 - 10 000 cycles per year [10].

Behind-the-meter

Behind-the-meter storage is customer-sited stationary storage systems. It can however be used for utility-scale storage as well. PV-BESS (renewables integration) and peak shaving applications are included in the group [17]. Since renewable energy sources are highly dependant on location, weather etc., an energy storage system can provide flexibility and safety for the grid by smoothing out the output power curve. This works especially well with wind and solar plants. When peak demand mismatches the power production from the plant, the energy storage secures a power supply [24]. The technical requirements are then a power capacity of 1 - 100 MW and a discharge duration between 15 minutes and 1 hr [10].

The load profile will usually have low and high demands during the day. Peak shaving in storage systems are then used to charge up the system when the demand is low and discharge when the demand is high, thus smoothing the demand curve, as shown in Figure 6.2 [10].

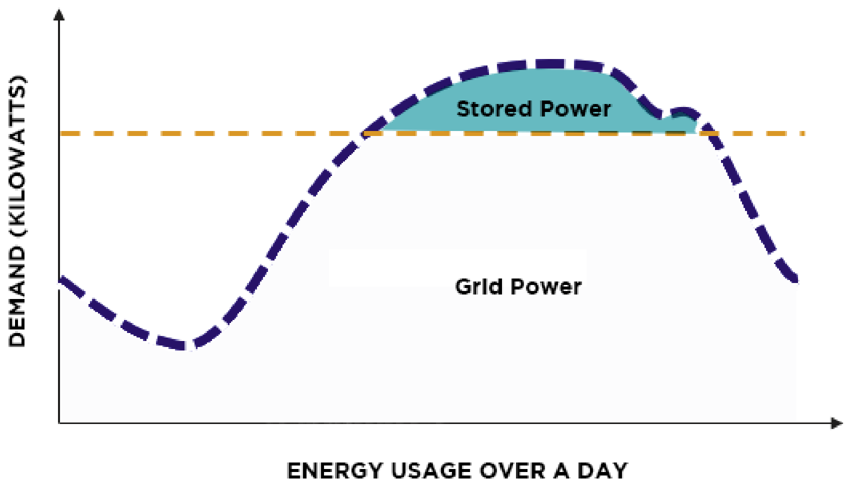


Figure 6.2: Peak shaving principle, where the blue stippled line is the load and the yellow stippled line indicates the peak shaving. [95]

Energy trade
This is also known as storage arbitrage. In economy, arbitrage is known as buying and selling an asset in different markets to exploit price differences. The same term can be applied for BESS, where it relates to charging the battery during low-peak hours and discharging during high-peak hours. This is essential if one wishes to obtain the highest possible income [45]. The electricity tariff will often correlate to the load profile. When the demand is low, the prices are low, while the prices are high when the demand is high as well. This will also mean that charging will happen while the electricity prices are low and the opposite for discharging [58]. Behind-the-meter, which was mentioned previously, can also act like storage arbitrage [17].

The important system properties in this case are the sizing of the system, discharge duration and cycle life. For a peak shifting system, the sizing range is between 1 - 500 MW, the discharge duration is <1 hr and the cycles per year is 250+ [10].

Grid support and investment deferral
Voltage fluctuations in the grid can occur due to renewable energy production variation and changes in load. These fluctuations can reduce with integration of a BESS. A storage system will also be beneficial with integration of electric vehicle charging with providing more capacity to the grid [58]. Investment deferral involves using the ESS to delay or avoid investments due to capacity distribution. It can be such things as an upgrade/replacement of several grid components. Such storage systems would require a size of 500 kW - 10 MW, discharge duration of 1-4 hr, and 50 - 100 cycles per year [10].

Combined applications
A multi-use BESS can be economically beneficial. One example of use is in supporting a micro-grid. It can provide frequency regulation, voltage support and even out the supply/load differences all at once [58].

6.3 System components

The utility-scale storage system mainly consists of the battery components, system operation components, power electronics and grid connection components. As seen in Figure 6.3, there are several control, monitoring and management units which allow the system to operate in normal and safe conditions.

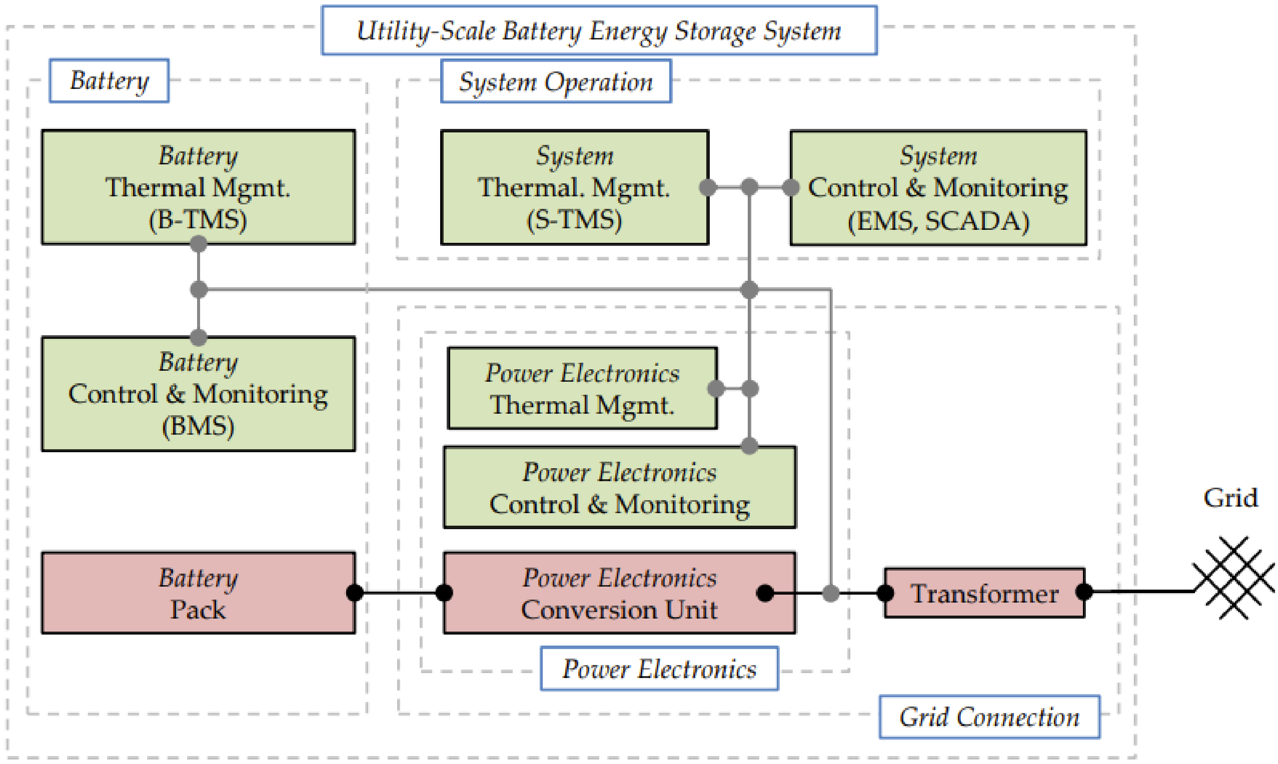


Figure 6.3: Main components and connections of the grid-scale storage system [58].

6.3.1 Battery

The battery components are the thermal management (B-TMS), control and monitoring (BMS) and the battery pack itself. B-TMS controls the battery cell temperature levels, allowing them to operate in rated conditions. BMS manages the voltages, currents and temperatures, in addition to balancing the SoC-variations in the cells [10]. The management systems make the operation safe and also prevent battery damage, thus prolonging the battery life.

A battery pack consists of battery modules which again consist of several battery cells which are connected in series to match the needed power electronics voltage. They usually range up to 60 V. The modules are then connected in series-parallel to achieve the required capacity [58]. Packs can form bigger clusters, which are stored in battery containers as pictured in Figure 6.1. Several containers form the entire energy storage.

6.3.2 System operation

The components in the system operation are the system thermal management (S-TMS) and the control and monitoring (EMS and SCADA). S-TMS is responsible for the heating, ventilation and air conditioning of the system. EMS, energy system management, is necessary for power flow control/management/distribution. SCADA refers to supervisory control and data acquisition. It also controls fire protection and alarms [58].

6.3.3 Power electronics

This component group contains the thermal management, control and monitoring, in addition to the power conversion components. The first two have the same purpose as in the other component groups, only concerning the power electronics. The conversion unit is usually an inverter that inverts DC to AC-supply.

Inverters can be connected to the battery packs directly, forming a single string. This configuration is called dedicated and is shown in Figure 6.4(a). In this case the power of the battery packs can be controlled. In addition, if one of the strings should happen to fail, the error will not affect the operation of the other strings. Another configuration is called parallel, illustrated in Figure 6.4(b). The battery packs are connected to a common DC-bus where the inverters are then connected in parallel. In this case, the power electronics can be turned off at partial load. This will eliminate losses which occur due to several units in operation. The batteries must also meet the right technical requirements according to current fluctuations which will occur because of temperature variations and aging [58].

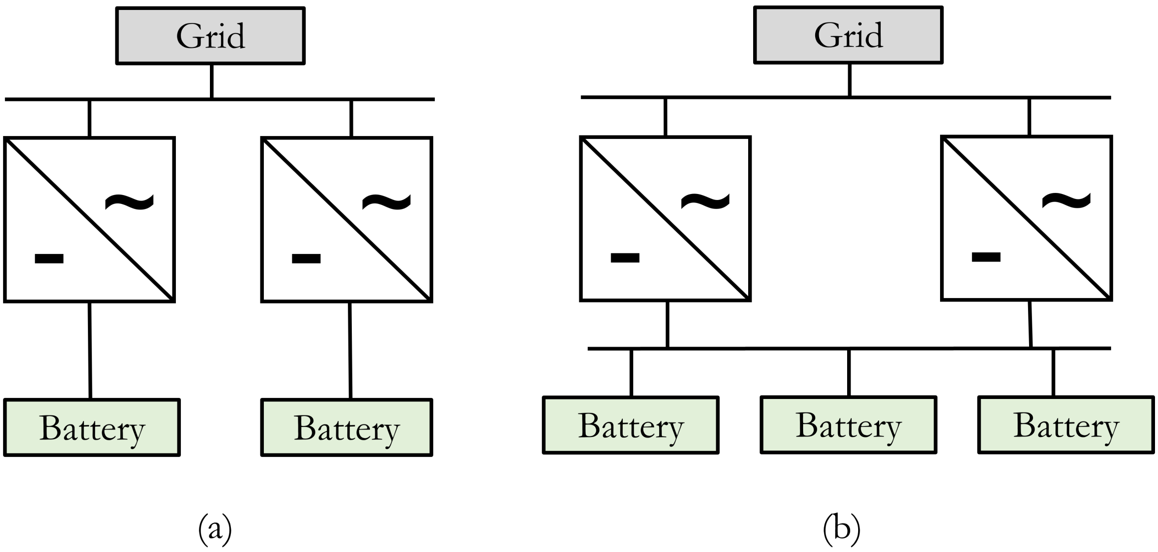


Figure 6.4: Battery-inverter-grid configurations where (a) is dedicated and (b) is parallel. Partially reproduced from [58].

Power electronics that have already been developed for motors and photovoltaics can be applied to utility-scale storage as they are to perform the same tasks. For example PV-inverters can be utilized in such a system. The power ranges up to several 100 kW per unit [58].

6.3.4 Grid connection

Grid connection is essentially all the power electronics in addition to a transformer, as one can see in Figure 6.3. The transformer connects the system to the grid voltage level which can be high or low. It is however optional if the system and the grid voltages are the same.

7 Battery technologies

This section will give a general overview on electrochemistry and the battery concept, and present five different battery technologies that are used in utility-scale storage. Their characteristics, manufacturers and market will be discussed. A metrics and safety comparison of these is given by the end of the section.

7.1 Electrochemistry

Electrochemistry is a part of chemistry that revolves around the connection between electricity and redox-reactions (reduction-oxidation-reactions). Redox-reactions are chemical reactions where one substance is reduced and the other is oxidized. Redox-reactions cause electrons to move, thus creating a current [96].

Oxidation

$$A \Longleftrightarrow A^{2+} + 2e^{-} \tag{7.1.1}$$

Reduction

$$B^{2+} + 2e^{-} \Longleftrightarrow B \tag{7.1.2}$$

Total redox-reaction

$$A + B^{2+} \Longleftrightarrow A^{2+} + B \tag{7.1.3}$$

As one can observe in Equation 7.1.1 and 7.1.2, during oxidation the substance is losing electrons while in the reduction reaction the substance gains electrons. This is what forms the basis of electrochemistry and battery technology overall [96].

7.1.1 Battery concept

A battery is an invention that converts chemical energy into electrical energy [54]. It was first invented in 1800 by an Italian scientist Alessandro Volta [7]. Battery technology is based on a redox-reaction which will be described in the next section. The batteries are divided into two main groups - primary and secondary. The difference between these is that secondary batteries are able to charge and discharge. This type of batteries is also the focus of the thesis and thus described further. Primary batteries are one-time use batteries which often consist of zinc in combination with other materials [14]. The main components in a battery are the electrodes, electrolyte and separator which are explained below.

Electrodes

An electrode is the substance conducting electricity in the battery. The electrodes create electrical contact with the non-metallic part of the battery. The electrodes consist of the anode and cathode which describe the direction of the current flow. When discharging battery, the anode is the negative terminal as this is where current flows into the cell, while the cathode is the positive terminal [137]. The oxidation happens at the anode, while the reduction happens at the cathode during discharge.

Electrolyte

The electrolyte is a medium that allows ionic contact and prevents electrical contact in the cell. An electrolyte should have good ion conductivity and thermal stability. The electrolyte should also be able to resist oxidation and reduction and other reactions without degradation [98].

Separator

The separator is a membrane between the electrodes. It is supposed to isolate the electrodes physically, still allowing the ions to flow, meaning that the cell is connected ionically. It has a pore size of <1 μm. Large holes involve ion flow, while small holes are meant to prevent the cell to short circuit. Membranes in commercial batteries with liquid electrolytes are usually made of microporous polymer which can be made of polyethylene, polypropylene or a mix of both. The latter type contributes to a more stable operation of the battery by preventing battery failure. If the battery happened to get higher cell temperature than the temperature limit, the polyethylene layer would melt off and fill the holes of the other layers, thus blocking the ion and current flow [98].

7.2 Lithium-ion battery (LIB)

The first rechargeable Li-ion battery was documented in 1976, but was not commercialized until 1991 by Sony Corporation [9, 98]. LIB-technologies have dominated the battery industry over a long period of time for the past years due to their advantages in energy density and cycle life to mention a few. In 2017, 90% of the battery energy storage was represented by Li-ion batteries [64]. Other areas of use are for example electronic devices and electric vehicles [10].

LIBs have high discharge/charge efficiency, high energy density and power density, and long cycle life, which makes the technology highly applicable for grid scale energy storage [24]. One of the disadvantages is the thermal instability (thermal runaway), which makes Li-ion batteries highly flammable with risks of ignition and explosion [10]. This requires a management and monitoring system incorporated into a BESS. There is a variety of Lithium-ion battery chemistries, depending on the ion, each with their own characteristics that fit the desired storage design [100]. Current grid-scale application areas for LIBs are frequency response, grid reliability services and peak shaving [18]. Different types of LIBs are discussed further below in the thesis.

7.2.1 Technology

A Lithium-ion battery's main components are the negative and positive electrodes, the current collector, the electrolyte and the separator. Common materials used as the positive electrode is a type of lithium metal oxide, while graphite is used as the negative electrode [98]. The materials must contact each other electrically (by a wire or by direct contact). The charged ions must be able to exchange to maintain charge neutrality when the electrons flow [6]. The current collectors for the electrodes are either made of aluminium (positive electrode) or copper foil (negative electrode). The electrolyte is a lithium salt dissolved in organic solvents [98].

When the battery discharges, the positive electrode is reduced and the negative electrode is oxidized. The lithium ions flow from the negative electrode to the positive electrode. When the battery charges, the opposite happens. The ions move due to the potential difference between the negative and positive electrodes [98]. The charging and discharging reactions are illustrated in Figure 7.1:

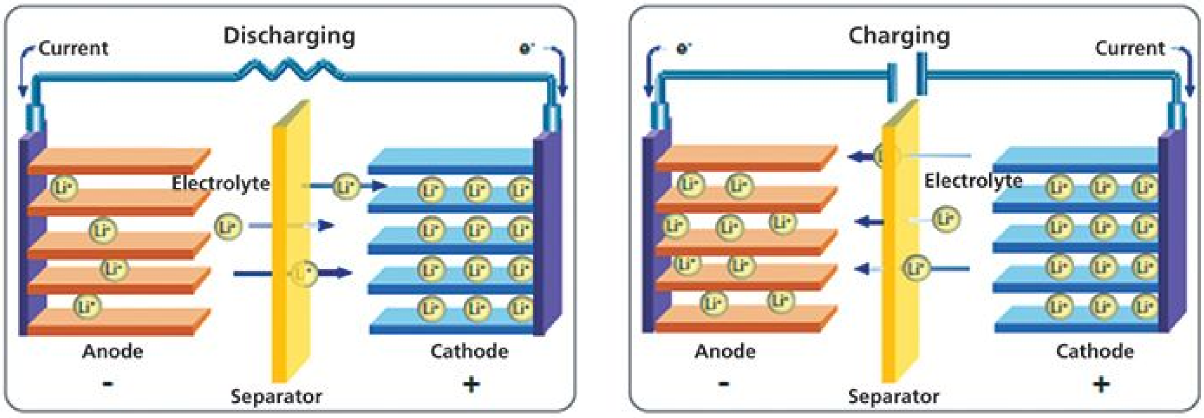


Figure 7.1: Discharging and charging processes for a Li-ion battery [141].

Negative and positive electrodes

The usual material for the negative electrode (anode) is graphite. Its advantages include low cost, stability over many cycles and contraction while discharging. The material also has a low potential, which affects the cell voltage which again affects the energy density [98]. Due to graphite's low energy density, other materials with better properties have been in development. These include silicon, alloy and metal oxides which have been beneficial for improving LIBs overall capacity and lifetime [24, 9]. LTO ($Li_4Ti_5O_{12}$) has recently been used as an anode-material in utility scale applications. Some of its advantages over graphite is good thermal stability, high discharge rate capacity and long cycle lifetime. However it is more expensive due to the titanium content and has a low energy density. The technology is still in the research stages, but gives promising results in BESS-application performance and might eventually get commercialised. [100].

The positive electrode (cathode) materials are usually divided into three groups based on the crystal structure - olivine, spinel and layered. The olivine structure has the highest experimental capacity of 160 mAh/g. The spinel structure's experimental capacity is 120 mAh/g. Both of the structures have flat discharge voltage profiles which is good for constant-power discharges. The layered structure has a capacity between 150 mAh/g and 200 mAh/g. The discharge voltage profile has a slope, meaning that the cell balancing is straightforward at any state of charge [98]. More on the different types of lithium-ion batteries and their characteristics in the following sections.

The general electrochemical equations for the redox-reactions are the positive electrode reaction in Equation 7.2.1 and the negative electrode reaction in Equation 7.2.2.

$$LiMO_2 \Longleftrightarrow Li_{1-x}MO_2 + xLi^+ + xe^- \tag{7.2.1}$$

$$xLi^+ + xe^- + C \Longleftrightarrow Li_xC \tag{7.2.2}$$

where M is a transition metal, such as Fe, Co, Ni or Mn, x is the stoichiometric coefficient and e is the electron [107]. The reaction goes to the right when charging and to the left during discharge.

The overall reaction is given in Equation 7.2.3:

$$LiMO_2 + C \Longleftrightarrow Li_xC + Li_{1-x}MO_2 \tag{7.2.3}$$

7.2.2 Types of lithium-ion batteries

This section will give an in-depth examination of the different lithium-ion battery technologies, especially focusing on the technologies used in the grid-scale storage.

LFP (Lithium Iron Phosphate)
LFP, or $LiFePO_4$, has an olivine cell structure and a lower energy density compared to other electrode types due to lower cell voltage [100, 98]. However it has an overall good electrochemical performance with low resistance. The main advantages of this type are high current rating and long cycle life, as well as low discharge rate, good thermal stability, low costs and enhanced safety [10, 100]. This has therefore made LFP highly applicable for grid-scale storage [98]. Further improvements of LFP include carbon coating and doping of vanadium or titanium that can lead to better performance [100].

NMC (Lithium Nickel Manganese Cobalt Oxide)
By combining nickel, manganese and cobalt at equal ratios, one gets $LiNiMnCoO_2$ [9]. This type of LIB has a layered structure and was developed by incorporating different metals into already existing lithium cobalt oxide (LCO) and lithium nickeel oxide (LNO). With higher nickel content, the energy density of NMC increases, also leading to lower costs and less environmental harm due to the decrease of cobolt content in the battery [9, 98]. It has a high capacity and is overall a safe material to use in utility-scale applications [9].

It has an even better performance in combination with lithium manganese oxide (LMO), $LiMn_2O_4$, which has a spinel structure. This specific structure has benefits of high average potential and specific energy [98]. Other advantages include high thermal stability and good safety [10]. The use of manganese leads to lower costs compared to other electrode materials such as nickel and cobolt [98]. Some drawbacks LMO has are the limited cycle and calendar life, and low theoretical capacity [10, 98]. Pure LMO is therefore not common in grid-scale storage, however it is applicable in combination with other materials such as NMC [98]. Their characteristics balance each other which makes the technologies work well for grid-scale storage systems [100].

NCA (Lithium Nickel Cobalt Aluminium Oxide)
This type emerged from LCO as well. By adding nickel, it gave the benefits of high energy density. However this structure had thermal issues. By adding small quantities of aluminium, thermal and other electrochemical properties were enhanced, creating the new battery chemistry

- NCA, or $LiNiCoAlO_2$. Among other benefits are higher energy density and lower costs compared to NMC. However it experiences issues of degradation due to higher voltage operations [100].

Table 7.1: Comparison of different LIB-chemistries [1][18] [2][100]

	LFP	***NMC***	***NCA***
Energy density[1] [Wh/L]	220 – 250	325	210 – 600
Power density[1] [W/L]	4 500	6 500	4 000 – 5 000
Cycle life[1]	2 000	1 200	>1 000
Safety[2]	+++	++	+
Costs advantage[2]	++	++	+
BESS performance[2]	+++	++	++

Table 7.1 shows the three discussed LIB-technologies and their performance metrics compared to each other. One has to consider the specific design needs when choosing the battery technology. LFP has more advantages compared to NMC and NCA, despite having lower energy and power density. According to the future trends and predictions, LFP also has the most potential when it comes to cost reduction and enhancement of cycle and calendar life [100].

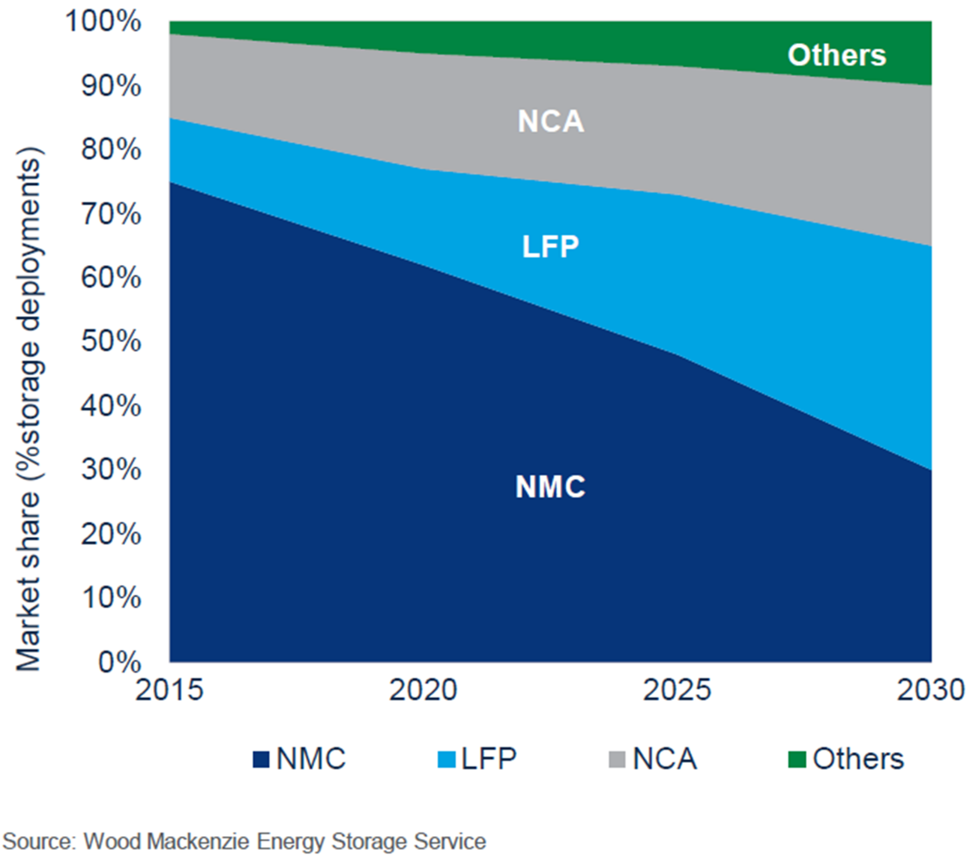


Figure 7.2: Energy storage system market share forecast, 2015-2030 (Wood Mackenzie Energy Storage Service) [81].

NMC has dominated the market, but it is predicted that LFP will overtake in the future, as seen in Figure 7.2. According to [81], safety, low costs and good cycle life will be valued more than energy density and reliability. That is where LFP is better than NMC and NCA-technologies. In addition, cobalt is an expensive material which is of less availability compared to materials in LFP.

7.2.3 Economics

The price of a lithium-ion battery depends on several factors, such as the size of the system and the type of battery. LIB also represented 90% of the installed utility-scale storage capacity in 2017 [64]. Due to the popularity growth of the Li-ion batteries, the prices have decreased with years. This is caused by inexpensive raw material prices, efficient manufacturing and technological development due to electrical vehicle prevalence [89]. The price has declined by 89% from 2010 to 2018 and will continue declining in the future [17].

As mentioned earlier, LFP batteries are expected to have a large price reduction in the future. In 2016 the approximate price for LFP was around 600 USD/kWh, and was predicted to get reduced to around 250 USD/kWh by 2030. The price reduction will be affected by the improved cathode technology (cheaper materials, enhanced performance) as well as improved manufacturing and increased automation [100]. An approximate price for all grid-scale LIB-technologies is given in Table 7.2.

7.2.3.1 Large Manufacture

The manufacturing capacity was 103 GWh in 2017 lead by such companies as LG Chem, BYD and Panasonic [30]. Other companies in the grid-scale battery industry are Kokam, Toshiba, Samsung SDI and Tesla. More on some of these further. Figure 7.3 shows global LIB-manufacturing with Asian countries being the most prominent contributors.

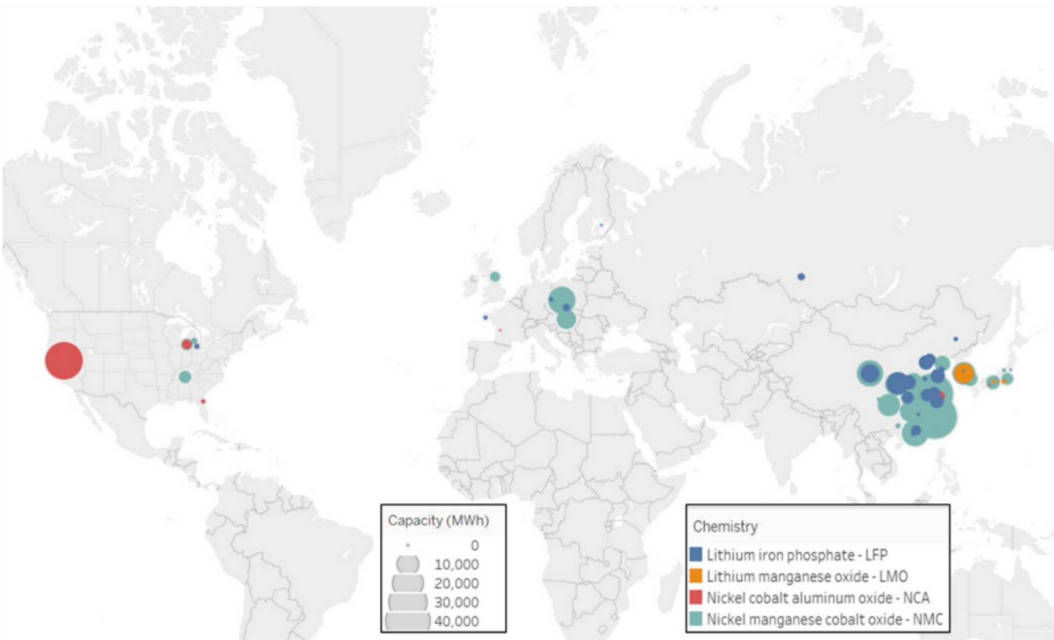


Figure 7.3: Global lithium-ion battery manufacturing based on the technology type, 2020 [38].

LG Chem
LG Chem is a South Korean chemical company which has been in the industry since the 1940s. Their scientific fields include batteries, petrochemicals and advanced materials [3]. The daughter company LG Energy Solutions develops batteries for electric vehicles, residential use ESS and grid-scale ESS. By the end of 2020, LG Energy Solutions had installed 14.8 GWh of large scale projects all over the world. The company claims to manufacture LIBs of higher energy density, long lifespan and enhanced safety. The type of ESS that can be provided is peak shifting, frequency regulation and renewable integration [75].

BYD
BYD is a company in China founded in the 1990s that develops vehicles, electronics and batteries. They use LFP-technologies to provide grid-scale storage solutions for both peak shifting and frequency regulation. The company also focuses on integrating battery storage with solar energy [13]. Their ESS are used worldwide, including South Africa. BYD's LFP batteries claim to be highly efficient, environmental friendly and safe. Besides the lithium-ion batteries, BYD also has the largest market share for nickel-cadmium batteries [21].

Kokam
Kokam was founded in 1989 in South Korea. Today the company provides different battery technologies for such applications as ESS, EVs, aerospace/aviation and marine/off-shore [77]. Kokam has total of 420 MW ESS installed all around the world. The type of Li-ion batteries they have developed are LNMC which claim to have high energy and power capacity, in addition to enhanced cycle and calendar life and the ability to operate in high temperatures [72].

7.3 Lead-acid battery (LAB)

Lead-acid batteries are an old and mature technology. It was the first rechargeable battery, invented in 1859 by Gaston Planté. This type of battery is often used in vehicles and other applications requiring a high load current. Typically, the lead–acid battery consists of lead dioxide (PbO_2) which is used as the negative electrode, metallic lead (Pb) as the positive electrode, and sulfuric acid solution (H_2SO_4) as the electrolyte. There are several types of LABs, including flooded acid, gelled acid, and advanced absorbed glass mat (AGM) [106].

There are several advantages to using the lead-acid battery. It has a low capital cost and is simple to manufacture. The cost per watt-hour is also low. It has a high specific power, and is capable of high discharge currents. Good performance at both low and high temperatures is also an advantage. However there are also some disadvantages, including a low specific energy, slow charging and a limited cycle life; repeated deep-cycling reduces battery life [10].

7.3.1 Technology

The components of the lead-acid battery is the current collector (lead), negative electrode (lead), positive electrode (lead dioxide), separator (porous polymer/woven non-conducting mesh), electrolyte (sulphuric acid) and the battery housing, including terminals and connections to cells [106]. This can be seen in Figure 7.4.

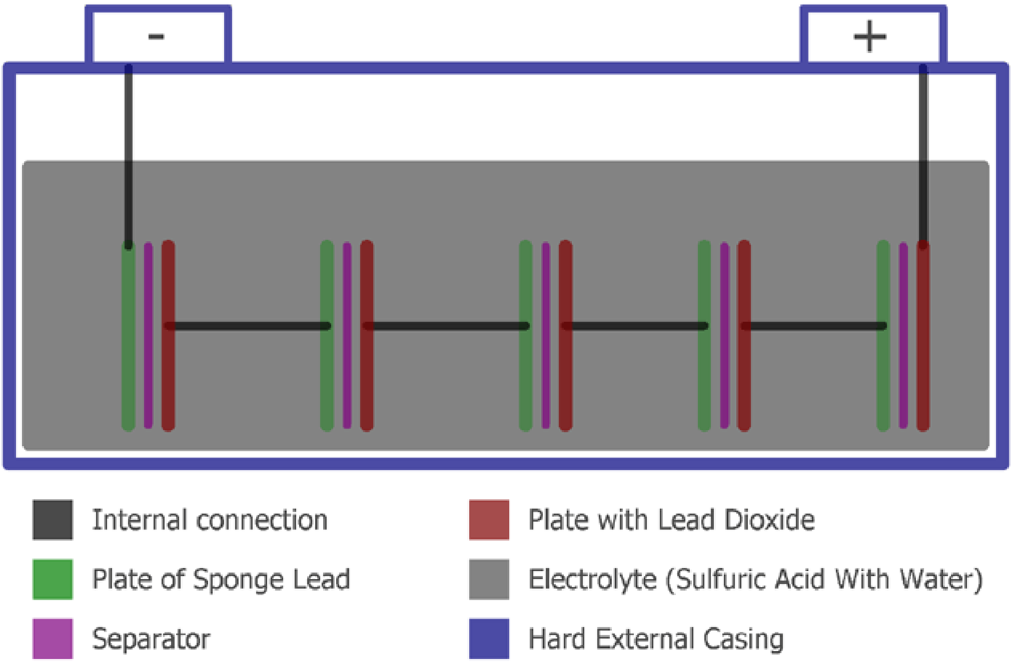


Figure 7.4: LAB-schematic showing the components [35].

Lead-acid batteries are based on the electrochemical conversion of lead and lead dioxide to lead sulfate. The sulfuric acid works as both the reactant and the ionic transport medium through the battery [39]. The net cell reaction for a lead-acid battery is given in Equation 7.3.1. The reaction shifts to the right when discharging and to the left during charging.

$$PbO_2 + Pb + 2H_2SO_4 \Longleftrightarrow 2PbSO_4 + 2H_2O \tag{7.3.1}$$

On the anode, lead reacts with sulfuric acid to form lead sulfate, as shown in Equation 7.3.2.

$$Pb + H_2SO_4 \Longrightarrow PbSO_4 + 2H^+ + 2e^- \tag{7.3.2}$$

On the cathode, lead oxide reacts with sulfuric acid, forming lead sulfate as well, as can be seen in Equation 7.3.3.

$$PbO_2 + H_2SO_4 + 2H^+ + 2e^- \Longrightarrow PbSO_4 + 2H_2O \tag{7.3.3}$$

The lead-acid battery can be either flooded or sealed, where the sealed LABs can be either AGM or gel.

Flooded

In flooded LABs, the electrodes sit in a liquid electrolyte, where the electrolyte is free to move in the battery encasement. The battery needs maintenance for it to reach the potential lifespan. Distilled water needs to be added so that the battery does not dry out. This type of LAB is often used for automotive starting batteries. They are the most cost effective type of LAB, and also the longest lasting ones. However they release toxic hydrogen gas when charging, meaning they need to be enclosed and vented to avoid gas being collected, thus creating a dangerous environment [47].

Enhanced flooded battery (EFB), is a type of flooded LAB where the grids are narrow and the number of plates is increased. This causes the battery to have an improved charge acceptance and greater cyclic durability compared to other flooded batteries. It also has a lower cost than AGM technology [33].

Sealed/valve regulated

Sealed or valve regulated lead-acid battery (VRLA), is a type of LAB where the electrolyte is sealed inside. Therefore it is not needed to add distilled water. A valve is added to ensure safety during charging by allowing gasses to escape. The manufacturer adds enough electrolyte to ensure use within warranty. The one-way pressure relief valve results in a spill-proof design. The battery is maintenance free and very common nowadays, thus used in many applications [47, 106].

AGM, Absorbent glass mat construction, is an advanced version of the VRLA. The battery is maintenance free and leak proof, making it ideal for vehicles and mobile applications. The electrolyte is bound to an absorbent glass mat separator. AGM batteries have three times more charging cycles compared to flooded LABs. However they are more expensive than flooded LABs, and have a shorter lifespan [47].

Another type of VRLA is the gel LAB. Silica additive is used to create a gel-like electrolyte. This battery has lower recharge voltage and higher internal resistance compared to AGM. The battery is more sensitive to over-voltage charging and cold starts, and is typically used for very deep cycle and hot weather applications. This is also the most expensive battery out of the VRLA batteries. Because of the cost, they are not ideal except for some specific solar applications [47].

Figure 7.5 shows the difference between the types of lead-acid batteries. The main difference is the type of electrolyte used.

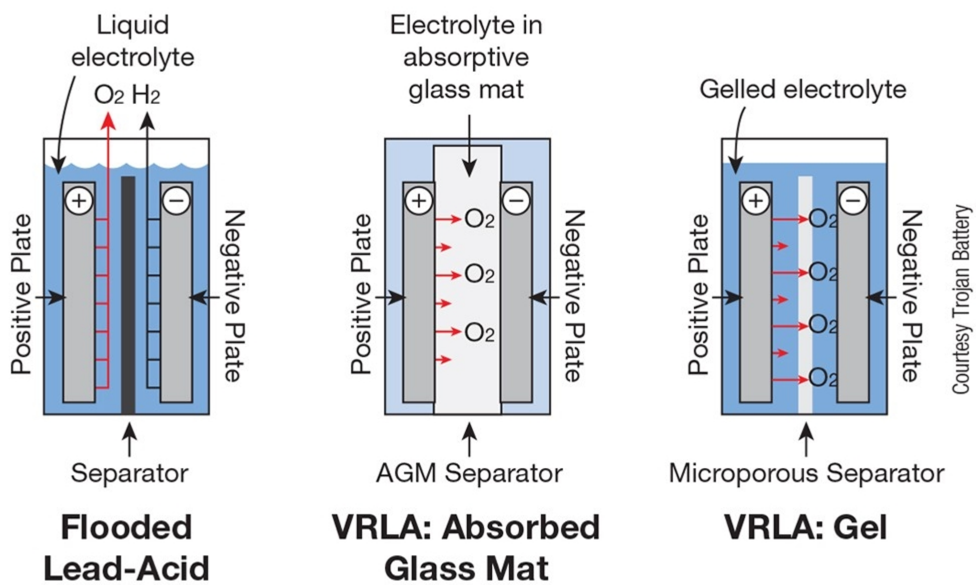


Figure 7.5: Comparison of the lead-acid battery types [114]

7.3.2 Economics

The global lead-acid battery market is rapidly growing. The market was valued at USD 39.93 billion in 2020 and is estimated to reach USD 54.45 billion by 2027. This is caused by a growing automotive sector and the low price of lead. Increasing use of renewable energy also leads to a need of energy storage, benefiting the LAB market. However, the decreasing price of lithium-ion batteries will decrease the growth of the lead-acid battery market. There has been an increased focus on research and development of the battery because of this competition. The Asia-Pacific region dominates the market, with most of the demand coming from India, China and Japan [73].

The capital cost of lead-acid batteries varies, depending on the size of the system, manufacturer, type of LAB, etc., but is estimated to be 100-480 USD/kWh [100].

7.3.2.1 Large Manufacture

The lead-acid battery market is fragmented, meaning there is a competitive market without dominant players. Some of the largest manufactures of LABs are Panasonic Corporation, GS Yuasa Corporation, EnerSys, East Penn Manufacturing Co. and Leoch International Technology Limited [73]. Among these companies, GS Yuasa Corporation and East Penn Manufacturing Co. are some of the companies offering grid-scale batteries, and are described further.

GS Yuasa Corporation
GS Yuasa Corporation is a Japanese company producing several kinds of batteries. The company offers industrial batteries, among other things, which can be used for a variety of large energy storage applications. Within the lead-acid battery sector, there are many options and different series of the VRLA battery type. The batteries are promoted to have a long lifespan of over 10 years, and some over 15 years. The SLR series of VRLA batteries have high capacity cycling cells and is suitable for large-scale energy systems. The SLR-1000 battery is an advanced nano-carbon valve regulated lead-acid battery. Easy installation and maintenance, as well as reduced site space are some of its advantages [29].

East Penn Manufacturing Co.
East Penn Manufacturing Co. is a private, family-owned company based in North America. The company focuses on VRLA batteries. The UltraBattery is one of the batteries relevant for grid-scale battery systems. This is an advanced lead-acid battery with increased cycle life. It is a low-cost, high-performance energy storage solution for grid-scale applications, and is scalable for energy storage systems [34].

7.4 Sodium-sulfur battery (NAS)

The sodium-sulfur battery is a type of molten metal battery based on sodium and sulfur. It exhibits a high energy density, high efficiency of charge and discharge, and has a long cycle life. Because of the inexpensive materials it is made of, it has a relatively low cost. It is primarily used for large-scale non-mobile applications such as electricity grid energy storage because of the sodium. Pure sodium is highly corrosive and can present a hazard when released into nature. The battery has also high operating temperatures of 300°C-350°C, meaning there are extra costs to maintain the high temperatures [10].

7.4.1 Technology

The components of a sodium-sulfur battery are molten sulfur as the positive electrode and molten sodium as the negative. They are separated by a ceramic, beta-Al_2O_3, which serves as both the separator and the electrolyte. The cell is enclosed in a sulfur housing with a gas tight seal to avoid leakage. Figure 7.6 shows a schematic of the components of the battery [83].

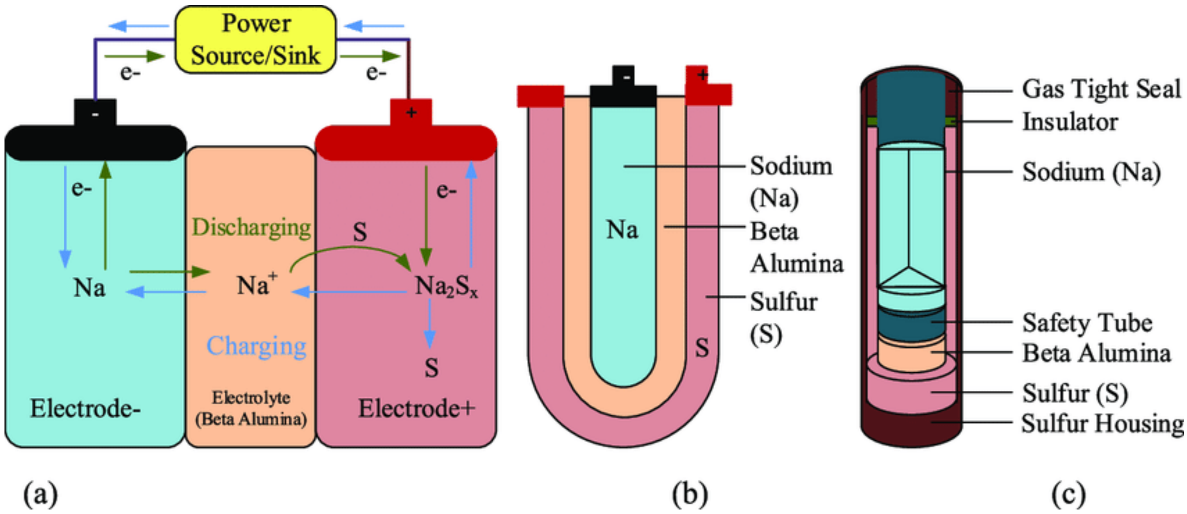


Figure 7.6: Sodium-sulfur battery schematic. (a) shows the electrochemical reaction, while (b) and (c) give an overview of the components [83].

The sodium-sulfur battery is based on the electrochemical reaction between sodium and sulfur, where the product is sodium polysulfide. During discharge, the sodium metal is oxidized to Na^+-ions in the anode reaction and is transported across the beta-Al_2O_3 ceramic electrolyte membrane. It combines with reduced sulfur anions from the cathode reaction to generate sodium polysulfide, NaS_x, in the sulfur compartment. Equation 7.4.1 and 7.4.2 express the anode and cathode reaction, respectively [136].

$$2Na \Longrightarrow 2Na^+ + 2e^- \tag{7.4.1}$$

$$xS + 2e^- \Longrightarrow S_x^{2-} \tag{7.4.2}$$

Equation 7.4.3 shows the total reaction, which goes to the right while discharging.

$$2Na + xS \Longleftrightarrow Na_2S_x \tag{7.4.3}$$

The battery operates at high temperatures where both the reactants and products are liquid, meaning there is a high reactivity of the electrodes. Therefore, the battery has a high power and energy density. The theoretical specific energy density at 350°C can reach nearly three times the specific energy density of lead acid batteries. This means approximately one third the spaces required for the lead acid battery need to be used for the sodium-sulfur battery in similar applications. The typical specific energy density ranges from 150 to 240 Wh/kg. As the battery is completely sealed and allows no emissions during operation, it is considered environmentally friendly. More than 99 wt.% of the battery materials can be recycled. However, sodium must be handled as a hazard material [136].

7.4.2 Economics

The global sodium-sulfur battery industry is a growing market. This is due to an increasing number of renewable energy projects and the many benefits of this type of battery. Ongoing research of the battery to overcome some challenges, like the high working temperature, may also create opportunities for growth in the market. Some of the limitations are, however, the corrosive sodium polysulfides, which causes the battery to not be suitable for portable mobile applications. The Asia-Pacific region dominates the market due to the high amount of battery production in the region [110].

Sodium-sulfur batteries costs varies, with the estimated price range of 260-740 USD/kWh [100].

7.4.2.1 Large Manufacture

The market is consolidated, meaning the market is dominated by just a few major players. Some of the biggest companies in the market include NGK Insulators Ltd., and BASF SE [110]. As sodium-sulfur batteries generally are used for stationary systems, both of these companies are relevant for a battery storage system. The companies are partnered on developing the next generation of NAS batteries.

The companies describe the NAS batteries as having a large capacity, and can be used for many power grid applications. The batteries can be containerized and used for large-scale systems. The NAS installations can be scaled up to many 10s or 100s of MW with durations of 6 to 7 hours. The lifetime of the batteries is 4500 cycles or 15 years [28]. Figure 7.7 shows how the NAS battery modules are installed in the containers. The battery cells are placed in battery modules, and these modules are stacked in the container.

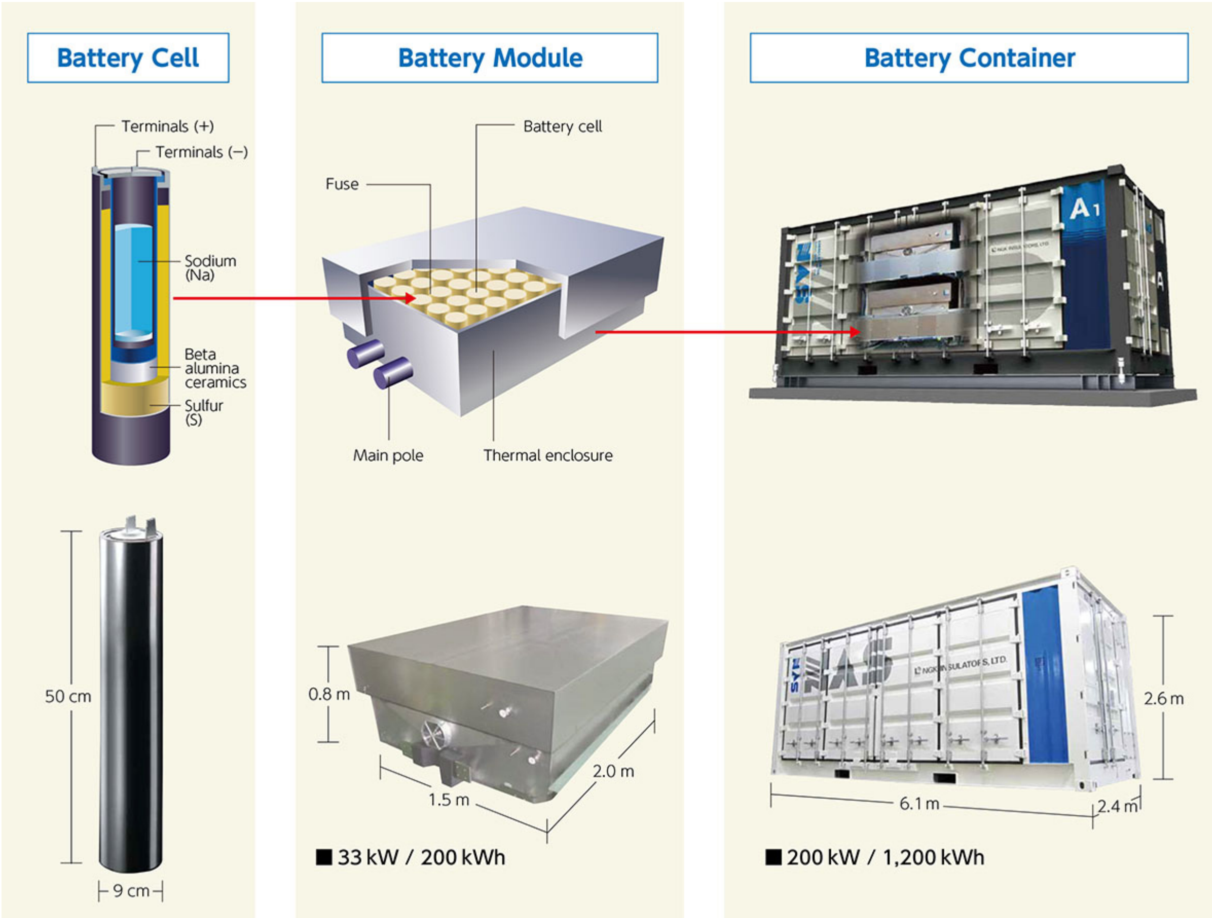


Figure 7.7: NGK Insulators Ltd. NAS battery system. How the battery containers are designed, showing the modules and cells [28].

7.5 Vanadium redox flow battery (VRB)

Flow batteries consist of two tanks with electrolyte which gets pumped into a reactor to generate a charge. The technology is quite mature when it comes to development, and has been around for the past 30 years. The vanadium redox flow battery (VRB) is the most widely studied and commercially developed of all the flow cell batteries. Flow batteries have emerged as strong contenders for large-scale grid-connected energy storage systems, much due to their extended life cycle. They are also fully dischargeable, the costs improve with scaling and they have several great safety features [12, 125].

7.5.1 Technology

As mentioned above, flow batteries differ from traditional batteries. Their active material is two redox couple solutions that are stored in external tanks and pumped through a stack of electrochemical solutions, which are separated by an ion exchange membrane. The membrane prevents the two solutions from mixing. One can observe the schematic of this in Figure 7.8. By doing this, flow batteries are free of the processes that could lead to a breakdown of the active material and thus offer a longer cycle life under deep discharge operations, as well as the greatest flexibility power to energy rating, as the capacity is defined by the volume of electrolyte stored in the external tanks [79, 125].

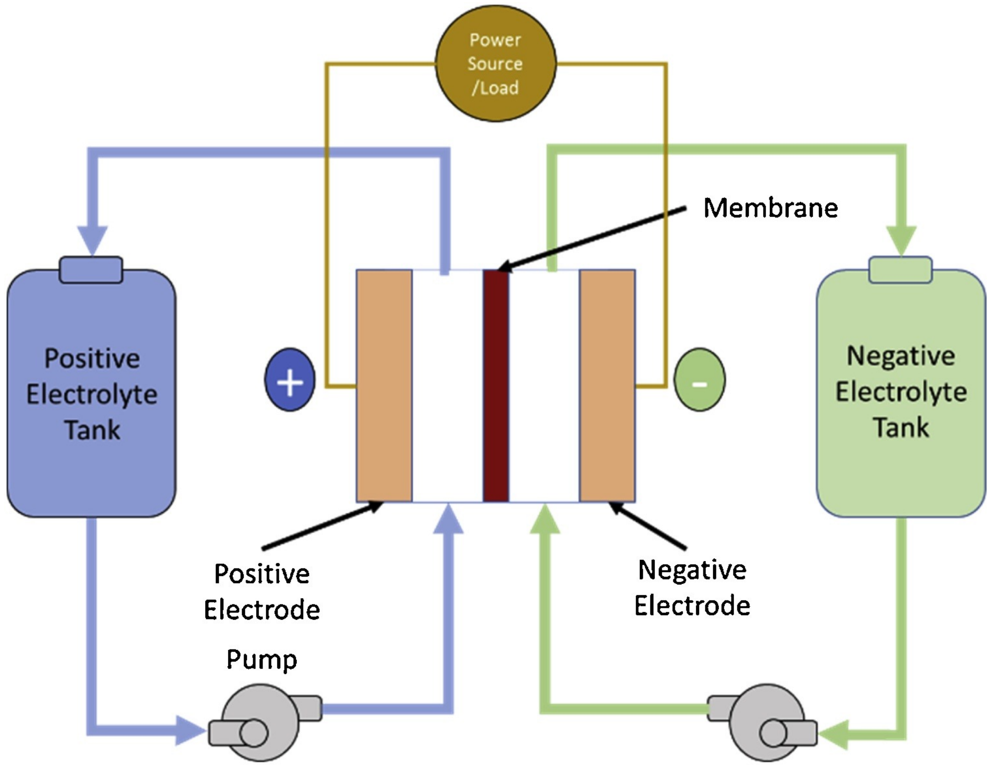


Figure 7.8: Vanadium redox flow battery schematic [79].

The VRB typically uses two separate tanks for storing vanadium ions in four different oxidation states: $V^{2+}, V^{3+}, V^{4+}(VO^{2+})$ and $V^{5+}(VO_2^+)$. This way it ensures that there is a redox couple in each tank. The negative tank contains V^{2+} and V^{3+}, while the positive contains the remaining two. The electrolytes are fed into separate half-cells inside the battery and then returned and recycled [79]. The half-cell reactions are represented in Equation 7.5.1 and Equation 7.5.2, and the total cell reaction is depicted in Equation 7.5.3.

Positive electrode reaction

$$VO_2^+ + 2H^+ + e^- \Longleftrightarrow VO^{2+} + H_2O \tag{7.5.1}$$

Negative electrode reaction

$$V^{2+} \Longleftrightarrow V^{3+} + e^- \tag{7.5.2}$$

Total cell reaction

$$VO_2^+ + V^{2+} + 2H^+ \Longleftrightarrow V^{3+} + VO^{2+} + H_2O \tag{7.5.3}$$

When fully discharged, the negative and positive electrolytes contain only V^{3+} and V^{4+}. Respectively when charging occurs, the negative electrolyte is reduced to V^{2+} and the positive is oxidized to V^{5+}. This type of VRB is generally known as a generation 1 VRB [79, 125].

Key technological advantages

Because of the design of the flow battery, it gains many technological advantages compared to its BESS counterparts.

The energy is stored in a solution, so no changes of solid-phase occur. By doing this, it eliminates the possibility of short-circuiting or shedding of the active material. The solution can also be stored for longer periods with relatively no self-discharge occurring in the electrolyte tanks. The electrolyte flowing through the cell stack acts as a coolant to remove and prevent thermal runaway, thus enhancing the battery safety.

RFB can also be fully charged or discharged without the risk of loss of capacity, battery life or damage. Another advantage is the separation of energy and power rating which provides a great flexibility in the system design. The power rating of a RFB is therefore a function of the number of cells in the cell stacks and the electrode area, while storage capacity is a function of the electrolyte volume and active material concentration. Capacity is also increased by increasing the volume of the electrolyte-solutions, thus the cost per kWh drops rapidly as the storage capacity is increased. This is especially significant in large-scale energy storage systems that require energy capacities of multiple hours [125].

Performance

The performance of the VRB is measured in terms of its cycle life and the round trip efficiency, which are dictated by the coulombic and voltage efficiencies of the specific cell and stack design. The cycle life is not only influenced by the cell materials, but also by the battery management system that ensures that the battery runs within safe limits. The efficiency is dependent on electrode material and type of membrane, additionally the cell geometry and design [125].

The battery life is mainly affected by the stability of the membrane in the highly corrosive environment some vanadium ions can create in the charged positive half-cell electrolyte. Recent years have shown that one could have membranes that last for 10 years of operation in the VRB, before the membrane must be replaced for a further extension of life. However, the cycle life, with a good battery management, could theoretically have an unlimited life with some research recording values of over 200 000 cycles [125].

There has been made progress with the technology surrounding the VRB, with both a generation 2 and 3 VRBs in research and development, however these are still some years off from being commercially available [125].

7.5.2 Economics

Vanadium redox batteries are a compelling technology which can be adjusted to any situation. This makes them attractive for a lot of applications. The VRB has the potential to surpass the LIB because it is safer, more scalable and has greater cycle life. In addition, it is more vanadium in the earth's crust than lithium. However, vanadium extraction is expensive which hinders the economic progress. Researchers are working on how to improve cell and stack design, as well as a way to lower the cost of vanadium extraction. It is predicted that VRBs could cost less than half of LIB in the future [125, 135].

The vanadium redox battery is easily scalable, as one would just need to increase the tank size of the electrolyte. In fact, the price per kilowatt hour decreases when increasing the size, making it ideal for large grid-scale storage systems [26].

The European Commission reports that the current broad price-range for vanadium redox batteries lays between 550-1320 USD/kWh. In order for it to be competitive, the VRB needs to reach a price-range from 100-300 USD/kWh [25]. Additionally, there has been done research on some types of flow batteries where the cost could be as low as 25 USD/kWh. This was done by using more inexpensive and abundant materials such as manganese and sulfur. However, further research must be completed on this subject [23, 59].

7.5.2.1 Large Manufacture

Manufacturers of vanadium redox flow batteries are oriented on the market for large-scale grid systems, as this is the area where VRB excels. Some large manufacturers are VRB Energy, VFlow Tech and Invinity which will be further presented below.

VRB energy
VRB energy is a Canadian company that claims to be leading in VRB-technology. According to the company, they have developed the longest-lasting and most reliable VRB in the world. VRB energy is working to promote and demonstrate that the VRB is one of the best options for grid storage solutions [132].

VFlow Tech
VFlow Tech is a Singapore based company. VFlow tech aims to develop a VRB which can be regarded as the most affordable and reliable in the world. Their batteries are unique as they base themselves on industry focused research to produce scalable and long-duration energy solutions [131].

Invinity
Invinity was created by merging two flow battery providers, UK-based redT and North American-based Avalon. They claim to produce safe and durable VRBs with a long lifespan and with the potential of high revenue. They distribute their services all over the world [129].

7.6 Solid-state battery (SSB)

Solid-state batteries are a battery technology that utilises both solid electrodes and a solid electrolyte. In a sense, the solid-state battery is a variation of the LIB. SSBs are perceived as a safe and stable energy storage solution which could potentially provide solutions for the many problems the LIB experiences. There still exists some key issues with the battery which remain unsolved, preventing a full-scale commercialization [66].

7.6.1 Technology

The technology of the solid-state battery is revolving around its use of a solid electrolyte. Besides that, it is quite similar to a regular lithium-ion battery.

Solid electrolyte (SE)

Most batteries use liquid electrolytes, which are easy to work with and are of low cost. However, there are safety issues present, as these liquid electrolytes are combustible. In opposition, the solid electrolyte can provide some beneficial features:

SEs only allow transfer of lithium-ions and it will act as functional separators with only a minor self-discharge. In liquid electrolytes, both lithium-ions and anions are mobile which is causing critical concentration of the conducting salts during the current flow, thus limiting the cell current. For the SE, however, only lithium-ions are mobile, which is preventing this to occur. This is something one can observe in Figure 7.9. Thus higher current densities and quicker charging times are achievable for the SE [66].

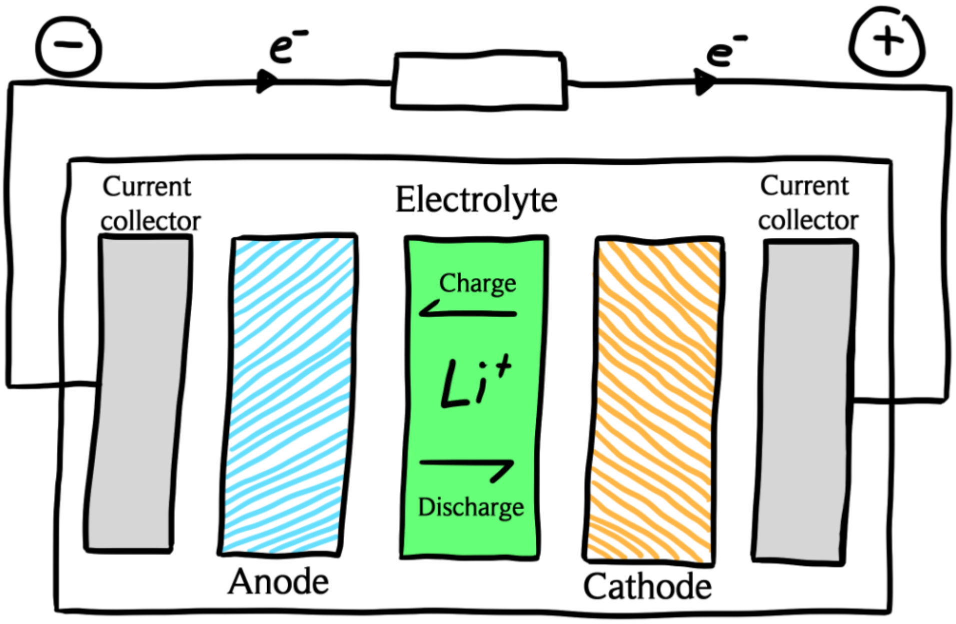


Figure 7.9: Solid-state battery schematic.

The solid electrolyte can be divided into two groups: inorganic solids and organic solid polymers. The inorganic solids could be glass, glass-ceramic or crystalline, but organic polymers are the preferred material. The reason for this is that polymer based batteries can compensate for volume changes of electrodes by being elastic and by plastic deformation. However, the lithium-ion conductivity of polymer electrolytes is too low for battery operation at room temperature and for operations in EVs that requires temperatures above 80°C. Even at that point, their rate capability is limited, preventing swift charging. Research into stable polymer electrolytes is therefore one of the challenges the engineers and scientists will have to face. Hence, polymer based SSBs are not ready for the wider market [66].

Inorganic SEs have recently shown to have the potential to improve battery performance at high currents, dispelling the myth that SEs are poor conductors at room temperature. A number of inorganic solid electrolytes have been reported to have room temperature conductivities higher than the typical liquid electrolytes. Many inorganic SEs, on the other hand, have a low thermodynamic stability, which is a severe disadvantage. Like their liquid counterparts, most solid electrolytes reduce easily at low potentials and oxidize at intermediate potentials. To stabilize the contact between the electrolyte and electrode, a protecting interphase is required. The highest lithium-ion conductivities in SSB today are found in crystalline inorganic SEs, with phosphates and oxides coming close. Phosphates are ductile and can easily form dense cathode composites, while the oxides are brittle and shatter easily [66].

Some inorganic SEs are stable at higher temperatures, improving the safety of the battery. In addition, their conductivity increases as the temperature increases, which results in conductivities higher than their liquid counterparts [66].

Performance

As SSBs are a variation of LIBs, they have to outperform them at key areas. But while SSBs may have the potential to do so, they have many challenges to overcome.

By replacing liquid electrolyte with solid electrolyte, it leads to improvement of the present capabilities of energy density. Lithium metal forms unwanted dendrites in a liquid-based battery system, which both compromises battery safety and cycle life. Thus by replacing highly reactive liquid electrolyte with a SE, one increases the battery's energy density without compromising safety. Suppressing the dendrite formation is one of the many key goals to achieve a high energy density. This will all depend on the separator material, but once it is able to overcome this challenge, it could reap the benefits of higher energy density, faster charging, longer life cycles and safety [102].

A high power density from a SSB is yet to be demonstrated. This is due to a small ionic conductivity and huge interfacial impedances of lithium electrode contacts. The latter issue - which stems from from the SEs poor chemical, electrochemical and physical compatibility with electrodes, is more important in the regard for the power density. More work has to be done with the SE to achieve a suitable power density [143].

An important feature with the solid-state battery is that it is a safety improvement from a regular lithium-ion battery. If only oxide-ceramic components were used, safety would be guaranteed. However, the best suited conductors are sulfides. In consequence, formation of SO_2 by the oxidation of the solid electrolyte, or the formation of H_2S in case of battery damage, may present itself as a possible risk. Protection of some sort may be required, but this leads to a more complex production and a higher price. Therefore, safety in SSBs may not automatically be enhanced, especially if there is a risk of mechanical failure [55, 66].

7.6.2 Economics

The SSB has the potential to deal with a lot of the concerns surrounding the LIB. However, there are many areas for improvement, making the costs remain quite high. DNV's technology outlook for 2030 claims that at this stage and in the initial phase of development, the price could still be as high as 400-800 USD/kWh by the year of 2026 [127]. Further development and research has to be done in order to lower the cost for the technology.

7.6.2.1 Large Manufacture

The driving force in research within solid-state batteries is the electric automotive industry, with Toyota at the front. The reason for this is that SSBs are seen as a safer technology, in addition to other potential benefits, which could improve the current battery situation. Other large manufacturers are Samsung and Panasonic, who are both electric devices producers [85].

The most promising producer for energy storage applications appear to be Quantumscape. Their main focus is in EVs, but they acknowledge stationary storage as a bigger market and an interest for the future [19].

Currently the SSB is dependent on success within the automotive industry before it can be exploited further in grid-scale storage systems.

7.7 Comparison between the battery technologies

The comparison of the different types of batteries is presented in Table 7.2. The data for LIB, LAB, NaS and VRB is taken from [100]. The numbers might differ from the previously mentioned properties in the sections above. However, the same reference is used in order to better compare the different technologies.

Since no data on SSB was included in the reference, the comparison with the other battery technologies is less sufficient. Solid-state batteries are still under ongoing research and have yet to be fully commercialised. This leads to values like energy density, cycle life and costs not being publicized.

Table 7.2: Battery technologies compared to each other

	LIB	***LAB***	***NaS***	***VRB***
Energy density [Wh/L]	200 - 740	50 - 100	140 - 300	10 - 70
Power density [W/L]	100 - 10 000	10 - 700	120 - 160	1 - 2
Cycle life	500 - 10 000	250 - 2 500	1 000 - 10 000	>10 000
Installation costs [USD/kWh]	200 - 840	100 - 480	260 - 740	310 - 1 000
Round-trip efficiency [%]	92 - 96	80 - 83	84	60 - 85
DoD [%]	80 - 100	50 - 60	100	100
Self-discharge [%/day]	0.09 - 0.36	0.09 - 0.4	0.05 - 1.0	0.0 - 1.0

7.7.1 Safety

Safety is an important metric within battery technologies and it is regarded as elementary to compare the technologies within this subject.

The electrolyte used in the LIB is the most flammable component and it is closely related to its safety. Monitoring the temperature may be required. Design and usage of more stable electrolytes is regarded as an effective way to solve safety issues, and is something that is becoming more mature and prominent, providing a potential future of high-safety LIBs [134]. Safety of the different LIB-chemistries was discussed in more details in the earlier sections.

This is where SSB can be looked-upon as it can be regarded as a safety improvement of the LIB, with lowering the risk of thermal runaway. Although this depends on the solid electrolyte material [55, 127].

Lead-acid batteries have a mature technology, which means that most of the initial faults will have been removed, thus improving its safety. The valve-regulated LABs are the safest type of LAB because of the reduced spillage risk. However, lead is toxic and may be a restricted material in some applications or locations due to the toxicity [100]. Due to its many maintenance requirements, especially for the flooded type, there are also some reliability issues related to the battery [6].

Due to the sodium-sulfur battery being operated at over 300°C and the highly reactive nature of metallic sodium, which is combustible when exposed to water, there are some safety concerns regarding the battery [10]. However, the enclosing is constructed to prevent leakage and to hold high temperatures. NGK Insulators Ltd. has done safety tests with third-party authorities, concluding that the NAS battery was safe as it passed all of the tests. The tests included fire exposure, submerge, drop and short circuiting of the battery [104].

The VRB is considered to be a safe battery. External short-circuits are very unlikely and measures have been taken to hinder them. Internal short-circuits are rare, but can occur. Although this does not lead to a significant increase in temperature. The electrolyte has a high heat capacity and is therefore beneficial when acting as a coolant which removes and prevents thermal runaway. The only real safety concern of the VRB is that it can have issues related to leakage, as it bases itself on large liquid tanks. However, overall the VRB is considerably safer than other battery types [125, 140].

8 Economics

Economics will play a key part in this thesis, thus some major economic terms, in addition to important formulas, will be explained in this section.

8.1 Capital Expenditure (CAPEX)

Capital expenditure is the funds used by a company to acquire, upgrade or maintain assets. CAPEX is often used in relation to investments or new projects. It works by acting as a financial outlay made for companies to get a better overview of their projects or add an economic benefit to the process [43].

CAPEX is any expense that the company capitalizes, or is regarded as an investment, rather than being seen as an expenditure. To capitalize the expense, the cost of the expenditure has to be spanning over the assets' whole useful lifetime [43].

8.2 Operating Expenditure (OPEX)

The operating expenditure or operating expense, is an expense a company incurs during normal operation. OPEX can include rent, insurance, payroll, maintenance and funds allocated for research and development. One of the responsibilities the management must work with is to decide how to reduce OPEX without affecting the company negatively [69].

Operating expenditure is a necessary and unavoidable part of running a company. Regulating the OPEX to gain advantages and increase earnings without compromising integrity and quality of operations is a difficult task, but rewarding if done correctly [69].

8.3 Net Present Value (NPV)

Net present value describes the present value of all future cash flows (amount of money that is being transferred in or out of the investment) through the whole lifetime of the product. It is an important factor to consider when investing in a product or a project, and essentially tells if the product is worth investing in [93]. Equation 8.3.1 shows the general formula for calculating NPV [93, 94].

$$NPV = \sum_{t=0}^{T} \frac{CF_t}{(1+r)^t} = -X_0 + \sum_{t=1}^{T} \frac{CF_t}{(1+r)^t} \tag{8.3.1}$$

CF_t = Net cash flow during a single period t
r = Discount rate
T = Total number of periods, product's lifetime
t = Number of time periods
X_0 = Investment in period 0/beginning

A positive NPV-value indicates a profitable project, while a negative value indicates nonprofit. The goal is therefore a positive NPV [94].

8.3.1 Weighted Average Cost of Capital (WACC)

WACC is often used as the discount rate for calculating the net present value. Weighted Average Cost of Capital represents the company's average cost of capital from sources such as common stock, preferred stock, bonds, and other forms of debt. WACC determines the rate of return that is needed in order to provide the company with capital [56].

If the investment has a high risk, the WACC-value is increased. A low WACC-value is ideal, as it indicates that the business is well-established and is able to attract investors at a lower cost [56].

8.4 Internal Rate of Return (IRR)

The internal rate of return is a financial metric used to find the profitability of an investment. It is the expected annual growth of an investment. IRR sets the net present value to zero, in order to find the discount rate [44]. The formula is given in Equation 8.4.1, and is similar to Equation 8.3.1 as it uses the same concept.

$$0 = NPV = \sum_{t=1}^{T} \frac{C_t}{(1+IRR)^t} - C_0 \tag{8.4.1}$$

C_t = Net cash inflow during the period t
C_0 = Total initial investment costs
IRR = The internal rate of return
t = The number of time periods

This type of equation cannot be easily solved analytically, and needs to be calculated through trial and error or by using a software that does such calculations, such as Excel. The higher the IRR-value is, the more profitable the investment is [44].

8.5 Levelized Cost of Storage (LCOS)

The cost of storage is an important factor when comparing different types of energy storage technology. LCOS is the total cost of the ESS over the course of its life cycle. LCOS can be calculated using Equation 8.5.1. The total cost is divided by the energy discharged. As there is no internationally approved calculation method for LCOS [87], the formulas often vary from one research to another. Equation below is modified based on [42, 87] and [92], and is used in this specific thesis.

$$LCOS = \frac{Capital + \sum_{t=1}^{T}(O\&M_t + Fuel_t) \cdot (1+r)^{-t}}{\sum_{t=1}^{T} MWh_t \cdot (1+r)^{-t}} \tag{8.5.1}$$

where MWh_t can also be expressed as MWh_t = Energy capacity · Cycle life · Round-trip efficiency

$Capital$ = total CAPEX over the years
$O\&M_t$ = Fixed operations and maintenance costs in year t

$Fuel_t$ = Charging cost in year t
MWh_t = Energy discharged in MWh in year t

The output is given in price per megawatt-hour. The higher the LCOS-value is, the more costly the technology is.

Methods

This section will give a detailed description of the system background, calculation methods and assumptions that were made. All the mentioned calculations and other important data that are not specified in this section, are given in the Appendix. The calculations were done in Excel, MATLAB and the Python IDE, PyCharm.

9 Hybrid system overview

The hybrid system consists of three 70 MW solar plants and two 140 MW wind plants. The total installed capacity for the hybrid plant is therefore 490 MW. The plant is currently in the developing phase, but as the purpose of this thesis is designing a storage system, it is assumed that the plant already exists. Therefore the system consists of the plant, in addition to a potential BESS. The whole system's lifetime is assumed to be 30 years. It is located in the Northern Cape, South Africa, near highway N1. The approximate location is shown in Figure 9.1.

Figure 9.1: The approximate location of the hybrid plant in Northern Cape, South Africa, indicated with a red circle [130].

Figure 9.2 depicts the hybrid system, where the undefined BESS part of the system is of particular interest and to be economically assessed. The system is regulated in the control center, which consists of several monitoring and control components such as S-TMS, B-TMS, EMS and SCADA. The control center is also connected to the grid, where energy is brought in and out of the system. The application area of the BESS is primary storage arbitrage. Energy is sold based on the existing consumer tariff, shown in Appendix A.

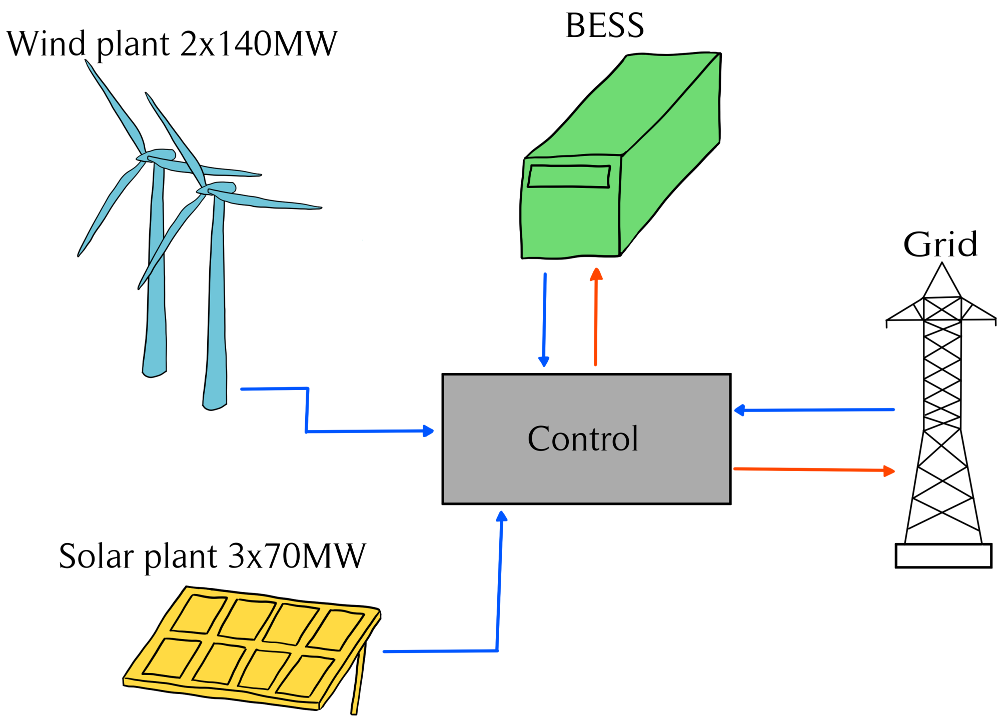


Figure 9.2: Simplified schematic of the hybrid system being analyzed in this thesis.

9.1 Solar plant

It is assumed that there is no shading for the solar plant and thus no shading losses. However some additional losses were considered in the production data-series provided by Norsk Vind. The panel type used is JAM60S20-380 from JA Solar. The panel parameters are given in Table 9.1.

Table 9.1: Parameters for the solar panel.

Parameter	*Value*
Panel elevation [°]	30
Panel rated power [W]	380
Panel efficiency [%]	22
Panel size [m^2]	1.86
NOCT [°C]	45
y_{Pmax} [%/°C]	-0.35

9.2 Wind plant

The wind turbine used is Nordex N149 at 4.2 MW. The wind turbine parameters are presented in Table 9.2. Some losses were considered in the production data-series provided by Norsk Vind.

Table 9.2: Parameters for the wind turbine.

Parameter	*Value*
Efficiency [%]	28
Rated power [MW]	4.2
Cut-in wind speed [m/s]	3
Cut-out wind speed [m/s]	20
Rotor diameter [m]	149.1
Swept area [m^2]	17.46
Hub height [m]	164

9.3 BESS

The BESS was designed for storage arbitrage. Energy is stored at low-price periods and is sold when the price is high. Based on the literature review, the battery technologies chosen for analysis were LFP and VRB. The power capacity range that was analyzed was 1-200 MW, and discharge duration with a range of 1-5 hrs, potentially testing for additional hours for better optimisation. Initially the core goal is to be able to sell as much power as possible when the peak is at its highest. Therefore one should be able to discharge most of the energy in an instant.

Most of the calculations are based on the Appendix B to make the economic estimations as credible as possible. Hence the corresponding system parameters were assumed for the analysis. SoC was found through the relation between SoC and DOD that was mentioned in the literature review. The parameters are presented in Table 9.3.

Table 9.3: System parameters for LFP and VRB based on Appendix B

Parameter	*LFP*	*VRB*
SoC	20%	10%
Round trip efficiency	88%	70%
Calendar life	10 years	15 years

10 Production data

The group received estimated values for wind and solar production. These were provided by Norsk Vind and are not to be disclosed. The data was for a 70 MW solar plant and a 140 MW wind farm. Thus the production data was multiplied by three and two respectively, to adjust to the total capacity of the hybrid plant.

The production was based on the existing wind measurements and solar data. The wind production was estimated from a model that allows to predict the future production, while the solar production estimates were calculated by formulas. The calculations were done by Norsk Vind and are thus not included in the report.

The production data was given in MW for the whole year with an interval of 10 minutes. In order to get hourly production, each value was multiplied by 1/6 hr. To obtain hourly production data (MWh/h), every 6th values were summed, which was achieved in Excel.

11 Income calculations

As mentioned earlier, the charging and discharging of the battery depend on the electricity tariff during the day and the seasons found in Appendix A. The tariff, SoC and RTE were considered when simulating charging/discharging of the battery system throughout the year.

11.1 Income from the plant

The pricing was decided according to the existing TOU-tariffs which is shown in Appendix A. South Africa's pricing system is divided into the high-demand season (winter) and the low-demand season (summer). From there it is divided into high-peak, standard and low-peak. In addition, the prices vary depending on whether it is a weekday, Saturday or Sunday, making it a 6-price system. To match the production data with the right corresponding price-point, an IF-loop was created in Python, which can be observed in Appendix E.1. From there the correct price for the corresponding hour was multiplied with the hourly production in Excel.

The currency was converted from South African Rands (ZAR) to American Dollars (USD), to get a better overview. This was done with a rate of 1 ZAR = 0.069 USD, found on 24th of March 2022 [118].

The seasons were also defined and simplified to make the estimations easier. The high-demand season (winter) in South Africa is from June to September, while the low-demand season (summer) is from December to March. Spring and autumn are not defined in the high- and low-demand seasons. To solve this, it was assumed that autumn (April and May) was to be included in the high-demand, and spring (October and November) was to be included in the low-demand season.

11.2 Income from the BESS

When calculating the income from the hybrid plant with a BESS, the capacity and storage duration of the BESS had to be determined. SoC-values for both batteries were taken into account to keep the storage within an acceptable level to prevent deterioration. It was also determined that the battery should be charged from 22:00 the previous day till 06:00 the next day, as this is a low-peak period on weekdays as seen in Appendix A.

The approach that was taken into account for this was different from the one used for the hybrid plant, although it was based on what was found there. The aim was to convert the production for each hour to the total production for each day and separate it into the six different prices. In addition one had to make sure that the production between 22:00 and 00:00 would be added to the next day, as this energy would be then stored and discharged. To do this, the data previously found through the Python code in Appendix E.1 was used in a new Python code as seen in Appendix E.2. Then the data was converted over to an Excel file. As the BESS charges in all the low-peak hours during the weekdays, the production was further divided into what would be stored and excess energy which could be sold directly in the low-peak.

In some periods between 22:00 and 06:00, the production is below the capacity of the BESS. To utilise all the storage possibilities of the BESS, it was simulated that energy was bought and stored from the grid. By that, the BESS was charged fully up to its capacity with the low-peak price and sold and discharged later for the high-peak price. However, this was not done on Sundays, as the tariff is at its lowest during the entire day, resulting in the BESS being operational for 312 days during the year.

Losses based on the RTE found in Table 9.3 were used to determine losses during charging and discharging of the battery. The value was set to 6% for LFP and 15% for VRB, to get the losses for charging and discharging separately. Losses by self-discharge were not accounted for in the calculations.

These income calculations were first done for 100 MW systems ranging from 1-5 hrs. Five hours was set as the highest limit as this is the highest amount of hours the high-peak price was available in the weekdays according to Appendix A. Then this was used in the NPV calculations to determine which hours are the most beneficial resulting in positive NPVs. To check if 5 hr discharge duration was the peak, other durations were tested as well. For testing hours beyond five, the battery capacity was divided into energy sold for the high-peak and standard price. When the ideal storage duration was found, other capacities such as 1, 10, 25, 50, 75 and 200 MW were tested to see if they would lead to positive NPVs.

To make sure that the income calculations are somewhat correct, one took the average of the price differences from Appendix A, and estimated the income for an average year. It would be sufficient enough with checking for one system, which in this case was a LFP-system of 100 MW/1 hr (100 MWh) with its RTE of 88%. Additionally, the same currency rate of 1 ZAR = 0.069 USD was used, and it was taken into account that Sundays are non-operational days.

12 Economic assessment

Based on the income results from charging/discharging of the BESS, an economic assessment was performed. Appendix B shows the cost estimations that were used for the LFP and VRB. The estimations are given for the total energy system in 2030 (Figures B.1 and B.2). As seen in the Appendix, the costs include other components of the system and the development and installation costs. Other battery parameters, such as cycle life and downtime are also seen in the Appendix. Downtime is not accounted for in the calculations, while cycle life is partially irrelevant.

12.1 Costs estimations

Appendix B shows the cost estimates in 2030. It is assumed that the BESS is planned to be operational by 2030. Therefore the costs are based on Appendix B. The costs are divided into different categories. Since the designed battery system is getting installed in addition to an existing hybrid plant, some of the costs had to be adjusted. These involve systems integration, engineering, procurement, and construction, project development and grid integration. All of these are assumed to be partially accounted for when the hybrid plant was initially installed. Therefore for the BESS, 50% of the systems integration and engineering, procurement and construction was assumed to be already covered, in addition to 80% of the project development and grid integration. The assumptions were suggested by Norsk Vind. When summing up the categories which resulted in a total CAPEX, the costs were multiplied by either energy capacity (MWh) or power capacity (MW), based on the given unit.

The operating costs are divided into three different categories - fixed and variable O&M (operations and maintenance), and system RTE losses, all given in different units. The first mentioned cost was already given in a per-year-unit, making it suitable for further economic calculations. Thus the other two parameters were converted into a per-year-unit by dividing the values by the calendar life, which is 10 years for LFP and 15 years for VRB. Fixed O&M was multiplied by the power capacity of the storage, while the other two were multiplied by the energy capacity.

In addition to the three parameters, the charging costs from the bought energy were also assumed to be a part of OPEX. The charging costs were found by simulating charging/discharging of the battery described in the previous section. The sum of these four parameters resulted in the total OPEX per year.

CAPEX and OPEX were calculated by using a MATLAB-code, given in Appendix D. As there are only three system sizes given in Appendix B, some assumptions had to be made when scaling up/down to other power capacities. To assume reasonable costs, an approximate trend of the costs was found with the help of extrapolation. Extrapolation was performed in Excel by making a graph of the three given power capacities and finding a trendline that fit the existing curve. The trendline resulted in the estimate function. For a chosen duration time, the given costs of 1, 10 and 100 MW were extrapolated which resulted in a estimate function, seen in Appendix C. Based on the graph, 1 MW-systems were based on the costs for 1 MW in Appendix B, 10-25 MW-systems were based on the costs for 10 MW, and 50-200 MW-systems were based on the costs for 100 MW. These assumptions were made because Figure C.1 in Appendix C shows approximate linear behavior/small price variation in the chosen intervals.

When finding price estimates for the chosen duration time, a mean value was found. For example, for a 3 hr-system, the mean values of 2 hr and 4 hr-systems were used. For 1 hr-systems, a slope between 2 hr and 4 hr was found and then divided by two to find the slope per hr. That slope was assumed for the values below 2 hr, meaning that the slope value was subtracted/added from/to (depending on CAPEX or OPEX) the cost of a 2 hr-system. The code for calculations is shown in details in Appendix D.

12.2 Storage optimisation

To find the best storage solution, the optimisation started with deciding the most optimal discharge duration. By assuming a power capacity of 100 MW, NPV and IRR were calculated for initially 1-5 hrs. When the most profitable system was found, the chosen discharge duration was optimized by changing the power capacity. This was done for both battery technologies, where the systems with the largest NPV and IRR were chosen. Then, if both batteries resulted in profitable systems, the technologies were compared to each other by their LCOS-values which determined the most profitable technology. Methods descriptions of the economical parameters are given in the following sections.

12.2.1 NPV

Net present value was calculated with Equation 8.3.1 in Excel. Based on the given system properties, shown in Table 9.3, there had to be made a reinvestment in years 10 and 20 for LFP, and year 15 for VRB. These are indicated as X_0. The total BESS costs resulted in CAPEX. The OPEX is subtracted from the found income, resulting in CF_t. The income is assumed to be the same each year, and is based on the income from buying the missing energy. WACC or r, is based on the assumption that the investment may receive 80% loan funding of 5% interest rate, and 20% equity funding with 15% expected return on capital. This gives a weighted cost of capital of 7%. T is equal to the system's lifetime of 30 years.

12.2.2 LCOS

LCOS was calculated by using Equation 8.5.1 after finding the total amount of energy discharged per year. The discharged energy is found by multiplying the energy capacity with the operational days of the BESS. This value is then multiplied by $(1 - RTE)/2 + RTE$ to account for losses when discharging. It is assumed that the same amount of energy is discharged every year. The fuel, or the charging costs, is calculated by finding the cost of the energy bought when production from the hybrid plant was insufficient to fully charge the battery. The charging costs are thus different for different energy capacities.

12.2.3 IRR

When calculating IRR, the goal seek-function in Excel was used. It essentially finds the IRR-value by solving Equation 8.4.1. The NPV is set equal to zero, and C_t, C_0 and T are set to the same values as in the NPV-calculations.

Results

In this section the results from the production and the economical calculations obtained from Excel, MATLAB and Python will be presented. It is divided into the production results, income calculations and the economical assessment results.

13 Energy production

With the provided production data from Norsk Vind, the total energy production of the hybrid-system was found with Excel, as seen in Figure 13.1. The wind plants are the biggest contributors to the system, being responsible for 77% of the total production. The total production after 30 years results in 39.6 TWh from the entire plant.

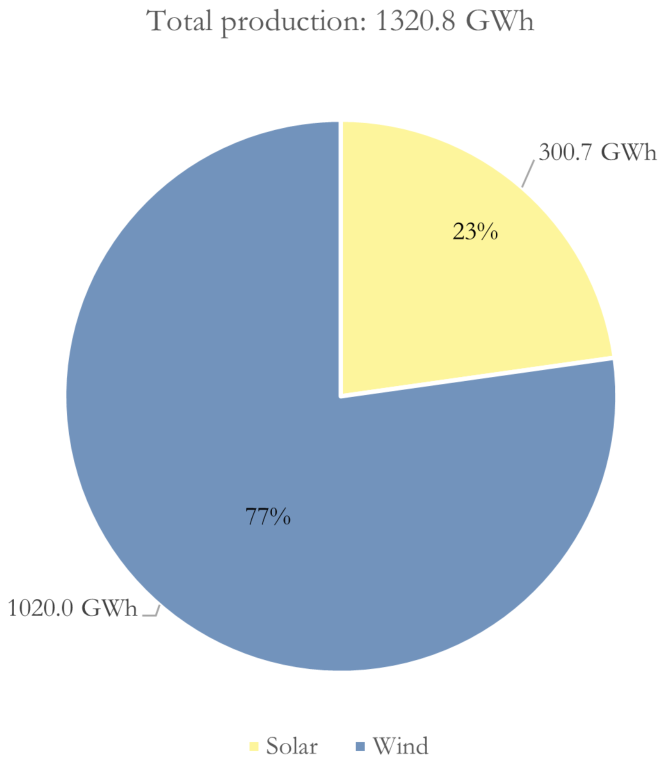


Figure 13.1: Annual production from the solar and wind plants, given in GWh and percentage.

Figure 13.2 shows the daily plant production for two selected months. It depicts the production difference in summer and winter months.

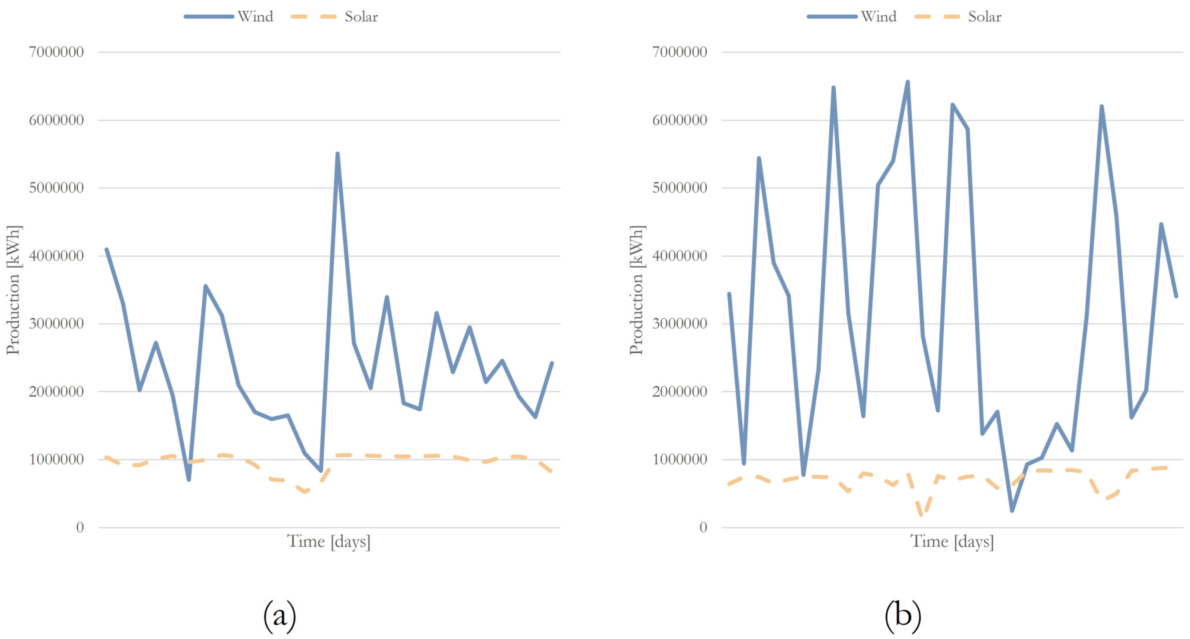


Figure 13.2: Daily energy production throughout the whole month from the hybrid plant in (a) Summer month 2021 and (b) Winter month 2021.

Figure 13.3 shows average hourly production for one day. Energy production for wind is prevalent from 00:00 to 06:00 and 12:00 to 00:00, while solar energy production is prevalent from 06:00 until 12:00.

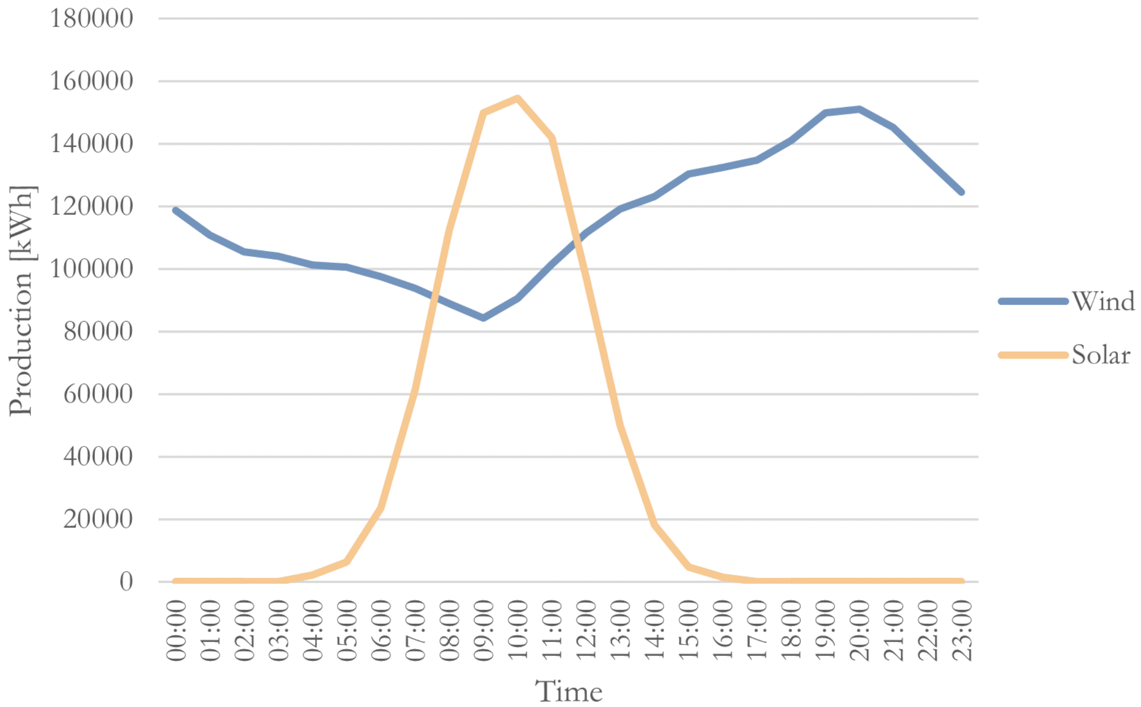


Figure 13.3: Hourly average energy production from the hybrid plant during one day.

Figure 13.4 illustrates the combined potential of the hybrid plant. With production being at its highest from 09:00 until 11:00.

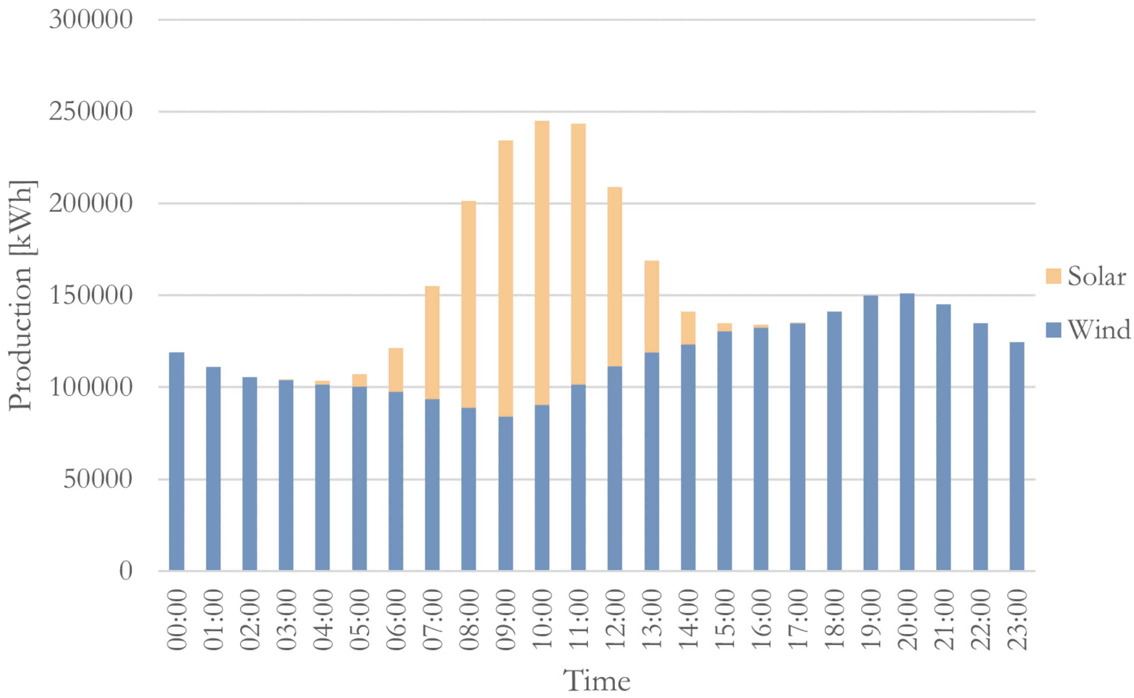


Figure 13.4: Combined hourly average energy production from the hybrid plant during one day.

14 Income calculations

These estimations and results are dependent on the TOU-tariffs which can be found in Appendix A and the Python code in Appendix E.1 and E.2.

14.1 Annual income from the hybrid plant

In Figure 14.1, the total annual income from the hybrid plant can be observed to be 76.7 MUSD. The income from the wind and solar reflects what was seen in Figure 13.1, as wind is the biggest contributor. The total income over 30 years is 2.30 billion USD.

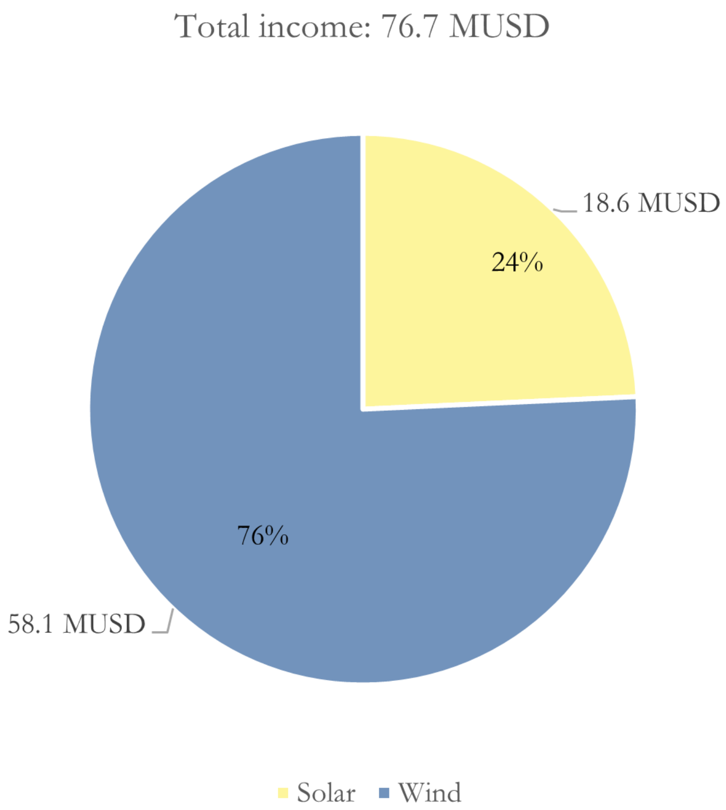


Figure 14.1: Annual income from the solar and wind plants, given in MUSD and %.

14.2 Annual income of the BESS

In Figure 14.2 one can observe the graphed income of a 100 MW LFP and VRB ESS for the two income scenarios. Income 1 is the scenario where just the production from the hybrid plant is used to charge the BESS. In the Income 2 scenario, energy is bought from the grid in the low-peak periods if the production from the hybrid is not sufficient enough to fully charge the BESS. As seen in the figure, the Income 2 scenario offers a higher income. The annual incomes found in Appendix F are based on the Income 2 variation.

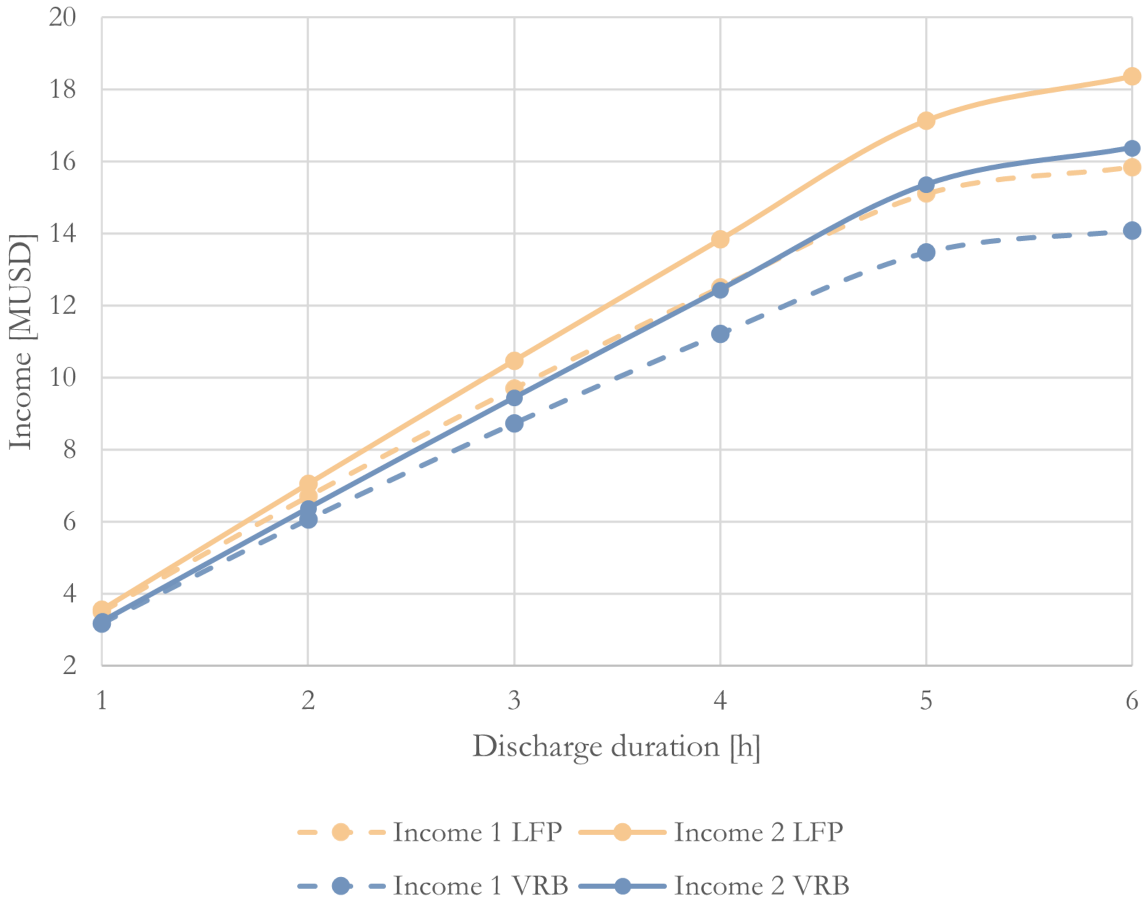


Figure 14.2: Different scenarios for the income for 100 MW LFP and VRB-systems.

14.2.1 Calculation check

The price difference average determined with the data from Appendix A was found to be 104.25 USD/MWh. For a 100 MW/1 hr (100 MWh) LFP-system, with a RTE of 87%, the income for the system was then calculated:

$$100\ MWh \cdot 93.5\% = 93.5\ MWh$$

$$93.5\ MWh \cdot 104.25\ USD/MWh = 9747.4\ USD$$

$$9747.4\ USD \cdot (365 - 53) = 3041181\ USD = \mathbf{3.04\ \ MUSD}$$

15 Economical assessment

In this section the results from the economical calculations will be presented. First there are results from optimisation, followed by results from profitable systems. LCOS-results are presented in the end. All the calculated values are shown in Appendix F.1 and F.2, and Appendix G.

15.1 Optimisation

Several graphs from the optimisation phase are presented below. These are mainly based on NPV-analysis with initial system sizes of 50, 100 and 200 MW ranging from 1-6 hr for LFP and 1-7 hr for VRB.

15.1.1 LFP

Net present values that formed the basis for the LFP-system optimisation are presented in Figure 15.1.

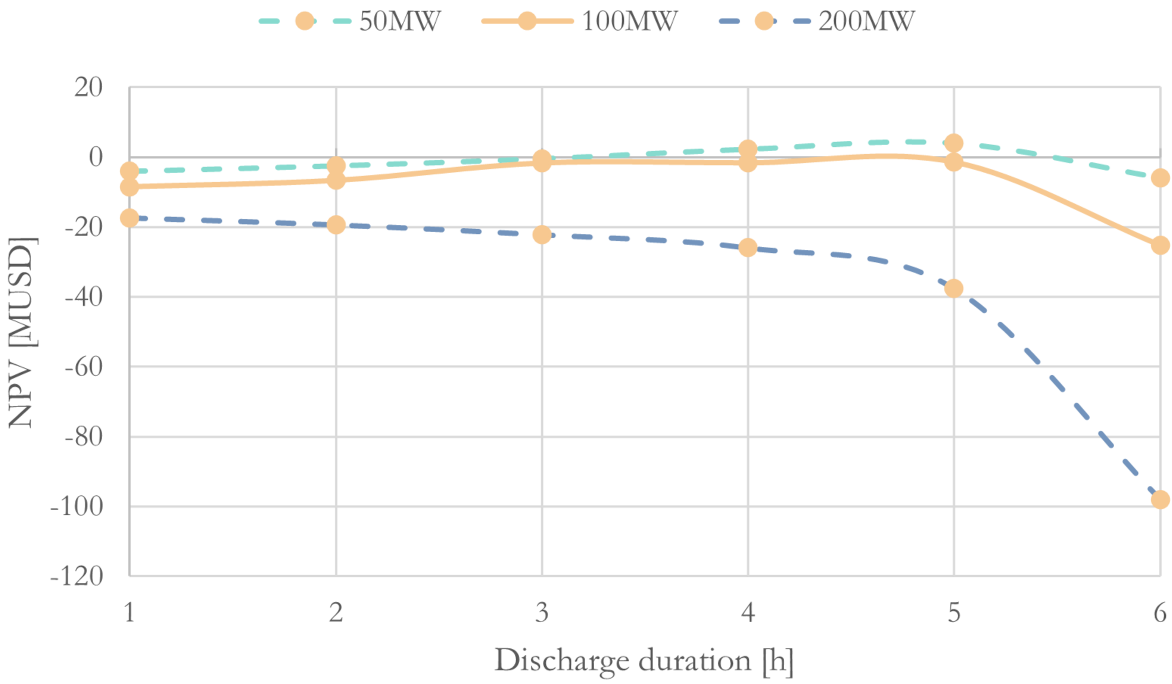


Figure 15.1: NPVs for three initial power capacities for LFP.

The three graphs are mostly below the x-axis, indicating negative NPVs. The 50 MW-curve is closest to the axis, hence more potentially profitable. The peak for both 50 MW and 100 MW is 5 hr, while 200 MW-curve is continuing to decrease with larger discharge durations.

The NPVs for the LFP-systems are presented in Figure 15.2, depending on discharge duration and power capacity. The green area represents the positive NPVs. A discharge duration of 5 hr is in most cases the duration that gives the highest NPVs. Therefore, an additional graph of NPV for 5 hr LFP-systems is given in Figure 15.3.

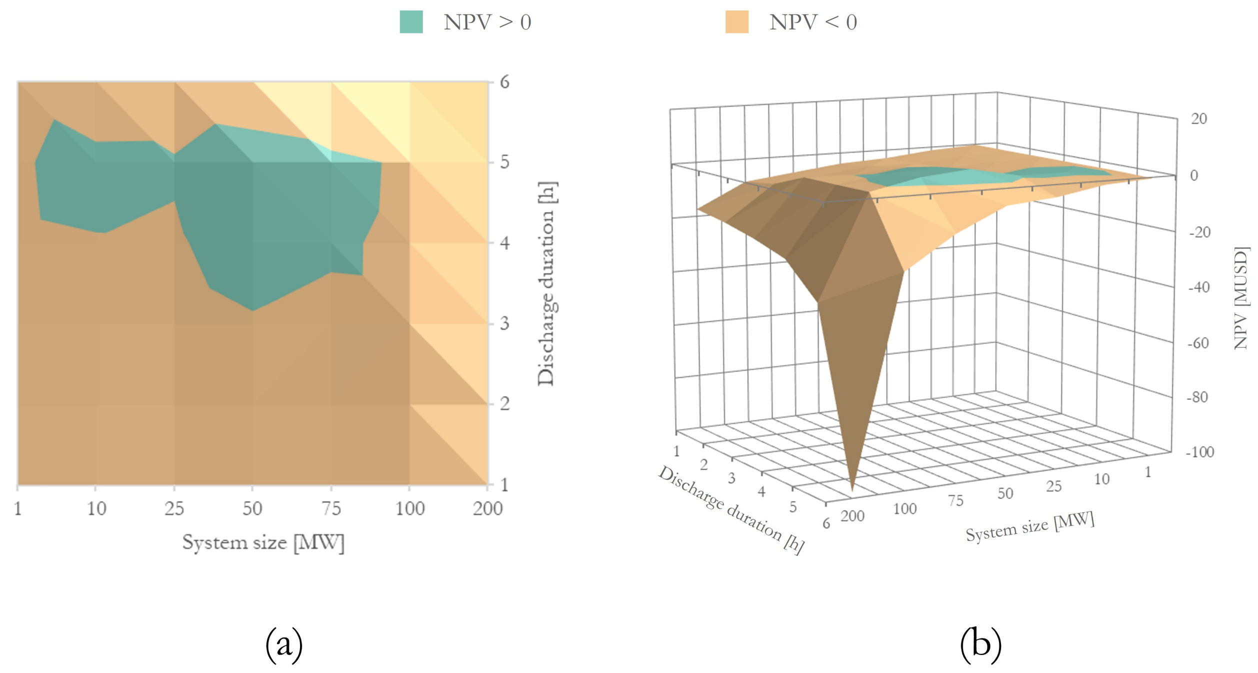


Figure 15.2: NPVs of LFP-systems where NPV>0 is profitable and NPV<0 is not. (a)Indicates all profitable and non profitable systems. (b)Indicates the range and the peaks of NPV for the analyzed systems.

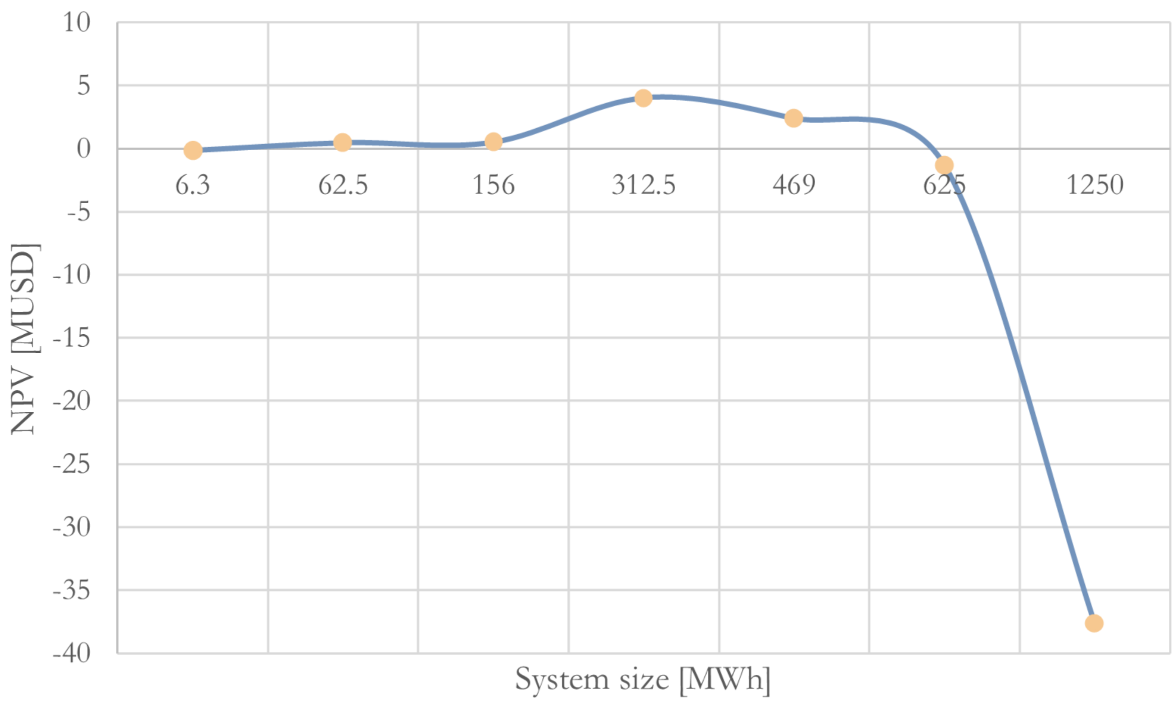


Figure 15.3: NPV for 1-200 MW 5 hr LFP-systems.

15.1.2 VRB

The net present values for the initial system sizes are seen in Figure 15.4. The least non profitable systems are the 1 hr discharge duration for 100 MW and 200 MW, and 5 hr for the 50 MW-system.

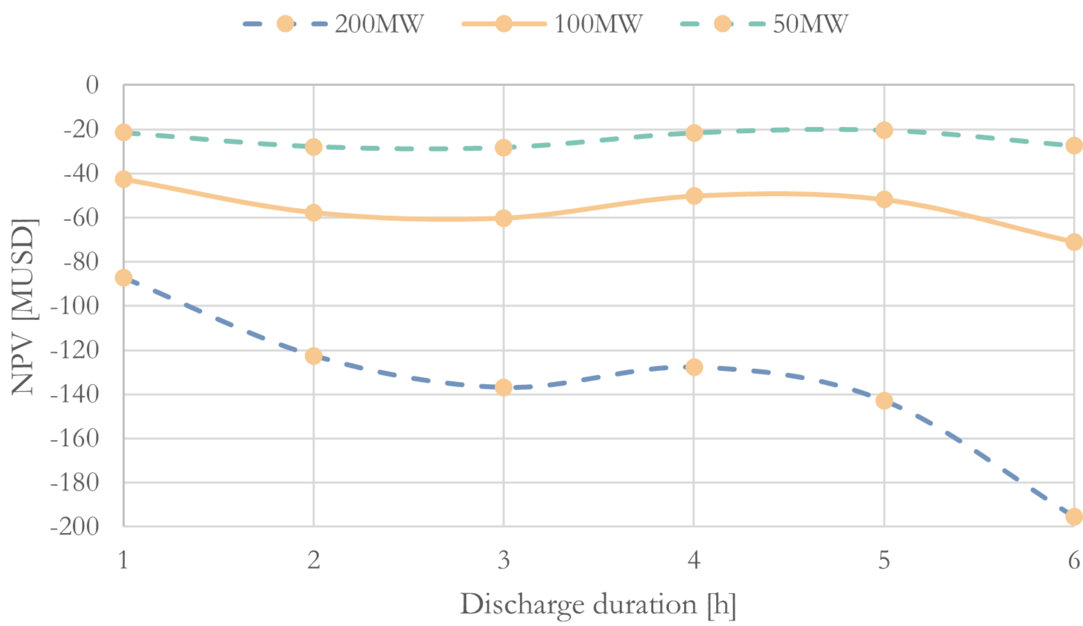


Figure 15.4: NPVs for the initial power capacities for VRB.

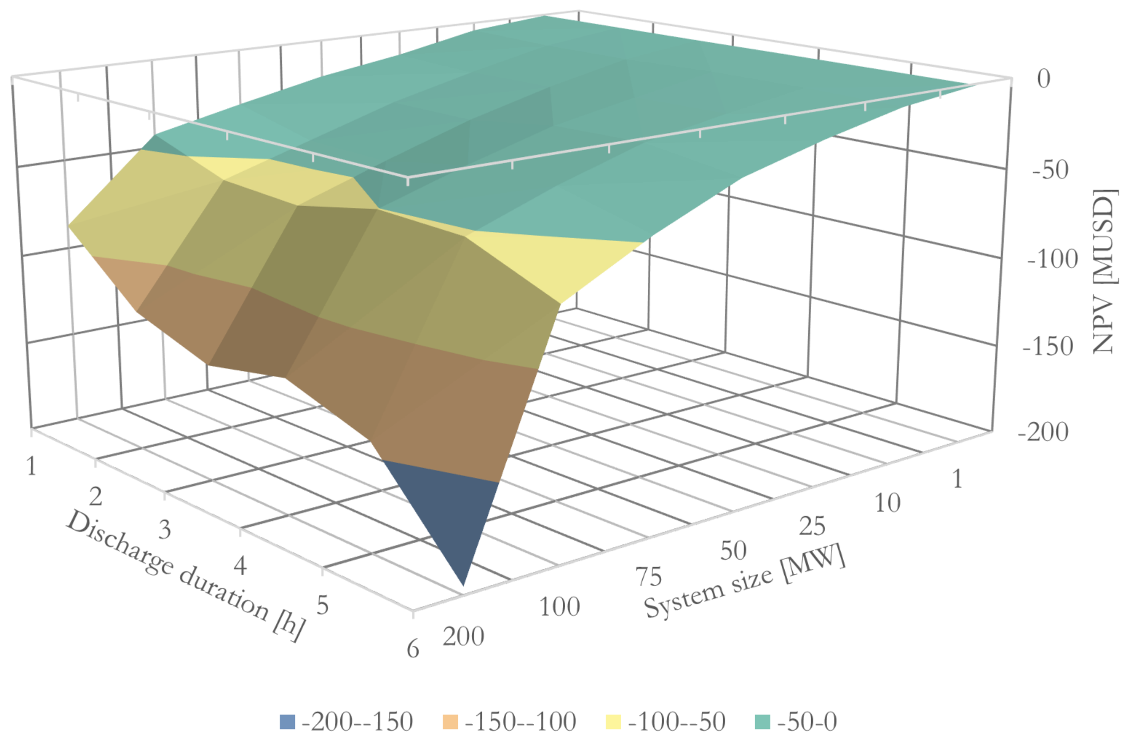


Figure 15.5: NPVs of VRB-systems. The different colours indicate how non profitable the systems are.

The NPVs for all of the tested VRB-systems are shown in Figure 15.5. The biggest 6 hr-systems have the lowest NPVs. The smaller systems are generally the least non profitable systems, although all of the VRB-systems have negative NPVs.

15.1.3 Profitable systems

Table 15.1 gives an overview of the profitable BESS, which were only LFP-systems. IRR was calculated for all the LFP-systems and is seen in Appendix F.1. The table below presents the IRR-values and LCOS-values for the systems with positive NPVs only.

Table 15.1: Profitable LFP-systems and their IRR and LCOS-values.

System size [MW/h]	***NPV [MUSD]***	***IRR [%]***	***LCOS [USD/MWh]***
10/5	0.46	7.50	202
25/5	0.49	7.21	203
50/4	2.31	7.65	198
50/5	4.02	7.92	195
75/4	1.06	7.20	200
75/5	2.40	7.37	198

Figure 15.6 shows the relationship between NPVs and IRR-values for all the profitable LFP-systems. The peak for both NPV and IRR appears at the same energy capacity of 312.5 MWh (50 MW/5 hr). Discrepancies between smaller and bigger system can be observed.

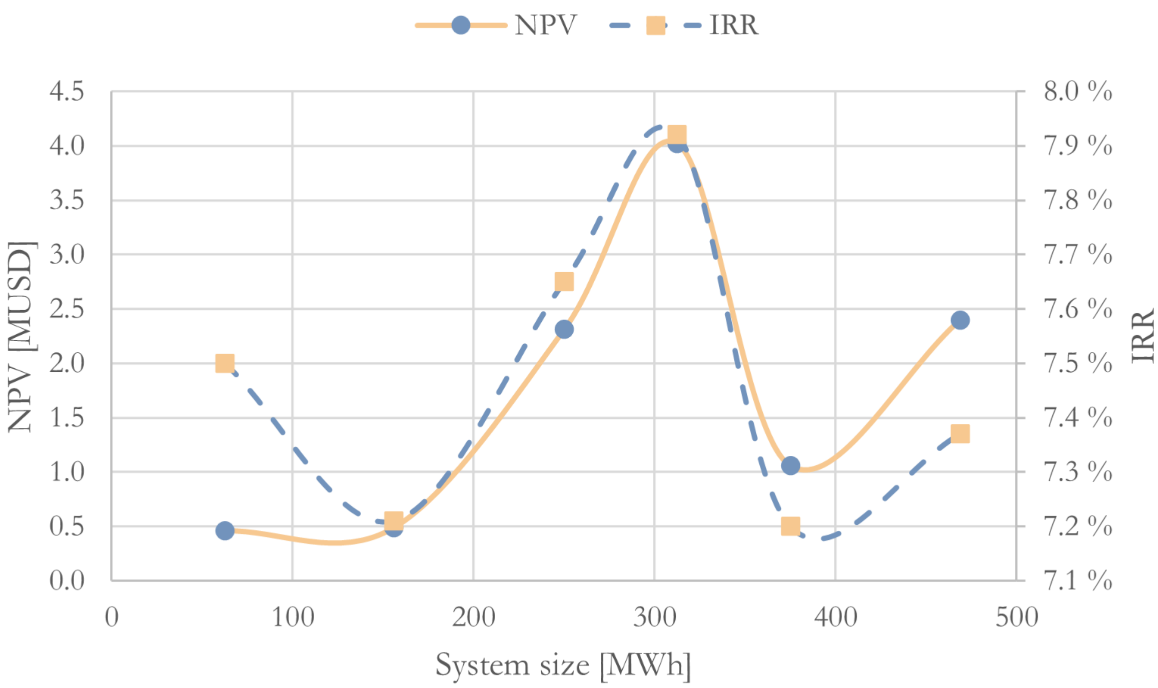
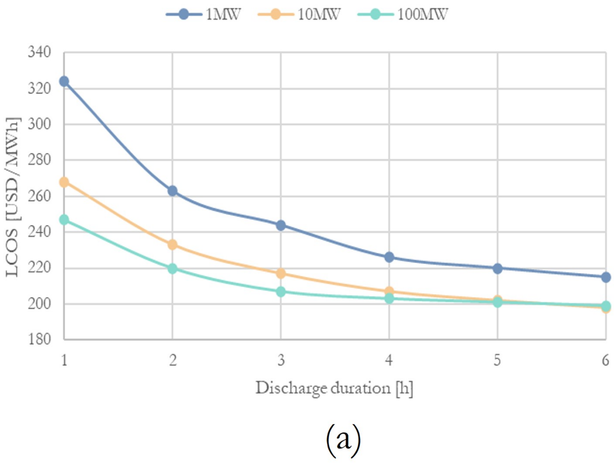


Figure 15.6: NPVs and IRR-values for profitable LFP-systems.

15.2 LCOS

As seen in Figure 15.7, the LCOS-values decrease as the system size increases. As the discharge duration increases, the LCOS-trend of the curve becomes more linear.



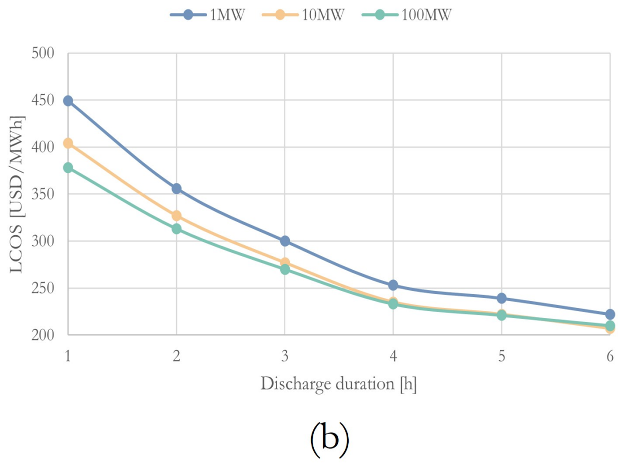


Figure 15.7: LCOS-trend for 1 MW, 10 MW and 100 MW where (a) is for LFP and (b) is for VRB

LCOS was calculated for the same system size so that the two battery types could be compared. The comparison of the systems is given in Figure 15.8.

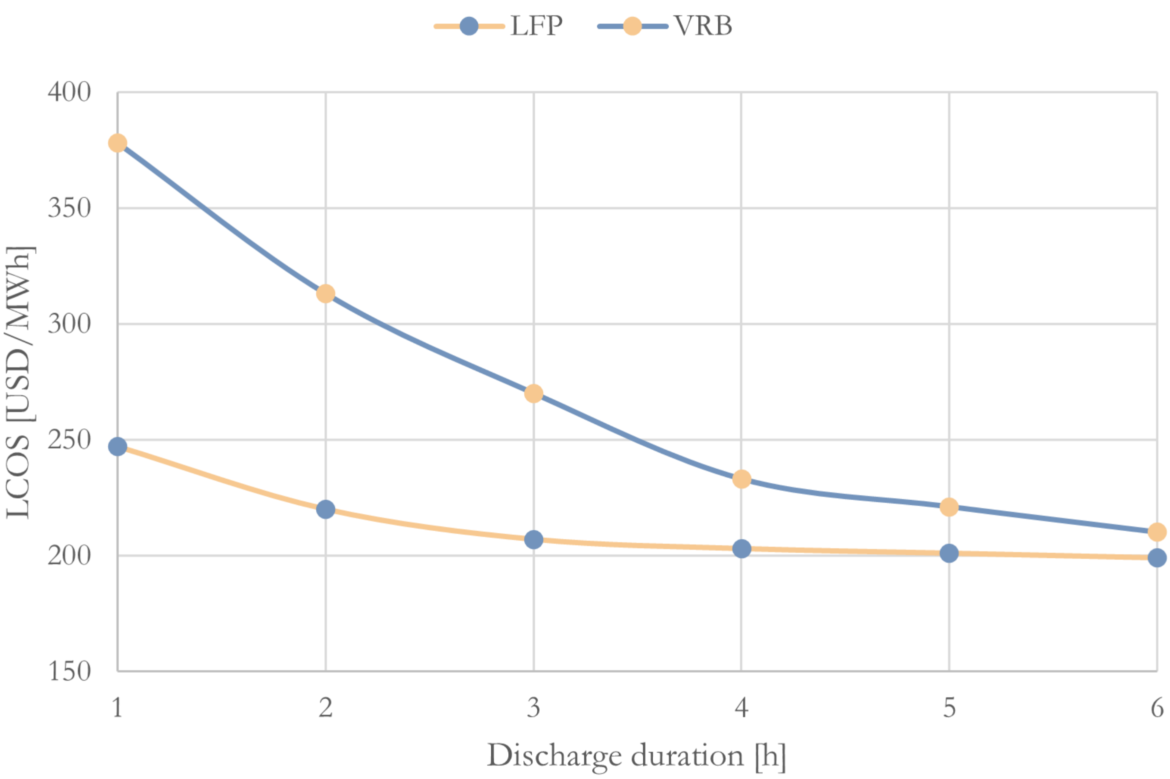


Figure 15.8: LCOS for 100 MW 1-6 hr LFP and VRB-systems.

Figure 15.9 illustrates the cost breakdown of the LCOS for the same system size of LFP and VRB. CAPEX constitutes for most of the LCOS-costs for both LFP and VRB.

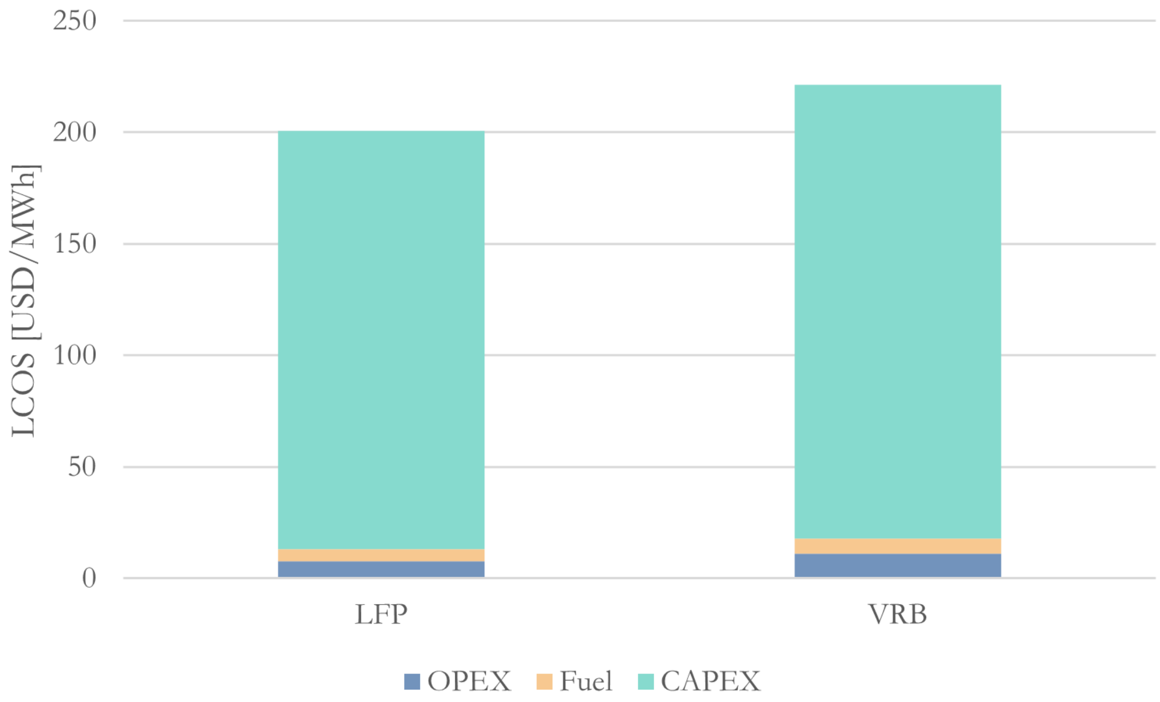


Figure 15.9: Cost breakdown comparison of LCOS for a 100 MW 5 hr-system in USD/MWh.

Discussion

In this section the results will be analyzed and discussed, as well as the feasibility of the project. A section with improvements is presented at the end. There is a possibility that some of the results have been misinterpreted.

16 The Republic of South Africa

The hybrid plant is located in the Northern Cape of South Africa and the specific location is seen in Figure 9.1. This location corresponds to areas with good wind and solar conditions as observed in the Figures 2.2a and 2.2b. Although, it can also be observed from these figures that there are better locations for the energy resources. Namely the northwest of the Northern Cape for solar, and north in the Eastern Cape for wind. The location is however more ideal for connection to the grid compared to other areas of the Northern Cape, because of the central position near highway N1. This can be seen in Figure 2.5, as there are several transmission lines in the southeastern parts of the Northern Cape.

The energy sector in South Africa relies heavily on coal, although with good conditions for wind and solar production, as seen in Figure 2.2a and 2.2b, the country should be able to implement more renewables. Renewables are gaining more traction and the technology is becoming cheaper and more accessible. In addition to the increase of fossil fuel prices, investments in renewable energy become more economically profitable, making it a viable option for energy production. Successful renewable projects will be vital for the future development of the South African energy sector. Furthermore, if renewable projects that utilise BESS are prosperous, renewables might become more attractive. Potentially it could contribute to renewable energy production replacing or reducing the need of energy production from coal.

Investments through REIPPPP make it possible to increase the renewable energy production in the country. Successful projects could bring more similar projects into the energy system. The REIPPPP is seen as a safe and secure programme, which lowers the risks of the investment. Some of the initial IPP-projects are finished and working, which also makes the risks appear lower. As seen in Figure 2.5, there are many REIPPPP-projects in the western part of South Africa. These are also the areas with larger quantities of wind and solar resources, as observed in Figure 2.2. Given that these resources are dependent on seasons, weather and time of the day, potential BESS installations could also be taken into consideration.

New projects could also lead to more new jobs, which could result in improving the high unemployment in the country. They may also lead to improving the national grid, as some areas in the Northern Cape province are underdeveloped in terms of large-scale grid infrastructure. As more power plants are built, the grid needs to be kept up-to-date to be able to deliver more energy. A lot of the existing power plants in South Africa are also poorly maintained. New, better functioning power plants have to be constructed and the older plants need to be replaced or refurbished in order to be able to increase the capacity.

With a young and growing population the need for energy will only increase. Renewable production sites will result in increased energy production which will help cover more of the energy demand, meaning load shedding and blackouts may be reduced. With the flexibility of energy storage, peak shaving could be done in certain time periods to avoid energy shortages. It is quite possible that a decrease in blackouts and load shedding could increase the general living standard of the South African people. Additionally increasing the energy production and improving the grid will also make it possible to electrify rural parts of the country. This could result in an increase in the amount of the population that has access to electricity.

17 Hybrid plant

A hybrid plant combines multiple energy production technologies under one. This leads to a hybrid plant being more versatile than energy production from a singular source. For this thesis, Norsk Vind has provided information surrounding a solar/wind plant project that is to be built. In a solar/wind power plant, one has two energy sources dependent on weather conditions and location. But when the production from the individual technologies could differ, one source could supply energy when the other is lacking, creating a more flexible and stable energy production.

17.1 Wind and solar contribution

From Figure 13.1 it becomes quite apparent that the wind production is the largest contributor to the system. The hybrid plant consists of two 140 MW wind plants and three 70 MW solar plants, thus the total power capacity of the wind plants is larger than the solar by 70 MW. Additionally wind turbines have a higher efficiency than solar panels, something that can also be seen in Table 9.1 and 9.2. Figure 13.3 displays another reason for the wind production being more prevalent during the day. On average, the wind production is the leading producer of energy during 18 hours of the day. While solar energy is dependent on the available sunlight and time of the day, with being the most prevalent during 06:00 to 12:00. Moreover, solar does not produce any energy on average during the night, while wind on average always has a production of at least 85 000 kWh. However, Figure 13.1 shows that solar is responsible for almost 1/4 of the total production, so it is still a large contributor, especially economically as its highest production starts around the same time high-peak prices occur according to Appendix A.

17.2 Dependability on conditions

The production is assumed to be constant every year for the entire lifetime of the plant, which is quite unlikely. The hybrid plant is based on wind and solar energy - two renewables that are heavily dependent on weather conditions. Therefore the actual production over the total lifetime would probably vary every year, but still be within predictable limits, thus still making the production viable. Production would also vary for the three solar and two wind plants, as their location and conditions would be different. So even if the production is an estimation, it can give an insight on how the plant would operate.

It is difficult to predict the weather to come for the next 30 years, but it is possible to assume that the weather will be mostly the same with some deviations. As seen in Figure 13.2, the weather varies throughout the year. In this case, one can observe that the wind production during summer is lower than the one during winter. This corresponds with theory as wind energy is more extensive during the winter.

Therefore a hybrid system should ideally be paired with an ESS, and in this case a BESS, to be able to store and supply energy when needed.

18 BESS

Battery energy storage systems are seen as a great solution for solving the issue of availability surrounding variable renewable energy sources such as wind and solar. These energy sources only produce energy when the right conditions are met, which is not necessarily when the energy is needed the most. The aim for the BESS is to be as economically profitable as possible, thus the BESS utilises storage arbitrage.

18.1 Storage arbitrage

The storage arbitrage used in this thesis is for storing energy in the low-peak price and discharging in the high-peak price. It was assumed to store from 22:00 the previous day until 06:00 the next day. These 8 hours are the low-peak price hours, thus the thought behind storing here is that the income will be higher from selling this energy in the high-peak periods.

From both Figure 13.3 and 13.4, one can see that it is the wind energy that would be stored in the battery, as the solar energy does not start to sufficiently contribute before the high-price occurs. This leads to the question of if the BESS should be charged for more than these 8 hours.

Figure 13.4 illustrates that the energy is at its highest after the early high-peak hours seen in Appendix A. Thus a lot of energy would be sold for just the standard price, when it possibly could be stored and sold later for the high-peak price around 17:00 to 19:00 in high-demand, and 18:00 to 20:00 in low-demand season. The income from the price difference between standard and high-peak price is of significant importance in the high-demand season, where it would be at a staggering 206.64 ZAR cents per kWh. By doing this, the charging costs in the additional hours also increase if the energy production is lacking. Although there still should be a sufficient price difference to sustain this.

In the subsequently income calculations the system is presumed to be able to charge the needed amount of energy during the 8 hour period when the low-peak price is available. This however may not be the case, and it could quite possibly be a longer period needed for charging. The battery could also take damage if it is charged too fast. Since there was no specific C-rate assumed, it is difficult to make sure that the battery will be able to charge/discharge quickly.

Discharging, on the other hand, should be correct. Discharging is related to the storage duration. Its definition is the amount of time the BESS can discharge at full power capability. This has been taken into consideration, as one for example has 500 MWh discharge for a 100 MW 5 hr system. The battery must also additionally consider the SoC-values of the technology.

18.2 Combined application and income

As mentioned in the literature review, a BESS can have a multi-purpose. Potentially, the system of interest can serve as both storage arbitrage, ancillary service, and possibly grid support and investment deferral.

Frequency regulation could have been a useful service, especially for power production from solar, wind and also coal, which is still important in South Africa. When the power supply fails to provide the needed capacity, a BESS can quickly response with the needed power demand. In this case, the hybrid power plant consists of several wind and solar plants. If one of them, for example, the solar plant of 70 MW fails, the BESS could substitute for the power loss instantly. This could be an additional source of income for the system, especially when providing for a large amount of energy.

With more areas of use, thus more services sold, the income could have been increased, in addition to the system size. However, the different application areas often require specific system configurations, as in capacity, discharge duration and cycle life which were mentioned in the literature review. For example, for frequency regulation discharge durations of less than an hour would have been required. In that case, that could be an issue for VRB-technology due to its poor power density. This is discussed more in the later sections. For investment deferral, smaller capacities and discharge durations of 1-4 hrs are needed. This application area could be suitable for the chosen BESS, based on the optimal discharge durations, which are discussed later.

If the requirements were to suit several application areas, the BESS could have been exploited as combined application, increasing the chances of profitability.

18.3 Battery

When choosing a battery for grid-scale energy storage, characteristics such as energy and power density, costs, lifetime and efficiency need to be taken into consideration. There are several advantages to all the batteries presented in Chapter 7. However, it was decided that the LIB and VRB were to be compared further through the economic assessment. LIBs have both a high energy density and power density, which make them applicable for any type of energy storage. They also have good cycle life and low self-discharge. Especially LFP has low costs and long cycle life. VRBs are easily scalable, have some of the longest life cycles and enhanced safety compared to other battery technologies.

In the two next sections the reasons for why each of these battery technologies were chosen, will be further discussed.

18.3.1 LFP

The lithium-ion battery has many outperforming qualities, such as energy density, cycle life, RTE and self-discharge, as seen in Table 7.2. It also has relatively low costs, and in addition to the good performance metrics, the LIB is therefore a widely used battery technology. This is also why the technology was selected for the analysis in this thesis, as low costs, good cycle life and efficiency, and low self-discharge are important factors when making investment in a storage arbitrage system. The battery's safety is however a drawback, which is also crucial for normal battery system operation. That is why a safer option was chosen as the second technology for the analysis. More on that in the section bellow.

There is a variety of Li-ion batteries, however LFP was chosen for the analysis. It is the safest technology among the LIBs, in addition to the low costs and good cycle life. LFP also has a lower energy density compared to other LIBs, meaning that it will affect the total weight of the energy storage. However that would be crucial for EVs or other portable applications, but has not much importance for stationary grid-scale storage. As shown in Table 7.1, LFP's only downsides are the lower energy and power densities, while such important properties as cycle life, safety and costs are highly outstanding. The future predictions make the technology attractive as well. This includes improving the cell performance and making it even more cost effective due to cheaper materials and other manufacturing processes.

Although LFP was chosen as the LIB for optimisation, both NMC and NCA are good choices as well with better energy and power densities compared to LFP. However, such parameters as cycle life and costs are worse, making the LFP a better economical choice especially for storage arbitrage.

18.3.2 VRB

Vanadium redox flow batteries have several advantages that are relevant for a BESS. They are highly scalable by just adjusting the size of the electrolyte tanks, making them suitable for large-scale grid-connected ESS. They have some technological features which make them one of the safest battery technologies. The electrolyte has a high heat capacity which means that it works well as a coolant, thus preventing thermal runaway. This stands in contrast to such technologies as LIBs, which usually have a highly flammable electrolyte.

Another advantage of the VRB is that it has high cycle life, implying that it can run for the entire lifetime of large-scale production systems. It can also be seen in Table 7.2 that it has higher cycle life compared to the other batteries.

Economically, the VRB must further decrease its current pricing to be able to compete with the LIB. The biggest downside with the VRB is that it has lower energy and power densities than the other technologies, seen in Table 7.2. Thus one would have to evaluate which features are the most important for a project. However, as research continues and interest for large-scale BESS increases, the VRB could become one of the leading battery technologies in the future.

19 Income calculations

The calculation of annual income is essential for the other parts of the economic assessment. But as the calculations of annual income revolved around working with large quantities of data in Excel, human errors could occur. One error could lead to a different end result, and since there is no certain solution, there is no true way to know if all of the calculations are correct. Anomalies or errors should be considered a possibility. Nevertheless, this will be the data which will be worked with and discussed, as the results are considered to be plausible with the help of the calculation check done in Chapter 14. The result for the generalised income calculation for 100 MW/1 hr, was 3.04 MUSD while for the same system seen in Appendix F.1 and Figure 14.2 was found to be 3.56 MUSD. Although there is a difference of 0.52 MUSD, it indicates that the calculations have been done somewhat correctly.

19.1 Annual income from the hybrid plant

The annual income from the hybrid plant alone can be seen in Figure 14.1, where the total income is 76.7 MUSD. This is again based on an estimated production so it will in reality vary every year. As observed in both Figure 13.1 and 13.4, the wind energy is the biggest contributor throughout the year. It is therefore also contributing to most of the income, as observed from Figure 14.1. The annual income from the BESS is seen as a potentially extra income gain to the system as a whole. The solar contribution is also slightly bigger in Figure 14.1 than in Figure 13.1. The reason for a larger income contribution from the solar might be the fact that the solar plants are producing the most energy when the peak hours occur. In addition to only producing in high-peak and standard hours, in contrast to wind which also produces during the low-peak period.

19.2 Annual income from the BESS

The annual income from the BESS is the basis for the economic calculations. This is the income one gets by charging and discharging the battery, either by utilising energy from production or by buying the missing energy.

The tariffs used in the income calculations were the existing rates as seen in in Appendix A. However, there are some updated ratios as well with a larger price difference than the existing ratio. If these updated ratios would have been used, the income would also most likely increase. Additionally, the assumed tariff is consumer tariff, meaning that some additional fees, such as grid rent and taxes, must be included. Hence the actual electricity prices can be lower, affecting the income by making it smaller.

It was reflected upon that if one would use the whole energy capacity of the BESS every day, it would result in a higher income. Figure 14.2 clearly depicts this, for both the VRB and LFP. In the Income 2-scenario, energy is bought in the case that the production from the hybrid plant was insufficient, which gives an extra income. One would buy energy from the cheaper low-peak price and sell for the high-peak price. As seen in Appendix A, this is especially influential in the high-demand season where the price differences are at their highest. It is less influential in the low-demand season, but it still increases income.

A storage duration of 5 hr was initially used in order to exploit the entire high-peak tariff during the weekdays, as seen in Appendix A. The following bigger storage durations would have to rely on the much lower standard price. Although it is still higher than the low-peak price, so it results in gains. The income clearly stagnates as seen in Figure 14.2. Subsequently, values would likely have a smaller positive slope from this point, as the increase would not be as big as it is for example in 4 to 5 hr. One could potentially test out more hours as there is a total amount of 16 hours during the weekday with a higher price-point than the low-peak.

Figure 14.2, Appendix F.1 and F.2 display the differences in income between the LFP and VRB. The calculations for both technologies were equal, and the only differences come from the SoC-values and RTE. The SoC-values affected the energy capacity as it was 10% for VRB and 20% for LFP. Thus for a 100 MW/5 hr system, which is supposed to supply 500 MW, one would need to have 555 MWh for the VRB, and 625 for the LFP. This would most likely result in more cases of LFP needing to buy extra energy to fill the storage capacity, in the case of insufficient production. Here VRB has an advantage. However, when looking at the RTEs the VRB falls short. VRB has a RTE of 70%, while it is 87% for LFP. Low RTE is something VRBs generally suffers from and is one of the main issues with the battery technology. LFP, on the other hand, is a LIB-type, which usually have high RTE as Table 7.2 also exhibit. The low RTE of the VRB results in a 15% loss that must be accounted for at charge/discharge, while the LFP only has a 6.5% loss. This is the overall reason for LFP having a higher income despite the lower SoC-value of the VRB.

In Appendix F and Figure 14.2, it is observed that the income and system size correlate, as the income increases when the size of the system increases. This is logical as with a bigger system there would be an increased amount of available energy for sale. However, a larger system also leads to higher costs, thus through NPV-calculations it could prove to be unprofitable.

19.2.1 RTE error

After all the calculations were done, it was discovered that the RTE that was used in the calculations of the income of LFP was wrong. The value should have been 88%, as it is shown in Figure B.1, but the one used ended up being 87%. This error, although small, is still contributing to higher losses than it should have been. As it now is a 6.5% loss by charge and discharge, it could have been 6.0%. After the mistake was discovered, it was decided to use 87% for every following calculations dependent on LFP's RTE to upkeep consistency.

20 Economic assessment

In this section the results from the economical calculations, such as NPV, IRR and LCOS will be discussed.

20.1 BESS cost estimates

It was assumed that the battery costs decrease linearly between different discharge durations. That is however a rough assumption, and the trend might be exponential which leads to uncertainties in the cost estimations. As seen in Appendix B, the price difference between the different hours varies, meaning that the slope is not the same, hence not linear. This is especially affecting the 1 hr cost estimates, as it was beyond the given range of 2-10 hr, leading to even bigger uncertainties. The functions of the actual price trends are likely different for different power capacities as well. In addition, the costs have a big range, as indicated in the Appendix B.

Extrapolation when scaling the system size assumed an exponential function, as shown in Appendix C, Figure C.1. The assumed intervals, which were mentioned in the Methodology-section, were likely rough cost estimations, especially for 50 MW-systems. As Figure C.1 shows, the price difference between 50 MW and 100 MW, which the 50 MW-price was based on, differs with approximately 5-10 USD/kWh. This might have affected the CAPEX and the OPEX, making the system cheaper than it actually might be. The same goes to 25 MW-systems which were based on 10 MW-costs. 75 MW-systems is however the most accurate estimation, considering the linearity of the trend graph in that area.

The BESS costs were assumed to be the same over the course of 30 years, which is highly unlikely. According to the literature review, the prices will fall during the years for both LFP and VRB. Cheaper BESS would lead to increased NPV, hence some systems could be profitable. More on that in later sections.

As there were many values to work with, some mistakes during calculations could possibly occur and affect the results. However, no unreasonable trends or inconvenient results were observed post calculations processing. The errors, if there are any, are thus expected to be minor.

However, there is a source of error concerning the reinvestments. When new systems are getting reinstalled in 10 years (for LFP) or 15 years (for VRB), there are only a few components that need to be replaced. These are mainly the battery modules, storage balance of system, and possibly power equipment, controls & communication, and system integration. That means that the installment costs will either be heavily reduced or not included at all, since the system has already been installed before and only needs component replacement. This has not been taken into account, assuming the same CAPEX in the reinvesting years as in the year 0, which affects the total investment costs and thus profitability of the systems. However, as parts of these costs were already reduced, based on the assumption that these have already been invested in due to an earlier installation of the hybrid plant, the total CAPEX would perhaps not have been affected much.

20.2 Optimisation

As the size of the BESS increases, the income increases as well, but so does the cost of investment. A high investment cost means there is a bigger risk with the project, and that a high income is needed to make a profit in the company. Therefore a high income does not equal to an economically optimal system. Optimisation of the BESS was hence based on NPV-analysis which is discussed below.

The same electricity prices are assumed for each year of the system's lifetime. A constant electricity tariff throughout the years is highly unlikely, making the costs uncertainty bigger. This affects income which affects both NPV and IRR.

Income has also been assumed constant for each year. In reality, the BESS will not be operational during the times where the components are being replaced (reinvestment). The duration of the re-installation is difficult to predict and thus make a reasonable assumption. However, it would clearly lead to less income.

CAPEX, OPEX and income increase with the system's energy capacity, as seen in Appendix F. This is credible as both BESS costs and electricity tariff are given in price per energy unit.

20.2.1 LFP

Figure 15.1 illustrates the three initial power capacities that the LFP-system was optimised with. The 100 MW-curve, which was the first capacity tested, has negative NPVs, but a peak at 5 hr. The 3-5 hr is approximately linear and flat with the largest values of NPV among all tested discharge durations, indicating potentially profitable systems. Therefore systems of 50 MW and 200 MW were tested as well.

Figure 15.1 shows that the 200 MW-systems have negative values only, and are even more unprofitable than 100 MW-systems. The highest value appears at 1 hr, followed by a slight slope between 2 hr and 5 hr. The values fall and become more negative with larger discharge durations. As 1 hr gives the highest NPV, 200 MW could potentially be more profitable with smaller hours. The values are however approximately 20 MUSD below 0, which means that the smaller discharge durations might not be enough to make the system profitable.

The 50 MW-systems have NPVs that are generally close to 0, and the graph has less of a slope compared to 100 MW and 200 MW. It also resulted in 2 profitable systems of 4 hr and 5 hr discharge durations, as expected from 100 MW-system testing. Further testing with smaller power capacities was done, which is illustrated in Figure 15.2b, with the peaks appearing around 4-5 hr. The curve flattens out towards lower power capacities with lower discharge durations. The optimisation continued with 5 hr discharge duration, as it resulted in the highest NPVs. In Figure 15.3, the NPV range of all the existing systems of that duration is shown. The positive values, hence the profitable ones, appear between 60 MWh and 600 MWh. These correspond to power capacities of 10-75 MW. The largest NPVs belong to systems of 50 MW and 75 MW.

The reason to why 5 hr-systems are the most optimal ones might be the relationship between the CAPEX and OPEX, and income from the stored energy. The costs are low enough in addition to the storage being able to store a large amount of energy, and result in large enough income for the system to become profitable.

Systems of the same energy capacity, but with different power capacities, and thus different discharge durations, have very different economical results. This is for example the case for 50 MW/1 hr-system and 10 MW/5 hr-system, which both have an energy capacity of 62.5 MWh. The systems also have the same income-parameter, but very different CAPEX and OPEX, as seen in Appendix F.1. The system of 50 MW has a negative NPV, while the 10 MW-system has positive NPV, hence it is profitable. This indicates that the larger the power capacities, the more negatively it affects the profitability, assuming the energy capacity and the income to be constant. That is reasonable, as when the power capacity increases, the cost parameters given in price per kW will also increase. The same principle applies for VRB.

20.2.2 VRB

The economical calculations done for VRB indicate that this battery technology is not profitable when used in the hybrid system. The main results for VRB are therefore based on the NPV-calculations, as further investigations were deemed as not necessary. The VRB has high costs which leads to a big OPEX and CAPEX. The battery also has a low RTE of 70%. Although the battery has a calendar life of 15 years, the other parameters lead to a smaller income and high costs. Additionally, the source of error for the reinvestment affects the NPV negatively. The reinvestments should be lower, which would affect CAPEX. However, the non profitability does vary with system size and will be further discussed.

When calculating the NPV, the 100 MW-system was tested first. The NPVs have a negative trend, but has one peak at 1 hr and a smaller peak at 4 hr duration, as seen in Figure 15.4. The graph for 100 MW showed irregularities, as there are several peaks. To make sure that the NPVs decline after 4-5 hr, 6-7 hr were also tested for 100 MW. The NPV from 6-7 hr sank from -71.3 to -95.3 MUSD, seen in Appendix F.2, confirming a decline. Other system sizes were tested, and they showed the same trend. The exception is that the peak NPV varies. The bigger the system is, the more the peak shifts to 1 hr. The 1 MW-system is an exception among the smaller systems, as the peak here is also at 1 hr.

A reason for the peak being at 1 hr for the big systems could be that the BESS is not profitable, and therefore no BESS would be the best option. As the system size approaches zero, the NPV does the same. This can also be seen in Figure 15.5. Bigger systems lead to bigger negative NPVs. As mentioned before, the pricing for the 1 hr systems is also not accurate because of the assumed linear cost trend. This causes the price to be lower than it would be in reality, which contributes to the peaks being higher.

For the smaller systems of 10, 25 and 50 MW, the NPV peak was at 4 hr or 5 hr discharge duration. As seen in the NPV formula, Equation 8.3.1, the net cash flow and investment is what differs between the systems. In order for there to be a peak, the relationship between the income and costs need to be smaller compared to other system sizes. As the discharge duration increases, the income also increases. CAPEX and OPEX increase as well, but factors like lower battery costs per kWh or kW and an increase in only the energy capacity, lead to a peak.

For 1 MW the peak is at 1 hr instead of 4 hr/5 hr, and the NPV-curve becomes more linear compared to bigger power capacities, as seen in Figure 15.4. The reason may be the costs for 1 hr-systems, as they should be higher. This causes the net cash flow to be lower, so that the NPV-peak appears at 1 hr.

20.3 Profitable systems

Table 15.1 shows all the profitable systems which resulted in being LFP-systems only. The one with the largest NPV is 50 MW/5 hr, 312.5 MWh-system. It also has the largest IRR and lowest LCOS. The second best NPV is of a 75 MW/4 hr-system with the same LCOS.

All the profitable systems have IRR-values above the assumed WACC of 7%. That means that the projects can have a higher discount rate and still have all the initial investments returned fully. All non-profitable systems, as seen in Appendix F have IRR-values lower than 7%. A trend that occurs is shown in Figure 15.6, where IRR indicates a higher value, compared to the corresponding NPV. For example the second best system is 75 MW/4 hr according to its NPV, but the second best IRR-value belongs to a 50 MW/4 hr-system. This means that the latter system is able to return its initial investment faster, but results in a lower net present value. For 50 MW/4 hr-system and 75 MW/5 hr-system the NPVs are almost the same, but their IRR-values differ a lot, where once again a smaller system has a higher IRR. The reason for that can be that the smaller system is cheaper, hence a higher rate means more stability, whereas the more expensive system has more uncertainties associated with it.

The smallest systems of 10 MW/5 hr and 25 MW/5 hr are the least profitable with the lowest NPVs, shown in Table 15.1. The net present values are also very close to each other, by being 0.46 and 0.49 MUSD for 10 MW and 25 MW respectively. While 25 MW-system clearly has a slightly larger NPV, the 10 MW-system has a higher IRR-value, in addition to having a lower LCOS-value. Based on these, and the fact that the NPV is approximately the same, a 10 MW/5 hr-system would be a better solution than a 25 MW/5 hr-system. Both systems are also based on 10 MW-costs, making the 25 MW-system more uncertain.

NPV and IRR are both methods of evaluating a project's profitability. In this case, they both indicate that the 50 MW/5 hr-system is the most viable one. However, due to cost estimates uncertainties that were mentioned in a few sections above, the 50 MW-systems might actually be more expensive than estimated, affecting the profitability. The net present values for 75 MW-systems are more credible, as the cost estimates are closer in values to a 100 MW-system which there is given a certain price for (Figure B.1). Since other 5 hr-systems with smaller power capacities also result in positive NPVs (although with the same estimation uncertainties), the 50 MW-systems might still be profitable, although perhaps not the most profitable.

Several factors have affected the systems that resulted with negative net present values. In order to make them profitable, either the investment had to be much smaller, or the income had to be larger. For many of the systems, the income had to increase with a few millions in order for NPV to become zero. CAPEX and OPEX would also have to decrease, although they will likely decrease with the years. WACC, which in this case is equal to IRR, should be larger than the assumed value of 7%, as the results indicate. Larger IRR means more risks associated with the investment, as mentioned before.

LCOS-values given in Table 15.1 have a range of 195-203 USD/MWh, which is small, meaning that the cost of stored energy is approximately the same for all the profitable systems. However, this parameter is rather used when comparing two different technologies, in this case LFP and VRB. Therefore, a more detailed discussion of LCOS is given in the next section.

20.4 LCOS

The LCOS-formula that was used for the calculations, given in Equation 8.5.1, is a modified version, combined from different formulas from different sources. The reason for that choice was that some sources suggested to discount CAPEX, i.e. sum CAPEX, OPEX and Fuel, and multiply by $(1 + r)^{-t}$. The starting year in the formula is t=1. Since the first investment occurs in year 0, it would get excluded according to the formula. Therefore it was decided to combine the given formulas into a modified one, where the total CAPEX was only summed and not discounted. This essentially leads to a larger CAPEX compared to if it was discounted, affecting the LCOS-value in the end. With a smaller (discounted) CAPEX, the LCOS-value should be smaller, according to the formula.

Although, it is difficult to argue for the reliability of the computed LCOS-values. Proper research has not been done, making it difficult to decide if the values are within the ordinary LCOS-range. Because of the uncertainties around CAPEX, these could also result in much lower values. However, since LCOS is mainly used for comparing different technologies, the obtained results are still usable for making that comparison.

The general trend for both LFP and VRB-systems is approximately the same, as seen in Figure 15.7. LCOS-values vary more in comparison to power capacity for the smaller discharge durations, than for the larger durations where the curve flattens out. The gap between 10 MW and 100 MW-systems is especially small. The reason why the gap between 1 MW-systems and the rest is so much larger, might be due to the big difference between the actual system costs, which are shown in Appendix B. As mentioned before, the cost trend is exponential, and it makes sense for the smaller systems to differ more in comparison to the bigger systems. The principle applies for both increase in power capacity and discharge duration, i.e. the energy capacity.

That leads to the LCOS-value resulting in a larger range for smaller systems than for the bigger systems. For example, in Figure 15.7a, LCOS varies between approximately 250 USD/MWh and 320 USD/MWh for 1 hr-systems, resulting in a difference of 70 USD/MWh. For a system of 6 hr, the variation is approximately 20 USD/MWh, in addition to 10 MW and 100 MW being ca. of the same LCOS. The reason for that might be the relationship between the costs and the discharged energy, as Equation 8.5.1 indicates. For a 10 MW-system the costs will be larger and the discharged energy smaller, while it is the opposite for a 100MW-system. Hence the LCOS will result in approximately the same values.

Figure 15.8 shows that the LCOS-value declines and flattens out as the system size increases. This is caused by the trends of the curves of CAPEX, OPEX, fuel and discharged energy. The relationship between the costs and discharged energy stays almost the same as the system size increases. LFP has a lower LCOS, as the LFP-costs are lower than the VRB-costs. LFP also has a higher RTE, resulting in smaller losses compared to VRB, affecting the discharged energy. As seen from Equation 8.5.1, the LCOS output becomes smaller. It is also seen from the figure that the LCOS-values for LFP appear to have a smoother decline compared to VRB. This could be caused by VRB's high costs and differences between the costs for different systems. Because of the high values the source of error is bigger when the costs are assumed to be linear. The LFP-graph covers a smaller range of LCOS as well, making it appear more exponential. LCOS for VRB also has a bigger decline, which is due to bigger differences in CAPEX between each system size. Figure 15.9 indicates that CAPEX makes out the majority of the costs, and has the biggest say in LCOS.

It can also be seen from Figure 15.8 that there is a smaller difference between LCOS for LFP and VRB for the bigger systems. As already discussed for Figure 15.7, the relationship between costs and discharged energy for the two battery technologies is approximately the same when discharge duration increases. The same explanation can be applied here, as the VRB system is more expensive, in addition to having a lower RTE and thus less discharged energy.

The LCOS-values are generally high. One contributor is SoC, as it affects the discharged energy. As the stored energy always needs to be at a certain level, all of the energy cannot be discharged. From Equation 8.5.1, it is seen that as the value for discharged energy is lower, the output is higher. This also means that SoC equals to economical loss, as from this perspective, SoC is the energy that is never used. However, SoC is important for prolonging the battery life, especially for LFP. In that sense, the economical profit of SoC is in making the battery lasting longer, hence providing more income.

21 Battery comparison

As the results show, LFP outperforms VRB in most categories. It proved to be a cheaper technology according to the net present values and LCOS-values, which are mainly affected by the larger income and lower investment costs. The main benefits of VRB-technology is its enhanced safety and good cycle life, which LFP lacks of. However, for this specific BESS installation, which is essentially storage arbitrage, it is more beneficial with low installation costs, high RTE and either good power density or energy density. The two latter parameters are important when choosing the system size. If the storage system needs to charge/discharge rapidly, a good power density is needed. If it needs to store a large amount of energy, then it is important with a high energy density. VRB lacks of both of these metrics compared to LFP, as shown in Table 7.2. That means that if VRB was to be tested for smaller discharge durations, it might be unable to charge/discharge as rapidly as LFP. Additionally, if the energy capacity would increase even more, VRB would not be an ideal choice due to its lower energy density. Other aspects of the batteries were compared along the way in the previous sections.

22 Improvements

Because of the time frame of the bachelor thesis and assumptions made, the results may be less accurate. Following are some improvements that could have been made to further better the optimisation.

22.1 Other battery technologies

As the time frame for the thesis limited further analysis, only two battery technologies were compared. The other mentioned battery technologies could be feasible options, but these were not further investigated through calculations.

The lead-acid battery was looked into, but has a low energy density compared to the LIB and NaS-battery, as seen in Table 7.2. Cycle life and DoD is also lower than for the other batteries. Even though the battery has a lower installation cost, the performance metrics would most likely not make it profitable. The valve-regulated LABs have good safety and better performance, but is also more expensive than the flooded type. Because of the performance this battery technology was not investigated further.

Another option was the sodium-sulfur battery, which has a high energy density and cycle life. However, it also has a high self-discharge. Although it is suitable for large-scale energy storage, it could have more safety hazards compared to the other batteries because of the highly reactive sodium.

The SSB was not looked further into because of the lack of specific data on the battery, and it is currently more centered around EVs than BESS. However, because of the beneficial properties of the SE, it is considered a safer version of the LIB. Additionally, some SEs have the potential to improve energy density as well. The SSB could prove itself to be a contender for a great BESS in the future, but as it stands, its technology needs to be further developed.

22.2 Testing for hours beyond

Theoretically and realistically it is possible to discharge for 16 hours with gains in income. As seen in Appendix A, there are several hours where the standard pricing is present in the weekdays. This pricing is higher than the low-peak price and thus there are possibilities for economical gains by discharging in these hours as well. However this would also increase costs related to the increased energy capacity, and with a potential increase in both CAPEX and OPEX, it could affect the NPV negatively. Another important point is that one would be dependent on battery's ability to charge the increased capacity within the eight low-peak hours of the weekday.

It could possibly result in more profitable systems if smaller ($< 1\ hr$) discharge durations were tested as well, as the energy capacity, and thus also the costs would decrease. NPV-results indicate a potential increase in values for $< 1\ hr$ for both LFP and VRB-systems. However, as discussed earlier, a poor power density for VRB might be an issue.

22.3 Storing energy from standard hours

There is also the possibility of storing energy from the standard hours. As the price difference between high-peak and standard still should result in income gains, even if one would have to buy extra energy in the standard hours. This opens up for new possibilities with five hour systems with larger power capacities, which might become more relevant. However there still would be the questions of costs, which would increase with the increased size.

22.4 Metrics to consider

Some metrics were not taken into account in the calculations, but they may still be of importance and lead to a different end result. Below are some of the parameters that could be considered for a more realistic approach.

Self-discharge was not taken into account when doing the income calculations. The self-discharge is a daily discharge of the battery, thus affecting the energy capacity on a daily basis. The self-discharge depends on the battery type, as observed in Table 7.2. For the two battery types analyzed in this thesis, one could expect a self-discharge value of 0.09-0.36%/day for the LFP and 0.00-1.00% for the VRB. Although these are small percentages, the self-discharge is prevalent throughout the day which leads to less possible energy sold, and should be taken into account for a more precise and realistic calculation.

In both tables in Appendix B, a downtime of 5% is assumed. This indicates that during the lifetime of the BESS, there are various periods where it is not operational. If taken into consideration, this would affect the income negatively. A downtime of 5% may be assumed due to unexpected errors in the system or maintenance throughout the year. 5% would equal to 18 days of downtime each year.

Cycle life has not been accounted for when working with the lifetime of the batteries. With the battery running for every day except Sundays, it would equal to 3120 cycles over 10 years for LFP and 4680 cycles over 15 years for the VRB. In Appendix B the cycle life of LFP is 2100 and for VRB it is 5201. This could indicate that the LFP system running in this thesis would last less than 10 years. The VRB system in this thesis would potentially run for more years than 15, as it is less than the given value. This would affect the reinvestment in NPV calculations.

The duration corresponding to cycle life is another metric that has not been taken into consideration. It is calculated by dividing cycle life by number of cycles per year, where downtime is accounted for. As seen in Appendix B, it is 6.06 years for LFP and 15 years for VRB. LFP has a calendar life of 10 years, while for VRB it is 15 years. This indicates that VRB requires less maintenance, as the electrolyte essentially does not degrade and the membrane can last for 10 years. LFP has a lower duration corresponding to cycle life compared to calendar life, so 10 years may not be a realistic calendar life. A lower calendar life would affect the LFP-calculations negatively.

With a defined C-rate it would be easier to work around the charging principle of the battery. As with a known C-rate, one could be certain for how long the battery would need to charge, thus creating a better analysis.

22.5 BESS cost estimates

The cost estimates, which resulted in CAPEX and OPEX, are the base of all the NPV, IRR and LCOS-calculations. Therefore, changing these parameters would affect the outcome greatly. There are some sources of error concerning CAPEX and OPEX, which were mentioned previously, that could have been eliminated. Since the reinvestments were constant during the entire lifetime of the system, some of the costs should have been taken out or reduced even more. That would lead to a smaller total CAPEX, increasing the chances of profitability. It would also affect LCOS by decreasing the value, hence making it cheaper to store the energy.

Another step that could have improved the profit is extrapolating of the costs during the years. The same costs of 2030 were used for the course of 30 years, stretching to approximately 2050-2060. By that time, the battery prices should decrease, as mentioned in the literature review. 2020-costs are also given from the same source [89], and could be used with the 2030-estimation to extrapolate for the later years. This would again lead to lower costs, thus increasing profitability of some systems. That could especially have a bigger impact on VRB-systems as none of them resulted in being profitable. However, as the income from VRB was still quite small, it is difficult to determine if decreasing the investments would be enough for NPV to become larger than zero. The extrapolation was not performed due to the time limits.

Extrapolation could also be performed for discharge durations, as it was assumed to have a linear trend. It would also be beneficial for scaling the power capacities, where extrapolation was actually performed for one system (Appendix C). Because the time of the thesis was limited, and extrapolation of the given large amount of different systems would take much time, it was not actually used. It was rather used as a base where linear behavior could be assumed. With that said, extrapolation would be a better and more accurate method for costs estimations.

In Appendix B, there is given a disclaimer that the costs do not include warranty, insurance, or decommissioning costs. These extra costs are important to consider in CAPEX. Larger costs would lead to less profitability of the systems.

Additionally one could look into different sources for the cost estimates to the corresponding technologies. Different sources could provide different foundations for the calculations.

22.6 Economical parameters

Such economical parameter as WACC is important when calculating NPV and LCOS. The value is generally low. In reality, WACC is heavily dependent on the company and the investment location. Better research of a proper WACC-value would have led to more accurate results. A lower value would result in a higher NPV and lower LCOS, while a higher WACC would result in the opposite. A lower WACC is therefore preferable. It can be achieved with more loans or cheaper loans. The risk of the project must then reduce by securing stability. This can be using a well-known technology, solid suppliers etc. In addition, if the project was a part of REIPPPP-program, which is claimed to be reliable and thus of lower investment risks, the WACC-value could have been assumed to be low.

22.7 Assuming variable parameters

As mentioned in the Methods section, many parameters were assumed constant for each year of the lifetime. Assuming a decrease/increase in electricity tariff would make the case more realistic, as the prices depend on various factors and thus will likely vary from time to time. Inflation should therefore be an important factor to consider, also in CAPEX and OPEX. That could possibly lead to more profitable systems, which could also be larger. The assumed electricity tariff, which is a consumer tariff, should also be substituted with an electricity price only. It would also make the results more accurate if the production and hence the income would vary each year. In addition, several economical parameters can be assumed to be non-constant, as discussed previously.

An important influential factor to the income calculations is the rate of currency. As here the rate of 1 ZAR = 0.069 USD, has been used for every day of the year. Currency rates fluctuate day to day due to socioeconomic changes. Looking at previous rates and assuming an average rate would have been a better approach.

22.8 Simulation software

To avoid sources of error in the calculations and make the optimisation more accurate, simulation software designed for BESS analysis could have been used. Software was not considered or researched, but with more time than given for this thesis, such a tool could have been explored and utilised for a more professional approach.

Conclusions

This thesis explored the possibility of designing a BESS for a hybrid power plant in South Africa. An economic evaluation was done in order to determine whether adding a BESS would be profitable or not. The LFP- and VRB-technologies were compared to find the most optimal battery option.

The income of the systems was based on large data series which could easily lead to errors. Although, it is presumed that the calculations that were done are plausible enough. Utilising a BESS increased the income of the hybrid plant and could be further improved by either increasing the storage duration or extend the hours of charging, however this could also lead to additional losses and costs, depending on the battery technology. Several other metrics such as self-discharge, downtime and cycle life should be taken into consideration for further work.

Optimisation showed that adding a BESS is economically feasible, and it resulted in six profitable systems. A 50 MW/5hr LFP-system (312.5 MWh) is the most profitable and viable choice for a storage arbitrage system for a hybrid plant in South Africa. It had both highest net present value of 4.02 MUSD and IRR-value of 7.92%, in addition to the lowest LCOS-value of 195 USD/MWh. VRB-systems, which were also tested, were not profitable at all. VRB-technologies are however not a bad technology, just not a viable choice for this specific case. Considering the source of errors, LFP-systems of 75 MW (4hr and 5hr discharge durations) could be a better choice, but there are uncertainties attached to it as well. In general, the results showed that LFP-systems of 4-5 hr discharge durations and corresponding 10-75 MW power capacities are profitable energy storage systems.

Such estimation methods as extrapolation could have been used, which would lead to lower investments and more realistic results, which could possibly result in more systems with positive NPVs. Other economical factors such as WACC, inflation and electricity tariff should have been reevaluated as well.

23 Future work

To conclude the previously discussed improvements, the following points should be taken into account to delve further into the subject.

Perform tests for additional battery technologies, such as the aforementioned technologies of lead-acid, sodium-sulfur and solid-state batteries. Look into different sources for the data of the battery technologies.

Test for larger discharge duration ranges, especially for durations of less than 1 hr. Consider storing energy from the standard hours as well for larger power capacities of 5 hr discharge duration. Consider several application areas for the battery system for potential increased profitability.

Consider relevant metrics like self-discharge, downtime, cycle life and C-rate for more accurate income estimations.

Perform extrapolation of the cost estimates for future prices and for the discharge durations. Include such factors as warranty, insurance and decommissioning costs as well.

Assume more accurate economical parameters, such as WACC. Include variable electricity tariff, energy production and income during the system's lifetime. Take into account inflation, another electricity tariff and assume an average for the currency rate to have a more realistic approach.

Research and use simulation software designed for BESS analysis.

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Appendices

A Eskom, TOU tariffs

Source [40]

Existing TOU time periods

	High			Low		
	Weekday	Saturday	Sunday	Weekday	Saturday	Sunday
0	3	3	3	3	3	3
1	3	3	3	3	3	3
2	3	3	3	3	3	3
3	3	3	3	3	3	3
4	3	3	3	3	3	3
5	3	3	3	3	3	3
6	1	3	3	2	3	3
7	1	2	3	1	2	3
8	1	2	3	1	2	3
9	2	2	3	1	2	3
10	2	2	3	2	2	3
11	2	2	3	2	2	3
12	2	3	3	2	3	3
13	2	3	3	2	3	3
14	2	3	3	2	3	3
15	2	3	3	2	3	3
16	2	3	3	2	3	3
17	1	3	3	2	3	3
18	1	2	3	1	2	3
19	2	2	3	1	2	3
20	2	3	3	2	3	3
21	2	3	3	2	3	3
22	3	3	3	3	3	3
23	3	3	3	3	3	3

Proposed new TOU time periods

	High			Low		
	Weekday	Saturday	Sunday	Weekday	Saturday	Sunday
0	3	3	3	3	3	3
1	3	3	3	3	3	3
2	3	3	3	3	3	3
3	3	3	3	3	3	3
4	3	3	3	3	3	3
5	3	3	3	3	3	3
6	1	3	3	2	3	3
7	1	2	3	1	2	3
8	2	2	3	1	2	3
9	2	2	3	2	2	3
10	2	2	3	2	2	3
11	2	2	3	2	2	3
12	2	3	3	2	3	3
13	2	3	3	2	3	3
14	2	3	3	2	3	3
15	2	3	3	2	3	3
16	2	3	3	2	3	3
17	1	2	2	2	3	3
18	1	2	2	1	2	2
19	1	3	3	1	2	2
20	2	3	3	1	3	3
21	2	3	3	2	3	3
22	3	3	3	3	3	3
23	3	3	3	3	3	3

Figure 10: Proposed changes to the peak, standard and off-peak periods of the TOU tariffs

4.4.2. TOU proposed peak, standard, and off-peak rate changes:

Based on requests to reduce winter prices, Eskom reviewed the prices and TOU ratios between the peak, standard, and off-peak periods as well as the high-demand and low-demand seasons. The final changes proposed using the above periods in Figure 10 considered the effect and impact of changing the rates.

Too much of a reduction of the winter (high-demand season) rates would increase the summer rates (low-demand season) drastically as well as reducing the signal for customers to respond to the tariff in winter. The winter TOU period is the time when the avoidance of load shedding is far more critical from a national health, economic, and safety perspective. The changes could not be based on only cost, but rather on price signals to ensure that demand would be managed in times of constraints and times of surplus.

The rates are as follows, comparing the WEPS rates before TOU restructuring and then the rates after the TOU restructuring).

Table 4: Wholesale purchase TOU rates excluding losses

Season	High-demand			Low-demand		
Period	Peak	Standard	Off-Peak	Peak	Standard	Off-Peak
1) Existing ratios	8.00	2.31	1.18	2.50	1.67	1.00
2) Existing WEPS existing TOU ratios c/kWh	296.43	89.79	48.77	96.73	66.55	42.23
Updated CTS WEPS existing TOU ratios c/kWh	349.70	100.97	51.58	109.28	73.00	43.71
4) New ratios	6.00	1.50	1.00	2.49	1.40	1.00
5) Existing WEPS new TOU ratios c/kWh	253.40c	63.35c	42.23c	105.16c	59.13c	42.23c
6) Updated CTS WEPS new TOU ratios c/kWh	304.82c	76.20c	50.80c	126.50c	71.13c	50.80c
'ference between current and new ratios c/kWh	8.39c	-13.59c	2.03c	29.77c	4.58c	8.57c
ference existing WEPS vs New CTS TOU c/kWh	53.27c	11.18c	2.81c	12.55c	6.45c	1.48c

When comparing the proposed WEPS rates to the existing WEPS rates, the following can be noted:

- The winter peak rate ratio has decreased from a 1:8 ratio to a 1:6 ratio (see points 1 and 4 above).
- This ratio change before updating the energy costs with the CTS reduced the winter prices and increased the summer prices (see points 2 and 5 above).
- All energy rates updated with the CTS energy cost, before the ratio change (see points 2 and 3 above) and after the ratio changes (see points 2 and 6 above), have been increased. This is due to the

B LIB and VRB cost estimations

Lithium-ion LFP
2030 Cost & Performance Estimates

Category	Parameter	Units	1 MW 2hr	1 MW 4hr	1 MW 6hr	1 MW 8hr	1 MW 10hr	10 MW 2hr	10 MW 4hr	10 MW 6hr	10 MW 8hr	10 MW 10hr	100 MW 2hr	100 MW 4hr	100 MW 6hr	100 MW 8hr	100 MW 10hr
ESS Installed Cost / Energy Storage System / Storage System	Storage Block	$/kWh	[89 - 129] 111	[87 - 128] 109	[87 - 127] 108	[86 - 126] 108	[86 - 125] 107	[85 - 123] 106	[83 - 122] 104	[83 - 121] 103	[82 - 120] 103	[82 - 119] 102	[81 - 118] 101	[79 - 116] 99	[79 - 115] 98	[78 - 114] 98	[78 - 114] 97
ESS Installed Cost / Energy Storage System / Storage System	Storage Balance of System	$/kWh	[27 - 37] 32	[25 - 35] 30	[25 - 34] 29	[24 - 33] 28	[24 - 33] 28	[26 - 36] 30	[24 - 33] 28	[24 - 32] 27	[23 - 32] 27	[23 - 31] 27	[25 - 34] 29	[23 - 32] 27	[22 - 31] 26	[22 - 30] 26	[22 - 30] 25
ESS Installed Cost / Energy Storage System	Power Equipment	$/kW	[59 - 77] 73	[59 - 77] 73	[59 - 77] 73	[59 - 77] 73	[59 - 77] 73	[51 - 66] 63	[51 - 66] 63	[51 - 66] 63	[51 - 66] 63	[51 - 66] 63	[44 - 57] 54	[44 - 57] 54	[44 - 57] 54	[44 - 57] 54	[44 - 57] 54
ESS Installed Cost / Energy Storage System	Controls & Communication	$/kW	[24 - 33] 28	[24 - 33] 28	[24 - 33] 28	[24 - 33] 28	[24 - 33] 28	[5 - 6] 5	[5 - 6] 5	[5 - 6] 5	[5 - 6] 5	[5 - 6] 5	[1 - 1] 1	[1 - 1] 1	[1 - 1] 1	[1 - 1] 1	[1 - 1] 1
ESS Installed Cost / Energy Storage System	Systems Integration	$/kWh	[42 - 51] 46	[37 - 46] 36	[35 - 44] 33	[35 - 42] 32	[34 - 42] 32	[38 - 47] 38	[35 - 42] 33	[33 - 41] 31	[32 - 40] 30	[32 - 39] 30	[36 - 44] 35	[33 - 40] 31	[31 - 39] 30	[31 - 38] 29	[30 - 37] 28
ESS Installed Cost	Engineering, Procurement, and Construction	$/kWh	[52 - 64] 57	[45 - 56] 50	[43 - 53] 48	[42 - 51] 46	[41 - 50] 45	[46 - 57] 51	[42 - 51] 46	[40 - 49] 44	[39 - 48] 43	[38 - 47] 43	[43 - 53] 48	[39 - 48] 43	[38 - 46] 42	[37 - 45] 41	[36 - 45] 40
ESS Installed Cost	Project Development	$/kWh	[62 - 76] 69	[54 - 67] 60	[52 - 63] 57	[50 - 62] 56	[49 - 61] 55	[55 - 68] 61	[50 - 61] 55	[48 - 59] 53	[47 - 58] 52	[46 - 57] 51	[51 - 63] 57	[47 - 58] 52	[45 - 56] 50	[44 - 54] 49	[44 - 54] 48
ESS Installed Cost	Grid Integration	$/kW	[23 - 28] 25	[23 - 28] 25	[23 - 28] 25	[23 - 28] 25	[23 - 28] 25	[18 - 23] 20	[18 - 23] 20	[18 - 23] 20	[18 - 23] 20	[18 - 23] 20	[15 - 18] 16	[15 - 18] 16	[15 - 18] 16	[15 - 18] 16	[15 - 18] 16
	Total ESS Installed Cost*	$/kW	[650 - 854] $757	[1105 - 1460] $1,266	[1555 - 2059] $1,780	[2002 - 2654] $2,290	[2447 - 3245] $2,797	[575 - 757] $661	[1008 - 1334] $1,156	[1437 - 1905] $1,645	[1863 - 2471] $2,131	[2287 - 3035] $2,614	[531 - 699] $610	[944 - 1249] $1,081	[1353 - 1793] $1,547	[1758 - 2333] $2,010	[2162 - 2870] $2,471
	Total ESS Installed Cost*	$/kWh	[325 - 427] $378	[276 - 365] $317	[259 - 343] $297	[250 - 332] $286	[245 - 325] $280	[287 - 378] $330	[252 - 333] $289	[240 - 317] $274	[233 - 309] $266	[229 - 303] $261	[265 - 350] $305	[236 - 312] $270	[225 - 299] $258	[220 - 292] $251	[216 - 287] $247
Operating Costs	Fixed O&M	$/kW-yr	[1.86 - 2.29] 2.07	[3.26 - 4] 3.61	[4.63 - 5.7] 5.13	[6 - 7.38] 6.65	[7.36 - 9.05] 8.16	[1.65 - 2.03] 1.83	[2.98 - 3.67] 3.30	[4.29 - 5.28] 4.76	[5.6 - 6.88] 6.20	[6.89 - 8.48] 7.64	[1.54 - 1.89] 1.70	[2.8 - 3.44] 3.10	[4.05 - 4.98] 4.49	[5.29 - 6.51] 5.86	[6.53 - 8.03] 7.23
Operating Costs	Variable O&M	$/MWh	0.5125					0.5125					0.5125				
Operating Costs	System RTE Losses	$/kWh	0.004					0.004					0.004				
Performance Metrics	Round Trip Efficiency	%	88%					88%					88%				
Performance Metrics	Response Time	sec	1-4					1-4					1-4				
Performance Metrics	Cycle Life	#	2,100					2,100					2,100				
Performance Metrics	Calendar Life	yrs	10					10					10				
Performance Metrics	Duration Corresponding to Cycle Life**	yrs	6.06					6.06					6.06				

* Does not include warranty, insurance, or decommissioning costs
** Assumes 80% depth of discharge, one cycle/day, and 5% downtime

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Figure B.1: LFP cost estimations, 2030 [89]

Vanadium Redox Flow
2030 Cost & Performance Estimates

Category	Parameter	Units	1 MW 2hr	1 MW 4hr	1 MW 6hr	1 MW 8hr	1 MW 10hr	10 MW 2hr	10 MW 4hr	10 MW 6hr	10 MW 8hr	10 MW 10hr	100 MW 2hr	100 MW 4hr	100 MW 6hr	100 MW 8hr	100 MW 10hr
ESS Installed Cost / Energy Storage System / Storage System	Storage Block	$/kWh	[244 - 350] 307	[183 - 263] 231	[163 - 234] 205	[153 - 219] 193	[147 - 210] 185	[232 - 333] 293	[175 - 250] 220	[155 - 223] 196	[146 - 209] 183	[140 - 200] 176	[221 - 316] 278	[166 - 238] 209	[148 - 211] 186	[138 - 198] 174	[133 - 190] 167
ESS Installed Cost / Energy Storage System / Storage System	Storage Balance of System	$/kWh	[46 - 63] 54	[35 - 47] 40	[31 - 42] 36	[29 - 39] 34	[28 - 38] 32	[44 - 60] 51	[33 - 45] 38	[29 - 40] 34	[28 - 38] 32	[26 - 36] 31	[42 - 57] 49	[31 - 43] 37	[28 - 38] 33	[26 - 36] 31	[25 - 34] 29
ESS Installed Cost / Energy Storage System	Power Equipment	$/kW	[108 - 141] 133	[108 - 141] 133	[108 - 141] 133	[108 - 141] 133	[108 - 141] 133	[93 - 121] 114	[93 - 121] 114	[93 - 121] 114	[93 - 121] 114	[93 - 121] 114	[80 - 104] 99	[80 - 104] 99	[80 - 104] 99	[80 - 104] 99	[80 - 104] 99
ESS Installed Cost / Energy Storage System	Controls & Communication	$/kW	[24 - 33] 28	[24 - 33] 28	[24 - 33] 28	[24 - 33] 28	[24 - 33] 28	[5 - 6] 5	[5 - 6] 5	[5 - 6] 5	[5 - 6] 5	[5 - 6] 5	[1 - 1] 1	[1 - 1] 1	[1 - 1] 1	[1 - 1] 1	[1 - 1] 1
ESS Installed Cost / Energy Storage System	Systems Integration	$/kWh	[57 - 70] 63	[41 - 50] 45	[36 - 44] 40	[33 - 41] 37	[32 - 39] 35	[52 - 64] 58	[38 - 47] 42	[33 - 41] 37	[31 - 38] 34	[30 - 37] 33	[49 - 60] 54	[35 - 44] 39	[31 - 38] 34	[29 - 36] 32	[28 - 34] 31
ESS Installed Cost	Engineering, Procurement, and Construction	$/kWh	[64 - 79] 71	[47 - 57] 52	[41 - 51] 46	[38 - 47] 43	[37 - 45] 41	[60 - 74] 67	[43 - 53] 48	[38 - 47] 42	[36 - 44] 39	[34 - 42] 38	[56 - 69] 62	[40 - 49] 45	[35 - 44] 39	[33 - 41] 37	[32 - 39] 35
ESS Installed Cost	Project Development	$/kWh	[81 - 99] 89	[59 - 73] 66	[52 - 65] 58	[49 - 60] 54	[47 - 58] 52	[73 - 90] 81	[54 - 67] 60	[48 - 59] 53	[45 - 56] 50	[43 - 53] 48	[68 - 84] 75	[50 - 62] 56	[45 - 55] 49	[42 - 51] 46	[40 - 49] 45
ESS Installed Cost	Grid Integration	$/kW	[23 - 28] 25	[23 - 28] 25	[23 - 28] 25	[23 - 28] 25	[23 - 28] 25	[18 - 23] 20	[18 - 23] 20	[18 - 23] 20	[18 - 23] 20	[18 - 23] 20	[15 - 18] 16	[15 - 18] 16	[15 - 18] 16	[15 - 18] 16	[15 - 18] 16
	Total ESS Installed Cost*	$/kW	[1139 - 1523] $1,356	[1614 - 2163] $1,922	[2095 - 2811] $2,495	[2578 - 3461] $3,070	[3062 - 4112] $3,645	[1040 - 1393] $1,240	[1488 - 1996] $1,773	[1941 - 2608] $2,314	[2397 - 3221] $2,856	[2852 - 3835] $3,399	[967 - 1296] $1,153	[1388 - 1864] $1,656	[1815 - 2440] $2,165	[2244 - 3018] $2,676	[2673 - 3597] $3,187
	Total ESS Installed Cost*	$/kWh	[569 - 761] $678	[403 - 541] $480	[349 - 468] $416	[322 - 433] $384	[306 - 411] $365	[520 - 696] $620	[372 - 499] $443	[324 - 435] $386	[300 - 403] $357	[285 - 383] $340	[483 - 648] $576	[347 - 466] $414	[303 - 407] $361	[281 - 377] $334	[267 - 360] $319
Operating Costs	Fixed O&M	$/kW-yr	[3.55 - 4.37] 3.94	[5.03 - 6.18] 5.57	[6.5 - 8] 7.21	[7.98 - 9.81] 8.84	[9.45 - 11.62] 10.47	[3.24 - 3.99] 3.59	[4.65 - 5.71] 5.15	[6.05 - 7.44] 6.70	[7.45 - 9.17] 8.26	[8.86 - 10.89] 9.82	[3.02 - 3.72] 3.35	[4.36 - 5.36] 4.83	[5.69 - 7] 6.31	[7.03 - 8.64] 7.79	[8.36 - 10.28] 9.26
Operating Costs	Variable O&M	$/MWh	0.5125					0.5125					0.5125				
Operating Costs	System RTE Losses	$/kWh	0.0129					0.0129					0.0129				
Performance Metrics	Round Trip Efficiency	%	70%					70%					70%				
Performance Metrics	Response Time	sec	1-4					1-4					1-4				
Performance Metrics	Cycle Life	#	5,201					5,201					5,201				
Performance Metrics	Calendar Life	yrs	15					15					15				
Performance Metrics	Duration Corresponding to Cycle Life**	yrs	15					15					15				

* Does not include warranty, insurance, or decommissioning costs
** Assumes 90% depth of discharge, one cycle/day, and 5% downtime

Figure B.2: VRB cost estimations, 2030 [89]

C Cost trend estimation

The figure below is an example of extrapolation of the costs (CAPEX) for a LFP-system. The found trend is exponential, as the function indicates. The same trend applies for other discharge durations for both LFP and VRB, also OPEX.

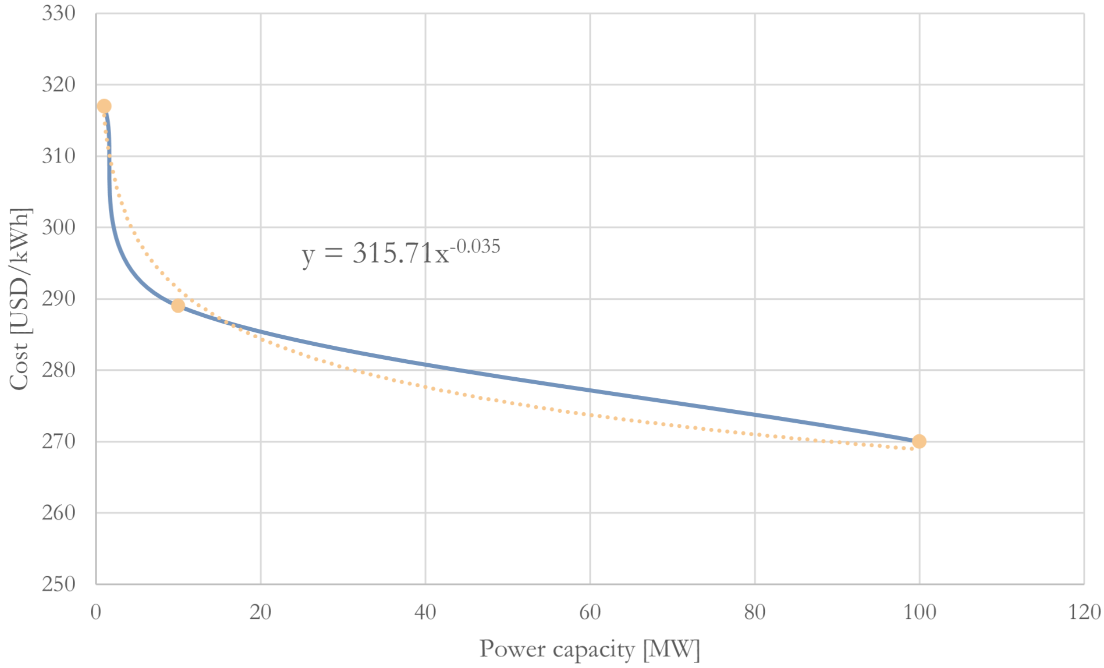

Figure C.1: Cost trend for a 4hr LFP-system. The trend is indicated with dotted line.

D MATLAB-code for cost estimates

The code below is an example of a 100MW/625MWh (5hr discharge duration) LFP-system. There are a total of 18 algorithms for one battery technology, 6 per MW-size with the cost estimations based on the Appendix B. The two inputs are the power capacity in MW and the energy capacity in MWh. The charging cost was also changed depending on the system size.

```
%% 5hr 100MW

%% inputs
MW = 100*10^3;                          %power capacity [kW]
MWh = 625*10^3;                        %energy capacity [kWh]

%% storage system
storage_block =(98+99)/2;   %storage block [USD/kWh]
storage_BOS = (27+26)/2;    %storage balance of system [USD/kWh]

%% power electronics and integration
power_eq = 54;                     %power equipment [USD/kW]
cont_com = 1;                %controls&communication [USD/kW]
sys_integ = ((31+30)/2)*0.5;     %system integration [USD/kWh]

%% engineering, development and grid integration
eng_pro_con = ((43+42)/2)*0.5;    %engineering procurement and construction [USD/kWh]
proj_develop = ((52+50)/2)*0.2;   %project development [USD/kWh]
grid_integ = 16*0.2;              %grid integration [USD/kW]

%% CAPEX
total_CAPEX = (storage_block*MWh+storage_BOS*MWh+power_eq*MW+cont_com*MW+sys_integ*MWh+eng_pro_con*MWh+proj_develop*MWh+grid_integ*MW)*10^-6;

%% OPEX
fixed = (3.1+4.49)/2;        %fixed O&M [USD/kW-yr]
variable = 0.5125/10;        %variable O&M [USD/MWh-yr]
RTE = 0.004/10;              %system RTE losses [USD/kWh-yr]
ch_cost = 0.4216;            %charging cost [MUSD/yr]

total_OPEX = (fixed*MW+variable*MWh*10^-3+RTE*MWh)*10^-6+ch_cost;
```

E Python code

Below are the two Python code sequences needed to process the data-series given for this thesis. PyCharm was used as the Python IDE, while Pandas was the tool used to process the data. Appendix A provided additional essential parameters for the code to work as intended. It was the existing TOU data that was utilised.

E.1 Processing the production data-series.

```python
import pandas as pd
data = pd.read_excel(r"Input_file.xlsx")
import datetime as dt


def find_price(row):
    price = 0

    if row["month"] in [4, 5, 6, 7, 8, 9]:
        # High-season
        if row["weekday"] in [0, 1, 2, 3, 4]:
            # Weekday
            if row["hour"] in [0, 1, 2, 3, 4, 5, 22, 23]:
                # Green
                price = 48.77
            elif row["hour"] in [6, 7, 8, 17, 18]:
                # Red
                price = 296.43
            else:
                # Yellow
                price = 89.71
        elif row["weekday"] == 5:
            # Saturday
            if row["hour"] in [0, 1, 2, 3, 4, 5, 6, 12, 13, 14, 15, 16, 17, 20, 21, 22, 23]:
                # Green
                price = 48.77
            else:
                # Yellow
                price = 89.71

        else:
            # Sunday
            price = 48.77
    else:
        # Low-season
        if row["weekday"] in [0, 1, 2, 3, 4]:
            # Weekday
            if row["hour"] in [0, 1, 2, 3, 4, 5, 22, 23]:
                # Green
                price = 42.23
            elif row["hour"] in [7, 8, 9, 18, 19]:
                # Red
```

```
                price = 96.73
            else:
                # Yellow
                price = 66.55
        elif row["weekday"] == 5:
            # Saturday
            if row["hour"] in [0, 1, 2, 3, 4, 5, 6, 12, 13, 14, 15, 16, 17, 20,
    21, 22, 23]:
                # Green
                price = 42.23
            else:
                # Yellow
                price = 66.55

        else:
            # Sunday
            price = 42.23

    return price


data = data.dropna()
data['weekday'] = data['Date/Hour'].dt.dayofweek
data['month'] = pd.DatetimeIndex(data['Date/Hour']).month
data["hour"] = data['Date/Hour'].dt.hour
data["pricepoint"] = data.apply(lambda row: find_price(row), axis=1)

data.to_excel("Output_file1.xlsx")
```

Listing 1: Code for processing the production data-series.

E.2 Adapting the previous output to suit a situation with a BESS.

```
import pandas as pd
df = pd.read_excel(r"Output_file1.xlsx")

dayfirst=True
df["Date/time"] = pd.to_datetime(df["Date/time"])

is_green1 = df["Price-point"] == 42.23
is_green2 = df["Price-point"] == 48.77
is_after_22 = df["Date/time"].dt.hour >= 22
df.loc[is_green1 & is_after_22, "Date/time"] += pd.offsets.Day(1)
df.loc[is_green2 & is_after_22, "Date/time"] += pd.offsets.Day(1)

df_sum = df.groupby([pd.to_datetime(df["Date/time"]).dt.normalize(), "Price-point"
    ]).sum().reset_index()

df_pivot = df_sum.pivot(index="Date/time", columns="Price-point", values="
    Production (MWh)").reset_index()

df_pivot["Date/time"] = df_pivot["Date/time"].dt.strftime("%d.%m.%Y")

df_pivot.to_excel("Output_file2.xlsx")
```

Listing 2: Code for adapting the previous output file to suit the BESS estimation.

F Calculated economical values for the battery systems

IRR-values were not calculated for VRB-systems as none of them had positive NPVs. The income values are the same as Income 2, which is the income from buying the missing energy.

F.1 LFP-systems

Power capacity *[MW]*	Discharge duration *[hr]*	Energy capacity *[MWh]*	CAPEX *[MUSD/year]*	OPEX *[MUSD/year]*	Income *[MUSD/year]*	NPV *[MUSD]*	IRR -
200	1	250	58.6	0.21	7.05	-17.4	2.92 %
	2	500	103.1	0.82	13.8	-19.4	4.47 %
	3	750	145.3	1.59	20.4	-22.2	4.95 %
	4	1000	185.0	2.57	26.7	-26.0	5.12 %
	5	1250	226.3	3.79	32.8	-37.6	4.77 %
	6	1500	266.6	5.17	34.7	-98.0	1.89 %
100	1	125	29.3	0.12	3.56	-8.44	3.05 %
	2	250	51.5	0.28	7.05	-6.59	5.29 %
	3	375	72.6	0.51	10.5	-4.4	6.21 %
	4	500	92.5	0.79	13.8	-1.55	6.77 %
	5	625	113.1	1.14	17.1	-1.34	6.80 %
	6	750	133.3	1.56	18.4	-25.3	4.40 %
75	1	94	22.0	0.08	2.68	-6.22	3.13 %
	2	188	38.8	0.18	5.31	-4.54	5.44 %
	3	281	54.4	0.32	7.91	-1.88	6.55 %
	4	375	69.4	0.50	10.5	1.06	7.20 %
	5	469	84.9	0.71	13.0	2.4	7.37 %
	6	563	100.1	0.95	14.0	-14.0	5.13 %
50	1	62.5	14.6	0.05	1.79	-4.03	3.24 %
	2	125	25.8	0.10	3.56	-2.48	5.72 %
	3	187.5	36.3	0.18	5.31	-0.43	6.85 %
	4	250	46.3	0.26	7.05	2.31	7.65 %
	5	312.5	56.6	0.37	8.77	4.02	7.92 %
	6	750	66.7	0.49	9.47	-5.93	5.82 %
25	1	31	7.9	0.03	0.89	-3.1	1.55 %
	2	62.5	13.8	0.05	1.79	-2.66	4.40 %
	3	94	19.4	0.07	2.68	-1.85	5.73 %
	4	125	24.6	0.10	3.56	-0.53	6.71 %
	5	156	29.9	0.14	4.44	0.49	7.21 %
	6	187.5	35.2	0.18	4.81	-4.37	5.34 %
10	1	12.5	3.2	0.01	0.36	-1.22	1.66 %
	2	25	5.5	0.02	0.72	-1.01	4.55 %
	3	37.5	7.8	0.03	1.07	-0.7	5.80 %
	4	50	9.8	0.03	1.43	-0.07	6.90 %
	5	62.5	12.0	0.04	1.79	0.46	7.50 %
	6	75	14.1	0.05	1.94	-1.35	5.73 %
1	1	1.3	0.4	0.001	0.04	-0.19	0.00 %
	2	2,5	0.6	0.002	0.07	-0.25	1.49 %
	3	3.8	0.9	0.003	0.11	-0.19	3.97 %
	4	5	1.1	0.004	0.14	-0.19	4.56 %
	5	6.3	1.3	0.004	0.18	-0.13	5.69 %
	6	7.5	1.5	0.008	0.19	-0.4	3.38 %

F.2 VRB-systems

Power capacity [MW]	Discharge duration [hr]	Energy capacity [MWh]	CAPEX [MUSD/year]	OPEX [MUSD/year]	Income [MUSD/year]	NPV [MUSD]
200	1	222	120.6	0.66	6.37	-87.3
	2	444	198.2	1.24	12.4	-122.6
	3	667	253.8	2.14	18.2	-137
	4	889	286.6	3.27	23.7	-127.8
	5	1111	334.2	4.64	29.0	-143
	6	1333	374.3	6.22	30.5	-195.6
100	1	111	60.3	0.29	3.23	-42.6
	2	222	99.1	0.47	6.37	-57.8
	3	333	126.7	0.73	9.44	-60.3
	4	444	143.2	1.06	12.4	-50.3
	5	556	167.3	1.47	15.4	-51.9
	6	667	187.3	1.95	16.4	-71.2
	7	778	210.3	2.48	17.4	-95.3
75	1	83	45.1	0.21	2.43	-31.7
	2	167	74.5	0.32	4.81	-42.8
	3	250	95.1	0.48	7.15	-43.8
	4	333	107.4	0.68	9.44	-35.1
	5	417	125.4	0.92	11.7	-34.7
	6	500	140.4	1.20	12.6	-47.2
50	1	56	30.4	0.13	1.62	-21.5
	2	111	49.6	0.19	3.23	-27.9
	3	167	63.5	0.27	4.81	-28.3
	4	222	71.6	0.38	6.37	-21.6
	5	278	83.6	0.50	7.92	-20.4
	6	333	93.5	0.63	8.53	-27.5
25	1	31	17.8	0.07	0.81	-14.2
	2	56	26.7	0.09	1.62	-16.4
	3	83	33.7	0.12	2.43	-16.1
	4	111	38.0	0.15	3.23	-12.8
	5	139	44.4	0.19	4.02	-12.2
	6	167	49.9	0.24	4.36	-15.7
10	1	11	6.5	0.03	0.33	-4.74
	2	22	10.5	0.04	0.65	-6.29
	3	33	13.4	0.04	0.98	-6.22
	4	44	15.1	0.05	1.3	-4.76
	5	56	17.9	0.06	1.62	-4.73
	6	67	20.0	0.07	1.76	-5.89
1	1	1.1	0.7	0.003	0.03	-0.6
	2	2.2	1.1	0.004	0.07	-0.69
	3	3.3	1.5	0.005	0.1	-0.74
	4	4.4	1.6	0.006	0.13	-0.63
	5	5.6	1.9	0.006	0.16	-0.67
	6	6.7	2.1	0.007	0.18	-0.73

G Discharged energy

Discharged energy for LFP and VRB before discharging. The actual discharged energy is the values given below multiplied by (1 - round trip efficiency)/2 + round trip efficiency.

LIB and VRB MW/ h	1	2	3	4	5	6
200	62400	124800	187200	249600	312000	374400
100	31200	62400	93600	124800	156000	187200
50	15600	31200	46800	62400	78000	93600
75	23400	46800	70200	93600	117000	140400
25	7800	15600	23400	31200	39000	46800
10	3120	6240	9360	12480	15600	18720
1	312	624	936	1248	1560	1872

NTNU

Kunnskap for en bedre verden