# ENABLING TECHNOLOGIES IN MICROGRID DEPLOYMENT

**By**

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**Dissertation submitted in partial fulfilment of the requirements for the degree:**

**Master of Engineering in Energy (MEng: Energy)**

**in the Faculty of Engineering and the Built Environment**

**at the Cape Peninsula University of Technology**

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**Bellville**
**October 2022**

# *DECLARATION*

I, **Dominic Gerard April**, declare that the contents of this dissertation represent my own unaided work, and that the dissertation has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

**25 October 2022**

**Signed** **Date**

# ABSTRACT

Microgrids have seen significant development in recent years, enabling governments to address energy security, low energy access rates, increased energy consumption, and high carbon emissions due to fossil-fuel-powered generators. These micropower systems have evolved and are emerging from pilot demonstration sites into commercial markets, driven by technological advancement, reduced costs, and increased acceptance in recognition of their benefits.

This dissertation presents an overview of technologies that aid in microgrid deployment. The aim was to holistically explore the complete microgrid system in terms of planning, installation, commissioning and maintenance. Therefore, all aspects of the microgrid were researched, including generation technologies and their respective working principles, the various microgrid components, and ancillary components required for microgrid deployment. Priority was placed on exploring renewable energy technologies in the context of climate change and the worldwide effort for its mitigation. In certain aspects, reference to South Africa is made for context.

# ACKNOWLEDGEMENTS

I am thankful to God our Father and creator for His endless, unconditional love and grace and for Blessing me with the strength and protection to complete my Master’s studies.

Philippians 4:13

‘*I can do all things through Christ who strengthens me’*

I wish to thank my supervisor, Prof. Mohamed Tariq E. Kahn, for his motivation and guidance throughout the journey of this dissertation and for ensuring that all my administrative requirements were addressed. Thank you, prof, for everything, especially the formal and informal chats.

Also, to my colleagues and friends. Your continuous interest in the progress of this dissertation and inspiring words of encouragement kept me motivated. I will be forever grateful. Thank you.

The financial assistance of the National Research Foundation towards this research is acknowledged. Opinions expressed in this dissertation and the conclusions arrived at are those of the author and are not necessarily to be attributed to the National Research Foundation.

# DEDICATION

I dedicate this dissertation to my family:

- My wife, Arétha, thank you for being you: A God-fearing woman. Selfless. Caring. Encouraging. I would not have been able to complete this work without your love, support and understanding.

- To my children, Kiánnah and Matéo. Thank you for your love and support, especially your understanding that daddy sometimes had to “work”. Your beautiful smiles, laughter and random hugs motivate me to keep moving.

I love you guys and will forever be grateful to you for allowing me the time to complete my Master’s studies.

*Also,*

To the rest of my family. Thank you for your continued love and support. It is most valued and appreciated.

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# TERMS AND CONCEPTS

| | |
|---|---|
| AC | Alternating current |
| $Al_2O_3$ | Aluminium oxide |
| $CO_2$ | Carbon dioxide |
| CSP | Concentrated solar power |
| DC | Direct current |
| DG | Distributed generation |
| DNI | Direct normal irradiation |
| EGS | Enhanced geothermal systems |
| ESS | Energy storage system |
| EWEA | European Wind Energy Association |
| FC | Fuel cell |
| FESS | Flywheel energy storage system |
| GHI | Global horizontal irradiation |
| SA | South Africa |
| GTOE | Gigatons of Oil Equivalent |
| GHG | Greenhouse gas |
| GWEC | Global wind energy council |

| | |
|---|---|
| HFAC | High frequency alternating current |
| IEA | International Energy Agency |
| IRENA | International renewable energy agency |
| IRP | Integrated resource plan |
| kWh | Kilowatt-hour |
| LCOE | Levelized cost of energy |
| Li-ion | Lithium-ion |
| MWh | Megawatt-hour |
| m/s | Metres per second |
| NaS | Sodium-sulphur |
| Ni-Cd | Nickel-cadmium |
| PaT | Pump as turbine |
| Pb | Lead |
| PFAC | Power frequency alternating current |
| PHES | Pumped hydro energy storage |
| PV | Photovoltaic |
| RE | Renewable energy |
| REIPPPP | Renewable energy independent power producer procurement programme |
| RES | Renewable energy sources |

| | |
|---|---|
| RPM | Revolutions per minute |
| SOE | State-owned enterprise |
| SHS | Sensible heat storage |
| SMES | Superconducting magnetic energy storage |
| TES | Thermal energy storage |
| WWEA | World wind energy association |

# CHAPTER 1: INTRODUCTION

## 1.1 Background

South Africa (SA) is facing many challenges in its energy sector, evident from the number of planned power outages (load-shedding) the country has been experiencing in recent years. Several contributing factors to these challenges include an insecure supply of electricity, primarily utilising fossil fuels for electricity generation, low electricity access rates, increased electricity consumption, and high carbon emissions. Eskom, the country's state-owned electricity provider, which also controls the national electricity grid, produces around 95% of SA's electricity but has not been able to service the country's energy demand of late (Motjoadi, Bokoro and Onibonoje, 2020). The challenges faced in SA are not unique to the country, as these issues are global challenges within the energy sector, of which climate change is the primary concern.

There is a growing demand for renewable energy (RE) into the power system in the mitigation of climate change (Sen and Ganguly, 2017), as there is a direct relation between the release of greenhouse gases (GHG) and the production, consumption, and delivery of electricity. More than 80% of the world's greenhouse gas (GHG) emissions comprise carbon dioxide ($CO_2$), with the electric power industry contributing 38% of these emissions. (Alva *et al.*, 2017). Furthermore, the International Energy Agency (IEA) reports that global energy-related $CO_2$ emissions increased from 20.5 Gt in 1990 to 33 Gt in 2021, as illustrated in Figure 1.1.

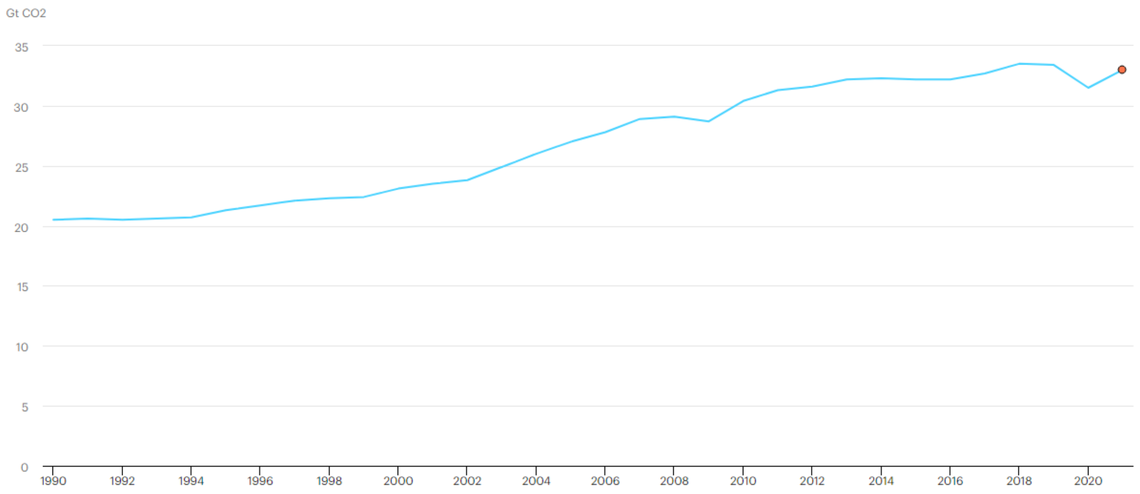

**Figure 1. 1: Global $CO_2$ emissions (energy-related), 1990-2021 (IEA, 2021a)**

The majority of GHG emissions released from the electric sector is due to using coal as an energy resource. Though this is not ideal given the context of climate change, there are countries still dependent on this resource for power generation. Approximately 0.97 metric tons of $CO_2$ is released when using coal for producing 1 megawatt-hour (MWh) of electric power, a ratio of almost 1 MWh to 1 metric ton of $CO_2$ (Alva *et al.*, 2017).

The diminution of fossil fuels is further motivation for an energy transition. As a consequence of industrialisation, fossil fuel extraction is happening globally at an alarming pace (Chauhan and Saini, 2014a). According to Abas, Kalair, and Khan (2015), global coal consumption was 2.2146 GTOE in 1990, 2.3429 GTOE in 2000, and 2.9297 GTOE in 2014, indicating a rise of 103 MTOE/year in the rate of consumption. This annual consumption rate exceeds the annual increase rate of 19.2 MTOE, which indicates that coal reserves will peak, decline, and deplete (Lin and Liu, 2010), as illustrated in Figure 1.2.

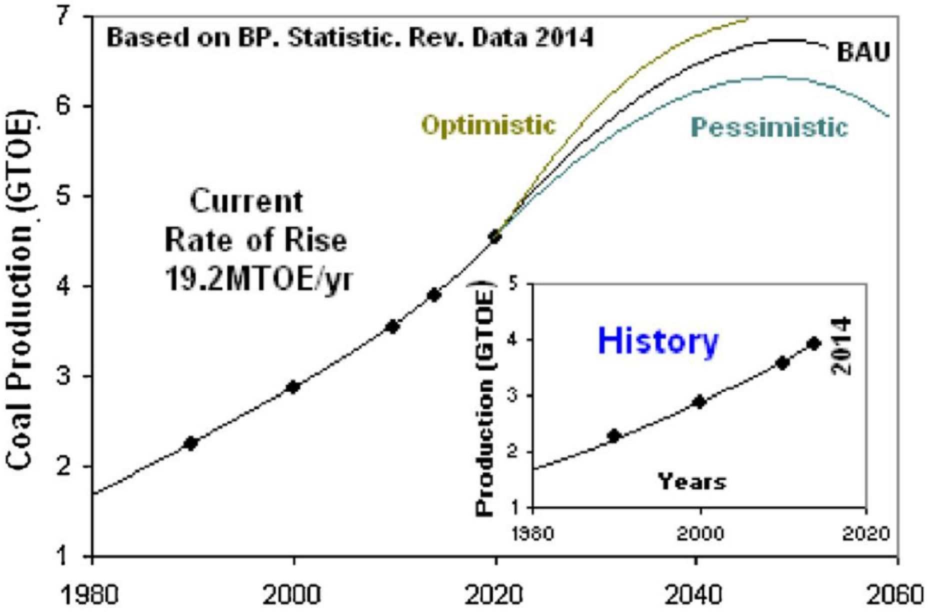

**Figure 1. 2: Global coal production (Abas, Kalair and Khan, 2015)**

However, there is an augmented interest in eco-friendly technologies, and the exploration of RE resources such as wind, solar, biomass, biogas, and micro-hydro is increasing (Chauhan and Saini, 2014a). In 2019, RE resource power plants accounted for 36.9% of the total global electricity generation capacity (IEA, 2021d). Without the integration of renewable-based power generation, total emissions from the power sector would have increased by 20% (Sen and Ganguly, 2017). However, the deployment of these power plants needs to be accelerated as the global surface temperature is still increasing. Though the average emissions intensity remained relatively constant from 1990 to 2010, it is expected to reduce significantly by 2030, as illustrated in Figure 1.3. With increased RE deployment, an additional reduction to 362 g/kWh is achievable, translating into a 40% decrease in intensity since 1990 (Sen and Ganguly, 2017).

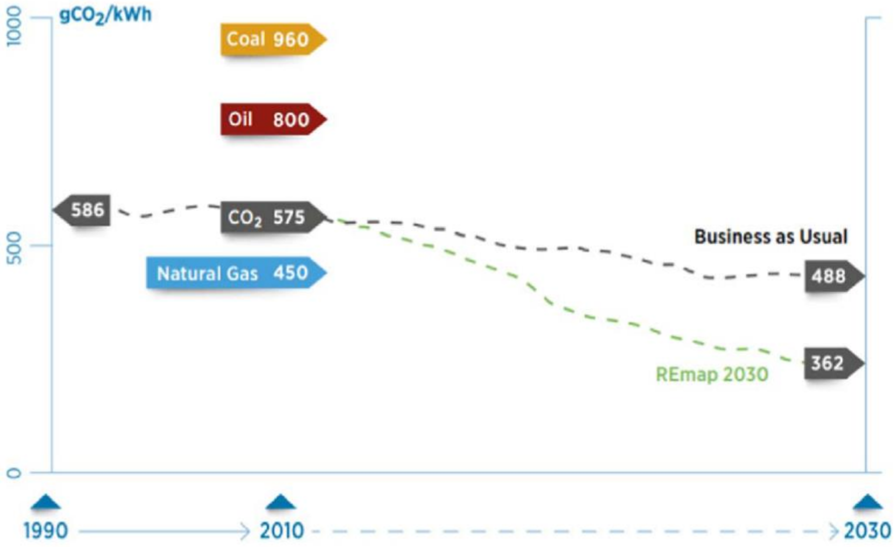

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**Figure 1. 3: CO$_2$ emissions intensity of power generation (Sen and Ganguly, 2017)**

Though there is a need for increased RE deployment, governments and technical role players should be mindful of proper future planning regarding the power transmission infrastructure. New transmission line planning aims to meet the power demand at minimum cost with adequate reliability and quality. However, it is challenging to integrate variable RE sources into an electrical system initially designed and built for predictable loads with dispatchable generation. Therefore, a microgrid project must be approached from a holistic perspective to plan, install, commission, and maintain the system as efficiently and economically as possible.

## 1.2 Statement of the research problem

Electrical power generation and distribution utilising the traditional, centralized grid have served well historically. However, increasing challenges such as fossil resource depletion and increased consumer demand have added pressure on the traditional electrical grid. Furthermore, the global drive to reduce CO$_2$ emissions, coupled with a need to improve resilience and reliability of ageing generation and transmission infrastructure, has forced government officials in SA and abroad to adopt RE perspectives by developing and implementing policies, standards, and alternative energy technologies.

A *microgrid* is a small electricity network operating autonomously through modern technologies. These micropower networks can be crucial in developing an electricity infrastructure built on RE resources. Moreover, microgrids can easily be interconnected and accelerate electricity access for isolated locations. Therefore, it is imperative that there is a transparent awareness and understanding of microgrid enabling technologies with regards to their working principle, developmental status, advantages, and shortcomings.

In support of the global effort in climate change mitigation and SA's newly adopted energy perspectives and policy implementations, this study aims to present a holistic overview of technologies currently available and in the developmental stage that would make microgrid deployment achievable.

## 1.3 Research aim and objectives of the study

This dissertation aims to research the energy sector and highlight the latest innovations and technologies available to aid microgrid deployment. It includes research on primarily RE-based generation technologies, microgrid components including storage and control, and various ancillary components necessary for effective microgrid deployment.

The objectives in support of the research aim are:

- To perform a comprehensive literature review on current technologies employed in microgrids and the relative global and locally installed capacities.
- To present the working principle and current development status of the latest commercially available generation technologies.
- To highlight emerging renewable energy technologies' working principles and development status.
- To present the working principle and development status of the latest storage technologies that are commercially available.
- To present the working principle and development status of the latest ancillary components available to aid microgrid planning and development.
- To highlight challenges and factors to consider when planning a microgrid.
- To conduct research into South Africa and its current energy situation, focusing on the country's energy potential, policies, standards, and interventions for energy security.

## 1.4 Research methodology

The nature of this study is exclusively theoretical. Therefore, an analytical research approach was adopted, with data extracted from reliable, peer-reviewed scientific papers, journals, and other credible sources where applicable. There is a magnitude of information in the literature concerning microgrids, therefore, the most recent technological advances were reviewed and discussed. For some scenarios, context relating to South Africa was applied.

## 1.5 Significance of the study

Globally, the sustainability of energy supply is firmly dependent on successfully integrating RE resources into the power sector. The dependence on fossil fuels for electricity generation cannot continue, as the planet needs to be preserved for future generations. The extensive literature of current, advanced, and novel technologies relating to energy supply will benefit decision-makers, stakeholders, and technical role players with making informed decisions regarding microgrid deployment for future energy security and sustainability.

## 1.6 Organization of the dissertation

The dissertation aims to meet the objectives in seven chapters. Below is a summary of the content of each chapter.

**Chapter 1** presents a perspective on the research performed within the dissertation. It includes the research background, statement of the research problem, the research aims and objectives, research methodology, and the significance of the research.

**Chapter 2** presents a comprehensive review of recent literature on microgrid systems. The chapter is disseminated into ten sub-sections as follows:

- Sections 2.1-2.3 presents an overview of the chapter, explaining the concept of a microgrid, and giving historical insight into RE development.
- Sections 2.4-2.5 presents the different microgrid topologies and types.
- Section 2.6-2.8 delves into the literature on the different generation, storage, and smart grid technologies.
- Section 2.9 details some of the challenges experienced in microgrid protection.
- Section 2.10 delivers some insight into the current energy situation in South Africa.

**Chapter 3** explores some of the most advanced generation technologies currently available, as well as some emerging technologies and concepts. The chapter is disseminated into eight sub-sections:

- Section 3.1 presents an overview of Chapter 3 and its contents.
- Section 3.2 presents a resource assessment of South Africa, which is necessary for context throughout the dissertation.
- Sections 3.3-3.7 detail the technologies available to harness energy from solar, wind, hydropower, biomass, and fuel cells.
- Section 3.8 presents some emerging technologies with limited commercialisation, which are currently not widely demonstrated.

**Chapter 4** presents detail on the different microgrid topologies, as well as the latest storage technologies that are available commercially.

**Chapter 5** details ancillary tools and components that are useful in the planning and commissioning phases of microgrid deployment. The chapter is disseminated into five sub-sections as follows:

- Section 5.1 provides a summary of the chapter's contents.
- Section 5.2 summarises software tools that are useful when planning a microgrid system.
- Section 5.3 presents detail on different microgrid controllers.
- Section 5.4 explores different power converters and their respective functionalities.
- Section 5.5 details the value of proper metering in a microgrid and how these meters developed in recent years.

**Chapter 6** reviews the technical and economic aspects of microgrid planning and implementation and presents an overview of considerations to be taken when developing a microgrid. It is disseminated into six sub-sections as follows:

- Section 6.1 presents an overview of the chapter
- Section 6.2 discusses techno-economic planning
- Section 6.3 presents detail on technological considerations
- Section 6.4 presents an overview of institutional support and the impact it has on microgrid deployment
- Section 6.5 explores some safety considerations
- Section 6.6 concludes the chapter with a collection of globally installed microgrids with different capacities and load requirements.

**Chapter 7** concludes the research with some final remarks and observations. Recommendations are proposed based on some of the findings within the dissertation.

# CHAPTER 2: LITERATURE REVIEW

## 2.1 Overview

This chapter presents a detailed review of recent literature pertaining to technologies that enables microgrid deployment. The chapter is disseminated into ten sub-sections, each representing a different aspect or component of the microgrid. First, some of the significant distributed energy resources (DER) are introduced, in which each technology's respective global installed capacity and future potential are highlighted. Then, the chapter concludes with a section that summarises the current energy situation in South Africa.

## 2.2 Concept of the microgrid

A microgrid is a compact electrical system that combines load, distributed energy generation, and energy storage. These micropower networks can play a crucial role in developing an electricity infrastructure built around renewable energy resources and technologies (Mousavi G *et al.*, 2017).

The transition from the traditional centralized power system to a decentralized power system, enabled by modern microgrids, allows for increased access to electricity. Accelerated deployment of RE-based power systems will improve the living conditions of many, in terms of job creation and health benefits. Globally, around 10.3 million people are employed in the RE industry. Millions of jobs can be produced in Africa with focused skill development and visionary industrial policy (IRENA, 2019). Additionally, increasing the share of RE twofold by 2030 will boost the global gross domestic product by 1.1% and provide additional economic value, which might lead to the creation of 24 million jobs in the industry, representing an increase in welfare of 3.7% (IRENA, 2019). Other benefits of microgrid deployment (Hatziargyriou *et al.*, 2007; Fu *et al.*, 2015; Chandak *et al.*, 2018):

- Enables the integration of numerous different power sources.
- Climate change mitigation.
- Highly flexible, as it can operate in grid-tied and island mode.
- Can operate at a higher efficiency at a reduced cost.
- Provides exceptional dynamic response.
- Reduced transmission losses.
- Increased power reliability.
- Reduce grid overload.
- Quick installation.
- Diversified risk as opposed to a centralized risk.

## 2.3 Renewable energy development

Data and statistics from the last decade reveal a significant increase in the installation and commissioning of RE power plants (Bhattacharya *et al.*, 2016). Furthermore, the penetration of RE into the electricity market is expected to increase due to the growing demand for climate change mitigation and other influencing factors, including improvements in power converter technologies, government incentives, and technological developments in large-scale production (Obi and Bass, 2016). Figure 2.1 depicts the global increase in RE capacity from 2011 until 2020, with Figure 2.2 displaying the RE capacity for the same period for Africa (Irena, 2021).

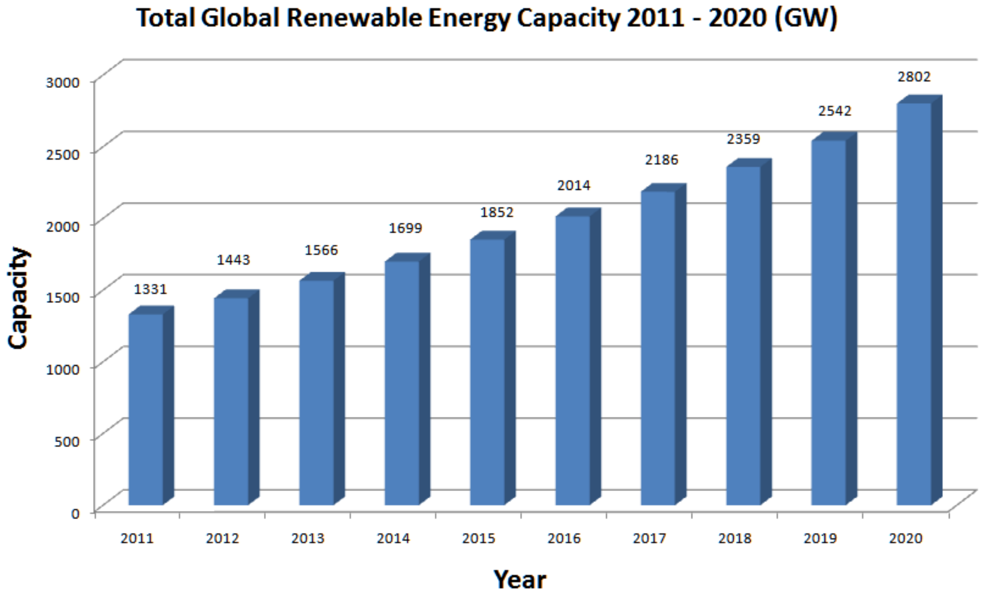

**Figure 2. 1: Total worldwide capacity for renewable energy**

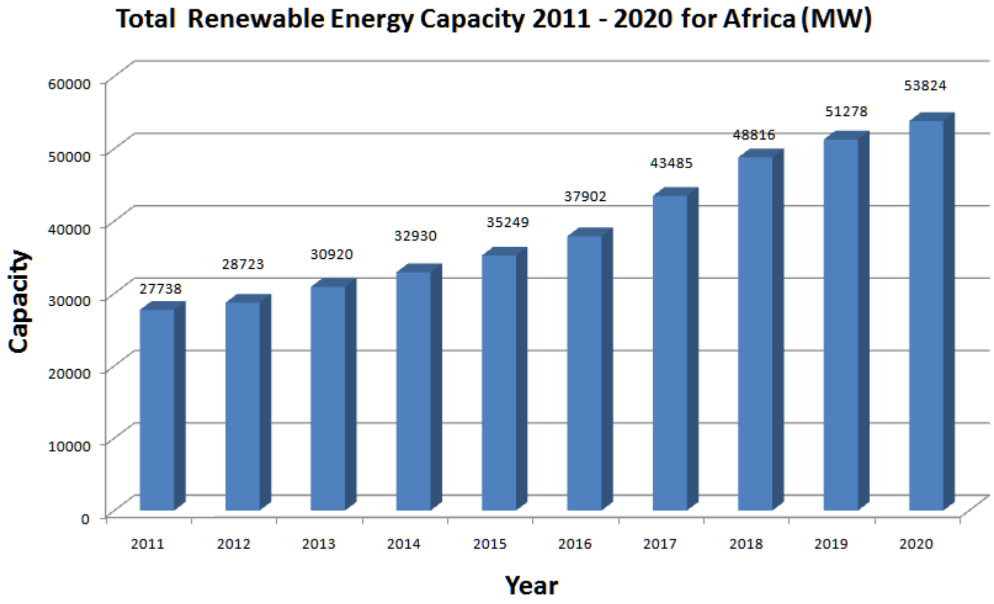

**Figure 2. 2: Total renewable energy capacity in Africa**

These figures show that installed RE capacity globally and in Africa has almost doubled over the last decade.

### 2.4 Microgrid topologies

Enforcing a consistent process for integrating energy into the electrical system is required since different RE sources have different operating characteristics (Chauhan and Saini, 2014a). Therefore, the architecture of a microgrid is classified according to its infrastructure, application, and end-user requirements. There are three possible configurations to achieve this: hybrid-coupled configuration, direct current (DC) coupled configuration, and alternating current (AC) coupled configuration, of which the latter has been the most preferred type (Chandak and Rout, 2021).

#### 2.4.1 DC microgrid system

In a DC-coupled configuration, there is a single DC bus to which all RE sources connect through power electronics interfacing circuits (Chauhan and Saini, 2014a). Energy sources that directly connect to the DC bus include solar photovoltaic (PV) systems, which provide DC electricity. In contrast, an inverter is used to supply power to AC loads, and DC-DC converters are used to supply power to DC loads. As inverters supply power to AC loads, issues may occur when the inverter goes faulty, affecting the system's power delivery. However, using several synchronized inverters connected in parallel can eliminate this problem (Chauhan and Saini, 2014a).

Integrating RE sources into the electrical system is simple, as there is no need for synchronization. In addition, DC microgrids operate with higher efficiencies, have fewer conversion processes than AC microgrids, and are used commercially in electric vehicles (EVs), telecommunication, and shipboard power systems (Chandak and Rout, 2021).

#### 2.4.2 AC microgrid system

AC-coupled power systems can be divided into two configurations: high-frequency AC (HFAC) and power frequency AC (PFAC) (Chauhan and Saini, 2014a). A PFAC configuration connects various energy sources to an AC bus. DC loads connect to the bus through AC-DC converters, whereas AC loads are directly linked to the bus (Chauhan and Saini, 2014a).

#### 2.4.3 Hybrid microgrid system

This setup has both a PFAC and DC bus. The PFAC bus provides energy to AC loads, while DC loads draw energy from the DC bus. As a result, PFAC energy sources can be coupled straight to the bus without interfacing circuits, eliminating the need for converters and reducing losses, which increases efficiency (Chauhan and Saini, 2014a).

### 2.5 Microgrid types

A microgrid can operate in either “grid-tied” or “island” mode. A standalone/islanded microgrid, also known as an autonomous microgrid, is required to fulfil demand at all times as it is entirely separated from the grid. However, due to the variable nature of the resources employed, this type of system is typically plagued with reliability concerns and typically only has economic and technological viability (Bukar and Tan, 2019).

When connected to a more extensive independent network, such as a utility grid, a microgrid is called a “grid-connected” or “grid-tied” microgrid. Excess energy generated by a grid-tied microgrid may be fed into the grid for compensation. Similarly, when the system experiences a shortfall, energy can be secured from the primary grid (Bukar and Tan, 2019).

### 2.6 Distributed generation systems

Distributed generation (DG) systems operate on diverse energy sources, including renewable energy sources (RES) and non-renewable sources (Lasseter and Paigi, 2004). A RES refers to a power generator that uses RE as a primary resource for electricity production and typically includes technologies such as PV, solar thermal power, wind power, hydropower, biomass, geothermal power, and ocean energy. The following section provides a brief overview of RE resources and generation technologies, emphasizing each one's global installed capacity and future prospects.

#### 2.6.1 Solar energy

The global installed capacity of solar PV systems currently exceeds all other RE sources combined. According to data retrieved from IRENA (2021), the total cumulative installed solar technology (solar PV) for 2010 was 40,334 MW. However, these figures increased substantially in the following ten years, with total cumulative solar PV increasing to 709,674 MW (Irena, 2021). Furthermore, solar PV development over the same period has trended in Africa, with solar PV increasing from 194 MW installed capacity in 2010 to 9,551 MW in 2020. Solar energy is a favourable energy resource for countries like those in Africa, as most of these countries, on average, receive 6-8 kWh/m$^2$/day of solar irradiation, amongst the highest globally. Furthermore, solar systems have low maintenance requirements, require little auxiliary electrical power and have an average lifetime of 20 years (Seme *et al.*, 2020).

Obi and Bass (2016) claim that the production cost of PV modules has drastically decreased, from more than $100 per watt in the 1970s to less than $1 per watt in 2014. The claim of reduced PV prices is corroborated by the International Renewable Energy Agency (IRENA), which estimated an 80% decrease in solar PV since 2009. These factors might explain the increase in total installed capacity of solar PV systems, as presented in Figure 2.3.

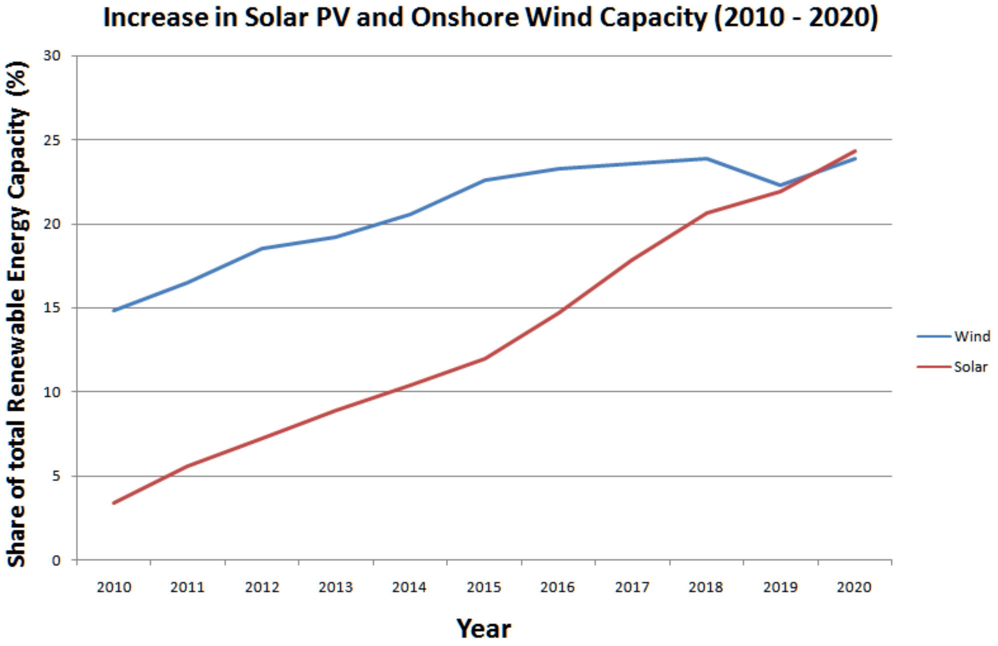

**Figure 2. 3: Share (%) of renewable energy capacity of solar PV and onshore wind (2010-2020)**

In its 2013 annual review, the Solar Energy Industry Association (SEIA) stated that the average price for a PV system is $2.59 per watt (Obi and Bass, 2016). In addition, Figure 2.4 presents the global increase in solar PV electricity generation from 1990 to 2019 (IEA, 2021c), which further illustrates the industry's exponential growth.

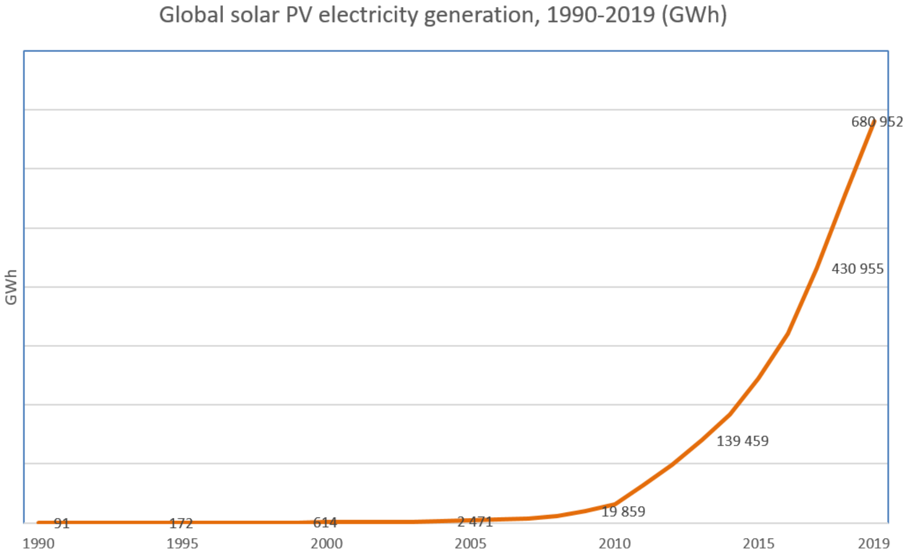

**Figure 2. 4: Global solar PV electricity generation from 1990-2019**

### 2.6.2 Wind energy

The wind industry has achieved significant milestones since 1982, when the first three-bladed wind turbine with a 22 kW capacity was first introduced, and the European Wind Energy Association (EWEA) was founded. The first offshore wind farm, Vindeby, located in Denmark, was established in 1991, with the World Wind Energy Association (WWEA) established later in 2001. During this same year, the average onshore wind turbine first exceeded a 1 MW capacity (IRENA, 2019). The Global Wind Energy Council (GWEC) was founded in 2005, and by 2008, the capacity of the world's wind farms had increased to 100 GW. In the wind energy industry, more than a million jobs were created by 2014, and by 2016, wind power supplied over 4% of the global electricity (IRENA, 2019).

Hywind, a Scottish floating offshore wind farm, was put into service in 2017, which was also the year Germany hosted the first offshore wind auction with "zero subsidies". The installed wind capacity reached 564 GW by 2018, with jobs within the wind energy sector increasing to more than 1.2 million. Furthermore, in 2019, commercially available 10 MW offshore wind turbines were first introduced (IRENA, 2019). According to IRENA (2021), the global installed onshore wind capacity was 698,043 MW in 2020 (Figure 2.5), increasing from 177,795 MW in 2010, with the global offshore installed capacity increasing from 3,056 MW in 2010 to 34,367 MW in 2020 (Figure 2.6).

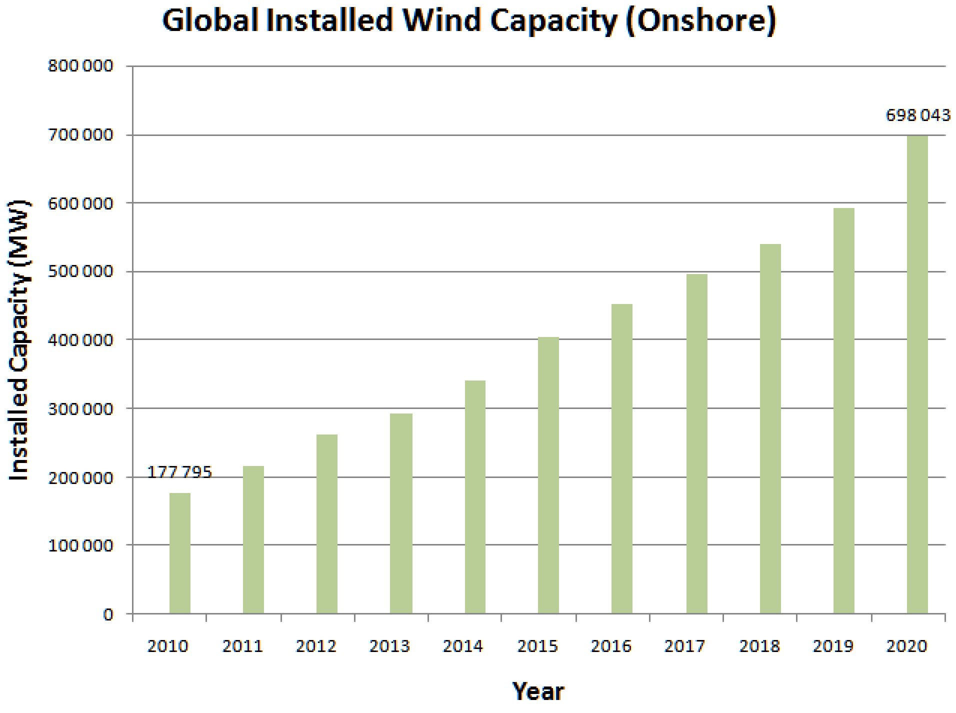

Figure 2. 5: Global installed wind capacity (onshore) from 2010-2020

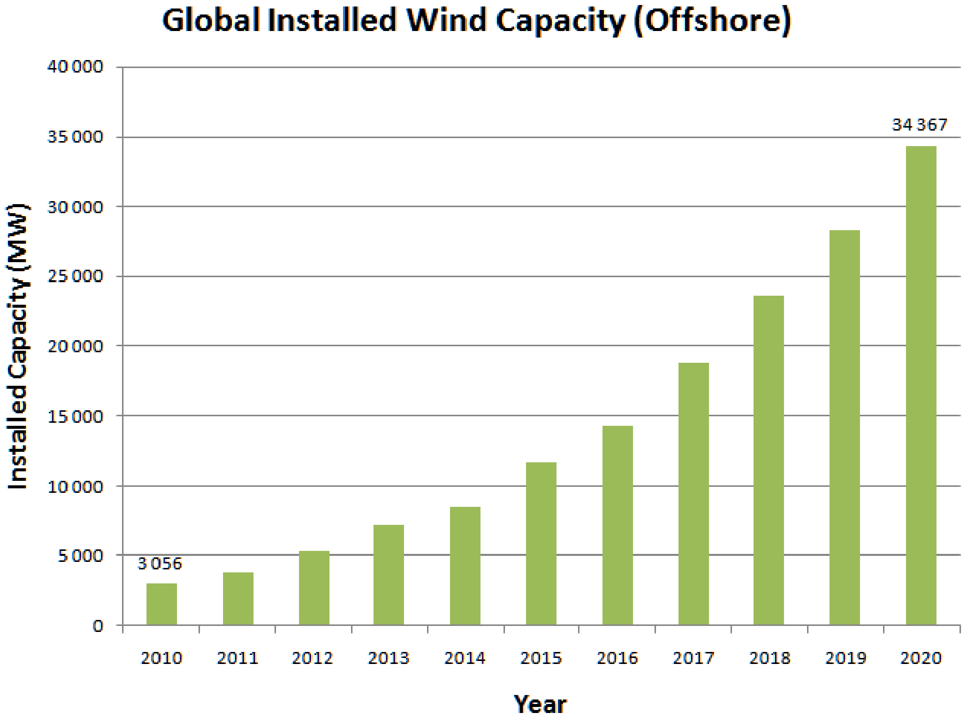

**Figure 2. 6: Global installed wind capacity (offshore) from 2010-2020**

### 2.6.3 Hydro energy

According to the International Energy Agency's "Net-zero by 2050" assessment (IEA, 2021b), installing 2,600 GW of hydropower by 2050 may be necessary to keep the rise in the global surface temperature below 1.5°C (IHA, 2021). This indicates that the same capacity installed over the past 100 years is required in the next 30 years.

Hydropower installed capacity for 2020 reached 1,330 GW, representing a year-on-year increase of 1.6% from 2019. However, this is well short of the 2% required from hydropower representation to mitigate climate change, as the IEA's report sets out.

China, with an installed hydropower capacity of more than 370 GW, remains the global leader in hydropower production, followed by Brazil (109 GW), the United States of America (102 GW), Canada (82 GW), and India (50 GW) (IHA, 2021). On the other hand, Africa, with an installed capacity of 38 GW (2020), is considerably lagging behind the rest of the world, as depicted in Figure 2.7.

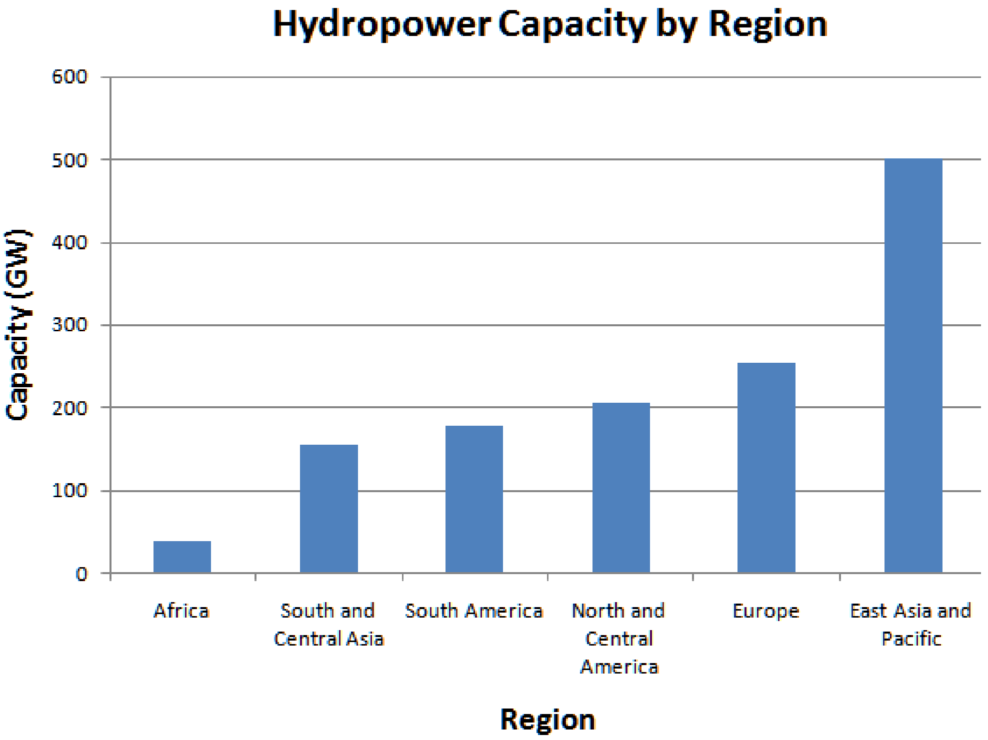

**Figure 2. 7: Hydropower capacity by region**

Globally, the installed hydropower capacity, excluding pumped storage, increased from 666,385 MW in 2000 to 1,176,962 MW in 2021 (IRENA, 2018), as presented in Figure 2.8.

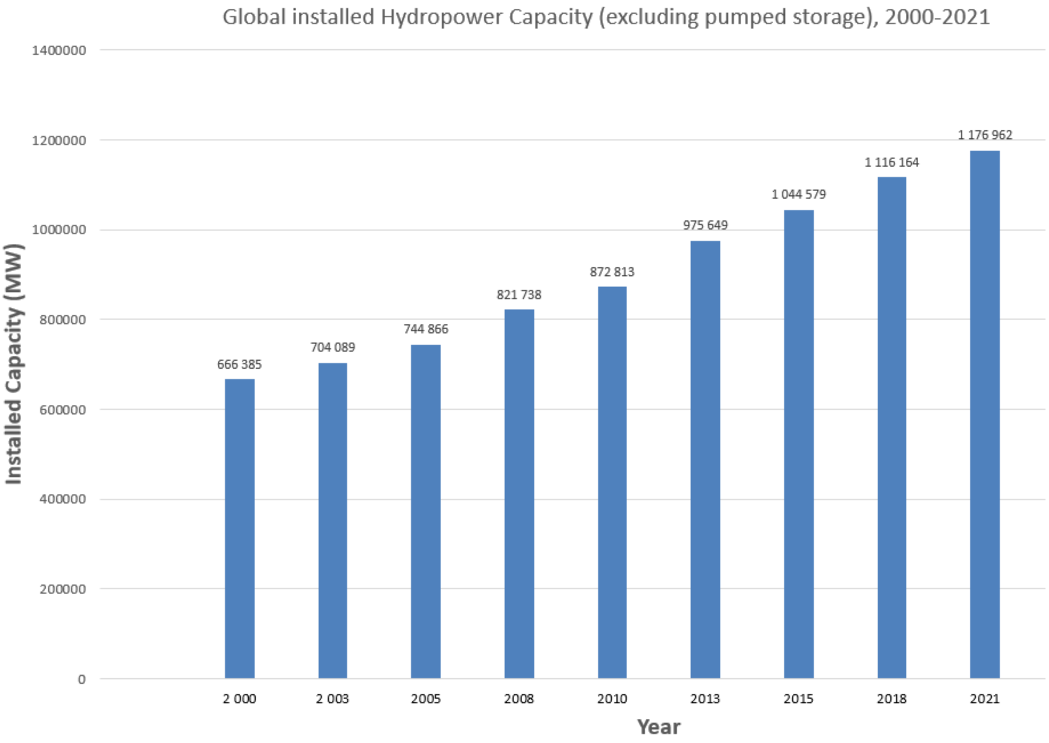

**Figure 2. 8: Global installed hydropower capacity (excluding pumped storage)**

### 2.6.4 Biomass energy

*Biomass* is a chemically biodegradable material capable of energy generation through various processes. It includes numerous materials (Figure 2.9), including food waste, industrial wastewater, energy crops, virgin wood, and agricultural residues, to name a few.

**Figure 2. 9: Biomass energy resources (Mohammed *et al.*, 2017)**

Biofuel generators operate on the same functional principle as standard petrol/diesel generators but are fuelled with environmentally friendly energy sources such as biodiesel, biogas and vegetable oil. Figure 2.10 presents the share of bioenergy in the global energy mix.

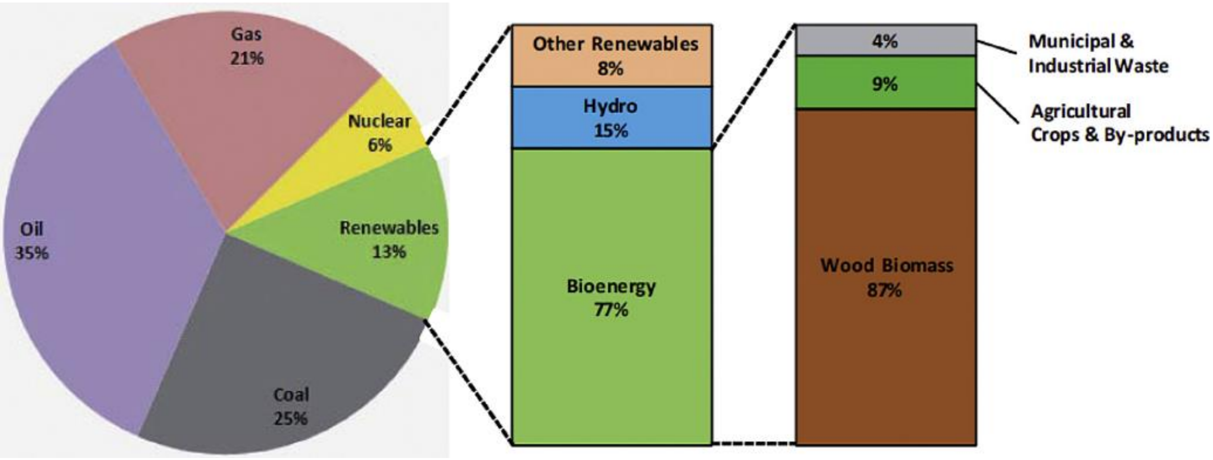

**Figure 2. 10: Share of bioenergy in the global primary energy mix (Toklu, 2017)**

### 2.6.5 Fuel cells

An electrochemical power source known as a fuel cell (FC) transforms chemical energy (in the form of fuel) directly into electrical energy while developing thermal energy and forming water as a by-product (Wilberforce *et al.*, 2016). The direct conversion of chemical energy into electrical energy is an advantage over the combustion-based heat engine, with its multi-step processes. Contrary to conventional electro-chemical systems like batteries, which store reactants within a cell, fuel cells are continuously supplied with reactants from external sources (Wilberforce *et al.*, 2016). Furthermore, unlike batteries, which consume electrodes permanently in primary cells and reversibly in secondary cells, fuel cells do not include electrodes in the reaction. According to Lucia (2014), FCs are one of the most promising technologies regarding RE development. As shown in Figure 2.11, the fundamental physical composition of the FC consists of an electrolyte layer in contact with two porous electrodes.

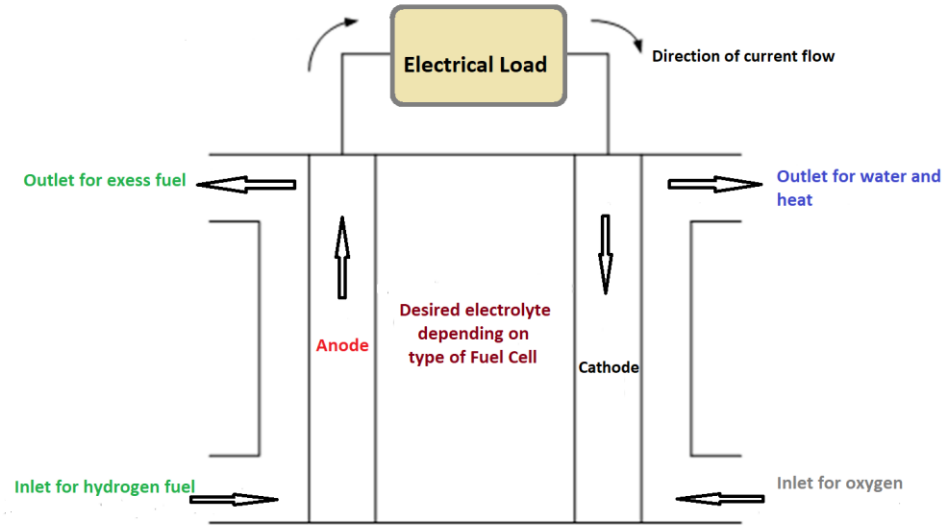

**Figure 2. 11: Basic Fuel Cell operation**

The operation of the hydrogen FC is essentially the reverse of the electrolysis process: hydrogen and oxygen recombine, producing an electrical current along with water as a by-product (Larminie, Dicks and McDonald, 2003). Equation (2.1) presents the overall reaction as:

$$2H_2\,(g) + \; O_2(g) \rightarrow 2H_2O + energy\;(electrical\;and\;thermal) \qquad (2.1)$$

According to the operating parameters and the technology adopted, there are several types of FCs, as illustrated in Figure 2.12.

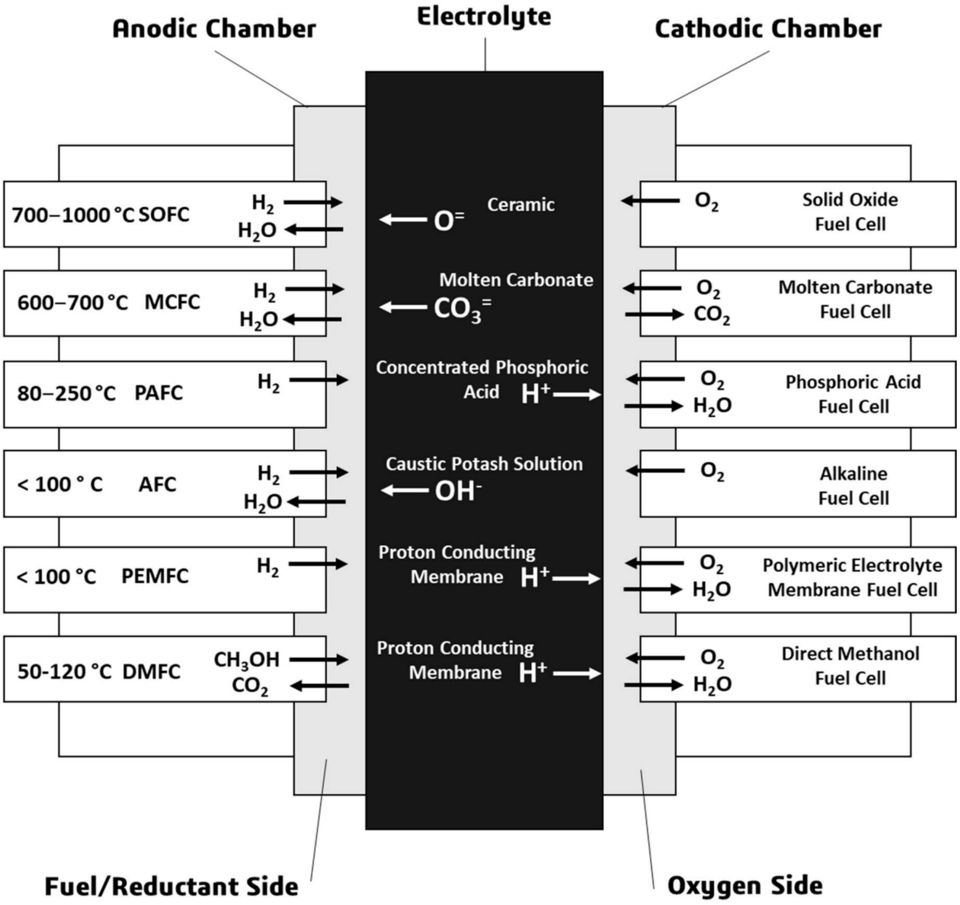

**Figure 2. 12: Overview of Fuel Cell technologies (Cigolotti, 2021)**

FCs are modular units assembled in stacks, making them scalable and capable of delivering power between 1 watt and several megawatts (Figure 2.13). Furthermore, FCs have a high power-to-area ratio, allowing for a more compact installation (Cigolotti, 2021).

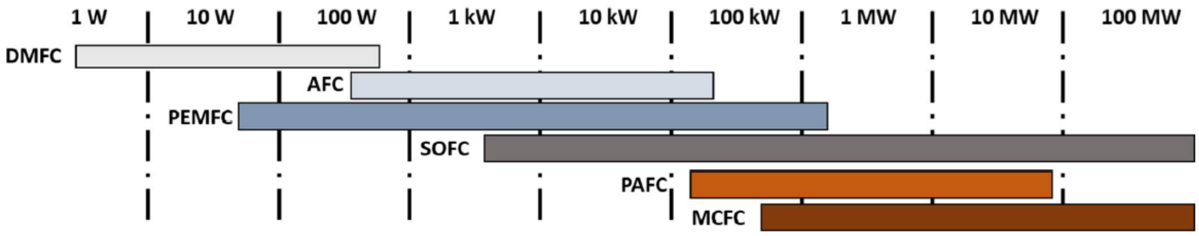

**Figure 2. 13: Fuel Cell application range (Cigolotti, 2021)**

### 2.6.6 Nuclear fission

There are currently several technological advances within the nuclear energy industry, which raises its potential to significantly impact the future energy mix. An example is the Pebble Bed

Modular Reactor (PBMR), which benefits from its inherent safety features and small size. Unfortunately, due to high construction costs and extended construction periods, the utilisation of nuclear technologies has not been competitive in the energy market. Though costs have fallen significantly, they cannot be validated due to limited projects.

Additionally, there is a misperception amongst the general public about the safety of nuclear energy, largely as a result of what happened after America used nuclear weapons against the Japanese cities of Hiroshima and Nagasaki in 1945. A recent example is the Fukushima-Daiichi nuclear accident, caused by an East-Japan earthquake, which damaged the Fukushima Nuclear reactor plant (Komiyama and Fujii, 2017).

Regarding the energy resource for nuclear production, namely uranium, there is an abundant supply available. SA is amongst the world's top countries in terms of uranium reserves, with an estimated 433,364 tons of uranium on hand, or approximately 7% of the world's supply, which can provide enough fuel to last for at least another 100 years. The use of thorium as fuel for a nuclear power plant is an additional option, with the following benefits over uranium:

- It is three times more abundant than uranium.
- Less thorium is required to produce similar amounts of energy.
- Thorium cannot be used to construct weapons of mass destruction because of its "proliferation resistance" property.

## 2.7 Storage

The relatively slow development of energy storage technologies plays a significant role in the delayed deployment of microgrids. The intermittent nature of RE sources, such as solar and wind, and the seasonality of hydropower, leads to a disparity between energy demand and supply, which fails to guarantee a continuous, reliable power supply (Kuang *et al.*, 2016). Energy storage techniques are essential to cope with the volatile characteristics of RE power generation. Redundant, real-time RE can be transformed into electromagnetic, mechanical, and chemical energy through various energy storage systems (ESS) (Luthra *et al.*, 2014). The stored energy will then be available when the power supply from RE is insufficient, creating an energy buffer for power output variation (Kuang *et al.*, 2016).

ESS can be classified into three groups: short-term (capacitors, flywheel, and superconducting magnetic storage), medium-term (FCs, batteries, and compressed air energy storage), and long-term (pumped storage). These groups can be further divided into electrical-, chemical-, and mechanical energy storage (Chauhan and Saini, 2014a).

### 2.7.1 Mechanical energy storage

Mechanical ESS are an efficient and sustainable option for energy storage. These systems can be classified into three types: compressed air, flywheel, and pumped hydro. When selecting a mechanical ESS, it is crucial to consider certain aspects, including the energy source, the load's nature, and the available space (Mahmoud *et al.*, 2020).

#### 2.7.1.1 Compressed air energy storage

Gas (usually air) is pre-compressed during off-peak times using grid power and stored in storage reservoirs (Mahlia *et al.*, 2014). However, should energy be required during the high peak, the gas is expanded in a turbine, and the stored energy is converted into mechanical energy, available at the shaft of the turbine (Amirante *et al.*, 2017).

#### 2.7.1.2 Flywheel energy storage

With a flywheel energy storage system (FESS), energy is stored by converting surplus energy into the kinetic energy of a spinning mass (flywheel) (Amirante *et al.*, 2017). An electrical machine's shaft is connected to a high-speed rotating disc that stores kinetic energy. A rotor is typically mounted in an evacuated cylinder, allowing high-speed rotation. The system operates during off-peak times, storing energy as rotational kinetic energy (Rohit, Devi and Rangnekar, 2017).

#### 2.7.1.3 Pumped hydroelectric storage

Pumped hydro energy storage (PHES) is a mature technology that has been used and applied in large-scale utilities for many years. PHES makes up more than 95% of the world's storage capacity and is currently the most widely used large-scale (>100 MW) RE storage technology (Chen *et al.*, 2013).

Using surplus electricity generated during off-peak hours, water is pumped from a lower to a higher altitude reservoir (Amirante *et al.*, 2017). The gravitational potential of the stored water, when released, is transformed into mechanical energy, which is then transformed into electrical energy (Rohit, Devi and Rangnekar, 2017). The hydraulic machine utilised is usually a "pump as turbine" (PaT), which is "a reversible machine capable of operating both as a pump and as a turbine" (Amirante *et al.*, 2017). Figure 2.14 presents a schematic diagram of a typical PHES system.

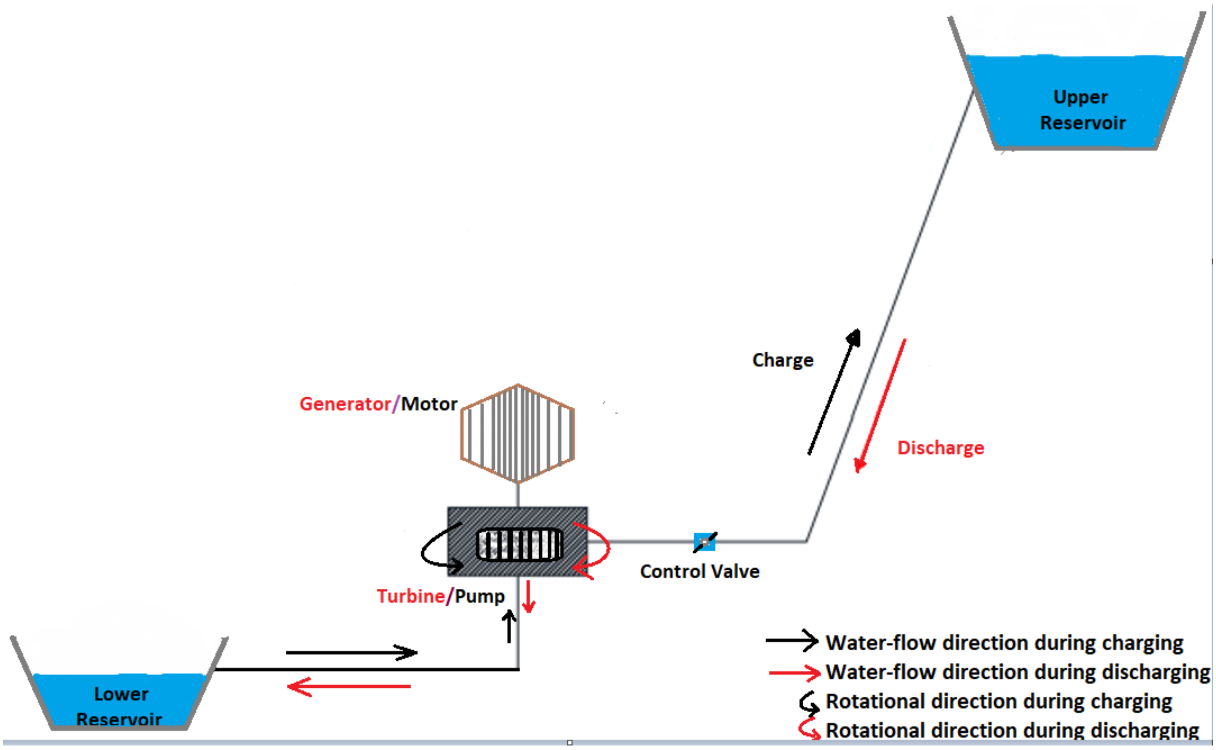

Figure 2. 14: Pumped hydro storage system

### 2.7.2 Electrochemical energy storage

Electrical energy stored electrochemically is referred to as “electrochemical storage”. The most used electrochemical storage devices are batteries and capacitors, of which batteries are the most matured technology. Batteries have high energy densities and voltages, can be found in various sizes, are quite advanced, and can be utilised in various applications (Rohit, Devi and Rangnekar, 2017). There are several types of batteries used in industry, including nickel-cadmium (Ni-Cd), lithium-ion (Li-ion), sodium-sulphur (NaS), lead-acid (Pb-acid), lead-carbon, flow batteries, and zebra batteries (Koohi-Fayegh and Rosen, 2020). Figure 2.15 presents the energy density of various battery technologies relative to that of gasoline.

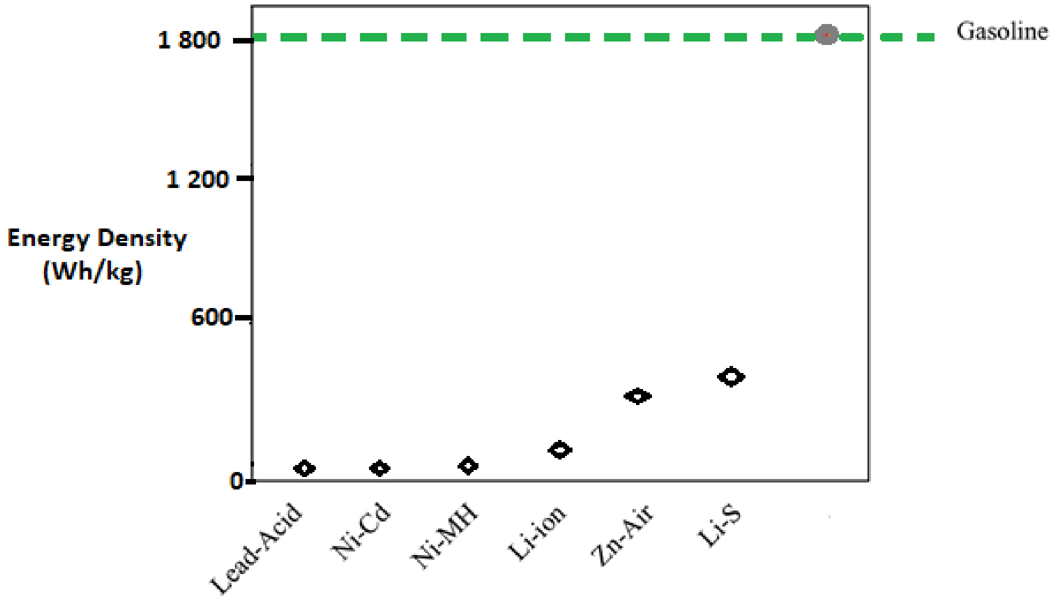

**Figure 2. 15: Energy density of some battery technologies relative to gasoline**

### 2.7.3 Electrical energy storage

The key electrical energy storage devices are supercapacitors and superconducting magnetic energy storage systems.

#### 2.7.3.1 Supercapacitors

This energy storage method employs high energy density capacitors, and although it uses thinner dielectrics, it is otherwise identical to conventional capacitors. These capacitors have electrodes with a larger surface area for storing significant amounts of charge carriers and capacitances (up to 5,000 F) (Rohit, Devi and Rangnekar, 2017). According to Amirante *et al*. (2017) current research is concentrated on developing inexpensive, multi-layer supercapacitors utilising materials such as paper, carbon and graphene (Amirante *et al.*, 2017).

#### 2.7.3.2 Superconducting magnetic energy storage

With a superconducting magnetic energy storage (SMES) system, energy is stored in a magnetic field created by cryogenically cooling the flow of direct current in a conductor to significantly low temperatures (Rohit, Devi and Rangnekar, 2017). Though these systems benefit from a fast response time, its major drawbacks are the high cost and environmental issues associated with solid magnetic fields. Figure 2.16. presents a typical SMES system.

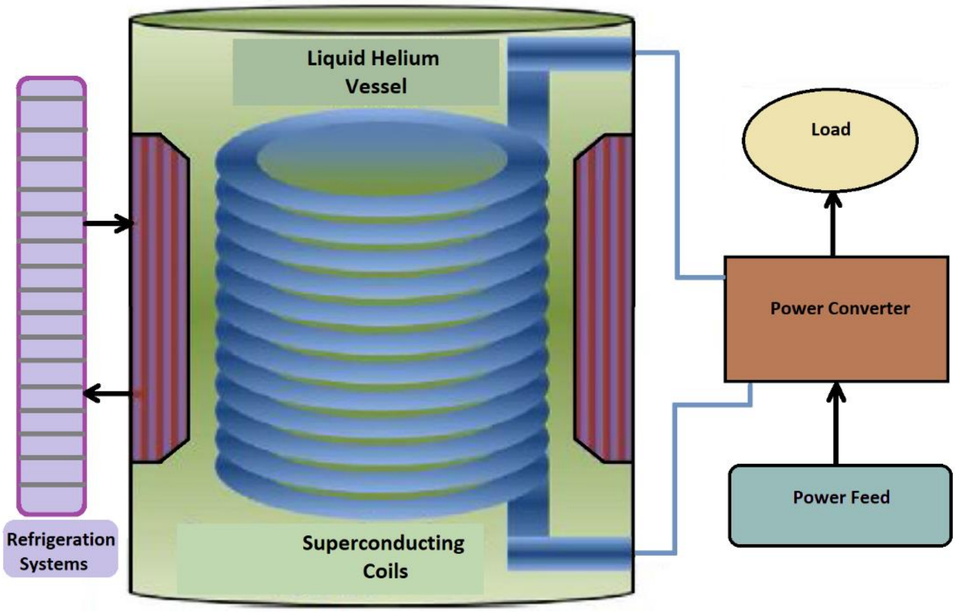

**Figure 2. 16: Typical superconducting magnetic energy storage system**

### 2.7.3.3 Thermal energy storage

With a thermal energy storage (TES) system, materials that maintain either low or high temperatures are utilised to produce electricity by extracting heat or cold, maintained in insulated containments (Akinyele and Rayudu, 2014). During the charging period, a TES system transfers heat to a storage medium, which can be released later during the discharging period.

Sensible Heat Storage (SHS) systems are a type of TES that store thermal energy by raising the temperature of a solid or liquid without altering its phase. Typically, it comprises a storage space, a container, and inlet and output connectors (Zhang *et al.*, 2016).

## 2.8 Smart grid technologies

Smart grids were developed to mitigate climate change by modernising the electricity grid and improving power delivery. It allows for integrating and synchronizing power from RE resources into an electrical grid. The traditional grid can only distribute electrical power, whereas a smart grid can store energy, communicate with sub-divisions, and make decisions. Simply put, a smart grid is intelligent and capable of operating autonomously (Tuballa and Abundo, 2016).

Amongst others, the most common drivers for smart grids are: a rising demand for electricity, electrical supply shortages, the need to reduce losses, managing peak demand, integrating RE producing systems, and inefficient conventional power generation systems (Luthra *et al.*, 2014). Some of the areas where smart grid technologies aid in the deployment of microgrids are briefly discussed.

### 2.8.1 Demand response

As defined by the Federal Energy Regulatory Commission, demand response is: “Changes in electric usage by demand-side resources from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices, or when system reliability is jeopardised”. Demand response allows for consumer involvement in operations of the grid, as they can customise their peak-time electricity usage, benefitting through financial incentives (FERC, 2014; Tuballa and Abundo, 2016).

### 2.8.2 Metering and distribution automation

Smart meters put customers in control of their energy use, enabling two-way communication between the utility and meters by utilising sensors, power outage notification and power quality monitoring (Tuballa and Abundo, 2016).

### 2.8.3 Advanced electricity storage and peak-shaving

Electricity generation from RE fluctuates, making electricity storage and demand peak-reduction and moderation technologies indispensable. Surplus electricity is stored when the electricity supply is plentiful. The system then makes use of this energy as demand increases.

## 2.9 Microgrid protection

A challenge in microgrid networks is designing a good protection circuit as microgrids' fault currents constantly fluctuate due to distributed generation resources (Hosseini *et al.*, 2016). Furthermore, microgrids are dynamic networks that can operate in islanded and grid-tied mode. A load or distributed generator unit can disconnect or connect from the microgrid anytime, making conventional protection methods unsuitable. Therefore, a suitable design setup for both modes should be implemented to protect the network (Hosseini *et al.*, 2016). Some of the challenges in microgrid protection are discussed in the following sub-sections.

### 2.9.1 False tripping

False tripping occurs when the fault current from a distributed generator is combined with the fault current from a nearby feeder connected to a shared substation. In such conditions, the neighbouring feeder’s protection equipment might isolate the circuit, creating a problem known as “unnecessary outage of feeder” or “false tripping” (Memon and Kauhaniemi, 2015).

### 2.9.2 Blindness of protection

Innovative methods for addressing network protection challenges include isolating DG units during fault conditions, balancing numerous distributed generation technologies, utilising fault current limiters, adaptive protection and smart transformers (Hosseini *et al.*, 2016).

## 2.10 Current energy situation in South Africa

The total installed electricity generation capacity in SA is 58,095 MW, of which approximately 8.8% is generated from RE and 91.2% from thermal power stations (USAID, 2018). Eskom, the country's energy parastatal, remains its largest state-owned enterprise (SOE) and Africa’s principal energy producer. However, its prolonged crises of governance, spiralling cost, and poor service delivery have led to the government seeking the unbundling of Eskom into three units: generation, transmission and distribution. Eskom’s coal-fired plants, on average, are thirty-seven years of age, and their capacity has decreased from 90% in 2005 to less than 60% in 2019. The reduced capacity and increased load demand have resulted in Eskom implementing load-shedding, costing the country an estimated R1.4 trillion ($100 billion) between 2010 and 2020 (Lawrence, 2020).

The South African government, however, plans to procure 20 GW of RE and decommission 11 GW of aged coal-fired power plants. Furthermore, the Integrated Resource Plan (IRP) 2010-2030, established in March 2011, highlights the government’s intent to deliver affordable electricity and reduce GHG emissions. The IRP initiative also led to the establishment of the Renewable Energy Independent Power Producer Procurement Program (REIPPPP), which resulted in a total RE procurement of 6.4 GW, of which 3.8 GW is operational and connected to the grid (Lawrence, 2020; Motjoadi, Bokoro and Onibonoje, 2020).

# CHAPTER 3: GENERATION TECHNOLOGIES

## 3.1 Overview

Generally, a system's operating mode, operation architecture, generation source, type of load, and size or capacity classify a microgrid (Figure 3.1). This chapter details various generation technologies currently in use or development that might aid engineers in planning or developing a microgrid.

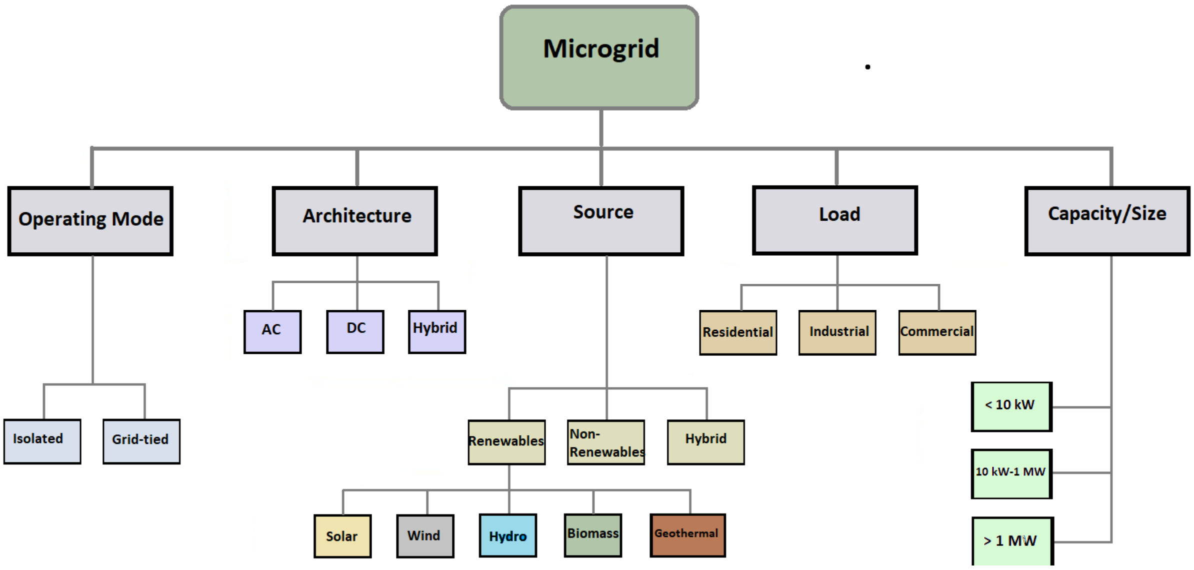

**Figure 3. 1: Microgrid classification**

Renewable Energy Technologies (RET) operate on energy sources that are environmentally benign and sustainable in that they are manageable for indefinite utilisation. Therefore, these technologies can help societies satisfy their energy needs through microgrid deployment. Furthermore, the decentralized nature of RETs allows for deployment that can match the unique requirements of different rural locations.

Firstly, a resource assessment of SA is presented, as it is imperative to understand the available resources within a dedicated service area. Thereafter, several available supply-side technologies are discussed, with RETs employed in rural areas presented first. These include technologies utilising the more established energy resources such as biomass, wind, small-scale hydro, and solar. Furthermore, advanced technologies used for mitigating intermittency and seasonal variations of the matured technologies are briefly discussed.

## 3.2 Renewable energy resource assessment – South Africa

South Africa is the southernmost country in Africa, circumscribed by neighbouring countries, Namibia, Botswana, Zimbabwe, Mozambique and Swaziland, and the Atlantic and Indian Oceans. It is a country with RE resources that have huge potential to contribute immensely to its energy sector, society and economy. The most abundant resource in SA is solar, followed by wind and biomass, with only some specific locations suitable for hydropower exploration (IRENA, 2020).

### 3.2.1 Solar energy

The most prevalent technologies used to produce electricity from solar irradiation are concentrated solar power (CSP) and PV. However, it is essential to note that Direct Normal Irradiation (DNI) indicates the potential for CSP applications, whereas Global Horizontal Irradiation (GHI) indicates the potential for solar PV applications.

SA receives amongst the highest Direct Normal Irradiation (DNI) globally, with annual irradiation levels in the Northern Cape province reaching 3,000 kWh/m$^2$ per year. It is also evident from Figure 3.2 that the central parts of SA exhibit DNI levels of 2,500 kWh/m$^2$ per year. These irradiation levels are comparable to areas in Europe, where 50 MW CSP plants, such as Manchasol and Helios, are operational (IRENA, 2020).

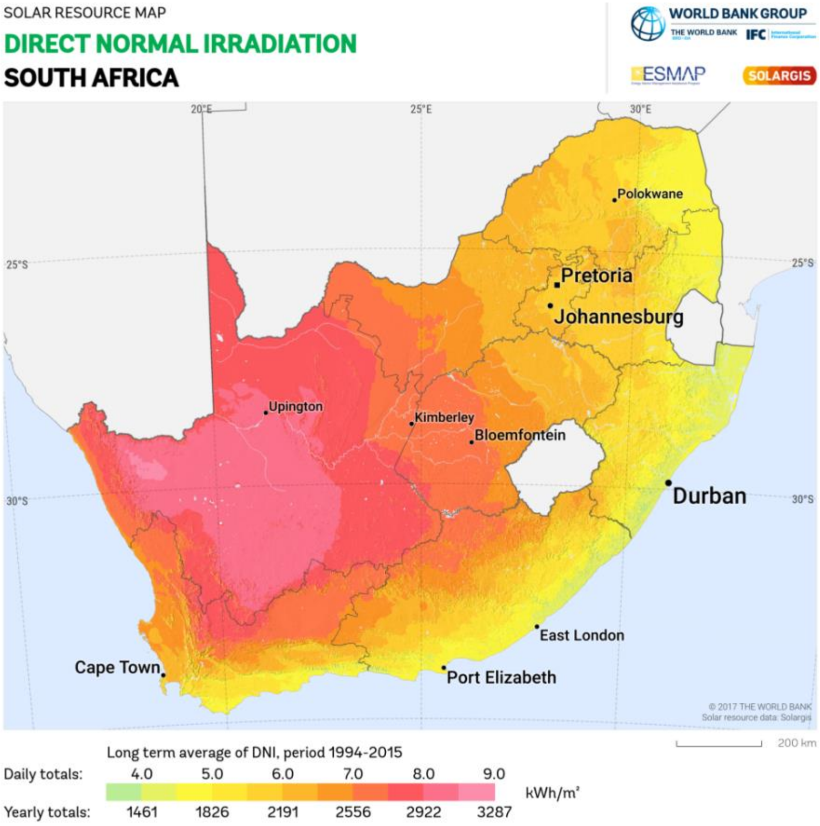

**Figure 3. 2: Direct Normal Irradiation (DNI), SA (Global Solar Atlas, 2020)**

As demonstrated in Figure 3.3, the entire landscape of SA exhibits GHI levels greater than 1,300 kWh/m$^2$ per year, which signifies favourable conditions for PV power generation. Furthermore, this denotes that virtually any site in SA is theoretically suitable for solar PV deployment (IRENA, 2020).

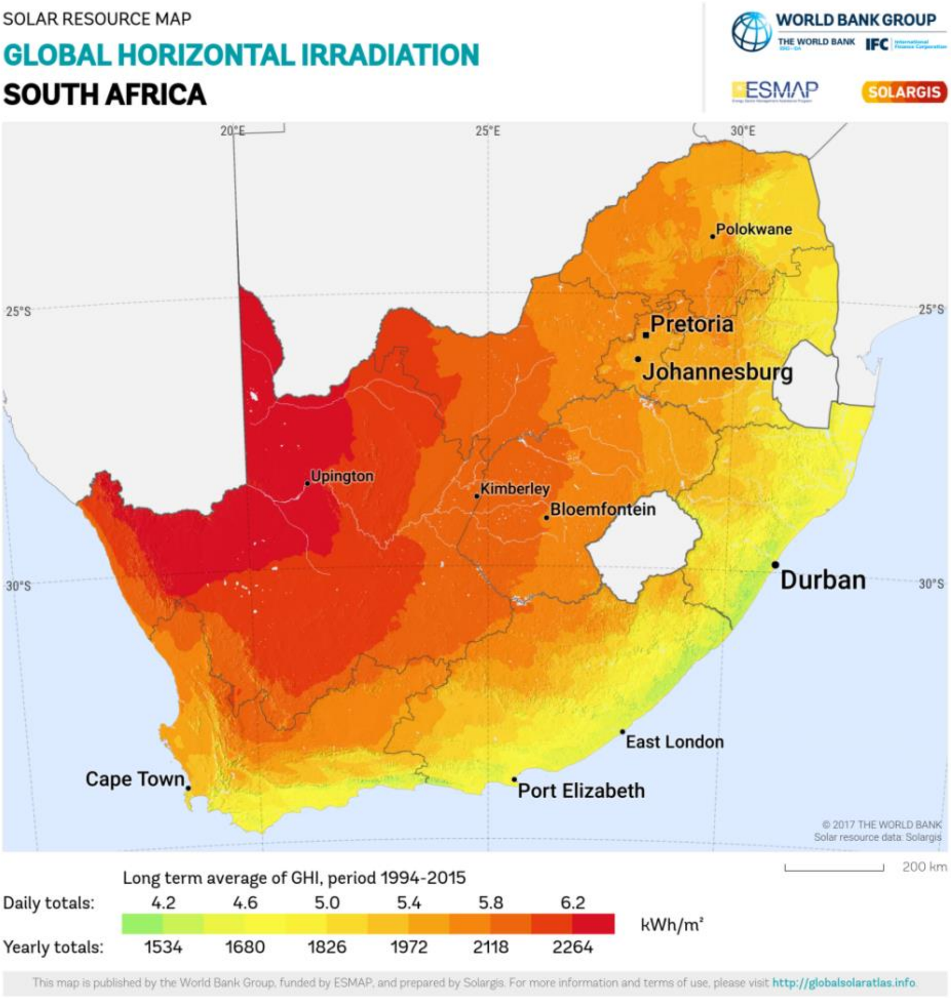

**Figure 3. 3: Global Horizontal Irradiation (GHI), SA (Global Solar Atlas, 2020)**

### 3.2.2 Wind energy

SA exhibits decent wind potential, experiencing significantly higher wind speeds in the coastal regions. The country's yearly wind energy potential is 60 TWh, with average wind speeds of 6 m/s at a 10 m altitude (Sichilalu, Mathaba and Xia, 2017). Figure 3.4 presents the South African Wind Atlas with data collected at an altitude of 100 m. It is evident that around a third of the country, along the South and East coast, is suited for wind exploration, as these areas experience favourable wind speeds above 9 m/s.

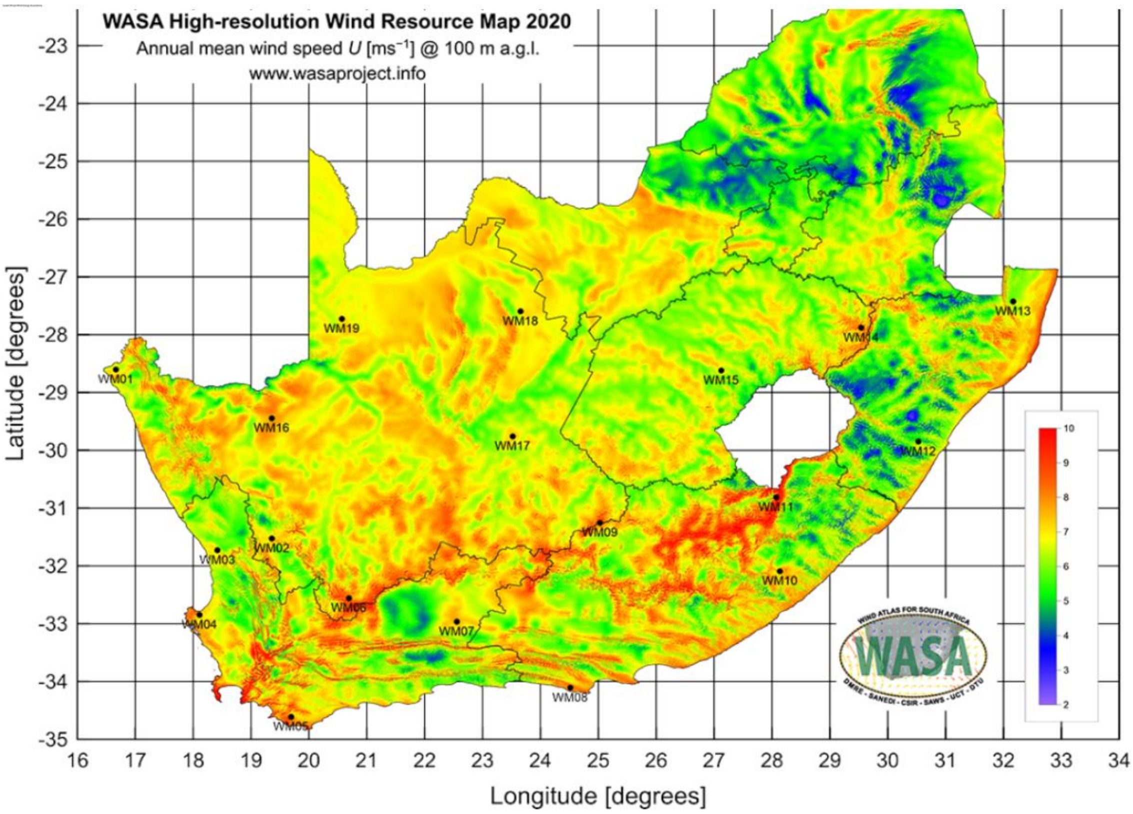

**Figure 3. 4: Mean wind speed (m/s at 100 m) – SA (SAWEA, 2021)**

### 3.2.3 Hydropower

The sun's rays cause water to evaporate from the earth's surface, rise into the atmosphere, and fall to the surface again. This process fills dams and rivers, from which hydropower can be generated. The topography of an area usually determines the flow of these rivers, which ultimately dictates the energy potential from hydro resources (Aliyu, Modu and Tan, 2018).

SA has relatively good potential for hydropower, with the south-eastern coastal areas most suitable for assessing the viability of hydropower projects. However, the country has received less rainfall in recent years, with water shortages becoming an increased concern for policymakers. Therefore, there is a shift of priority which limits the potential and deployment of hydropower (IRENA, 2020). Furthermore, by international standards, except for the 7 MW plant at the Sol Plaatjie Municipality, no substantial development of hydropower has been noted in more than 30 years (Kusakana and Vermaak, 2013). Figure 3.5 is a presentation of the high-water yield areas within the country.

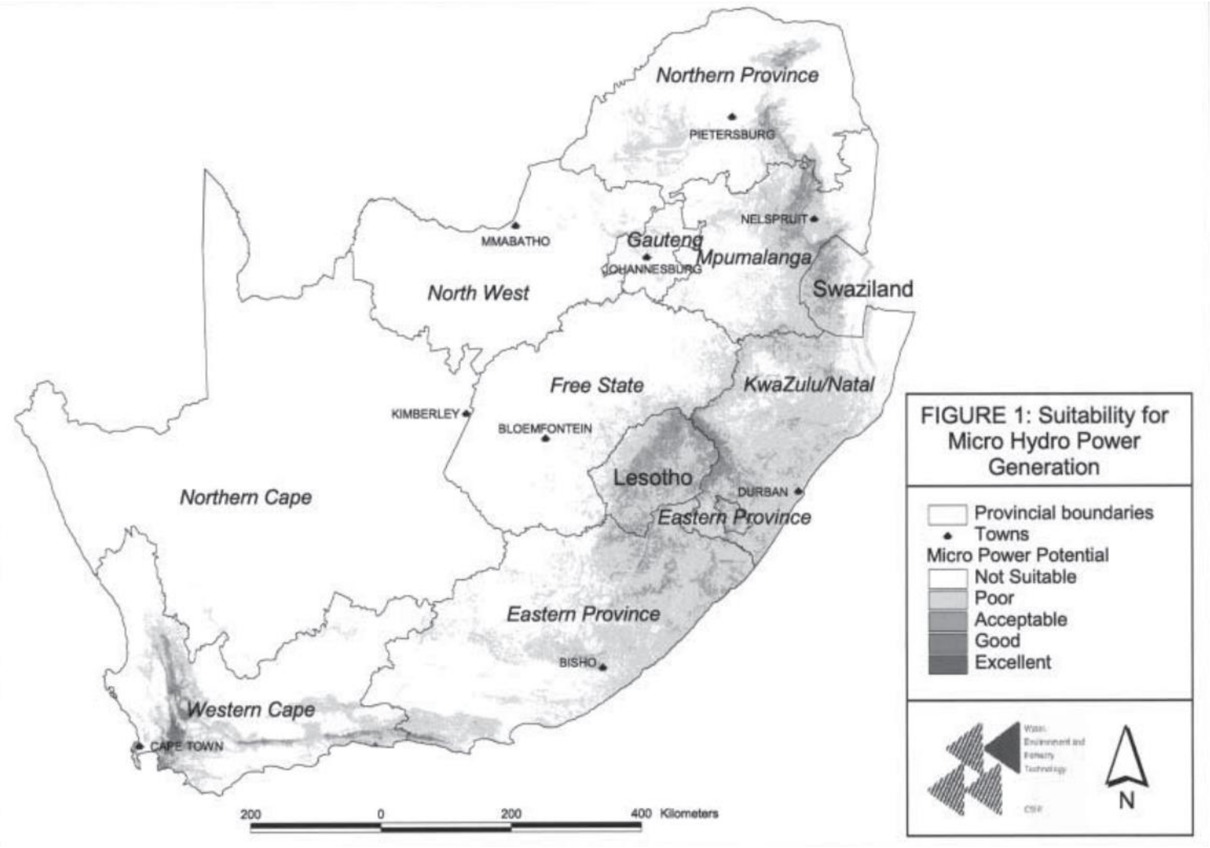

**Figure 3. 5: Micro-hydropower potential, SA (Ballance *et al.*, 2000)**

Eskom maintains around 3.4 GW of installed hydropower in SA, of which more than half is pumped storage hydropower (IRENA, 2020). Table 3.1 presents a summary of hydropower potential in SA.

**Table 3. 1: Hydropower potential, SA (Kusakana and Vermaak, 2013)**

| | Size | Installed Capacity (MW) | Estimated Potential (MW) |
|---|---|---|---|
| **Macro Hydropower (>10 MW)** | Imported | 1,450 | 36,400 |
| | Pumped Storage for peak supply | 1,580 | 10,400 |
| | Diversion Fed | | |
| | Dam storage regulated head | -- | 5,200 |
| | Run of river | 662 | 1,520 |
| | | -- | 270 |
| **Small Hydropower (<10 MW)** | Dam storage regulated head and Run of river combined | 29.4 | 113 |
| | Water transfer | 0.6 | 38 |
| | Refurbishment of existing plants | 8 | 16 |
| | Gravity water carrier | 0.3 | 80 |
| **Sub-total for all types** | | 3,730.3 | 53,837 |

| | | | |
|---|---|---|---|
| **Excluding imported from abroad** | | 2 280.3 | 17 437 |
| **Excluding pump storages utilising coal-based energy** | | 700.3 | 7 237 |
| **Total 'green' hydro energy potential** | | -- | **7 237** |

### 3.2.4 Biomass

Biomass is material from plants or animals that are used as fuel to produce electricity or heat. Historically, SA's residential sector has used bioenergy for cooking, heating, on-site power generation, and industrial activities. However, biomass has also recently been used to generate power at a utility-scale. (IRENA, 2020). The Bioenergy Atlas for SA noted the significant potential for future bioenergy deployment for the country. However, the prioritisation of food security, low productivity, and inconsistent annual weather patterns constrain bioenergy development (Hugo, 2016). The Bioenergy Atlas summed up various options for biomass utilisation, with a potential total of 487 PJ/year, as summarised in Table 3.2.

**Table 3. 2: Summary of Biomass potential - South Africa (IRENA, 2020)**

| Source | Mass Potential (Million t/year) | Mass Available (Million t/year) | Energy Equivalent available (PJ/year) | % of total estimated bioenergy potential |
|---|---|---|---|---|
| **Waste agricultural products** | 36.2 | 5.8 | 58 | 11.9 |
| **Sugar cane bagasse/residues** | 10.4 | 0.6 | 6 | 1.2 |
| **Plantation residue** | 6.7 | 1.5 | 18.8 | 3.9 |
| **Sawmill waste** | 3.1 | 1 | 9.9 | 2 |
| **Invasive species** | 11.3 | 8.1 | 118.6 | 24.3 |
| **Fuelwood** | 14 | 4 | 58.8 | 12.1 |
| **Organic solid waste/sewage** | 9 | 8.1 | 81 | 17 |
| **Purposefully cultivated crops** | 9.3 | 9.3 | 136.1 | 27.9 |
| **Total** | | | **487.2** | **100** |

*Note that the total potential of biomass utilisation for power generation, excluding purposefully cultivated crops for food security, amounts to 350 PJ/year.*

### 3.3 Solar energy technologies

There are three primary technologies used to harness energy from the sun. The first is solar PV energy, where sunlight is converted directly into electricity. The second technology, solar thermal processes, involves concentrating solar energy utilising collectors to vaporise fluids and create steam to drive electric turbines. The third technology, known as solar cooling and heating systems (SHC), collects thermal energy for air conditioning or water heating (Settino *et al.*, 2018). Figure 3.6 presents a basic classification of the three primary solar energy technologies.

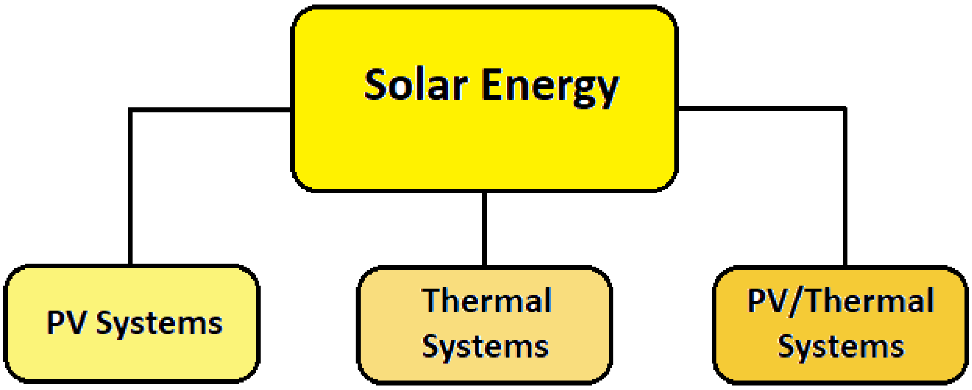

**Figure 3. 6: Classification of solar energy technologies**

### 3.3.1 Solar PV systems

PV systems contain cells that convert solar radiation directly into electricity. Inside each of these cells there are layers of a semi-conducting material. Sunlight falling on the cells creates an electric field across the layers, which induces the flow of current. Power generated by the solar cells is proportional to the intensity of the solar radiation. The basic components of a generic PV system include:

- PV panels that may be connected either in parallel or series.
- An MPPT (maximum power point tracker) that enables efficient operation at maximum power.
- An inverter that converts DC generated by the PV array to AC for local use or injection into the grid.

The equivalent circuit of a primary solar cell is modelled as a current source with a parallel diode, as presented in Figure 3.7.

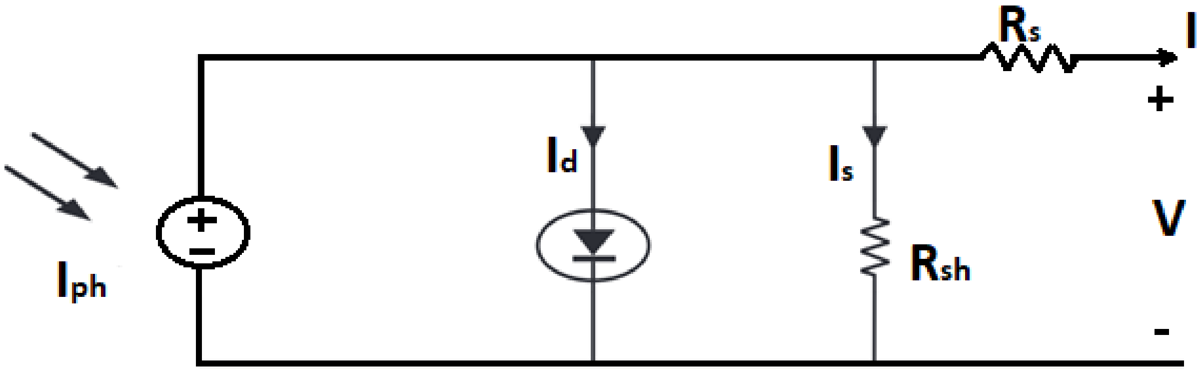

**Figure 3. 7: One-diode model of a PV cell**

The evolution of PV technology depends on the materials used and the development of their structure. The primary semiconductor elements of a PV panel will continue to be solar cells linked in series or parallel.

A study by Razykov *et al*. (2011) on solar PV electricity concludes that three generations of PV cells are distinguishable: crystalline silicon, thin-film technologies comprising Ci(G)S, CdTe, a-Si, and PV cells based on a double junction, triple junction, and organic materials (Settino *et al.*, 2018).

The first generation of PV cells comprised a raw material known as silicon. Silicon is a semiconductor known for its non-toxicity and excellent stability under external ambient conditions. The most developed PV technology commercially is monocrystalline silicon cells, which have the best efficiency of conventional silicon cells. However, the drawback of these PV cells is that the production process wastes 50% of the high-purity silicon (Settino *et al.*, 2018). Furthermore, the vast material needed during manufacturing results in a high cost of the final product.

The manufacturing process for polycrystalline silicon cells is less complicated than for monocrystalline silicon cells, resulting in lower amounts of wasted silicon and thus a reduced final cost. However, its multi-crystalline structure and additional defects result in reduced efficiency. Consequently, larger areas are required for an equivalent energy output (Settino *et al*., 2018).

In order to reduce manufacturing costs as far as practically possible, optimisation of the material used is key, which explains the intensive research on thin-film solar cells. A layer typically less than 10µm makes it more flexible, lightweight, and significantly thinner than crystalline silicon panels. Furthermore, these solar cells require a reduced amount of semiconductor material as they have a higher absorption coefficient, which results in reduced costs (el Chaar *et al*., 2011). As a result, four thin-film cells emerged: thin poly-crystalline silicon, amorphous cell, copper indium diselenide, and cadmium telluride (el Chaar *et al*., 2011).

One of the first thin-film technologies is amorphous silicon (a-Si), which differs from crystalline silicon in that its silicon atoms are distributed at random within the material. Its electrical properties are thus impacted, with the bandgap energy rising to 1.7 eV as opposed to 1.1 eV for crystalline silicon. A larger bandgap allows for improved absorption of the visible part of the spectrum relative to the infrared part. As a result, this technology presents an efficiency of up to 13.4%, depending on whether it is installed and used inside or outside of laboratory conditions (Settino *et al.*, 2018).

The third generation of solar cells is manufactured from a more comprehensive range of materials; some developed from new concepts. An example is emerging concepts based on nanotechnologies, including carbon nanotubes, hot carriers, and quantum dots.

An up-and-coming technology is multi-junction cells, utilising layers of diverse material with different bandgap energies. This technique increases the wavelength spectrum which is effectively converted into electricity, reducing thermal losses. Despite the remarkable efficiency of these cells, which may reach 40%, the production process is still relatively expensive. Therefore, the application is currently promoted with concentrated applications, utilising a reduced surface area (Settino *et al.*, 2018).

Another PV technology currently in development is utilising organic cells made from semiconducting organic polymers. Despite a low efficiency of 3-4%, this technology is considered due to its low cost, established manufacturability, and possible further improvement by forming multi-junction cells (Settino *et al.*, 2018). Table 3.3 provides a summary of the key properties of the various solar cell technologies.

**Table 3. 3: Main characteristics of solar cell technologies (Razykov *et al.*, 2011)**

| Generation | Technology | Commercial Cell Efficiency (%) | Laboratory Cell Efficiency (%) | Market Share | Average Model Cost ($/W) | Technology Readiness Level |
|---|---|---|---|---|---|---|
| **First** | Monocrystalline silicon | 15-19 | 25 | 24 | < 1.4 | H |
| | Polycrystalline silicon | 13-15 | 21.25 | 65 | < 1.4 | H |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Second** | Amorphous silicon thin Film | 5-8 | 13.4 | 1.4 | 0.8 | H |
| | CIS/CIGS thin-film | 7-11 | 20.4 | 2.6 | 0.9 | M |
| | CdTe thin-film | 8-11 | 19.6 | 6 | 0.9 | L |
| **Third** | Organic | 3-4 | 11.1 | N/A | N/A | R&D |
| | Multi-junction | 25-30 | 40 | N/A | N/A | L |

### 3.3.2 Solar thermal systems

Solar thermal energy systems use solar thermal collectors to capture solar energy and transform it into heat. These systems are used in many applications, including water heating, space heating, cooling and heat for the generation of power. For power generation, solar thermal systems often have conversion efficiencies that are substantially higher than that of solar PV systems due to the photon absorption limit.

A concentrating solar collector comprises a receiver, concentrator, and tracking unit. These collectors use a reflecting or refractive surface, such as glass, to reflect incident solar beams onto a reduced surface. Concentrators can be classified as point-focusing or line-focusing systems. Point-focusing concentrators include central receivers (see Figure 3.8) and parabolic dish collectors. Examples of line-focussing concentrators include linear Fresnel reflectors, compound parabolic concentrators, and parabolic trough collectors.

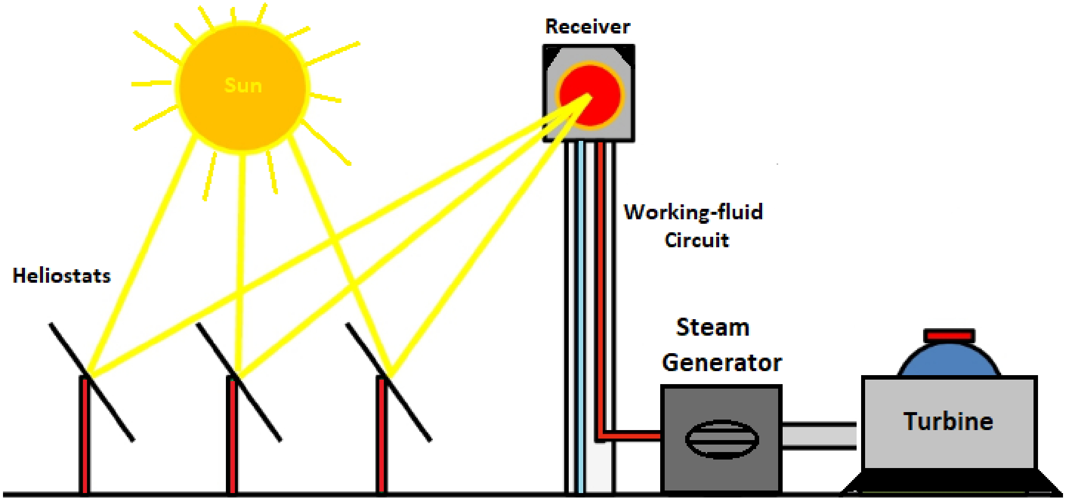

**Figure 3. 8: Schematic representation of a solar central receiver**

Four generations can be distinguished amongst solar thermal technologies. The original generation of solar collectors, known as "flat-plate" collectors, are typically made of copper or aluminium tubes covered with absorber plates, which are relatively effective with higher temperatures (18°C and more). However, problems arise during colder periods, as these collectors are not as efficient with heat management as other collector types. Furthermore, installing newer generation panels is much easier than flat plate panels. A study by Tong *et al.* (2019) revealed that the efficiency of flat-plate collectors could be improved by 20% if aluminium oxide ($Al_2O_3$) nanofluids are used instead of water.

The second generation of collectors has improved efficiency and is generally easier to manufacture compared to flat-plate solar collectors (Seme *et al*., 2020). The third generation comprises double-layer glass tubes used as heat-pipe solar collectors. Although these solar collectors are simple to produce, the double-layer glass tubes enclosing the absorber have the adverse result of reduced solar energy.

Modern solar collectors are frost-resistant, extremely effective in all weather situations, and have low thermal inertia. They also include one thick sheet of glass surrounding all active collecting pieces. Consequently, the heating fluid's temperature increases speedily, allowing the collector to use heat even during brief periods of sunlight (Seme *et al*., 2020).

### 3.3.3 Photovoltaic thermal systems

Excessive working temperatures of solar cells are unfavourable for the operation of the cells, accelerating the degradation of their electrical properties. Sufficient waste heat discharge can reduce these solar cells' operating temperatures and extend their lifespan. Solar cells can be cooled by a heat exchanger that exposes the surface area of the cells to a cooling medium, reducing its temperature (Seme *et al*., 2020). The waste heat can be utilised in applications like low-temperature heating systems that produce both thermal energy and electrical energy and are known as "photovoltaic thermal" or PV-T systems (G. Li *et a*l., 2018). Figure 3.9 presents a schematic diagram of a PV-T system.

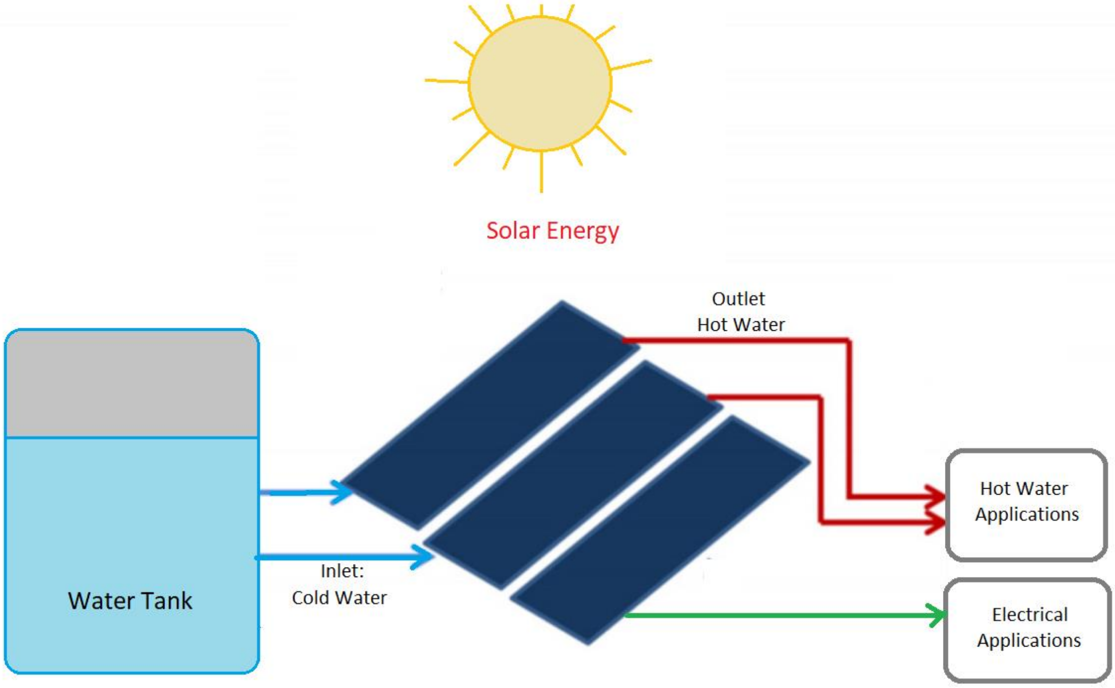

**Figure 3. 9: Schematic of a PV-T system**

Compared to standalone PV modules and solar collectors, the PV-T hybrid configuration has a considerable boost in conversion efficiency of solar energy into useable energy while using a smaller surface area.

### 3.4 Wind energy technologies

Wind is one of the most promising RE resources from which energy can be harvested and used. It can be used directly to generate mechanical power or indirectly by transforming its kinetic energy into electrical energy. This resource is also favourable regarding social acceptance, ranking second after solar (Kaldellis and Zafirakis, 2011). However, the unpredictable nature of wind speed and direction makes forecasting difficult (Yesilbudak, Sagiroglu and Colak, 2012) and remains one of its leading barriers to being selected as a RE resource. Furthermore, there are some minor adverse effects regarding wind power generation, including noise pollution, visual constraints, and climatic effects, though these are relatively small compared to fossil fuels (Leung and Yang, 2012).

The turbine is the key component in a wind energy conversion system, as it converts the kinetic energy of wind into mechanical energy, which can be used for a variety of purposes (Kumar *et al.*, 2016). The size and design of a wind turbine are its most crucial features, as maximum wind capture at minimum cost is the primary motive in wind turbine research (Kumar *et al.*, 2016). The amount of power, P, that a wind turbine can absorb is given by Equation (3.1) as:

$$P = \frac{1}{2} C_p \rho A v^3 \tag{3.1}$$

where $C_p$ is the power coefficient, $A$ is the area swept by the turbine, $P$ is the density of air and $v$ is the wind speed. The power coefficient is a function of the tip speed ratio $\tau$ (Tau), which represents the aerodynamic efficiency of the wind turbine, defined as:

$$\tau = \frac{\omega R}{v} \tag{3.2}$$

Where $\omega$ is the rotational frequency, $R$ is the radius of the turbine, and $v$ is the wind speed. Solidity (σ), is the relation between the swept area of the turbine and the blade area, and has different definitions, dependent on the type of turbine (Eriksson, Bernhoff and Leijon, 2008). Modern wind turbines are divided into two categories: vertical axis wind turbines (VAWT) and horizontal axis wind turbines (HAWT).

For a HAWT, the solidity is defined as:

$$\sigma = \frac{\beta c}{\pi R} \tag{3.3}$$

For a VAWT it is defined as:

$$\sigma = \frac{\beta c}{R} \tag{3.4}$$

For both equations, $R$ represents the radius of the turbine, $\beta$ represents the number of blades, and $c$ represents the chord length.

### 3.4.1 Horizontal axis wind turbine

Pioneered by Poul la Cour in Denmark in 1891 (Hau, 2006), HAWTs have greater efficiency and increased energy output compared to VAWTs and currently dominate the wind industry. HAWTs are usually configured with a two or three-blade configuration. The latter setup is preferred due to its symmetrical loading, which unfortunately also translates into an increased cost of around 50% compared to the two-blade system (Mittal, Sandhu and Jain, 2010).

The conventional HAWT setup requires a solid foundation for mounting a large tower. The tower is erected to position a rotor at a high altitude for increased generation output as the quality and quantity of the wind improve at a higher altitude (Kumar *et al.*, 2016). The tower supports a nacelle containing the generator, gearbox, power electronic units, and yaw mechanism. The generator transforms the rotor's mechanical energy into electrical energy, while the gearbox converts low rotor speeds (typically less than 100 RPM) to higher operating speeds for the generator (typically 1000-3,600 RPM). The nacelle can harness maximum energy as it rotates in relation to the wind's direction (Kumar *et al.*, 2016). The HAWT system is completed with rotating blades located on top of the tower, as presented in Figure 3.10.

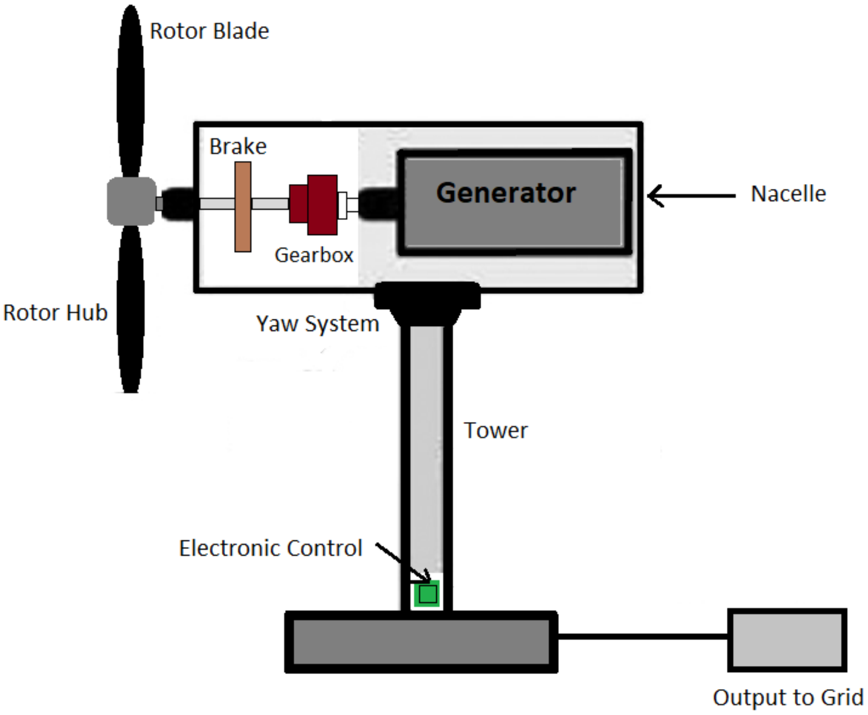

**Figure 3. 10: Horizontal Axis Wind Turbine system**

### 3.4.2 Vertical axis wind turbine

The vertical axis wind turbine was the first turbine utilised for harnessing energy from the wind. However, the technology got disregarded due to an initial belief that these turbines were not practical for generating significant amounts of electricity. Though HAWTs continued being the centre of wind energy research in recent decades, parallel research on VAWTs continued on a reduced scale, with researchers focussing on optimal conditions, techniques, and configurations for the efficient operation of the turbines (Aslam Bhutta *et al.*, 2012).

VAWTs generally have a smaller power output relative to HAWTs, as they are installed closer to ground level, where they are exposed to less wind energy. Therefore, these wind turbines have to be produced in greater sizes, which requires more material at a greater cost to compete with HAWTs' power outputs (Kumar *et al.*, 2016). However, VAWTs are still competitive in the market as they do have some advantages over HAWTs.

According to the literature, locations with high wind speeds and turbulent wind conditions are favourable for using VAWTs for electricity generation, where typically HAWTs are not suitable for efficient operation (Aslam Bhutta *et al.*, 2012). VAWTs also have low noise levels, making them suitable for installation in urban areas, and are omnidirectional with lower cut speeds, resulting in power output even at low wind speeds (Kumar *et al.*, 2016). Furthermore, with an omnidirectional turbine, there is no need for a yaw system, which includes an expensive drive mechanism that could malfunction when in operation.

The VAWT is equipped with a vertical rotation axis which makes the installation, operation, and maintenance of the turbine easy, as it allows for the generator to be placed at the base of the tower (Eriksson, Bernhoff and Leijon, 2008). Furthermore, since the nacelle is excluded for a VAWT, the tower is lighter, which reduces structural loads and issues during the erection of the tower (Brothers, 1998).

Currently, there are some issues with VAWT designs, such as low-efficiency, a low starting torque, blade lift forces, and poor building integration. However, engineers are creating novel design strategies to address these issues. Table 3.4 presents a comparison between the horizontal axis wind turbine and the vertical axis wind turbine.

**Table 3. 4: Comparison of HAWT and VAWT**

| | **Horizontal Axis Wind Turbine** | **Vertical Axis Wind Turbine** |
|---|---|---|
| Tower Sway | Large | Small |
| Yaw Mechanism | Yes | No |
| Overall Formation | Complex | Simple |
| Self-starting | Yes | No |
| Location of generator | Elevated | Ground level |
| Ground clearance | Large | Small |
| Operation space of blade | Large | Small |
| Noise level | Relatively High | Less |
| Obstacle to birds | High | Less |
| Direction of wind | Dependent | Independent |
| Efficiency (ideal) | 50 - 60% | > 70% |

### 3.4.3 Synchronous generator

The salient pole generator is generally used in wind energy conversion systems (WECS) as it has a higher number of poles, allowing for power generation at lower wind speeds (Mirecki, Roboam and Richardeau, 2007). The permanent magnet synchronous generator (PMSG) has the advantage of increased efficiency and requires less maintenance, as it has no slip rings. Furthermore, the PMSG has a lower weight and is more stable than the asynchronous generator. As depicted in Figure 3.11, the synchronous generator can be coupled with or without a gearbox. A gearless PMSG system requires the selection of multiple poles in order to operate at a lower rotational speed. A reduced weight, together with the option of gearless operation, makes this topology a viable option, as a lower weight placed on the tower is a significant advantage (Hossain and Ali, 2015).

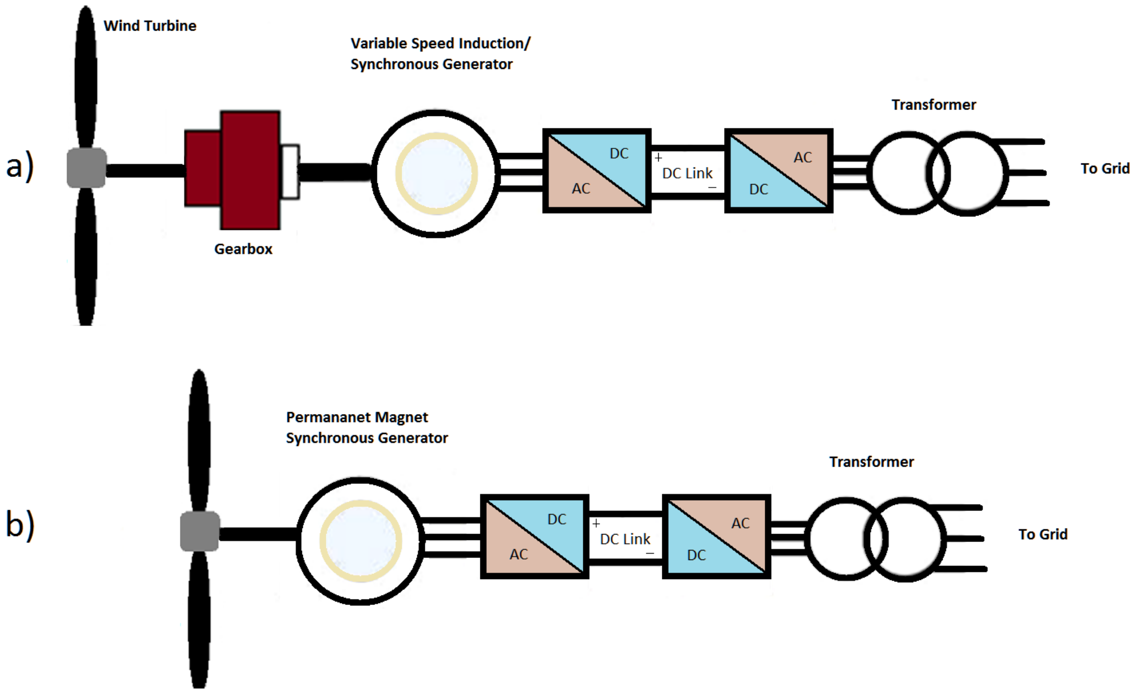

**Figure 3. 11: (a) Variable speed synchronous generator with power converter, (b) Variable speed, gearless, multi-pole PMSG-based WECS**

### 3.4.4 Asynchronous generator

The asynchronous (induction) generator has a brushless structure and is widely used in the WECS due to its ruggedness and lower cost (Mesemanolis, Mademlis and Kioskeridis, 2013). As depicted in Figure 3.12, fixed-speed induction generators can be coupled directly to the grid. However, a capacitor bank is necessary to compensate for the reactive power of the inductive generator. Furthermore, a soft-start/current limiting circuit is necessary to limit inrush current during the start-up of these induction generators (Chen, Guerrero and Blaabjerg, 2009).

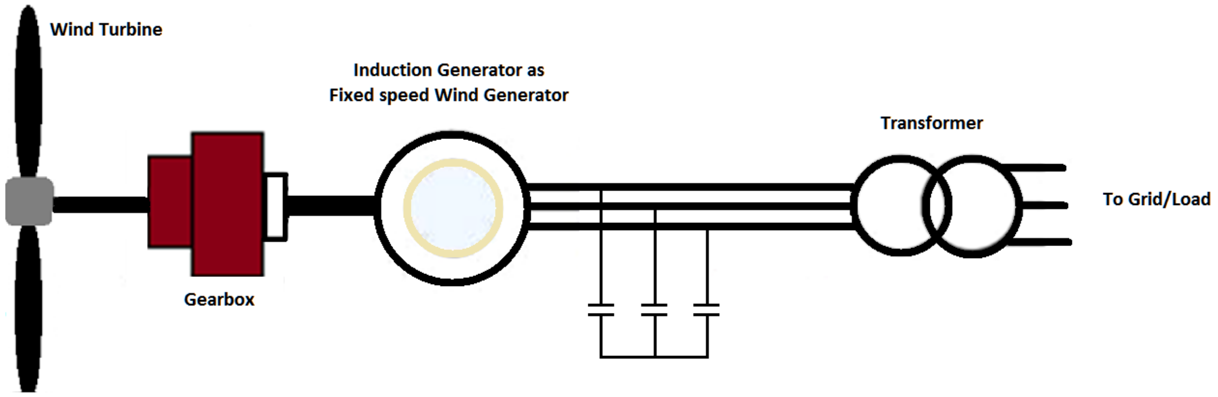

**Figure 3. 12 Fixed-speed induction generator (grid-coupled)**

### 3.4.5 Onshore wind turbines

Onshore wind turbines are installed on land and have rotor diameters that range from 50 to 100 metres, and tower heights between 50 and 100 metres. Modern turbines operate on a motor assembly speed of between 12-20 RPM, significantly lower than previous generation turbines, which generally ran at 60 RPM. Furthermore, using higher poles and extended blades also results in effective power generation at much lower wind speeds (Kumar *et al.*, 2016). These turbines are typically grouped in wind power plants with an output range of 5-300 MW.

### 3.4.6 Offshore wind turbines

Offshore wind turbines are installed in bodies of water, usually out at sea, where the wind blows more consistently and at higher speeds than on land. Higher capacity power plants utilising larger turbines can be deployed at offshore wind sites, which explains the increased interest and development of these turbines in recent years (Chen *et al.*, 2009). This technology, matched with offshore turbines, is very similar to onshore turbines, with only some minor discrepancies.

The major variation lies with the foundations of the turbines. With offshore turbines, towers are submerged under water, which requires special foundations. For deeper waters, manufacturers in recent times create floating turbines. For example, the SWAY RE firm in Norway has created a floating turbine operational at a water depth of 100-400 m. Another company, Statoil Hydro, is developing a turbine based on floating concrete, similar to those used in installations in the North Sea, designed to operate at a water depth of 700 m (Kumar *et al.*, 2016). Figure 3.13 presents some of the most common forms of offshore wind turbine foundations.

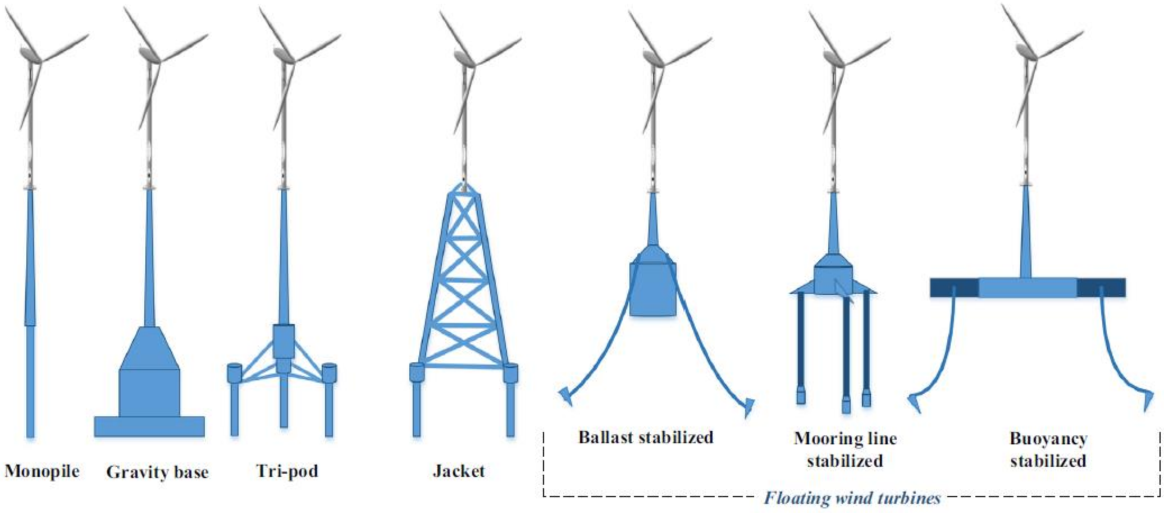

**Figure 3. 13: Different offshore wind turbine foundation types (Edenhofer *et al.*, 2011)**

### 3.5 Hydropower technologies

Hydropower, a relatively mature technology compared to other RE generation options, is power made available through the movement of water. Water runs via a channel to a waterwheel and strikes the wheel's bucket, resulting in the rotation of its shaft. The rotating shaft connects to an alternator or generator, which generates electricity, known as "hydroelectric" power. Though initial construction costs are high, the advantages of hydroelectric power plants are the low maintenance and low operating costs coupled with no running fuel cost (Manzano-Agugliaro*et al.*, 2017). The leading technologies currently used in hydropower plants are (Elbatran, Abdel-Hamed, *et al.*, 2015):

- Pumped storage.
- A dammed reservoir.
- In-stream technology.
- Run-of-river.
- Gravitational water vortex power plant.

The general equation for a hydropower system is given by:

$$P = \eta \rho g Q \mathrm{H} \tag{3.5}$$

where $\eta$ is the turbine's hydraulic efficiency, $P$ is the turbine's mechanical power (W) generated at the shaft, $\rho$ is the water volume density (kg/m$^3$), $g$ is the gravitational acceleration (m/s$^2$), $Q$ is the flow rate (m$^3$/s) passing through the turbine, and $\mathrm{H}$ is the effective pressure head of water (m) across the turbine (Elbatran, Yaakob, *et al.*, 2015). The installation of small and large hydropower plants with dams, utilising electrical control components and large turbines, proves very expensive and harms the environment. The objective of economical, clean electricity for rural countries is thus defeated with this costly equipment (Laghari *et al.*, 2013). Therefore, the need for using basic turbines to obtain the lowest possible cost is prominent in recent publications.

Using micro-hydropower (MHP) systems with a modern design and arrangement of electrical equipment is a more practical and economical approach for hydropower deployment. MHP is a branch of hydropower, characterised only by the installed capacity of the plant. A 100 kW installed capacity appears to be the upper limit referred to in the definition of MHP, however, there is no agreement on what this maximum should be (Kaunda, Kimambo and Nielsen, 2014). Using upgraded turbines may be the perfect solution to overcome operational and economic challenges, as the total installation and running cost of these hydropower plants will be significantly reduced. This section on hydropower technologies will focus exclusively on the different types of hydropower turbines utilised at micro-scale hydropower plants.

In a MHP system, water flows down a penstock and hits a turbine, causing it to rotate and generate mechanical power that is transformed into electrical power by a generator installed inside the powerhouse (see Figure 3.14). The components of a MHP plant can be divided into civil structures, generating apparatus, and a transmission system. These groups are presented in Table 3.5.

**Table 3. 5: Components and structures of a micro-hydropower plant**

| | |
|---|---|
| **Civil Structures** | Canal, weir, settling tank, penstock, forebay, valves. |
| **Generating equipment** | Power control system, electric generator, turbine, generator-turbine coupling system. |
| **Transmission system** | Electric poles, transformers, wires, switches, and related electronic components. |

Figure 3.14 illustrates the traditional method of generating hydropower through head and flow, in which water is fed into the turbine via a penstock. A portion of the river can be diverted to the MHP project, or water can be dammed into a reservoir. The former arrangement is referred to as a "run-of-river system", which is the most popular MHP technology (Kaunda, Kimambo and Nielsen, 2014).

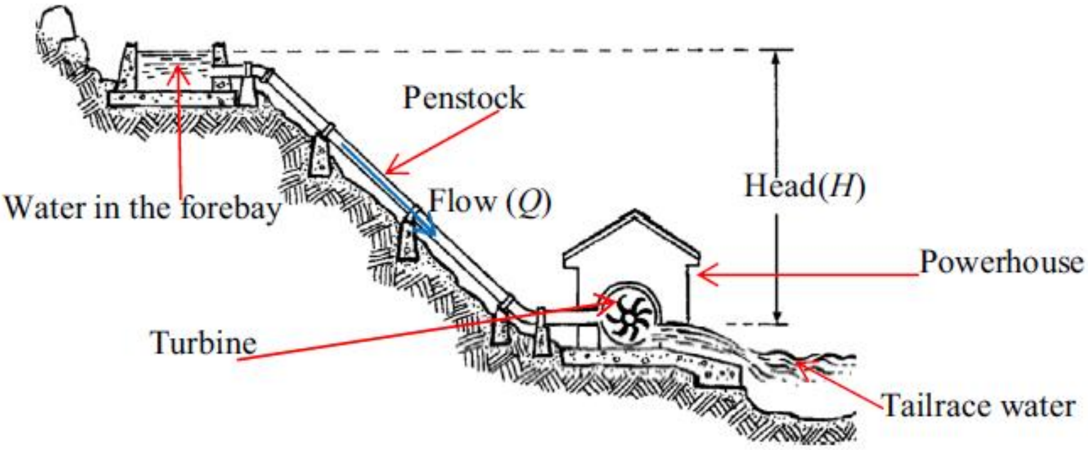

**Figure 3. 14: Micro-hydropower technology operating on head (CANMET_Energy_Technology_ *et al.*, 2013)**

### 3.5.1 Micro-hydropower turbines

Hydropower turbines are categorised (see Figure 3.15) as either reaction or impulse turbines, for which different types of heads and water flows apply.

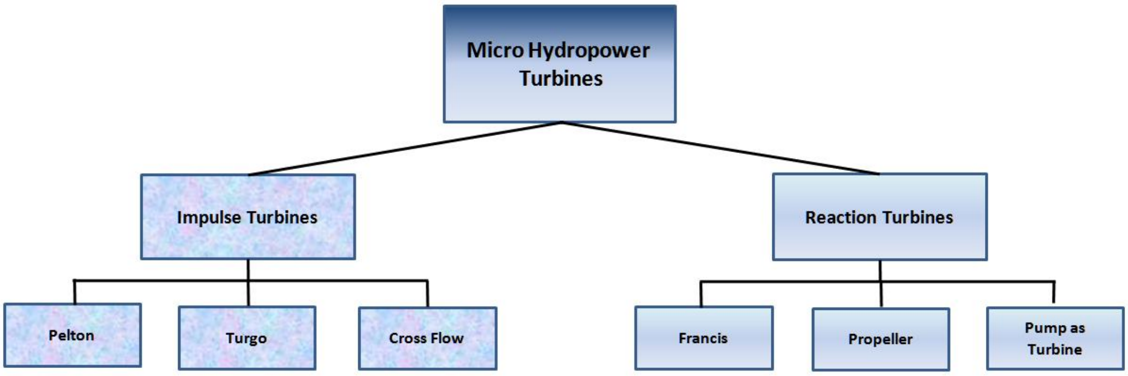

**Figure 3. 15: Classification of micro-hydropower turbines**

### 3.5.1.1 Reaction turbines

With reaction turbines, the runner blades rotate through an upward hydrodynamic force generated by the flow of water, with both velocity and pressure energies extracted from the running water (Kaunda, Kimambo and Nielsen, 2014; Loots *et al.*, 2015). Guide vanes regulate the direction and volume of water flow, acting as spouts for increased speed upon entering the runner blades. Though there are exceptions, these turbines are generally more suitable for low-head hydropower applications (Loots *et al.*, 2015).

#### 3.5.1.2 Impulse turbines

Impulse turbines use runners that rotate when water is jetted onto them at high velocities. When a water jet impacts the runner blade, a change of momentum creates a force on the blade, which causes the turbine to rotate (Kaunda, Kimambo and Nielsen, 2014). The runner is not covered in water; the turbine casing merely leads flow to the tailrace water, guards against water splashing, and protects internal components. Therefore, careful construction of impulse turbines is not as essential as in the case of reaction turbines, resulting in less costly manufacturing. Additionally, these turbines do not need special pressure seals and bearings, pressure relief valves, or specialised pressure cases, which gives it an economic advantage over reaction turbines. Furthermore, unlike reaction turbines, impulse turbines are less sensitive to water quality, favouring their use in areas where water quality is poor (Kaunda, Kimambo and Nielsen, 2014).

Impulse turbines have recently been utilised in lower-head micro-sites despite being more suitable for high and medium-head applications. These systems have become a widely accepted alternative practice in many countries due to their proven efficacy (Paish, 2002). The most common impulse turbines used in MHP systems include the Turgo, Pelton, and Crossflow turbines.

### 3.5.2 Hydrokinetic hydropower

Another method unique to MHP projects generates hydropower by using the kinetic energy of moving water, which eliminates the need for head. Sometimes referred to as “ultra-low head”, “zero-head”, “river-current” or “in-stream” hydropower, this technology is formally known as hydrokinetic hydropower. The turbine of a hydrokinetic MHP system operates similarly to a wind turbine system, which makes it perfect for installation in sections of high current rivers, gates of barrages, and irrigation canals (Kaunda, Kimambo and Nielsen, 2014). Like wind power systems, hydrokinetic MHP technology has low efficiency, with the power coefficient according to Betz's law limiting its output. However, these systems do have some advantages over traditional MHP systems (Kusakana and Vermaak, 2013), including:

- No dam construction is necessary.
- No destruction of land area.
- No alteration of the river’s direction of flow.
- Reduced destruction of fauna and flora.

As aforementioned, hydrokinetic MHP systems work similarly to wind turbines. The difference is that hydrokinetic MHP systems have the potential to retrieve close to a thousand times more energy from the same swept area (Kusakana and Vermaak, 2013). The power available for the system is calculated using the following equation:

$$P_{\mathrm{a}} = \frac{1}{2} \times A \times \rho \times V^3 \times C_\rho \quad (3.6)$$

where $A$ is the area in metres squared ($m^2$), $\rho$ is the water density (1000 $kg/m^3$), $V$ is the water velocity (m/s), and $C_\rho$ represents the power coefficient.

A comprehensive assessment of a candidate hydrokinetic MHP site must be performed based on its spatial flow and temporal properties. Existing hydrokinetic MHP water-energy sites are categorised as 1) canals and pumping stations, 2) rivers and streams, 3) piping systems, 4) tailrace flows from the power station, 5) wastewater hydropower, and 6) tidal energy (Zhou and Deng, 2017).

According to Betz's Law, using a power coefficient of 0.592 (59%), the river’s theoretical maximum power capacity is presented by Equation (3.6). However, a small-scale river turbine has a reduced power coefficient to the order of 0.25 (Kusakana and Vermaak, 2013).

### 3.6 Biomass energy

Biomass is biological material that stores energy through the photosynthesis process. Various conversion technologies can be used to transform it into a variety of energy types. Energy derived from biomass feedstock is termed “bioenergy”. There are three primary process technologies, each with several processing steps, that can be used to transform raw biomass into usable energy: bio-chemical, thermo-chemical, and physio-chemical (Adams *et al.*, 2018). Bio-chemical conversion includes two conversion processes: fermentation, where biomass is converted to ethanol, and anaerobic digestion, where biomass is converted to biogas. With thermo-chemical conversion, there are six main process options: combustion, pyrolysis, co-firing, gasification, liquefaction, and carbonisation (Patel, Zhang and Kumar, 2016). Physio-chemical conversion primarily entails a process of extraction, where oilseeds are crushed to extract oil. The main technology options for converting biomass into energy are briefly discussed below.

#### 3.6.1 Anaerobic digestion

Anaerobic digestion (AD) is a process through which complex organic waste is broken down by bacteria to produce biogas. Biogas is a versatile secondary energy carrier, which may be utilised for electricity or as fuel for heat generation. The AD process comprises three main stages: methanogenesis, fermentation, and hydrolysis (Cantrell *et al.*, 2008). Hydrolysis is a process where complex compounds are broken down into soluble components, preparing them for fermentation, where fermentative bacteria convert them into acetic acids, alcohols, and off-gas containing $H_2$ and $CO_2$. These products are metabolised into primarily $CO_2$ (30-40%), $CH_4$ (60-70%), and various other gases by methanogens (Cantrell *et al.*, 2008). Figure 3.16 presents the flow diagram of the basic AD process.

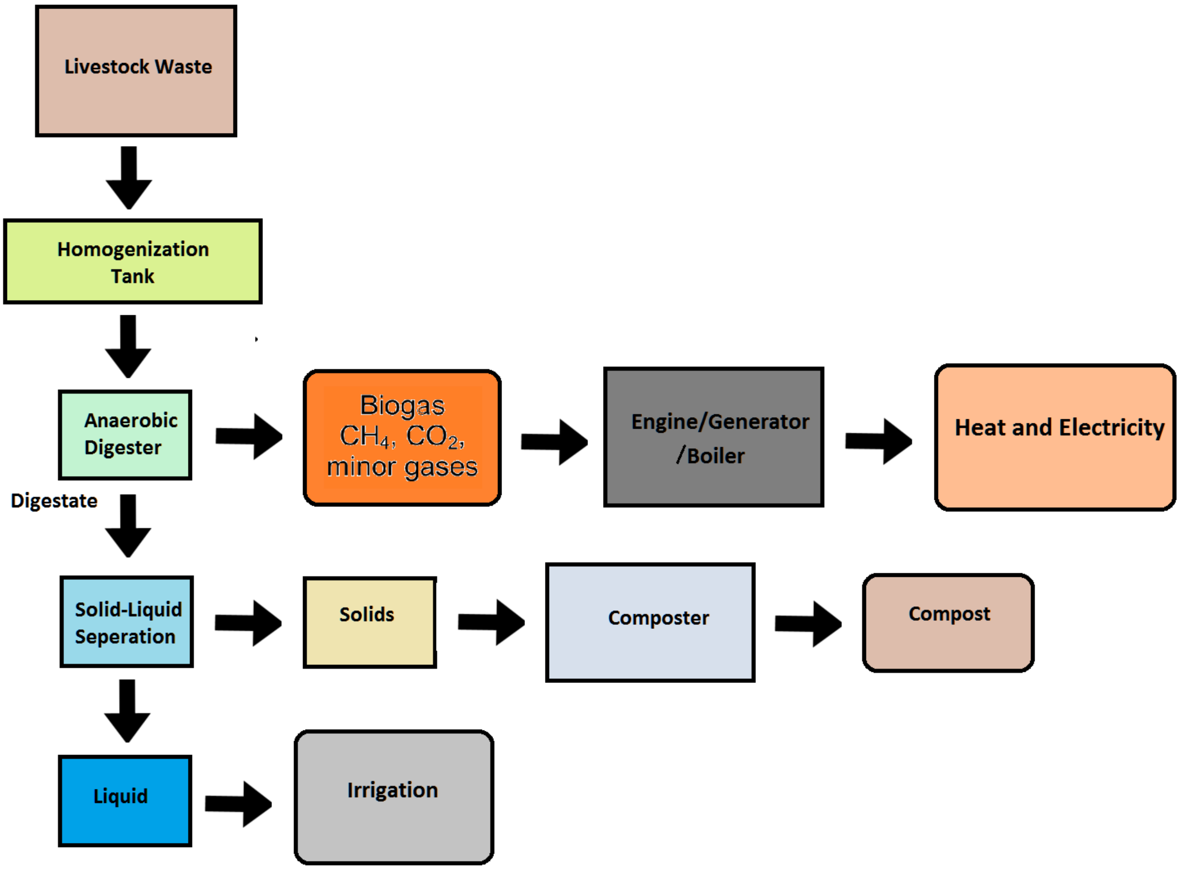

**Figure 3. 16: Anaerobic digestion flow diagram**

Biogas is produced in small-scale installations on farms and on a large-scale in landfill and sewage gas plants, where it is primarily used for power generation. However, electricity production also generates waste heat, which can be used as process heat or for residential and commercial benefits (Strzalka, Schneider and Eicker, 2017).

Biogas can be stored and used for electricity production during demand peaks, making biogas plants suitable for demand-driven generation, as these plants can start up relatively quickly (Strzalka, Schneider and Eicker, 2017). The modern biogas plant is built to address various economic, environmental, and social needs and is acknowledged as a substantial contributor to reducing GHGs through the use of bioheat, biofuel, and bioelectricity (Swaaij, Kersten and Palz, 2015).

### 3.6.2 Pyrolysis

Pyrolysis is a thermo-chemical technology that involves material thermal decomposition at elevated temperatures in the absence of oxygen. When lower processing temperatures, modest heating rates, and lengthier residence times are used, the process is known as “slow pyrolysis”, which is used for charcoal production. This process operates at a temperature of around 500°C, with a residence time of several hours (Suopajärvi, Pongrácz and Fabritius, 2013).

Fast pyrolysis is a process that maximises the yield of a liquid product, operating at higher heating rates, while quickly cooling the volatile products. As with the slow pyrolysis process, modest temperatures of around 500°C are employed, though the vapour residence time is short (Suopajärvi, Pongrácz and Fabritius, 2013). The process utilises a small particle size and requires reasonable temperature control. The main benefit of producing liquids from biomass includes an increased intensity of energy. It is also much easier to transport and store the liquid product. Figure 3.17 presents a simplified flowchart of the fast pyrolysis process.

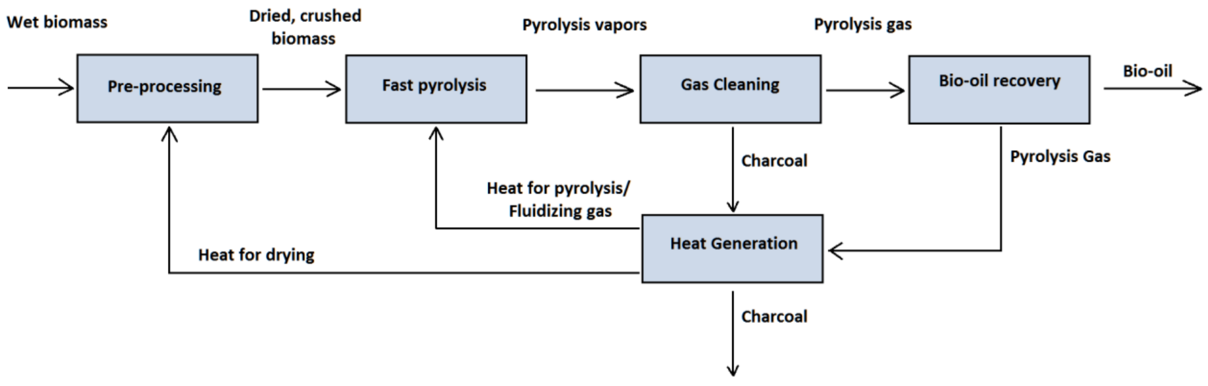

**Figure 3. 17: Simplified process flowchart of the fast pyrolysis process**

### 3.6.3 Gasification

The gasification process involves thermally decomposing biomass using a controlled amount of oxidising chemicals, such as steam, oxygen, or air, into a gaseous mixture known as syngas. This process delivers a gaseous mixture ($CH_4$, $N_2$, CO, $H_2$, and $CO_2$), which depends on the type of gasifier utilised, the gasifying agents, and operating conditions such as the type of feedstock and its level of moisture, equivalence ratio, catalyst, fuel particle size, and operating temperature (Inayat *et al.*, 2020).

There are primarily three types of gasifiers and agents utilised, each with advantages and disadvantages. The first is the fluidised bed gasifier with benefits such as a relatively high biomass-to-gas conversion ratio, uniform heat transfer and mixing, and the fact that it is suitable for large-scale production (Shahbaz *et al.*, 2021). The second is the fixed bed gasifier, which is more suitable for use where biomass has low moisture and ash content and is suited for small-scale use. The third type, the entrained flow gasifier, is not suited for use with biomass as fuel but rather with high-efficiency coal. Figure 3.18 presents a simplified schematic flowsheet of syngas production for electricity generation.

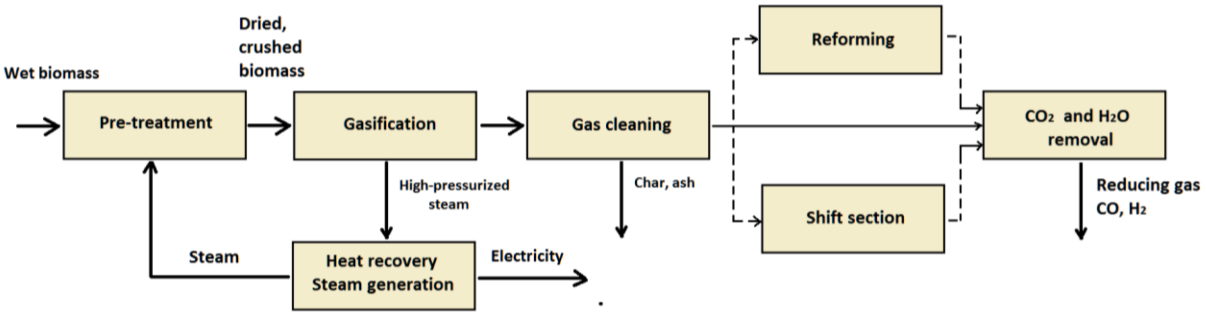

**Figure 3. 18: Simplified process flowchart of syngas production using biomass**

During pre-treatment, the biomass feedstock is dried and crushed in preparation for gasification, where it is converted to syngas. Following this is a gas cleaning process, where $CO_2$ and $H_2O$ are removed from the syngas to ensure adequate reducing ability (Suopajärvi, Pongrácz and Fabritius, 2013).

### 3.6.4 Liquefaction

Direct liquefaction, also known as hydrothermal liquefaction, is a thermochemical process where biomass is converted into liquid fuels. Biomass is processed in a hot and pressurised water setting where the solid bio polymetric structure is allowed to break down to a primarily liquid component, with gaseous, aqueous, and solid by-products (Gollakota, Kishore and Gu, 2018). Typical operating conditions include temperatures between 280°C and 370°C and 10-25 MPA pressures, with ongoing research on fine-tuning these critical operational parameters to improve the yield. The elemental composition of biomass feedstock suitable for direct liquefaction includes hydrogen (H), carbon (C), nitrogen (N), oxygen (O), and sulphur (S). The conversion of biomass into crude-like oil involves a number of complex reactions, therefore, the process mechanism is divided into two categories of feedstock: algal biomass (wet feedstock) and lignocellulose biomass (dry feedstock) (Gollakota, Kishore and Gu, 2018).

Biomass comprises various fragments. As such, lignocellulose can be sub-classified into hemicellulose, cellulose, and lignin (Dimitriadis and Bezergianni, 2017), while algal biomass can be sub-classified into lipids, carbohydrates, proteins, and algaenan. The process flow diagram of the direct liquefaction process, utilising both lignocellulose and algal biomass, is presented in Figures 3.19 and 3.20, respectively, as adapted by Gollakota, Kishore and Gu (2018).

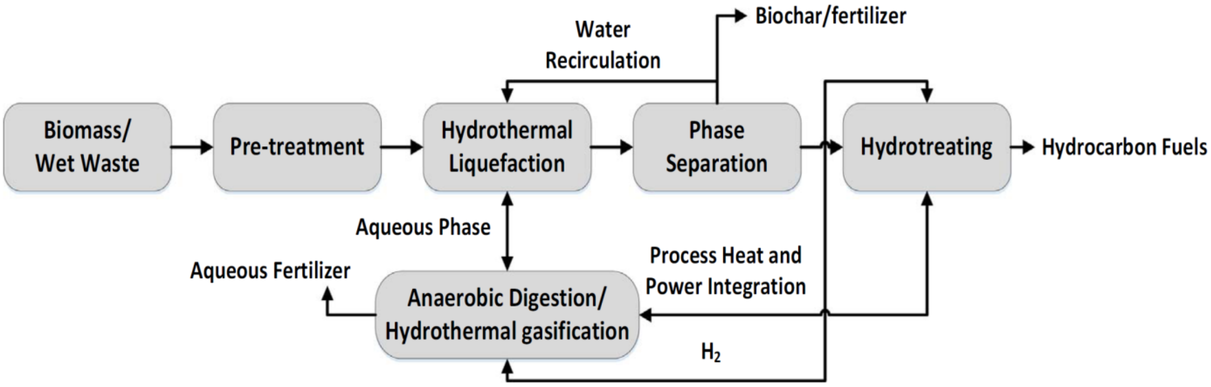

**Figure 3. 19: Process flow diagram of direct liquefaction process of lignocellulose biomass (Biller and Ross, 2016)**

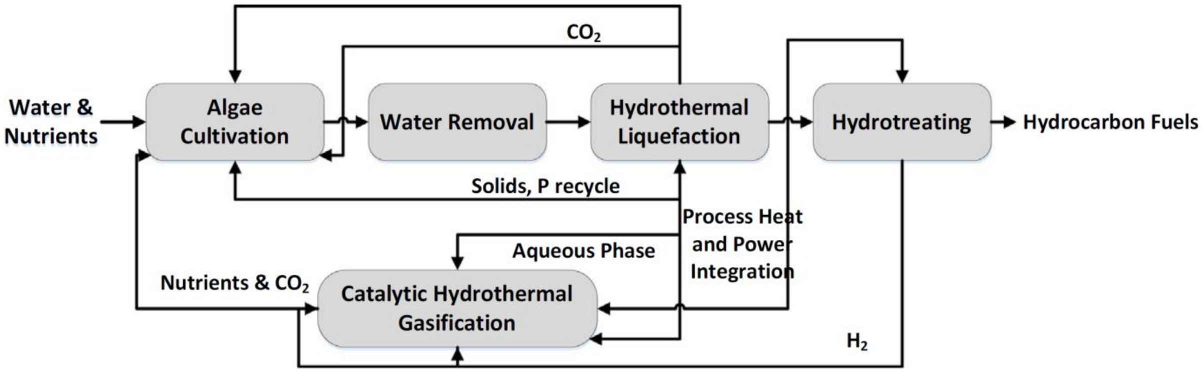

**Figure 3. 20: Process flow diagram of direct liquefaction of algal biomass (Biller and Ross, 2016)**

A summary of the key technology options for converting biomass into energy is presented in Table 3.6.

**Table 3. 6: Summary of different technologies to convert Biomass into energy**

| Conversion technology | Type of Biomass | Fuel examples | Main product | End-use |
|---|---|---|---|---|
| Anaerobic Digestion | Wet biomass | Sewage sludge, manure, vegetable waste | Biogas and by-products | Electricity (gas turbine, engine) and heat (boiler) |

| | | | | |
|---|---|---|---|---|
| Fermentation | Cellulosic material, starches, sugar | Woody biomass, corn, sugarcane | Ethanol | Liquid fuels, chemical feedstock |
| Combustion | Dry biomass | Pellets and chips, wood logs, solid biomass | Heat | Heat and electricity (steam turbine) |
| Co-firing | Dry biomass | Agro-forestry residues (straw) | Heat /electricity | Electricity and heat (steam turbine) |
| Gasification | Dry biomass | Pellets, wood chips, solid waste | Syngas | Electricity (engine, gas turbine) and heat (boiler) |
| Pyrolysis | Biogas, dry biomass | Pellets, wood chips, solid waste | Pyrolysis oil | Electricity and heat |
| Etherification/ Pressing | Oleaginous crops | Oilseed rape | Biodiesel | Transport fuels electricity (engine), heat (boiler) |

### 3.7 Fuel cell technologies

FC technology is gradually becoming a practical alternative to conventional combustion engine generators and batteries, with the stationary sector being the standout performer (Wilberforce *et al.*, 2016). FCs are used in different power capacity applications, ranging from small-scale grid-tied power units for domestic use to islanded backup systems that provide energy to critical infrastructure, and even to MW-scale systems designed as grid-tied power plants (Wilberforce *et al.*, 2016).

Compared to combustion engines, FCs require less maintenance and have no moving parts (except for compressors or pumps in some FC plants), which allows for relatively low-noise and vibration-free operations. In addition, operating temperatures ranging from 70°C to 1,000°C for the low and high temperature technologies respectfully, are much lower than combustion engines, where operating temperatures may reach 2,000°C. Furthermore, FCs provide nearly instantaneous recharge capability compared to conventional battery storage systems (Spiegel *et al.*, 2007; Pei and Chen, 2014). According to Larminie, Dicks and McDonald (2003), FCs are practical for the following:

- Applications with a requirement for emission minimisation (vehicles, airports, industrial facilities and urban areas).
- Management of biological waste gases.
- Applications where the reliability of power is critical (data processing, precision production services, telecommunication, and call centres).
- Applications where access to the grid is limited (remote areas, stationary and portable applications).

The following sub-sections review FC technologies used in stationary applications, ideal for isolated areas.

There are two main categories in which FCs can be classified which depend on the electrolyte used in their working arrangement (type, level of fuel purity, and oxidant) (Akinyele *et al.*, 2020). Furthermore, various fuel-oxidant chemical interactions distinguish the different kinds of FC systems. The most common FCs used in stationary power applications are proton-exchange membrane FCs (PEMFC). However, phosphoric acid FCs (PAFC), alkaline FCs (AFC), molten carbonate FCs (MCFC) and solid oxide FCs (SOFC) are also utilised (Spiegel *et al.*, 2007).

The overall reaction is the same as in Equation (2.1), though the half-reactions at each electrolyte differ. The charge carrier, which is negative for alkaline electrolyte FCs and positive for acid electrolyte FCs, is the primary difference (Wilberforce *et al.*, 2016).

### 3.7.1 Alkaline fuel cell technology

Alkaline FCs operate with pure hydrogen fuel and use an alkaline electrolyte, potassium hydroxide (KOH), with oxygen as the oxidant (Adamson, 2007). When operational, the anode is supplied with hydrogen fuel while the cathode is supplied with oxygen. Current flows as a result of the ion-exchange between the anode and cathode in the liquid KOH (Giorgi, 2013). Potassium titanate, zirconium phosphate, and ceria are some microporous separators used in alkaline FCs (Bagotsky, 2012).

Alkaline fuel cells are categorised as a low-temperature technology due to operating temperatures of 70°C, with Nickel (Ni), instead of the traditional platinum material commonly used as the catalyst. Silver (Ag) and Nickel are utilised as the cathode and anode. Equations (3.7) and (3.8) presents the cathode and anode reactions in alkaline fuel cells (Giorgi, 2013).

$$H_2 + 2OH^- \rightarrow 2H_2O + 2e^- \tag{3.7}$$

$$\frac{1}{2}O_2 + H_2O + 2e^- \rightarrow 2OH^- \tag{3.8}$$

An advantage of alkaline FCs is their relatively high efficiency. Though system-dependent, a single alkaline FC can produce 0.5-0.9 V with an efficiency of up to 65%. Furthermore, output power in the range of 5-150 kW (Giorgi, 2013) can be delivered, with newer systems capable of operating below 70°C (Adamson, 2007).

A major drawback of alkaline FCs is that potassium hydroxide is corrosive. In addition, it is more challenging to seal the anode and cathode gases with a liquid electrolyte than with one that is solid. (Adamson, 2007). Furthermore, potassium hydroxide absorbs $CO_2$, which reduces the electrolyte's conduction power, referred to as "$CO_2$ poisoning". The design of alkaline fuel cells is categorised into three groups: dissolved fuel type, mobile electrolyte, and static electrolyte, and are primarily utilised in submarine and space applications (Giorgi, 2013).

### 3.7.2 Molten carbonate fuel cell technology

The molten carbonate fuel cell utilises molten carbonate salt as an electrolyte and is classified as a high-temperature technology as it utilises liquid carbonate salts such as potassium carbonate, sodium carbonate, and lithium carbonate for operation, which occurs at a working temperature of about 650°C (Adamson, 2007; Bagotsky, 2012). These fuel cells can typically achieve an electrical efficiency of 60%, which can be increased to 80% by using waste thermal energy in a co-generation setup. At the working temperature, salts in the FC melt, forming carbonate ions ($CO_3^{2-}$), which moves to the anode from the cathode and combines with hydrogen to form electrons, carbon dioxide, and water. Direct current and heat are produced when electrons that are gathered at the anode moves to the cathode via an external circuit (Adamson, 2007; Giorgi, 2013). Molten carbonate fuel cells use Ni-5CR and NiO (Li) as electrode materials. Equations (3.9) and (3.10) presents the respective anode and cathode electrode reactions, with Equation (3.11) presenting the overall reaction.

$$H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^- \tag{3.9}$$

$$\frac{1}{2}O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-} \tag{3.10}$$

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \tag{3.11}$$

The molten carbonate FC can improve reaction kinetics through its high-temperature (between 600°C and 800°C) operation, implying that it is possible to conduct electrode reactions at a high rate without using platinum catalysts (Bagotsky, 2012). Furthermore, this FC uses a process known as "internal reforming" to convert light hydrocarbons and methane gas in the fuel to hydrogen, which negates the need for an external reformer. Compared to low-temperature technologies, Molten Carbonate FCs are less susceptible to carbon monoxide poisoning and can efficiently harness the reaction heat of electrical energy production (Adamson, 2007; Bagotsky, 2012). Compared to low-temperature technologies, these advancements result in lower prices.

The electrical power output of molten carbonate FCs, which are typically used for co-generation in decentralized energy systems, ranges from 100 kW to 2,000 kW (Giorgi, 2013). However, a significant shortcoming of the molten carbonate FC is the issue of durability, caused by the high temperature involved in the operation of the cells, which ultimately results in reduced performance (Akinyele, Olabode and Amole, 2020).

### 3.7.3 Solid oxide fuel cell technology

The solid oxide fuel cell (SOFC) uses zirconium oxide as an electrolyte. Zirconium oxide is a non-porous solid ceramic that has been stabilized with yttrium oxide (yttria-stabilized zirconia) (Adamson, 2007). It operates between 800°C and 1000°C, where the cathode is supplied with oxygen, and a reduction into oxygen ions occurs. The non-porous solid ceramic initiates the movement of oxygen, which sets off electron-flow through an externally connected circuit, generating DC (Adamson, 2007). As a result of the oxygen ions and hydrogen reaction, water is formed as a by-product, which occurs at the negative electrode. The chemical reaction at the anode and cathode of a SOFC is presented by Equations (3.12) and (3.13), respectively.

$$H_2 + O^2 \rightarrow H_2O + 2e^- \tag{3.12}$$

$$\frac{1}{2}O_2 + 2e^- \rightarrow O^{2-} \tag{3.13}$$

The cathode electrode of the SOFC is made of lanthanum strontium manganite (LSM), while nickel-yttria-stabilised zirconia (Ni-YSZ) is utilised for the anode electrode.

The SOFC can realise a fuel-to-electrical efficiency in excess of 60% with an even superior efficiency of 85% achievable in co-generation applications, where an output of 100-250 kW is achievable (Giorgi, 2013). As with MCFCs, the high-temperature process in SOFCs allows for “internal reforming”, which negates the need for an expensive catalyst in its operational arrangement, thereby reducing the cost of the cell structure design (Giorgi, 2013; Akinyele, Olabode and Amole, 2020). However, the corrosion issue that is prominent in this high-temperature technology needs mitigation. One solution to this problem involves using expensive materials and protective layers in the cell arrangements, which then drives up system costs (Adamson, 2007).

### 3.7.4 Phosphoric acid fuel cell technology

The phosphoric acid fuel cell (PAFC) operates at temperatures between 150°C and 220°C and uses liquid phosphoric acid ($H_3PO_4$) as the electrolyte. It falls in-between the low and high-temperature categories and can, therefore, be classified as a medium-temperature technology (Adamson, 2007; Bagotsky, 2012). Hydrogen ions (positive) flow to the cathode via the electrolyte, producing electrons at the anode, which can flow to the cathode via an external circuit. Oxygen reacts with hydrogen ions and electrons at the cathode, forming water as a by-product. Equation (3.14) presents the reaction at the anode, and Equation (3.15) presents the reaction at the cathode.

$$H_2 \rightarrow 2H^+ + 2e^- \tag{3.14}$$

$$O_2 + 2H^+ + 2e^- \rightarrow H_2O \tag{3.15}$$

The anode electrode of a PAFC is constructed from platinum or platinum-ruthenium, while platinum is used for the cathode electrode. According to Adamson (2007) and Giorgi (2013), a fuel-to-electrical efficiency of between 0.35 and 0.40 is achievable, which may improve to 0.85 when used in co-generation applications (heat and power). Furthermore, their simple structure design makes PAFCs less susceptible to electrolyte volatility and carbon monoxide (CO) poisoning. These FCs are generally used for power generation between 50 kW and 11 MW (Giorgi, 2013; Akinyele, Olabode and Amole, 2020).

A major shortcoming of the PAFC is its low efficiency relative to other FC technologies. Furthermore, the technology has an increased system cost as it requires the integration of corrosion-resistant components into the system to lessen the negative effects of the acid electrolyte (Akinyele, Olabode and Amole, 2020).

### 3.8 Emerging technologies

There has been substantial research in mainstream RE technologies in recent years. In addition to these established technologies, some emerging technologies have surfaced, attracting interest from the research community. However, these technologies are not widely demonstrated, with commercialisation still limited. The emerging technologies discussed in this section are:

- Micro nuclear fusion.
- Marine energy.
- Enhanced geothermal energy.

### 3.8.1 Micro nuclear fusion

Nuclear fusion, essentially the reverse of nuclear fission, is the reaction in which two or more nuclei collide and matter is converted into energy. Massive gravitational forces in the sun generate ideal conditions for fusion, where four protons are converted into a Helium-4 ($^4$He) nucleus comprising two neutrons (Ongena and Ogawa, 2016). However, this process is not economically feasible on earth, as the reaction entails the conversion of protons into neutrons, which has a very low probability as it is done through inverse beta decay. An alternative, more practical option is to utilise hydrogen (H) isotopes, which already contain the required amounts of protons and neutrons. The least complicated fusion reaction involving H isotopes is between deuterium (D) and tritium (T), as illustrated by Equation (3.16):

$$D + T \rightarrow\ ^{4}\mathrm{He}(3.5\ MeV) + n\ (14.1\ MeV) \tag{3.16}$$

In order to produce adequate fusion reactions, the core temperature of the $D$-$T$ plasma has to be heated to extremely high temperatures of around 150-200 million degrees Celsius and be kept stable and confined for a sufficient amount of time for the nuclei to fuse. The aim is to get the process to become self-sustaining and achieve “ignition”, which only occurs when sufficient fusion reactions take place. This results in a 14.1 MeV neutron and a 3.5 MeV helium nucleus (alpha particle), equating to a released energy of 17.6 MeV (Ongena and Ogawa, 2016). Furthermore, the high energy released from the fusion reaction requires minimal fuel. Other fusion reactions include:

$$D + D \rightarrow\ ^{3}He(0.82\ MeV) + n\ (2.45\ MeV) \tag{3.17}$$

$$D + D \rightarrow T\ (1.01\ MeV) + H\ (3.02\ MeV) \tag{3.18}$$

$$D + 3He \rightarrow 4He\ (3.6\ MeV) + H\ (14.7\ MeV) \tag{3.19}$$

These reactions are difficult to realise due to the high temperature required for operation but have the benefit of lower (or even the absence of) neutron energy.

The challenges faced are to heat the fuel to tens of millions of degrees and confine the extremely hot fuel long enough to achieve ignition. The two main experimental methods currently studied to achieve this are magnetic confinement and inertial confinement.

#### 3.8.1.1 Magnetic confinement

Magnetic confinement fusion is a process where strong magnetic fields confine hot particles for fusion power. As a result of the Lorentz force, charged particles follow a helical path along magnetic field lines. Movements perpendicular to the field are therefore restricted (Ongena and Ogawa, 2016), enabling it to confine a plasma within a space. Two main structural designs have evolved utilising the magnetic confinement method: the Tokamak and the Stellarator.

A *Tokamak* device confines the plasma chamber in the form of a torus using a strong magnetic field (Figure 3.21). Currently, the record for power produced versus input is by the European tokamak, JET (Joint European Torus), which uses an input of 24 MW to generate 16 MW of fusion power (Cowley, 2016).

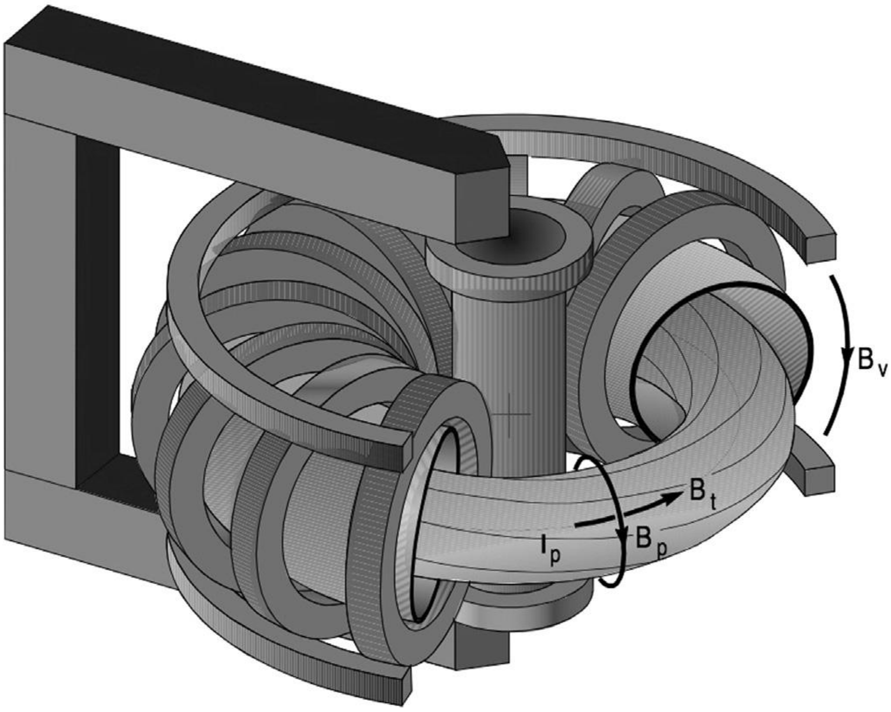

**Figure 3. 21: Schematic representation of a tokamak (Ongena and Ogawa, 2016)**

With the contribution of JET and many other experimental results worldwide, the largest tokamak reactor, ITER (International Thermonuclear Experimental Reactor), is currently in its construction phase as a collaboration project between 35 countries. It is expected that ITER will use 50 MW to produce 500 MW of fusion power, lasting approximately 400 seconds (Xu, 2016).

However, ITER is only a scientific experiment and will not be used to generate electricity. Beyond ITER lies the goal of producing electricity from a fusion-powered reactor. The magnetic fusion program aims at constructing a demonstration electricity-producing reactor (DEMO) capable of continuously generating several GWs of power. The aim is for this to be realised in the 2040s (Cowley, 2016).

*Stellarators* are toroidal magnetic confinement devices that generate almost all the confinement fields using external magnets and are generally free of the plasma terminating instabilities found in tokamaks (Gates *et al.*, 2017).

Wendelstein 7-X (W7-X) is a superconducting stellarator that started operations in December 2015. Since commissioning, it has consistently produced plasmas, initially from helium gas but also from hydrogen since February 2016 (Milch, 2016). In March 2016, more than 2,200 plasma pulses had already been successfully concluded. To improve the performance of the plasma vessel, physicians are now focused on modifications to extend the pulses and increase heating powers. Figure 3.22 illustrates a complex coil system utilised in a modern, optimised stellarator, such as W7-X.

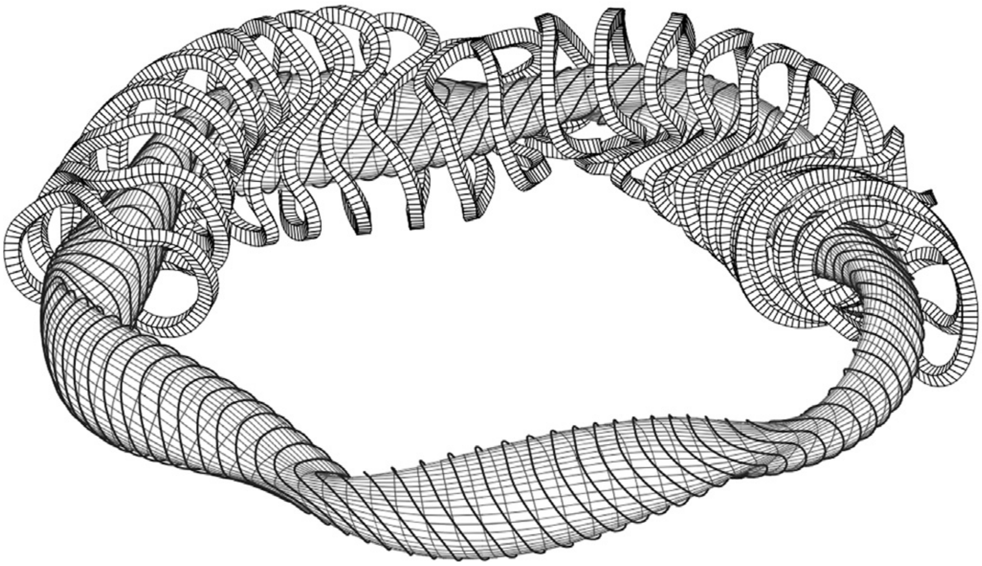

**Figure 3. 22: Complex coil system of a modern stellarator (Ongena and Ogawa, 2016)**

### 3.8.1.2 Inertial confinement

In the Inertial Confinement Fusion (ICF) process, thermonuclear fuel is compressed and heated to the point of fusion using strong laser beams. The “direct drive” approach entails focussing powerful laser light beams on a pellet containing an equal $D$- $T$ (hydrogen isotopes) mix (Ongena and Ogawa, 2016). The laser's rapid heating makes the target's outer layer explode. As the remaining target is driven inwards, the fuel inside the capsule is compressed. A shock wave is formed, further heating the fuel in a self-subsistent burn, which propagates outward through the capsule’s outer, cooler areas faster than the capsule can expand (Facility and Science, 1978). The plasma is confined by the inertia of its own mass, instead of magnetic fields, hence the term “inertial confinement” fusion.

The world's largest research facility, the National Ignition Facility (NIF), came into operation in March 2009. The facility host’s a laser-based research device that utilises roughly 40,000 optics to accurately focus laser beams onto a target. On 12 February 2014, researchers at NIF announced that they had achieved conditions where they produced more energy than the reactor initially absorbed. However, this was not a sustained reaction or ignition, which still does not solve the efficiency challenge of producing more fusion energy than is consumed.

A different approach employs a plasma zeta pinch (z-pinch), where the plasma is confined utilising an electric current that generates a strong magnetic field. Increased current leads to the compression of the plasma, which rapidly increases the fusion reaction rate, as seen in Figure 3.23 (Shumlak, 2020).

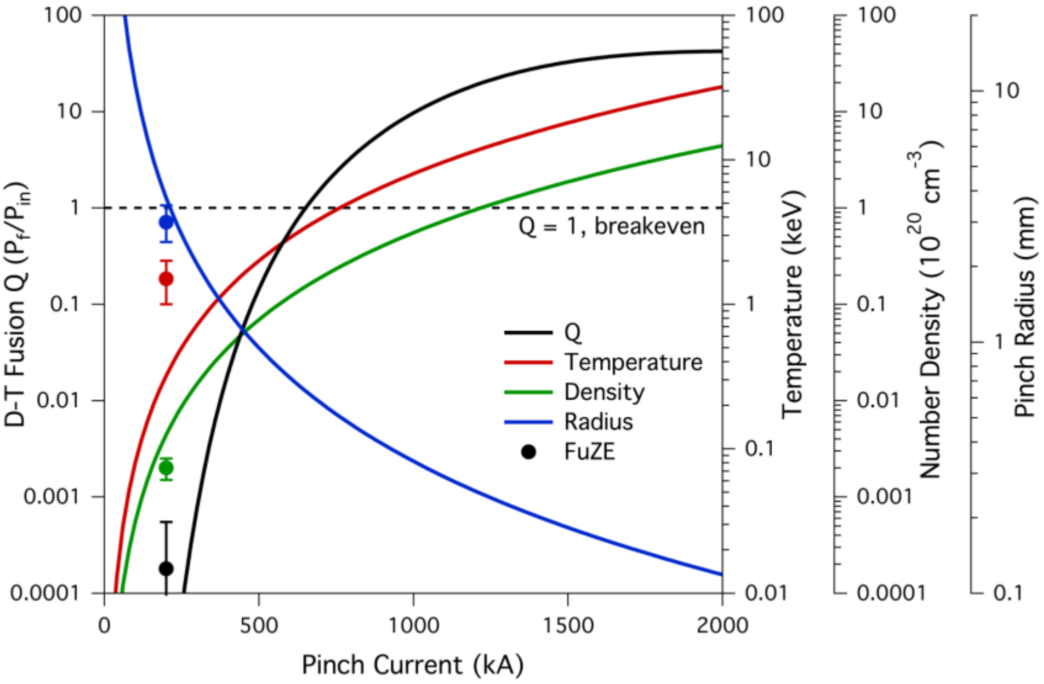

**Figure 3. 23: Z-pinch plasma parameters (Shumlak, 2020)**

### 3.8.2 Marine energy

The ocean covers roughly 75% of the earth. The techniques used to extract energy from the oceans are known as marine or ocean energy, which is stored in the form of waves, tides, currents, and heat, and has enough potential to meet the global power demand (Takahashi and Trenka, 1996). A significant advantage of marine energy is its predictability and consistency (Curran and Folley, 2008), with the potential of this technology comparable to the total of hydropower and nuclear power combined (Hussain, Arif and Aslam, 2017).

However, due to technological challenges, only a minute proportion of the global energy supply is contributed by marine energy technologies (Pelc and Fujita, 2002). The five leading marine energy technologies are ocean thermal energy conversion, salinity gradients, tidal currents, tidal energy, and wave energy. Tidal and ocean wave energy are the most researched and advanced technologies under marine energy. It is expected that these will contribute significantly to the energy supply in the future (Lewis *et al.*, 2011).

#### 3.8.2.1 Ocean wave energy

As wind passes over the oceans, waves are formed as energy transfers to the water. Wave energy converters can be used to harvest the kinetic and potential energy contained in these ocean waves to create electricity (Curran and Folley, 2008). However, the stochastic characteristics of the motion of waves make it challenging to calculate the power obtainable from them. It is, however, possible to estimate the wave power density ($P_{density}$), power per metre of wave crest ($P_{crest\ length}$), and power per metre of wave front ($P_{wavefront}$), as expressed in Equations (3.20), (3.21) and (3.22).

$$P_{density} = \frac{\rho g A^2}{2T} \tag{3.20}$$

$$P_{crest\ length} = \frac{1}{32\pi} \rho g^2 H^2 T \tag{3.21}$$

$$P_{wavefront} = \frac{1}{8\pi} \rho g^2 A^2 T \tag{3.22}$$

where $\rho$ (kg/m$^3$) is the water density, A (m) is the wave amplitude, H (m) is the wave height, T (s) is the wave period, and g (m/s$^2$) is the ground acceleration coefficient (Soudan, 2019). These are functional parameters to determine the feasibility of a wave energy installation in a specific area. In theory, wave energy can be harvested from waves in any water body. However, based on criteria such as the area's topography, geography, prevalent winds, and jet streams, some locations are more feasible than others (Soudan, 2019).

#### 3.8.2.2 Tidal current energy

Tidal current energy is dependent on the rise and fall of the ocean waters, known as tides, which occur during new and full moons (spring or high tide) and in waxing or waning half-moons (neap or low tides) when the earth is misaligned with the sun and moon (Khan *et al.*, 2017). These tides, ranging from 4 m to 12 m, have a projected potential of up to 10 MW per km along the seashore, with celestial and terrestrial gravitational differences affecting variations in power capacity (Khan *et al.*, 2017). The theoretical power extractable from tidal streams ($P_{ref}$) can be estimated using the following equation:

$$P_{ref} = \frac{\rho g A \omega a^2}{\pi} \tag{3.23}$$

where A is the area of the tidal outlet, g is the gravitational acceleration (m/s$^2$), $\rho$ is the density of water (kg/m$^3$), $\omega$ is the radial frequency of the tidal oscillation, and a is the tidal amplitude.

### 3.8.3 Enhanced geothermal energy

Geothermal energy is an energy resource stored in the earth's crust, which originates from the forming of the planet and the radioactive decay of its materials. In addition, a temperature differential between the earth's surface and its core, known as a geothermal gradient, continually drives a transfer of thermal energy (in the form of heat) from the core of the earth to its surface (Hussain, Arif and Aslam, 2017). As per traditional methods, geothermal energy extraction is achieved by locating natural reservoirs of hot water and steam, which limits the exploitation of this energy resource to these locations.

Enhanced geothermal systems (EGS) do not depend on the presence of these reservoirs, as reservoirs in this approach are engineered for energy extraction, making the installation of EGS possible in much more locations than conventional geothermal energy extraction. Parameters and considerations that determine the performance of an EGS plant include geological conditions, a reservoir, and the drilling and completion of a well. Drilling must be done to depths where the rock temperature is sufficient for energy extraction, while investment is still justified. Therefore, the most critical step in deploying an EGS-based powerplant is developing a reservoir, for which five steps need to be followed (see Figure 3.24), described in a U.S. Department of Energy report (2004) as:

1. Drill injection well into the hot basement rock with limited fluid content and permeability, usually occurring at depths greater than 1,500 m.
2. Inject water at adequate pressure to fracture or open existing fractures within the hot basement rock.
3. Continue water pumping to extend new fractures and re-open old ones.
4. Drill a production well and circulate water through the hot basement rock to extract heat.
5. Drill added production wells for additional power.

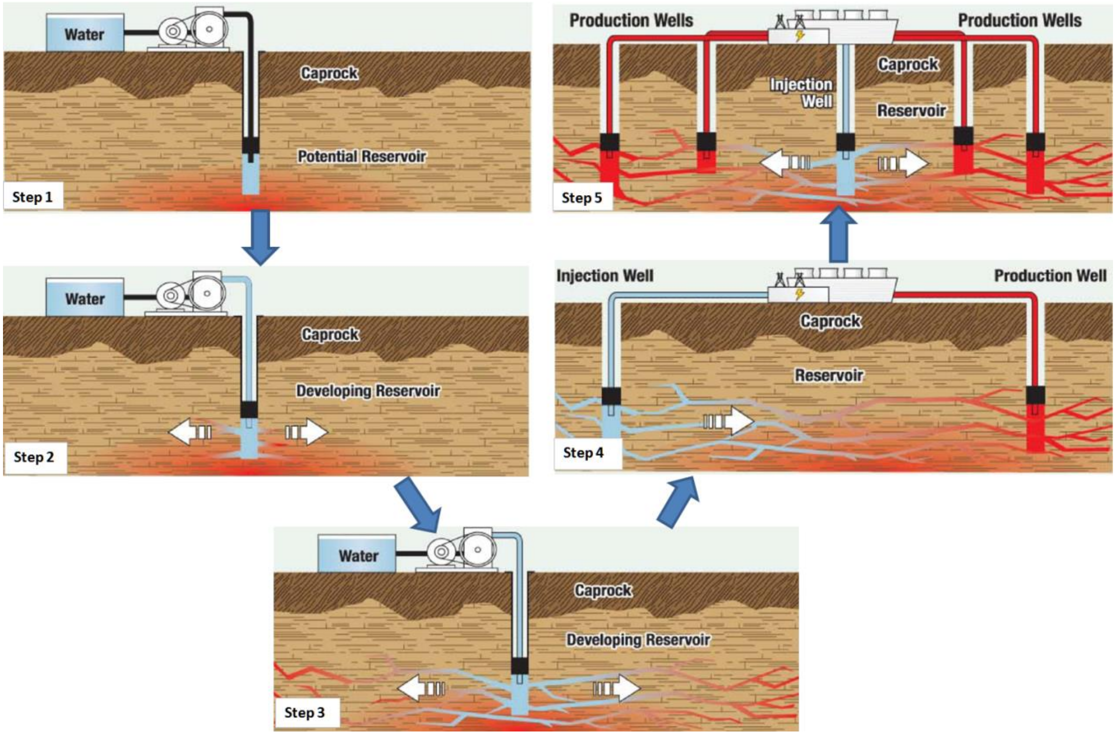

**Figure 3. 24: Development steps of an EGS reservoir. (Adapted fro**m (U.S. Department of Energy, 2004)

# CHAPTER 4: MICROGRID TOPOLOGIES AND STORAGE

## 4.1 Microgrid topologies

### 4.1.1 Overview

A debate on the fundamental aspects of electricity (how it is generated, transmitted, and used) occurred in the early 20th century and is known as the “war of currents”. Principally, Nikola Tesla and George Westinghouse supported AC, while Thomas Edison supported DC. However, DC power generation operates at low voltages, and generation plants had to be used locally as the voltage-drop over distance was critical. Consequently, the major disadvantage of DC generation was that power plants had to be in close vicinity of loads (Kumar *et al.*, 2017).

On the contrary, power delivery to remote end-users is possible with AC power systems, as the voltage can easily be stepped up and power transferred with minimal losses, and then stepped down when in reach of the end-users. Furthermore, Tesla’s invention of the induction motor made AC distribution the main form of electricity generation and delivery, ultimately leading to the expansion of the AC power transmission and the era of centralized power generation (C. L. Sulzberger, 2003).

During a microgrid's planning and designing phase, it is essential to consider factors such as locally available generation resources and the range thereof, the current network setup, and the load and distribution. Once these local conditions have been established, a power system can be designed, selecting the most suitable topology and power supply mode. There are three topology structures: AC-coupled, DC-coupled, and AC-DC (hybrid) coupled (Wei, Xiangning and Pengwei, 2018).

### 4.1.2 AC-coupled configuration

The AC-coupled approach has similar structure and control strategies to a traditional power distribution network, which has the advantage of the easy conversion of a conventional distribution network to an AC-coupled DG network (Wei, Xiangning and Pengwei, 2018). Furthermore, active power, reactive power, harmonics, and unbalanced components are some of the inherent issues experienced with AC microgrid systems (Dagar *et al.*, 2021).

AC-coupled power systems can be divided into power frequency AC (PFAC) and high-frequency AC (HFAC) (Chauhan and Saini, 2014a).

In a PFAC configuration, various energy sources connect to an AC bus (see Figure 4.1). DC loads connect through AC-DC converters, whereas AC loads connect directly to the bus (Chauhan and Saini, 2014a).

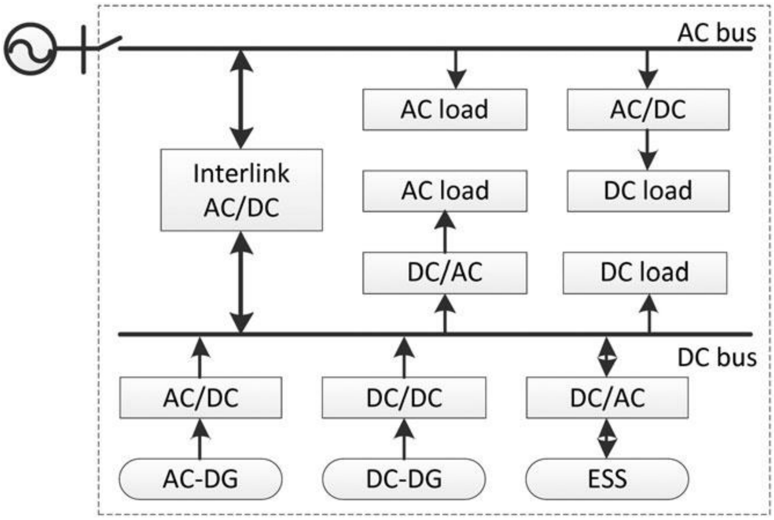

**Figure 4. 1: Power Frequency AC-coupled topology (Wei, Xiangning and Pengwei, 2018)**

Control strategies utilised in AC microgrids can be classified into three layers: Firstly, an inner and outer control layer that manages the output power (active and reactive) of RES, and control the output current. Secondly, a power sharing control layer that adjusts the frequency and amplitude of voltage reference values, also providing these values to the inner and outer loops. Thirdly, a supervisory control layer that restores frequency and voltage output, which controls the output power between the microgrid and utility (Alfergani *et al.*, 2018).

### 4.1.3 DC-coupled configuration

Recent literature on microgrids states that further improvement in the reliability and efficiency of electrical grids is achievable by using a DC microgrid. Distributed energy power generators, such as fuel cells and solar PV systems, generate DC electricity and many loads operate with DC, which leads to an increased interest in DC microgrids (Hirsch, Parag and Guerrero, 2018). Losses incurred during conversion between DC and AC seem to be the most prevalent disadvantage of DC microgrids. However, connecting these devices directly to a DC grid, as depicted in Figure 4.2, allows for the replacement of some of the conversion stages with highly efficient DC-DC converters. Furthermore, ESS can be coupled to the DC bus directly or through DC-DC converters. Therefore, the microgrid concept and modern power electronics make it possible to revive Edison's original vision for a DC power system (Chauhan and Saini, 2014b).

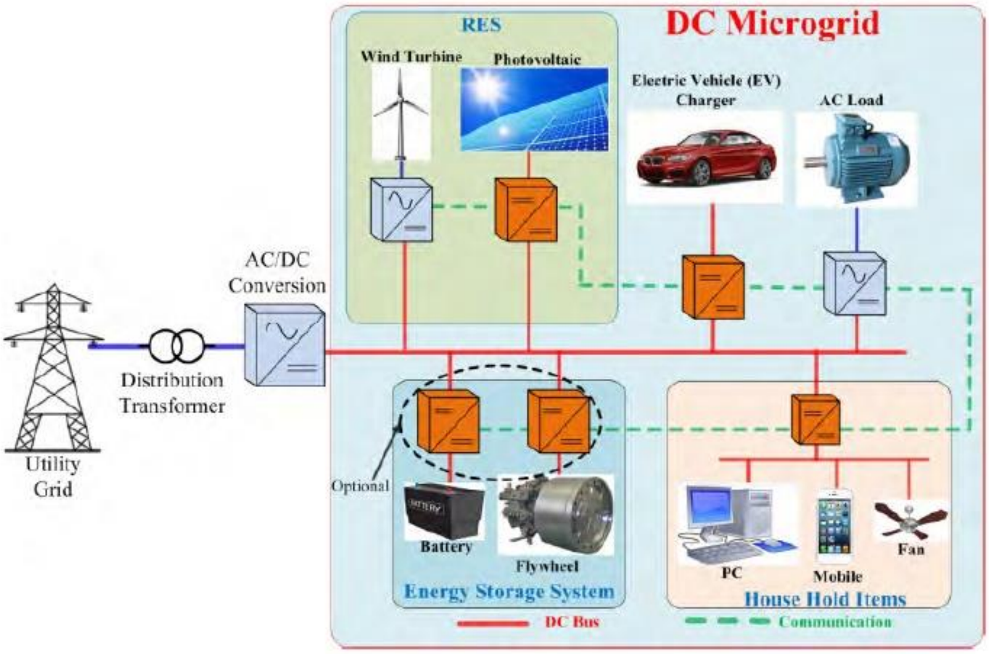

**Figure 4. 2: Typical DC microgrid (Kumar, Zare and Ghosh, 2017)**

Compared to an AC-coupled arrangement with an efficiency of around 60%, DC systems with DC loads have an efficiency of around 80% (Nasir *et al.*, 2018). Additionally, to a superior power conversion efficiency, a DC-coupled structure also has the advantage of less complex control systems without considering reactive power and circulating current components (Wei, Xiangning and Pengwei, 2018).

For the DC microgrid to be broadly accepted in commercial applications, it must overcome various obstacles, including security concerns and standardisation. Several organisations have committed to structuring practical guidelines supporting microgrid development (Nandini, Jayalakshmi and Jadoun, 2021). Table 4.1 lists the current standards regarding DC microgrids.

**Table 4. 1: DC microgrid standards**

| Standard | Description |
|---|---|
| IEEE 946 | “Supplementary DC control systems for power plants.<br>Voltage rating of DC equipment.<br>Typical architecture of DC system.” |
| IEC SG$_4$ | “LVDC distribution system with a maximum voltage of 1,500 V. Architecture that is entirely or one that is a combination of AC and DC.” |
| EMerge Alliance | “Standards for DC microgrids in buildings.<br>DC microgrid design and control system.” |
| National Electrical Code | “The implementation of DC technology is included in legal codes.<br>DC technology is introduced in Articles 393, 625, 690, and 692.” |

| | |
|---|---|
| IEEE 1547 | “Interconnection necessities for electric power systems with dispersed resources.<br>Applicable for islanding and grid-connected operation.” |
| NFPA 70 | “The current electrical building codes that refer to AC, subject to DC systems.” |

In terms of control strategies, DC microgrids are primarily divided into two categories: basic and multilevel control strategies. The former can be classified into three types: centralized, decentralized, and distributed. A centralized controller controls distributed units with a communication link, whereas the decentralized controller does not. Distributed control is an amalgamation of the centralized and decentralized control types. Primary level control manages the current and voltage of a system, while secondary level control maintains DC bus voltages to a set minimum. Power transfer between the utility grid and microgrid is controlled by a tertiary level controller (Nandini *et al.*, 2021). Table 4.2 lists the advantages, limitations, and applications of the different DC microgrid control strategies.

**Table 4. 2: DC microgrid control strategies**

| Control type | Advantage | Limitation | Application |
|---|---|---|---|
| Centralized | Controllable and observable | Single point of failure may reduce system stability | Suitable for small DC microgrid systems |
| Decentralized | Does not need a communication link between different components | Lack of information/status of other components reduces performance<br>Load dependency | Can be utilised to control DC voltage |
| Distributed | Relatively easy to balance the charge state and perform-voltage restoration, and power distribution | Analytical output complexity<br>Bus voltage fluctuation<br>Error in power tracking | Control of industrial processes |
| Primary | Favoured due to it being decentralized | Voltage variations<br>Inaccuracies in current distribution | DC-DC converters |
| Secondary | Eliminates voltage deviation and provides global voltage regulation | Less reliable due to single-point failure | All converter types |
| Tertiary | Reduced power flow losses<br>Reduced operational costs | Single point failure | Energy and power management |

### 4.1.4 Hybrid configuration

A hybrid configuration entails an amalgamation of a DC and AC microgrid, including the benefits of both. Figure 4.3 presents a typical hybrid configuration, where the AC and DC networks are visible. Moreover, several DC and AC loads can be observed: variable speed drives, AC loads, DC loads, a diesel generator, DG and ESS loads, and EV charging systems.

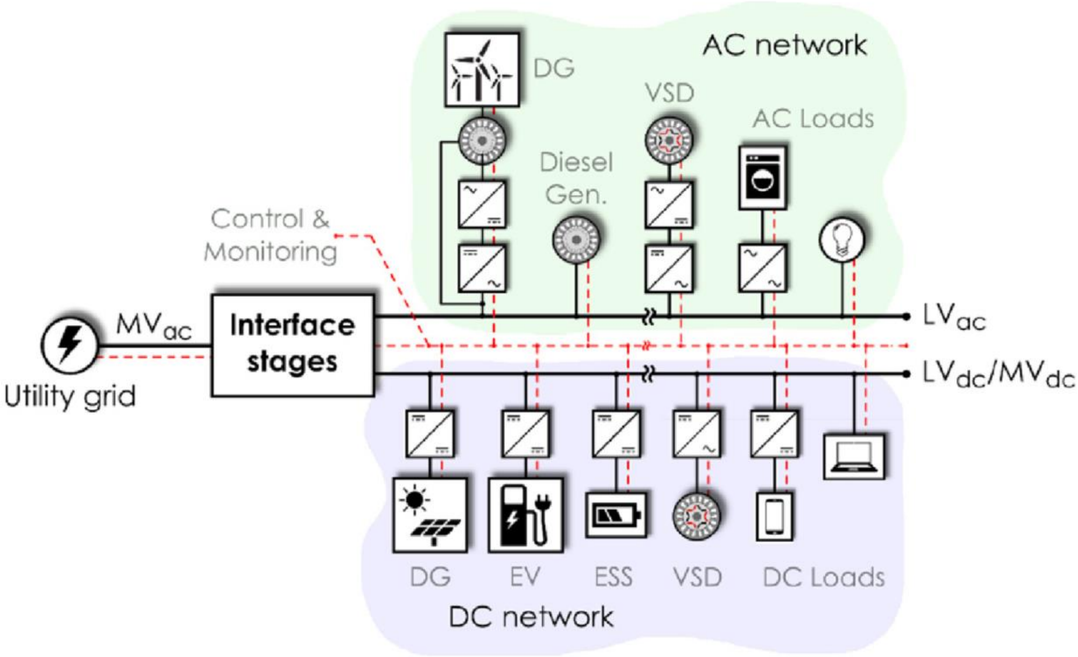

**Figure 4. 3: Hybrid microgrid system (Unamuno and Barrena, 2015)**

AC and DC microgrids interlink utilising bidirectional AC-DC converters. DC power generators are connected to the DC microgrid using DC-DC boost converters. Bidirectional DC-DC converters are used to connect ESS to DC microgrids, with DC-DC buck converters used to connect DC loads, such as EVs, to the DC grid. AC loads, such as AC motors, connect directly to the AC microgrid. Table 4.3 presents a summary of some advantages and disadvantages of the hybrid configuration.

**Table 4. 3: Advantages and disadvantages of a hybrid AC-DC configuration (Unamuno and Barrena, 2015)**

| Advantages | Disadvantages |
|---|---|
| **Integration**<br>• Direct connection of AC or DC devices to the network.<br>• Reduced conversion stages and energy losses. | **Protection**<br>• While there are a variety of protection devices for AC networks, this is not the case for DC networks. |

| | |
|---|---|
| • Ideal for integration of DC-based loads such as EVs, PVs, mobile devices, FCs, laptops, mobile devices and ESS, while the connection of AC-based devices to the network is maintained. | • Fault detection methods are simple for AC networks, utilising the “zero-crossings of current” method, which is not the case with DC networks. |
| **Synchronization**<br>• Synchronization of generation and storage units is not required.<br>• A simplified control strategy is required. | **Reliability**<br>• Less reliable than in AC microgrid as interfacing power converters are required to generate the DC link. |
| **Voltage Transformation**<br>• Voltage level modification on the AC side is simplified using transformers.<br>• Voltage conversion on the DC side is performed using DC-DC converters. | **Control complexity**<br>• Hybrid microgrid management is more complex as both AC- and DC-connected devices, and the required interlinking power converters, need to be controlled.<br>• Maintaining a reliable power source for both networks is challenging. |

There are two basic categories of interfacing devices used between AC, DC, and utility networks: coupled AC and decoupled AC designs (Unamuno and Barrena, 2015). The microgrid's AC network is connected to the power grid via a transformer in a coupled AC arrangement, and the DC network is connected via a DC-AC converter. However, there is no direct link between the power grid and the microgrid’s AC network in a decoupled AC configuration (see Figure 4.4), as it is coupled by an AC-DC and DC-AC stage.

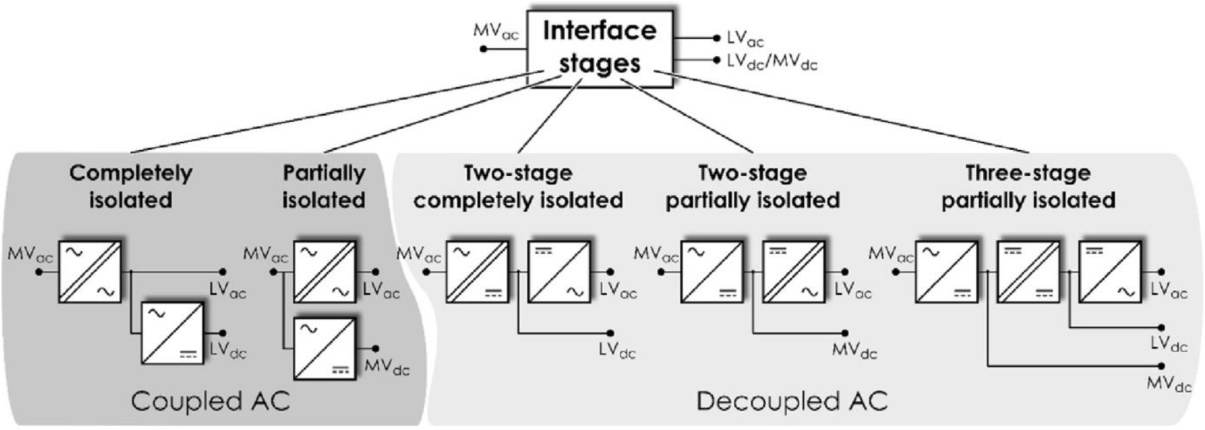

**Figure 4. 4: Hybrid microgrid architecture classification (Unamuno and Barrena, 2015)**

Though hybrid microgrids have many advantages (Table 4.4), they do require more complex control strategies for power management and control, when compared to AC and DC microgrids. The main strategies that can be employed for power management in hybrid microgrids include: power-sharing control and power generation control (Azeem *et al.*, 2021).

Table 4.4 presents an overview of the key advantages and disadvantages of the various microgrid topologies.

**Table 4. 4: Advantages and disadvantages of different microgrid topologies**

| System | Advantages | Disadvantages |
|---|---|---|
| DC microgrid | • Superior power reliability<br>• High system efficiency<br>• Simplicity of control measures<br>• Improved system safety | • Increased requirement of converters<br>• Inverters are required for AC loads<br>• Efficiency metrics issues<br>• High initial cost |
| AC microgrid | • No inverters required for AC loads<br>• Good synchronization for both isolated and grid-connected modes | • Control difficulties<br>• Operation difficulties<br>• Reliability Issues |
| Hybrid microgrid | • Economic feasibility<br>• Integration synchronization merit<br>• Voltage transformation | • Control and protection complexity |

## 4.2 Storage

### 4.2.1 Overview

Energy generation can be costly; hence running a power system as efficiently as possible is imperative. Storing energy can increase an energy system's efficiency and optimise it economically. As RESs are unpredictable, fluctuations in power generation raise issues with power quality, particularly with regard to voltage harmonics and voltage variance (Palizban and Kauhaniemi, 2016). Energy storage is thus crucial in mitigating these variations to sustain a reliable, stable supply for downstream loads.

Approaches for energy storage include thermal energy in storage such as molten salt, kinetic energy in flywheels, electrical energy in capacitors, potential energy such as pumped hydro, and electrochemical energy in batteries (McKeon, Furukawa and Fenstermacher, 2014). Pumped hydro storage offers the advantage of low cost but has geographical considerations as a limitation. Figure 4.5 presents a classification of different ESS according to their primary energy source, i.e., electrical, mechanical, thermal, electrochemical, and magnetic.

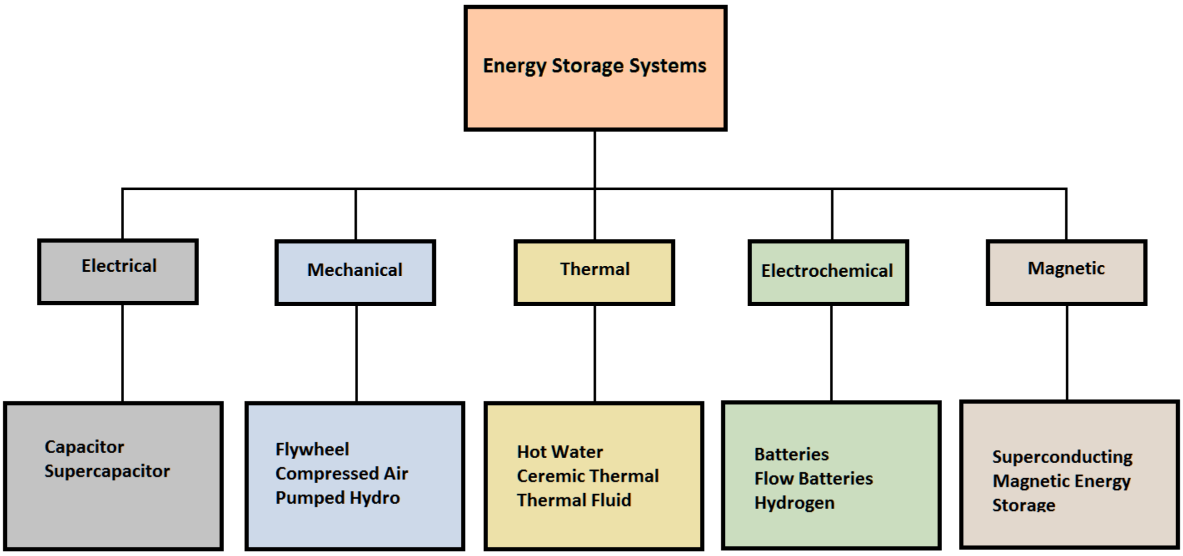

**Figure 4. 5: Classification of energy storage systems**

### 4.2.2 Electrical storage

Electrical devices known as capacitors use electrochemistry to store and deliver energy. These devices can be grouped as electrolytic, electrostatic, and electrochemical capacitors i.e., supercapacitors (Koohi-Fayegh and Rosen, 2020). Supercapacitors were attracting less interest until recent times when numerous applications started needing more responsive storage systems. The renewed interest resulted in significant development of supercapacitors, which included the replacement of a solid dielectric between two solid conductors with an electrolyte solution. This development resulted in a reduced physical size with increased capacitance and energy density. Figure 4.6 presents a schematic diagram of a supercapacitor system.

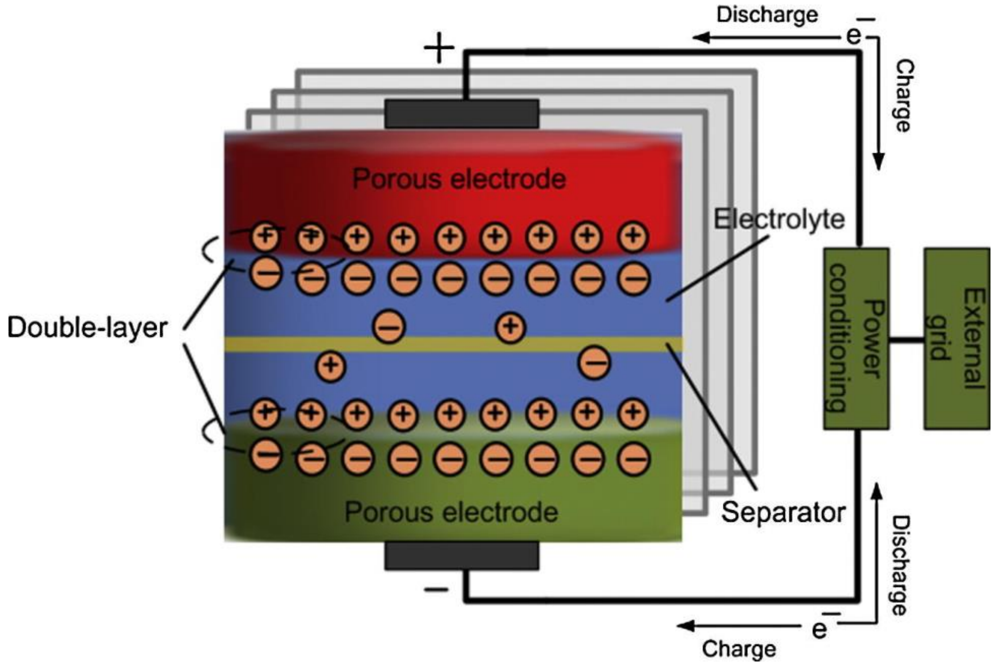

**Figure 4. 6: Schematic diagram of a supercapacitor system (Luo *et al.*, 2015)**

### 4.2.3 Mechanical storage

Mechanical energy storage systems can operate independently or in combination with an electrical system. The key difference is in the utilisation of the energy stored, which may occur directly or by transmission through an electric motor-generator (Mahmoud *et al.*, 2020). Mechanical energy systems offer several advantages over other energy storage systems regarding cost, environmental impact, and sustainability. The three primary mechanical energy storage systems are: Flywheel energy storage systems FESS, pumped hydro energy storage (PHES), and compressed air energy storage (CAES).

### 4.2.3.1 Flywheel storage

A FESS temporarily stores energy, in the form of kinetic energy, by utilising a rotating mass (Wicki and Hansen, 2017). Flywheels are utilised in various applications, including railway, marine, space, hybrid vehicles, and wind power systems. They are available in four shapes: thin ring, thick ring, solid disc, and disc of laval (Sebastián and Peña Alzola, 2012). Each flywheel is characterised by a shape factor (K), proportional to the specific energy stored per unit of mass, and represents the material utilisation. The flywheel rotates at a rotational speed $\omega$, with moment of inertia I, storing kinetic energy $E_c$ as:

$$E_c = \frac{1}{2} I \omega^2 \tag{4.1}$$

Moment of inertia is dependent on the flywheel geometry and mass as follows:

$$I = \int r^2 dm \tag{4.2}$$

where, r is the distance of each differential mass element $dm$ to the spinning axis. The main components of a modern FESS system are presented in Figure 4.7.

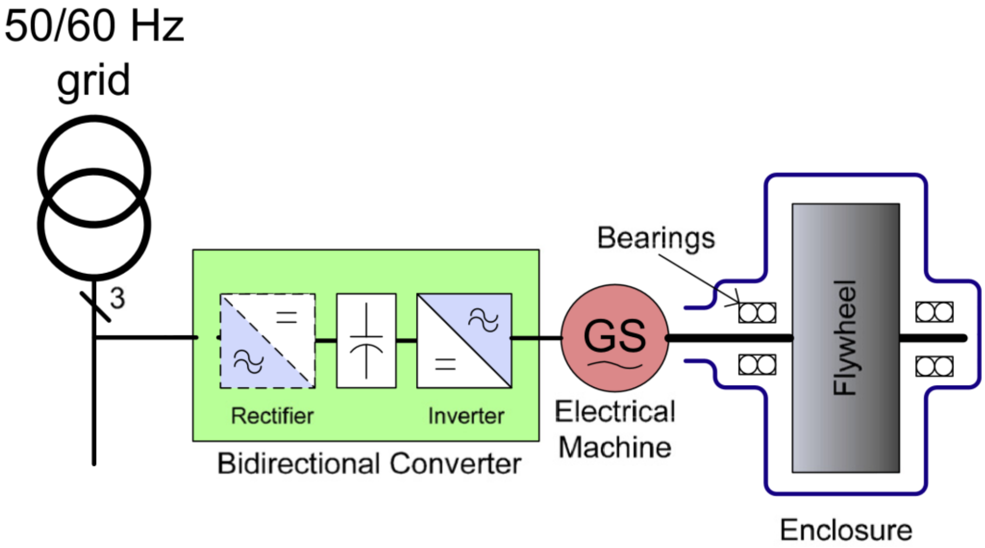

**Figure 4. 7: Main components of a modern FESS (Sebastián and Peña Alzola, 2012)**

Electrical energy at the machine frequency is converted into DC electrical power by a bidirectional converter. A second bidirectional converter transforms DC electrical energy into AC energy (Sebastián and Peña Alzola, 2012).

### 4.2.3.2 Pumped hydro storage

A PHES system is characterised by its flexibility, relatively low maintenance costs, and extended life cycle. Two water bodies located or constructed at higher and lower elevations are the fundamental aspect of a PHES system. There are three essential components: upper reservoir, hydro turbine, and the pumping system.

Water is pushed into the upper reservoir utilising surplus electricity during off-peak times, where it is temporarily stored. When a need for electricity arises or during peak times, water from this reservoir is routed through pipes to a turbine for electricity generation by a hydroelectric generator. Water is stored in the lower reservoir, after which it is pumped back into the upper reservoir, and the cycle continues (Mohd *et al.*, 2008). The operation of this system depends on potential gravitational energy to generate electricity employing the hydraulic turbine (Mahmoud *et al.*, 2020). Figure 4.8 presents the energy flow within a PHES system.

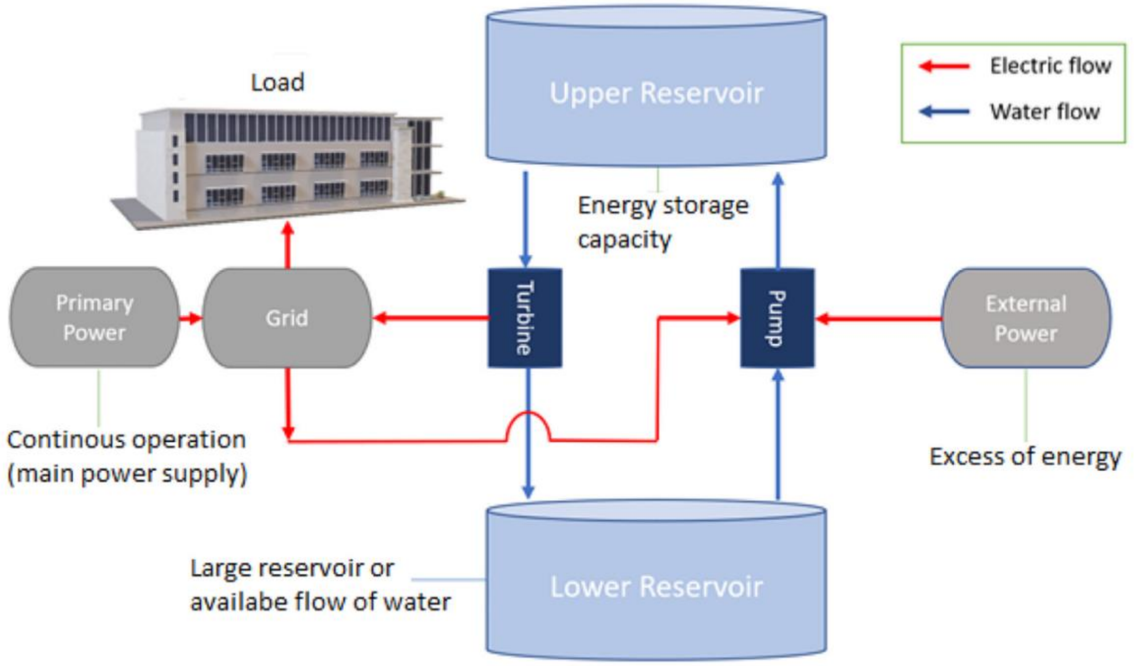

**Figure 4. 8: Flow of energy in a PHES system (Mahmoud *et al.*, 2020)**

### 4.2.3.3 Compressed air storage

A CAES system utilises surplus electric power during off-peak times to pressurise the air in an underground reservoir. Surplus energy is used to compress air up to 100 bar for storage in the underground cavern during the charging phase. During the discharging phase, compressed air is extracted from storage, heated and expanded through the turbine train, and used to drive a generator for power generation (Amirante *et al.*, 2017)

CAES is suitable for commercial use, as large-scale energy in excess of 100 MW may be stored for more than a year. The energy density of this system is 12 kWh/m$^3$ with an efficiency range of between 70% and 89%, which correlates with the selected compressor and turbine efficiencies (Amirante *et al.*, 2017). Figure 4.9 presents a schematic diagram of a typical CAES plant.

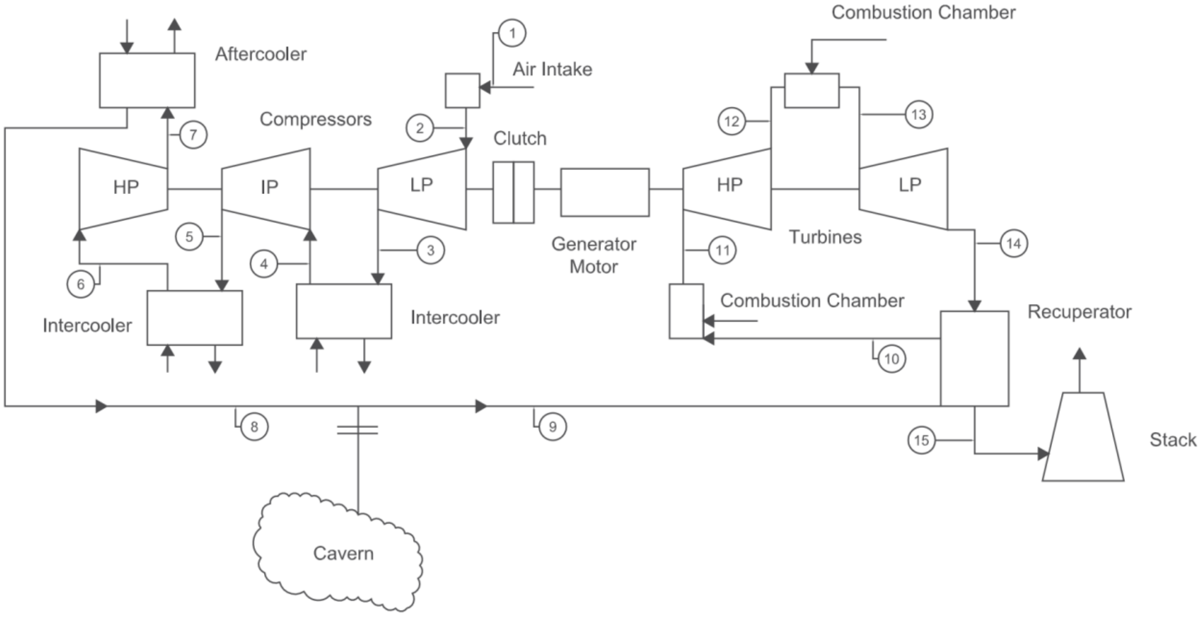

**Figure 4. 9: Schematic diagram of a typical CAES plant (Amirante *et al.*, 2017)**

### 4.2.4 Electrochemical storage

Electrochemical energy storage devices convert chemical energy into electrical energy. In this process, a chemical reaction between at least two reaction partners results in the release of energy in the form of an electric current at a specified voltage (Guney and Tepe, 2017).

#### 4.2.4.1 Batteries

The most popular energy storage technology within the electrochemical category is the battery, a mature device with a high energy density. Several modern electrolytes and electrode materials have been revised and recommended to improve safety, life-cycle, power density, energy density, and battery cost (Koohi-Fayegh and Rosen, 2020). Table 4.5 compares the different battery types. The values shown in the table are an average of recently published references as, in some cases, there is no current data on storage devices.

**Table 4. 5: Comparison of different battery types**

| Battery type | Power limit achieved | Energy density (mass) (Wh/kg) | Power density (kW/kg) | Cycle life | Self-discharge |
|---|---|---|---|---|---|
| Lead Acid | Multiple tens of MW | 35-50 | 75-300 | 500-1,500 | 2-5% per month |
| Sodium sulphur | MW | 150-240 | 90-230 | 2,500 | |
| Nickel cadmium | Tens of kW | 75 | 150-300 | 2,500 | 5-20% per month |
| Sodium nickel chloride | Low hundreds of kW | 125 | 130-160 | 2,500+ | |

| | | | | | |
|---|---|---|---|---|---|
| Lithium ion | Tens of kW | 100-265 | 200-315 | 1,000-10,000 | 1% per month |

Lead-acid (PbA) batteries come in various sizes and designs and are the most widely used rechargeable storage devices. These batteries show high efficiency (70-80%), have a high performance and can sustain high cell voltages (Faisal *et al.*, 2018a). However, the traditional PbA battery suffers premature failure due to sulfation, needs periodic water maintenance, and has a low specific energy and a short life cycle (500-2,000 cycles) (Faisal *et al.*, 2018b). These limitations have been mitigated by developing the valve-regulated lead acid (VRLA) battery, which is sealed and requires less maintenance (McKeon, Furukawa and Fenstermacher, 2014).

Lithium batteries are considered the frontier in electrical energy storage as a result of its high efficiency (up to 97%), low self-discharge rate (1% per month), quick response time (ms), and high energy density (150-200 Wh/kg) (Luo *et al.*, 2015; Koohi-Fayegh and Rosen, 2020). Figure 4.10 presents the basic principle of operation of the Li-ion cell.

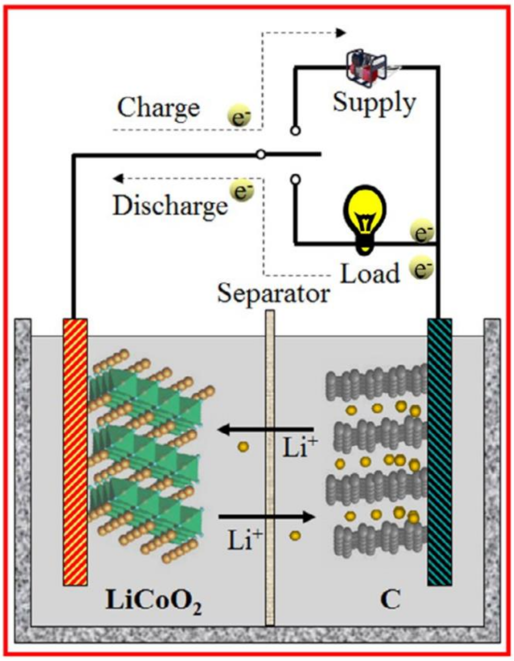

**Figure 4. 10: Principle operation of the Li-ion cell (Deng, 2015)**

The Li-ion battery is made of cells connected in series or parallel (for increased voltage and current, respectively) or in a combined configuration. Multiple battery cells can be integrated into a module, with multiple modules integrating into a battery pack. The basic lithium cell consists of a negative electrode (cathode) and a positive electrode (anode) in contact with an electrolyte containing lithium ions. A separator isolates these electrodes allowing lithium ions, but not electrons, to be exchanged. Other electrolytes that have been explored include polymer, gel, and ceramic (Deng, 2015).

#### 4.2.4.2 Flow batteries

An emerging storage technique is the redox flow battery (RFB), which has the key advantage of its energy capacity being independent of its power generation (Lourenssen *et al.*, 2019). The primary difference between the RFB and conventional electrochemical batteries is in its method of storing electrolytes, as flow batteries utilise external tanks separated from the battery hub (Bartolozzi, 1989).

The vanadium redox flow battery is the most promising RFB technology. Vanadium ions are kept in two tanks in four different oxidation states (V5+, VO2+, V3+ and V2+) each tank containing a different redox couple (Gundlapalli, Kumar and Jayanti, 2018). Figure 4.11 presents a diagram of a typical RFB.

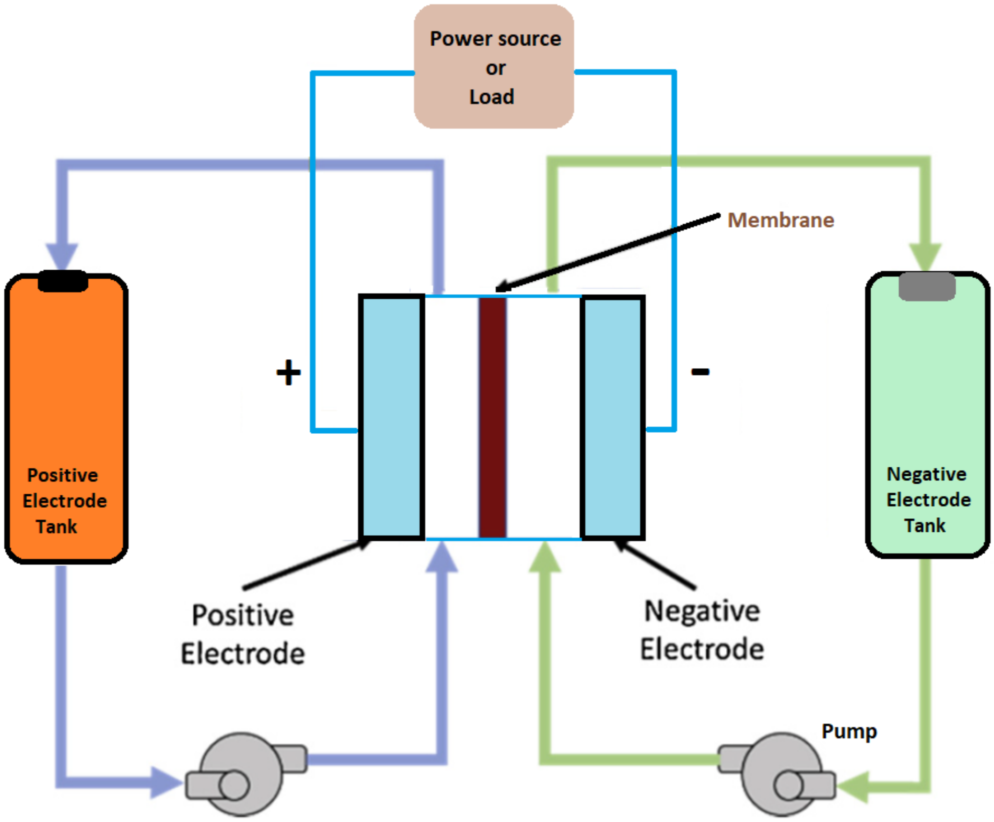

**Figure 4. 11: Schematic diagram of Redox Flow Battery**

Power generated by the flow battery is interrelated with the electrode size and active species. At the same time, its capacity is related to the number of electrolytes within its system (Ye *et al.*, 2018), which renders this technology's vast flexibility and scalability properties. Furthermore, these systems are relatively simple, with reduced moving parts, and are low maintenance, as little attention is required once the system is set up and running (Lourenssen *et al.*, 2019).

#### 4.2.4.3 Hydrogen gas

Hydrogen gas storage entails producing hydrogen from excess energy and storing it, after which energy can be recovered from the hydrogen when required. This is typically done through a traditional combustion engine or modern FC system (Hosseini and Wahid, 2016). Hydrogen has a high heating value of 141.8 MJ/kg and can burn in stoichiometric conditions with an air-to-fuel ratio of 34.33. In addition, its broad flammability limits allow for combustion with low fuel consumption (Amirante *et al.*, 2017). Traditional methods of hydrogen gas storage are through compression and liquefaction, of which the most common is producing pressurised hydrogen at 200 bar. Hydrogen has a low energy density (energy content per weight), therefore to increase quantity, it is stored at an increased pressure of 700 bar (Amirante *et al.*, 2017). However, this increases compression costs and also requires more resistant storage tanks.

The liquefaction process, in comparison, provides a superior storage system in terms of energy density. However, as the hydrogen needs to reach a temperature of -250°C, a cryogenic system is required, which increases the cost (Chilev and Lamari, 2016).

### 4.2.5 Magnetic storage

A SMES system is an ESS characterised as instantaneous and highly efficient (up to 95% for a charge-discharge cycle). The system comprises three technologies: power electronics, cryogenics, and superconductivity, of which the superconductor is the most critical component (Mukherjee and Rao, 2019a). DC flows through the system with negligible ohmic ($I^2R$) losses as the system is a “pure” inductor. Furthermore, with a high energy density (up to 100 MJ/$m^3$), the superconducting coil can sustain energy or current ($1/2\ LI^2$) for many years (Mukherjee and Rao, 2019b). These systems have recently seen significant development, with cooling conduction magnets cooled by solid conduction. Though the primary drawback of the SMES system remains its cost, researchers in material science have been working primarily on cost reduction methods to further develop this technology (Mukherjee and Rao, 2019b).

A comprehensive list of advantages and disadvantages of the various storage technologies is presented in the Annexure, as adapted by Koohi-Fayegh and Rosen (2020).

# CHAPTER 5:

# ANCILLARY COMPONENTS FOR MICROGRID PLANNING AND DEPLOYMENT

## 5.1 Overview

The planning phase of a microgrid deployment project is the most critical part, as there are many interlinked complex processes and variables to consider. This chapter discusses some tools available to assist during this crucial phase of microgrid deployment.

## 5.2 Software tools

The techno-economic analysis and planning of a microgrid system is a complex process, moreover, when multiple generation sources are considered. Therefore, using software tools has become standard practice to aid in the planning, design, analysis, optimisation, and economic viability of microgrid systems (Sinha and Chandel, 2014). For this reason, a comprehensive understanding of the features and shortcomings of all available software tools is crucial when planning, commissioning, or maintaining a microgrid system.
Software tools may be classified into four categories (Sinha and Chandel, 2014):

1. Pre-feasibility; primarily used for financial analysis and basic sizing.
2. Sizing; used to determine the ideal system component size and to provide detailed data on energy flow amongst components.
3. Simulation; used to simulate detailed behaviour of a system, through data input by the user.
4. Open architecture; the user is free to alter system interactions and algorithms.

There are various software tools available, of which HOMER, RETScreen, HYBRID 2, and iHOGA are the most commonly used. These software tools are found in publications and journals accepted within the scientific community (Kavadias and Triantafyllou, 2021) and are briefly discussed in the sections below.

### 5.2.1 HOMER

The “Hybrid Optimisation Model for Electric Renewables” (HOMER) is an open-source, software tool used for performing pre-feasibility, optimisation, and sensitivity analysis for various system configurations. It was developed in 1993 by the National Renewable Energy Laboratory for both off-grid and grid-tied applications. The tool uses various inputs, including manufacturer’s data, technology options, resource availability, and component costs, to simulate various system configurations. Some advantages and limitations of HOMER are presented in Table 5.1, and Figure 5.1 provides a schematic representation of the tool.

**Table 5. 1: Advantages and limitations of HOMER software tool (Sinha and Chandel, 2014)**

| HOMER SOFTWARE TOOL | |
|---|---|
| **Key advantages** | **Limitations** |
| • Can simulate a system for 8,760 hours of a year.<br>• Offers several system designs based on economic inputs.<br>• Can determine most cost-effective load serve policies to meet the load requirement.<br>• Simulator results can be displayed in a wide range of tables and graphs.<br>• Results can be exported. | • Discharge depth of battery bank is not considered and should be optimised with sensitivity inputs.<br>• Hybrid systems are not ranked as per LCOE.<br>• Only single objective function allowed for minimisation of net present cost.<br>• Variations in bus voltage are not considered.<br>• Intra-hour variability is not considered. |

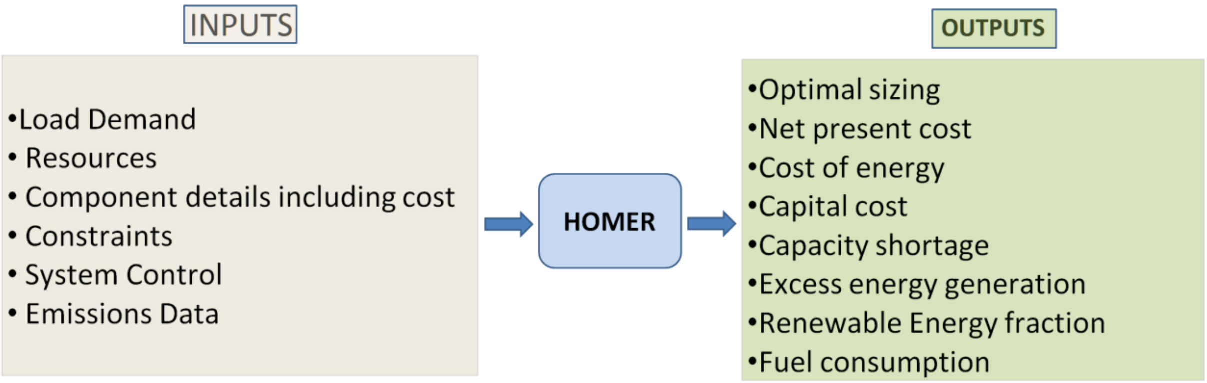

**Figure 5. 1: Schematic representation of HOMER**

### 5.2.2 RETScreen

The Canadian Ministry of Natural Resources developed RETScreen, an open-source feasibility study tool primarily used to evaluate environmental and financial costs, with the benefit of utilising different resources in various locations (Sinha and Chandel, 2014). The software was initially released in 1998 for grid-tied use but has since evolved, catering for various system applications, including islanded microgrids and water pumping systems. It includes a global climate database with more than 6,000 ground stations, wind turbine power curves, energy resource maps, hydrology data, and product data. Furthermore, the program supports more than 30 languages and provides a direct link to NASA's climate database (Sinha and Chandel, 2014). Figure 5.2 is a schematic representation of the RETScreen software tool.

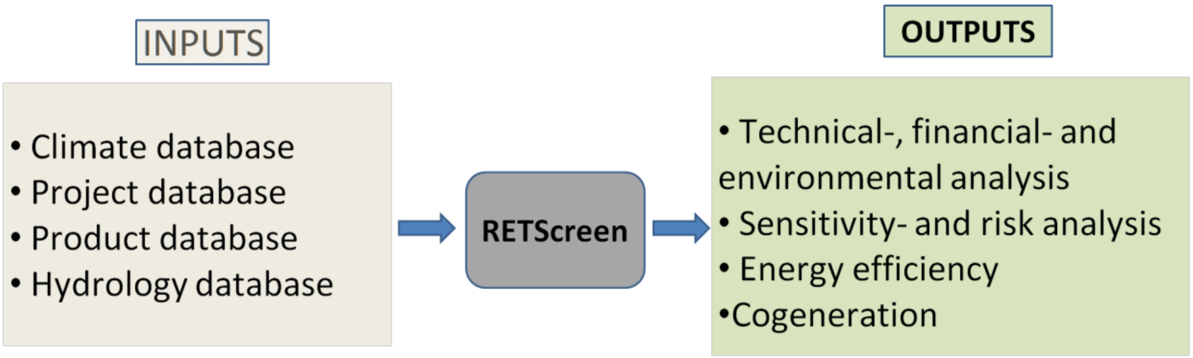

**Figure 5. 2: Schematic representation of RETScreen**

### 5.2.3 HYBRID 2

The University of Massachusetts' Renewable Energy Research Laboratory created Hybrid 2 in 1996. It is a time series/probabilistic software model that can assess the long-term performance of various hybrid systems, using statistical methods to account for inter-time step variations, and has many advantages such as (Sinha and Chandel, 2014):

- User-friendly graphical user interface (GUI) that simplifies project construction.
- Users can view detailed output data through a graphical results interface.
- It allows systems based on three buses, such as diesel generator, wind turbine, PV array, and battery storage.

Figure 5.3 is a schematic representation of the Hybrid 2 software tool.

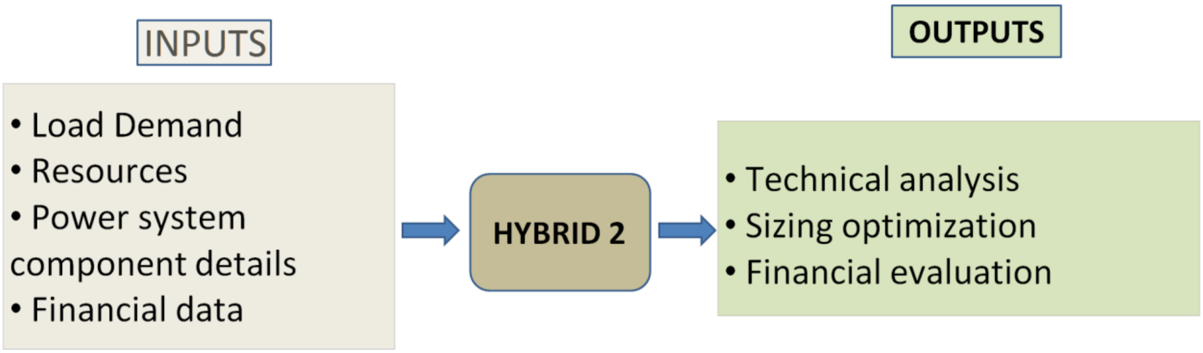

**Figure 5. 3: Schematic representation of HYBRID 2**

### 5.2.4 iHOGA

Improved Hybrid Optimisation by Genetic Algorithm (iHOGA) is a system optimisation software tool for optimum sizing hybrid energy systems. iHoga allows for probability analysis and is used to optimise the slope of a PV panel and calculate life-cycle emissions. Furthermore, the tool includes a database of components, sensitivity analysis, new constraints, degradation effects, and also allows for currency change (Sinha and Chandel, 2014). Figure 5.4 offers a schematic representation of the iHOGA software tool.

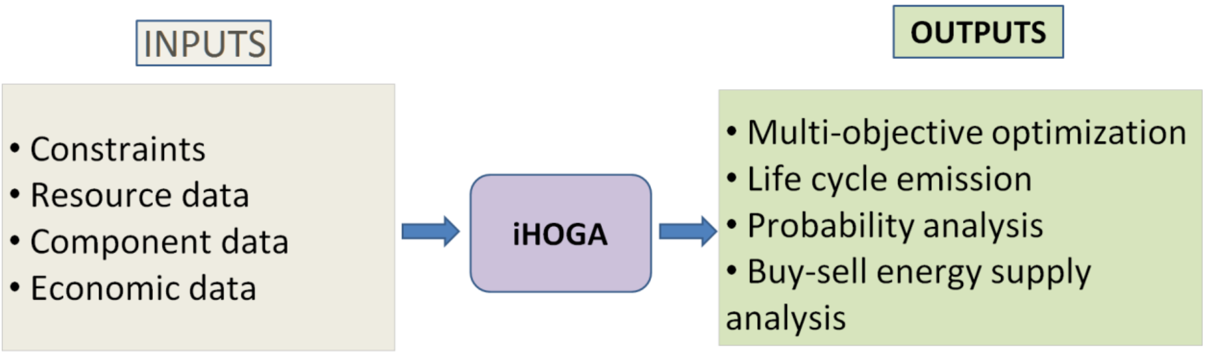

**Figure 5. 4: Schematic representation of iHOGA**

## 5.3 Microgrid control

At the core of a microgrid is a controller that controls, regulates, and optimises the microgrid during islanded or grid-connected mode, as well as transitions between these modes (Feng *et al.*, 2018). Modern microgrid energy systems are complex and require intelligent control mechanisms. These systems cannot be controlled through a single centralized or any level of decentralized control structure (Ahmethodzic and Music, 2021). Therefore, microgrid control systems are structured in a hierarchical control scheme, widely accepted as a standardised model of microgrid control. Functions that a microgrid controller should provide, as classified by the Institute of Electric and Electronic Engineers (IEEE), may be grouped into three categories (Ton and Reilly, 2017):

1. Primary level control (device-level control); local control of DG units, fault protection, frequency and voltage control, energy storage and load protection.
2. Secondary control (local area control); load and energy management, economic dispatch, automatic generation control, load-shedding control, and re-synchronization.
3. Tertiary control (grid-interactive control); power flow to microgrids from the utility, coordination between microgrids and market participation.

These control levels have different domains of operation, which correspond to different timescales of control tasks executable at each level, as shown in the hierarchical control structure depicted in Figure 5.5.

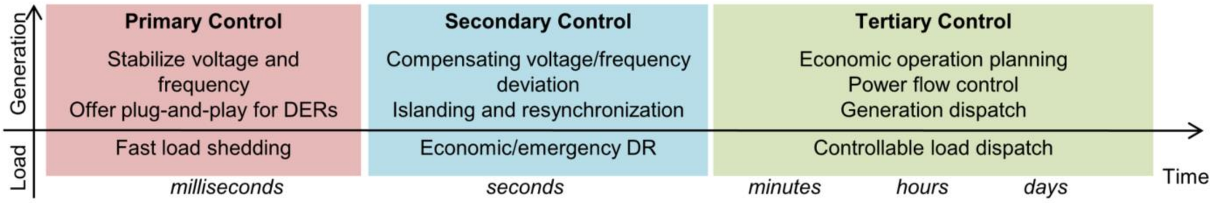

**Figure 5. 5: Key functional blocks of hierarchical control (Wu, Ortmeyer and Li, 2016)**

### 5.3.1 Primary control

The primary control level operates in the “milliseconds to seconds” range and deals with local DER outputs. It controls power converters (output voltage and current) and power-sharing and also monitors the microgrid state (grid-connected or island mode) (Ahmethodzic and Music, 2021). Furthermore, it enables active and reactive load sharing amongst all connected DERs and stabilises the voltage and frequency of the distribution network in real-time (Wu, Ortmeyer and Li, 2016).

### 5.3.2 Secondary control

Secondary control operates in the “seconds to days” range and maintains economical, secure, and reliable microgrid operation in both grid-tied and islanded modes (Feng *et al.*, 2018). In addition, this control level acts as a moderator between the primary and tertiary levels, where it corrects mismatches between set commands at the tertiary level and the actual power available in the microgrid, measured at the primary level (Ahmethodzic and Music, 2021).

### 5.3.3 Tertiary control

The highest hierarchical level of control in a microgrid is tertiary control, which operates in the “minutes to days” range. It operates in a domain where multiple microgrids collaborate and facilitates interaction with the macrogrid as a cluster. Core activities under tertiary control relate to energy markets, with the main issues arising from information barriers between individual entities (Feng *et al.*, 2018).

### 5.4 Power converters

Power converters have the function of interfacing the microgrid and utility grid to different ESS and RES. The type of converter, DC-DC or AC-DC for a DC microgrid, and AC-AC, DC-AC or matrix converter for an AC microgrid, depends on the shape of the generated power from RES (Ansari, Chandel and Tariq, 2021). The following section discusses some of these power converters, as per the classification illustrated in Figure 5.6. Table 5.2 presents a comparison of the different converters.

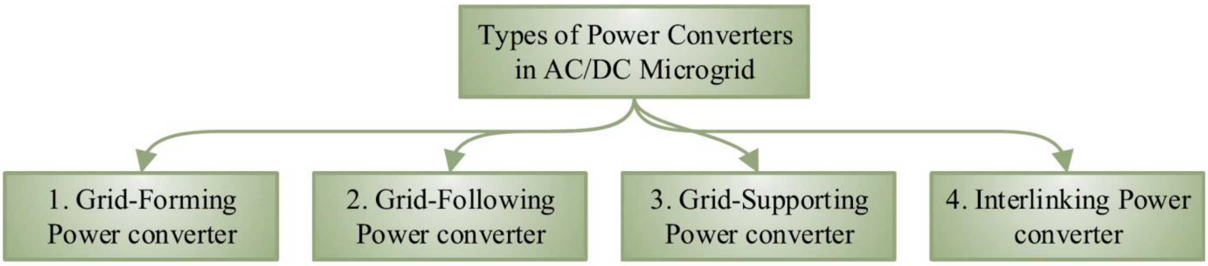

**Figure 5. 6: Classification of power converters in AC-DC microgrids (Ansari, Chandel and Tariq, 2021)**

### 5.4.1 Grid-forming power converter

Grid-forming power converters are primarily utilised with ESS in AC/DC microgrids. When operating in island mode, they maintain the reference voltage (DC sub-grid) and the reference voltage and frequency (AC sub-grid) (Ansari, Chandel and Tariq, 2021). When used in grid-tied mode, grid-forming power converters regulate the reactive and active power (AC sub-grid) and active power (DC sub-grid) to uphold the state of charge of the ESS. These converters also improve the power quality (AC sub-grid) and voltage profile (DC sub-grid) of a system and are considered current-controlled voltage sources with low series impedance (Rocabert *et al.*, 2012).

### 5.4.2 Grid-following power converter

Grid-following power converters are primarily utilised with non-dispatchable DG sources. These units continually track the grid reference frequency and voltage (AC sub-grid) and perform power factor correction by supplementing the grid with reactive or active power as required (Ansari, Chandel and Tariq, 2021). When a DC sub-grid is used, it supplements the grid with power or current while tracking the grid voltage (Dragičević et al., 2019). Grid-following converters do not perform power balancing and cannot operate in island mode without local synchronous generators or grid-supporting power converters. They operate in power or current control mode for reactive and active power control (AC sub-grid) and power or current control (DC sub-grid) (Ansari, Chandel and Tariq, 2021).

### 5.4.3 Grid-supporting power converter

Grid-forming power converters sometimes fail to maintain pre-assigned frequency and voltage setpoints, which may be due to limited reserve power or when the ESS unit absorbs power. In these cases, grid-supporting power converters are dispatched. These units are compared to sources of controlled current/voltage that are connected in parallel/series with high/low impedance, respectively (Rocabert *et al.*, 2012; Palizban, Kauhaniemi and Guerrero, 2014). These units support the network in grid-tied mode by improving voltage profile (DC sub-grid) and power quality (AC sub-grid). Furthermore, the units can operate in voltage and current control modes and realise the droop control strategy (Ansari, Chandel and Tariq, 2021).

A disadvantage of these power converters is that they offer low inertia to the microgrid, which subjects the grid to instability. However, research on providing a solution to this is ongoing, with good progress on concepts like “virtual synchronous generators” (Wang and Wu, 2016) and “virtual inertia devices” (Poolla, Groß and Dörfler, 2018).

### 5.4.4 Interlinking power converter

Interlinking power converters interlink a DC-and AC sub-grid to form the hybrid microgrid. These bidirectional units can operate as inverters, rectifiers, or in stop mode. Furthermore, they are capable of multi-grid connection with functionalities including power flow control, coupling to sub-grids regardless of the grid type, reduced complexity of the power network, enhanced stability, and improved ancillary services (Ansari, Chandel and Tariq, 2021).

**Table 5. 2: Comparison of power converters (Ansari, Chandel and Tariq, 2021)**

| | **Grid-forming power converter** | **Grid-feeding power converter** | **Grid-supporting power converter** | **Interlinking power converter** |
|---|---|---|---|---|
| Source Type | Controlled voltage source | Controlled current source | Controlled voltage/current source | Controlled voltage/current source |
| Output impedance | Low | High | Non-zero, finite | Finite |
| Combination | Series | Parallel | Series-parallel | Series-parallel |
| Power converter control | Constant voltage/frequency control (AC), constant voltage control (DC) | Power or current control (DC sub-grid), power quality control (AC sub-grid), | Voltage-current or voltage-power droop control in DC sub-grid) and Droop control (p/f and Q/V droop control in AC sub-grid) | Bidirectional droop control |
| Associated with | Dispatchable sources | Non-dispatchable sources | Generally, dispatchable sources | Two sub-grids |
| Output voltage and frequency | Fixed | Synchronized with sub-grids | Regulated | Regulated |

| | | | | |
|---|---|---|---|---|
| Application | Island | Grid-connected | Both island and grid-connected | Power exchange |
| Power flow control | Two-way | One-way | Primarily two-way | Two-way |

### 5.5 Metering

To effectively control and protect DGs and ESS in a microgrid, it is imperative to utilise reliable communication systems and networks for information exchange among the interconnected sub-systems. Commonly, standards and protocols including IEC Standard 61850, Distributed Network Protocol 3.0 (DNP3), and Modbus protocols are used as guidelines for communication, which can be applied in microgrid systems. Furthermore, the utilisation of proper metering is particularly important for reliable communication between the various sub-systems

#### 5.5.1 Grid-connected metering

Several problems can occur due to increased feed-ins which may negatively affect the grid should there be no intervention. For instance, the original direction of power flow can reverse when multiple power sources are coupled to the grid. Another problem is the volatility of renewables such as solar and wind, which can result in conditions where the grid cannot be effectively controlled within the constraints of its current infrastructure. For example, if there is a surplus or overload of production, load rejection may result in the isolation of a wind turbine generator that delivers carbon-free electricity.

In situations like these, it is challenging to steer without the assistance of information and communication technologies (ICT), especially in distribution grids (Wissner, 2011). Local networks managed by ICT can make a substantial contribution, especially in balancing the rising amounts of dispersed renewable production connecting to the grid. The electricity grid needs to become “smarter” for generation and consumption to coordinate in a demand-based and consumption-based manner. There must be a continuous flow of information between different companies and communication between the relevant stakeholders within the electrical supply network (Wissner, 2011).

#### 5.5.2 Smart metering systems

The most common type of electrical meter is the electromechanical watt-hour meter. When power passes through the meter, two induction coils produce magnetic flux on a metal plate (Avancini *et al.*, 2019). The disc's rotational speed is proportional to the power flux, and its revolutions account for consumed power billing. Though reliable for metering power consumption, these meters do not allow additional features. The modern microgrid requires advanced monitoring and controlling to improve functionality and efficiency, which warrants the need for improved metering.

Electronic meters are developed based on digital micro technology, which has evolved to become more compact and “smarter”, providing benefits for both consumers and energy providers (Avancini *et al.*, 2019). Advantages of smart metering systems include (Sun *et al.*, 2016):

- Automatic power consumption readback for the user.
- Automatic consumption control for an energy provider.
- Remote control of meters enables energy companies to implement load levelling and real-time pricing for enhanced power supply.
- Meters are modular, allowing for the addition of functionalities as and when required.

The development of the functionality of energy meters through time is presented in Figure 5.7.

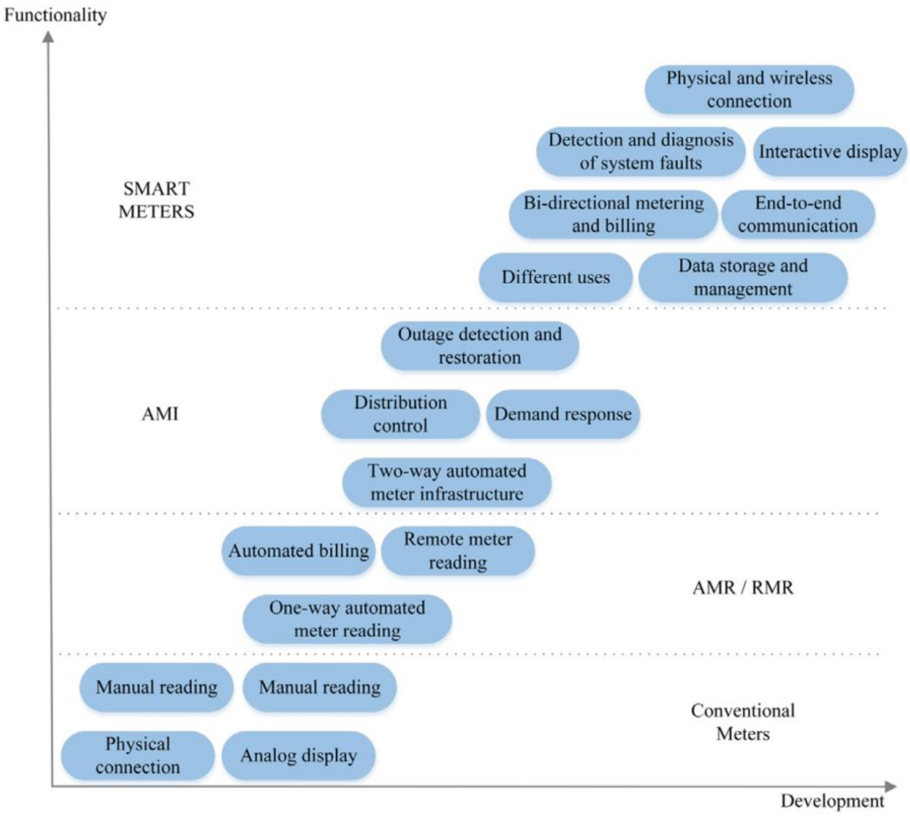

**Figure 5. 7: Development of the functionality of energy meters through time (Avancini *et al.*, 2019)**

# CHAPTER 6: MICROGRID PLANNING CONSIDERATIONS

## 6.1 Overview

This chapter reviews the technical and economic aspects of microgrid planning and implementation, giving an overview of factors to consider when developing a microgrid. The chapter concludes with examples of microgrids successfully commissioned around the world.

## 6.2 Techno-economic planning

Microgrids are expected to coexist with conventional power systems as part of the electric energy transition. Therefore, to ensure long-term stability, it is critical to consider economic feasibility when planning a microgrid system. Holistically planning a microgrid is a complex process, as there are multiple alternatives, goals, uncertainties and constraints, which usually conflict. Consequently, this results in different optimisation issues within the planning process (Gamarra and Guerrero, 2015). Several optimisation planning techniques discussed extensively in literature have been applied to RE sources and energy community systems (Sanaei and Nakata, 2012).

The optimisation algorithm selection depends on the type of optimisation problem, which may be classified according to the decision variable, objective function, and system constraints (Gamarra and Guerrero, 2015). However, any given optimisation method may not always find the optimum solution, as some optimisation problems have no feasible outcome due to the characteristics of these problems. As a result, numerous authors propose approximation techniques for solving optimisation issues, which include heuristic and meta-heuristic approaches (Gamarra and Guerrero, 2015).

Heuristic methods require less computational effort and are designed to secure a high-quality solution amongst a substantial set of realistic options (Erdinc and Uzunoglu, 2012). Furthermore, meta-heuristics can combine multiple heuristic methods to obtain the most feasible option from discrete search space, and can be classified as trajectory, population-based, and bio-inspired (Gamarra and Guerrero, 2015).

## 6.3 Technological considerations

In South Africa, there is a drive towards implementing RE projects, with the Department of Energy supporting the development of RE sources, such as solar and wind. However, there are several distinct factors with various trade-offs that must be considered when choosing a suitable RET for a particular site. This section discusses some general considerations and challenges associated with various energy technologies based on a framework developed in a study performed by Naicker and Thopil (2019). Criteria for the framework include the following factors: technical, economic, environmental, social, and political.

### 6.3.1 Technical feasibility

The potential of an energy source determines its feasibility, which is classified through theoretical, technical, market, and economic factors. Technical factors include the capacity factor: the ratio of the theoretical maximum capacity to the actual energy produced (running continuously at maximum rated power) (Trianni *et al.*, 2016). Theoretical potential presents the peak potential achievable, considering climatic and natural limitations. From this, one can derive the technical potential, which is the theoretical potential limited by technical factors, including topographical constraints. The economic potential of energy is based on its technical potential, considering competitive cost levels. The last technical consideration is market potential, where energy demand, competitive technologies, costs and subsidies are to be considered when estimating the amount of energy to be implemented (Naicker and Thopil, 2019).

### 6.3.2 Economic considerations

The Levelized Cost of Energy (LCOE) is a fixed number representing the complete cost of constructing and running a generation facility and should be determined considering the RE policy for a specific RE sector (Naicker and Thopil, 2019). It measures the overall cost over the lifespan of a system, including the original investment, capital costs, fuel, and operating and maintenance expenses, in addition to presenting the break-even sale price of energy (Wing Lee and Zhong, 2014). LCOE also reflects contributing factors such as service life, annual production, and efficiency (Troldborg, Heslop and Hough, 2014), and is widely used to calculate the lifetime energy cost of different energy technologies (Ouyang and Lin, 2014). Furthermore, costs associated with the upgrade or expansion of transmission grids should also be considered in the LCOE calculation, as transmission investment is affected by factors like geographical location. Economic aspects, including electricity unit price, cost of operations and maintenance, initial investment cost (capital cost), and fuel cost, are measured according to the unit electricity production cost or installed total capacity cost (Talinli, Topuz and Uygar Akbay, 2010). Table 6.1 lists the capacities and estimated capital costs of some microgrid projects commissioned in South Africa.

**Table 6. 1: Microgrid projects (SA) with capacities and estimated costs (ZAR) (Motjoadi, Bokoro and Onibonoje, 2020)**

| Project Name | Capacity (MW) | Estimated Cost (ZAR) |
|---|---|---|
| Robben Island solar PV | 1 | 25 million |
| Kalkbult solar power | 75 | - |
| Mulilo Prieska PV | 86 | 1.3 billion |
| Jasper Solar Park | 96 | 2.3 billion |
| Khathu Solar Park | 100 | 12 billion |
| Solar Capital De Aar Project 1 and 2 | 175 | 7.2 billion |

### 6.3.3 Environmental considerations

The environmental impact a product or technology may have through all its development stages may be assessed using a life cycle analysis approach (Troldborg, Heslop and Hough, 2014). However, this approach is only effective if the environmental impact is measurable. The total GHG emissions of an energy system is widely used to evaluate the impact of RE and are assessed in equivalent $CO_2$ emissions per unit of produced energy. When assessing and measuring emissions throughout the life-cycle of an energy system, the following factors are generally considered: operation and maintenance, construction, cost of fuel and transportation, and disposal (Naicker and Thopil, 2019). Furthermore, RETs compete for land with other industries (e.g. agriculture development), making land area requirement a vital consideration. The area requirement is quantified in $m^2$/kW of installed power (Troldborg, Heslop and Hough, 2014).

On the other hand, it is also important to perform a risk assessment of the environment where a microgrid is planned. The environment may pose physical threats that might impact the microgrid adversely in future. Such threats include natural hazards (floods, hurricanes, wild fires), changing climate (extreme temperatures), and human induced attacks (terrorist attacks) (Mishra *et al.*, 2020).

### 6.3.4 Social considerations

Job creation and new business remain a primary concern for many governments. The development and deployment of RETs motivate this objective, which can be measured qualitatively (Troldborg, Heslop and Hough, 2014). However, the public's acceptance of RE technologies determines its social acceptability, which is not easily measurable as acceptance varies between locations and public perception changes over time (Troldborg, Heslop and Hough, 2014).

## 6.4. Institutional support

The success of providing access to electricity for rural areas in African countries depends on governments, energy policymakers, and investors. A country like SA has excellent potential for microgrid systems, though it is threatened by skewed and limited policies, as current policies are structured for grid electrification. Existing energy sectors in SA are governed by rules, regulations, monopolistic laws, and competitive policies, which limits microgrid deployment in rural areas. However, the SA government and other African nations support and promote awareness of microgrid investment through the development of healthy policies and incentive structures. This also entails reviewing current policies and laws to include local private sector participation (Pegels, 2010; Motjoadi, Bokoro and Onibonoje, 2020).

### Existing Energy Policy Charter

SA stands in good stead in producing a practical policy framework as it is affiliated with IRENA, which supports and upholds renewable energy policies. There are three energy policy frameworks previously developed by the SA government; the “White Paper on Energy Policy of 1998”, the “White Paper on Renewable Energy Policy of 2003”, and the “National Climate Change Response Policy White Paper of 2011”. The detailed objectives of these policy frameworks include access to low-cost energy services, securing energy source diversity, enabling effective energy governance, ensuring and managing environmental impact, and encouraging cost-effective growth (Winkler, Hughes and Haw, 2009; Motjoadi, Bokoro and Onibonoje, 2020).

The “Integrated Energy Plan” (IEP) and “Integrated Resource Plan” (IRP) are two additional strategic policy documents drafted by the SA government as interventions for outlining RE deployment mechanisms. The former was gazetted in 2016 to encourage investment in the SA energy infrastructure and provide an imperative framework for the country's energy environment. However, the IRP was not approved by the SA government, which left the policy framework in a state of uncertainty, as the following strategic policy documents, i.e. “IRP 2013”, “IRP 2016” and “IRP 2018”, never received approval. The latest, “IRP 2019”, is still awaiting approval. This created a negative outlook in terms of SA RE policy, resulting in considerable reluctance to invest in the sector (Nasir *et al.*, 2019). Nevertheless, to accomplish an overall energy sector transformation within the next 20-40 years, an effective IRP implementation is necessary to meet energy diversity and demand across SA's rural and urban areas (Motjoadi *et al.*, 2020).

Support from government institutions must be in place to successfully implement microgrid systems. The fundamental recurring factors for consideration during the formulation of policy in aid of RE investment include the total cost required, non-economic effects on psychological and social factors, and inadequate implementation support systems (Motjoadi *et al.*, 2020). Therefore, a multi-lateral assessment of these factors is imperative in order to make an informed decision for microgrid implementation.

## 6.5 Safety considerations

### 6.5.1 Microgrid protection

In recent years, the DC microgrid has gained popularity due to its intrinsic capacity to interface ESS, DERs, and numerous DC loads. As a result, DC microgrids are rapidly evolving, offering numerous advantages over AC microgrids, including superior reliability and improved power quality. DC microgrids also have reduced power losses and increased power flow (√2 x) over its counterpart, as reactive power-drop issues and “skin effect” problems are inherently nullified. Additionally, fewer power conversion stages and simpler DER and load integration lead to higher system efficiency and excellent operational flexibility (Chandra *et al.*, 2020).

However, due to a lack of DC protection standards, the development of a proper protection system remains a challenge. Particular challenges include protection against arc faults, short circuit faults, and the relentless rise of initial DC fault current, augmented by low line impedance. Short circuit faults generally entail two conditions: a low impedance fault condition, known as “pole to pole” (PP), where conductors are directly connected, and a high impedance fault condition, known as “pole to ground” (PG), where one or both of the connectors are connected to ground (Bayati *et al.*, 2018).

### 6.5.2 Grounding

The safe operation of a power network requires proper grounding (earthling) of the generation system and grid-tied electrical components. The risk of electric shock, which may lead to severe injury or even death, can be minimised by an effective grounding scheme (Kumar *et al.*, 2017).

## 6.6 Microgrids and pilot projects around the world

Microgrid projects are gaining momentum worldwide, with more systems being planned and deployed. This section lists some examples of microgrid systems with different capacities that have been commissioned successfully and are currently in operation.

### 6.6.1 India

Since 2014, a small Indian village in north-eastern India has met its energy consumption needs after being ignored by local officials for many years. A 100 kW system now provides energy to

50 businesses, 450 houses, two schools, a training centre, and a healthcare facility in Dharnai, a small village with a population of 2,400 in one of Bihar's poorest areas. The village is 100% solar-powered, of which 30% is reserved and the rest coupled into the microgrid for general consumption. Battery storage ensures power is available 24 hours a day (Greenpeace, 2014). Figure 6.1 presents a picture of the installed system.

**Figure 6. 1: Solar microgrid installation, Dharnai - India (Greenpeace, 2014)**

### 6.6.2 Kenya

In Kenya's Makueni County, the Kitonyoni Village Market Solar Project was established in 2012 and operates on a 13.5 kW solar PV system. It is utilised for cooking and lighting within community businesses and successfully eradicates the reliance on candles and kerosene (Bahaj and James, 2019). The project, pictured in Figure 6.2, is an inspiring example in Africa, where millions of people lack access to electricity. As a result, the village has received many local and international visitors from Japan, Zambia, the United Kingdom, Germany, the World Bank, as well as many funding organisations.

**Figure 6. 2: Microgrid (13.5 kW) in Makueni County, Kenya (UoSouthampton, 2013)**

### 6.6.3 Tokelau Islands

Tokelau Islands, located in the South Pacific in Australia, was initially powered through three diesel generators, burning a daily amount of 2,000 litres of fuel. The island then became the first country in the world to produce all of its electricity from the sun after commissioning a 1000 kW solar PV microgrid comprising 4,032 solar panels, 392 inverters, and 1,344 batteries (Rocky Mountain Institute, 2013). The solar panel array of the project is pictured in Figure 6.3.

**Figure 6. 3: Solar Power array - Tokelau Island (Rocky Mountain Institute, 2013)**

### 6.6.4 South Africa

SA's state-run power utility, ESKOM, launched its ground-breaking pilot microgrid project in Ficksburg (Free State province) at the Wilhelmina Farm after its completion in November 2017. The microgrid demonstration plant (see Figure 6.4) comprises a 32 kW solar-powered system that provides 81 family members (14 households) with electricity. Three sets of lithium-ion batteries provide storage for the system, which in total provide 90 kW hours of energy backup (Zyl, 2018).

**Figure 6. 4: Wilhelmina solar microgrid, Ficksburg – SA (Zyl, 2018)**

The SA government recently started promoting the implementation of innovative microgrid systems. Examples include the Singita Kruger National Park project and the Robben Island solar PV microgrid (see Figure 6.5). Both these microgrids couple solar PV with lithium-ion battery storage. Both systems also integrate distributed control systems, integrated multiple controllers and intelligent power controllers of solar PV, ESS, and converters to ensure seamless power supply (Motjoadi, Bokoro and Onibonoje, 2020).

**Figure 6. 5: Robben Island Solar PV microgrid, Cape Town – SA (Pallet, 2017)**

In a first for RE in South Africa, the Ekurhuleni municipality has approved the grid connection of a large solar PV plant built for PepsiCo sub-Saharan Africa by the SOLA group. This 1.8 MW solar PV system, with 2.9 MWh lithium-ion battery storage (see Figure 6.6), will form one of the country's largest grid-tied microgrids, capable of stabilising the local electricity grid. PepsiCo has already received the requisite municipal and NERSA (National Energy Regulator of South Africa) approvals to connect to the grid, which will allow the company to sell excess energy back to the municipality (Smith, 2022).

**Figure 6. 6: Grid-tied Solar PV microgrid, Johannesburg – SA (Published with permission from SOLA group)**

# CHAPTER 7: CONCLUSION AND RECOMMENDATIONS

## 7.1 Conclusion

The research in this dissertation was performed to review the energy sector and explore the development status of the latest technologies concerning microgrid deployment. The aim was to explore the microgrid system holistically in terms of planning, installation, commissioning, and maintenance. All aspects of the microgrid were researched, including generation technologies and their respective working principles, the various microgrid components, and ancillary components required for microgrid deployment. The research also aimed at exploring analytical software tools that aid in microgrid planning while concurrently being mindful of techno-economic and technological considerations, which were also detailed in the study. Priority was placed on exploring RE technologies in the context of climate change and the worldwide effort for its mitigation.

The planning and techno-economic analysis of microgrid systems are crucial and complex processes, moreover, when multiple generation sources are considered. Software tools have become standard practice to aid in a microgrid's planning, design, analysis, optimisation and economic viability, and should be used at the onset of microgrid development. Various software tools were discussed, highlighting their respective functionalities and shortcomings in microgrid-planning and operation. Different control strategies and interlinking power converters were also included in this study, as these are essential for the efficient operation of a microgrid.

Solar and wind remain key RE resources for microgrid deployment, particularly in rural or isolated areas, with their installed capacities growing steadily over the last decade. PV and CSP are the most prevalent technologies used to produce electricity from solar irradiation. Global solar PV electricity generation has grown exponentially over the last decade. Concurrently, SA has also seen a vast increase in solar PV installations, possibly due to the country's favorable Global Horizontal Irradiance, reduced PV system prices, and the government's adapted attitude towards RE implementation. Further, the study found that there has been substantial development in recent decades in hydropower, biomass, and fuel cell technologies. The Bioenergy Atlas for SA noted the significant potential for future bioenergy deployment for the country. However, in a country like SA, bioenergy development is constrained by the prioritisation of food security, low productivity, and inconsistent annual weather patterns.

Another critical enabler of microgrid deployment is energy storage, installed to reduce imbalances in energy demand and supply. Storage is crucial in mitigating variations of RE resources to sustain a reliable, stable power supply for downstream loads. Batteries remain the chief technology in microgrid deployment, with lithium-ion preferred in both the residential and business sectors due to superior energy density (energy per unit volume) and specific energy (energy per unit weight) as well as a short response time, amongst other advantages.

Lastly, microgrid deployment and rural electrification require high capital investments per capita, especially in countries with low energy demand and population density. The solution to these financial challenges lies with government policymakers and technical implementers' understanding of technical challenges and cost-reducing opportunities in microgrid deployment.

## 7.2 Recommendations

This dissertation aimed to holistically touch on all enabling technologies, including hardware components and software tools required in microgrid deployment. Many technologies are available and the literature is flooded with examples of microgrids utilising various combinations of these technologies, given the different implementation scenarios.

The author recommends delineated research into emerging enabling technologies, as some of the technologies included in this study (e.g., pumped hydro, compressed air storage), though still relevant in their application, have reached technical maturity. Examples of emerging technologies include:

- Micro fusion power for remote microgrids.
- Solar cells based on nanotechnologies, including carbon-nanotubes and hot carriers.
- Marine energy.
- The application of the Internet of Things in microgrids.
- The application of artificial intelligent techniques in microgrids.

## 7.3 Publication

April D and Kahn MTE, (2021), ‘Electrical Energy Systems and Electric Transportation’, Proceedings of the ISASA 2021 Conference, 7-9 April 2021, Attaturk University, Turkey, ISBN: 978-605-68837-2-9, pp. 259–262.

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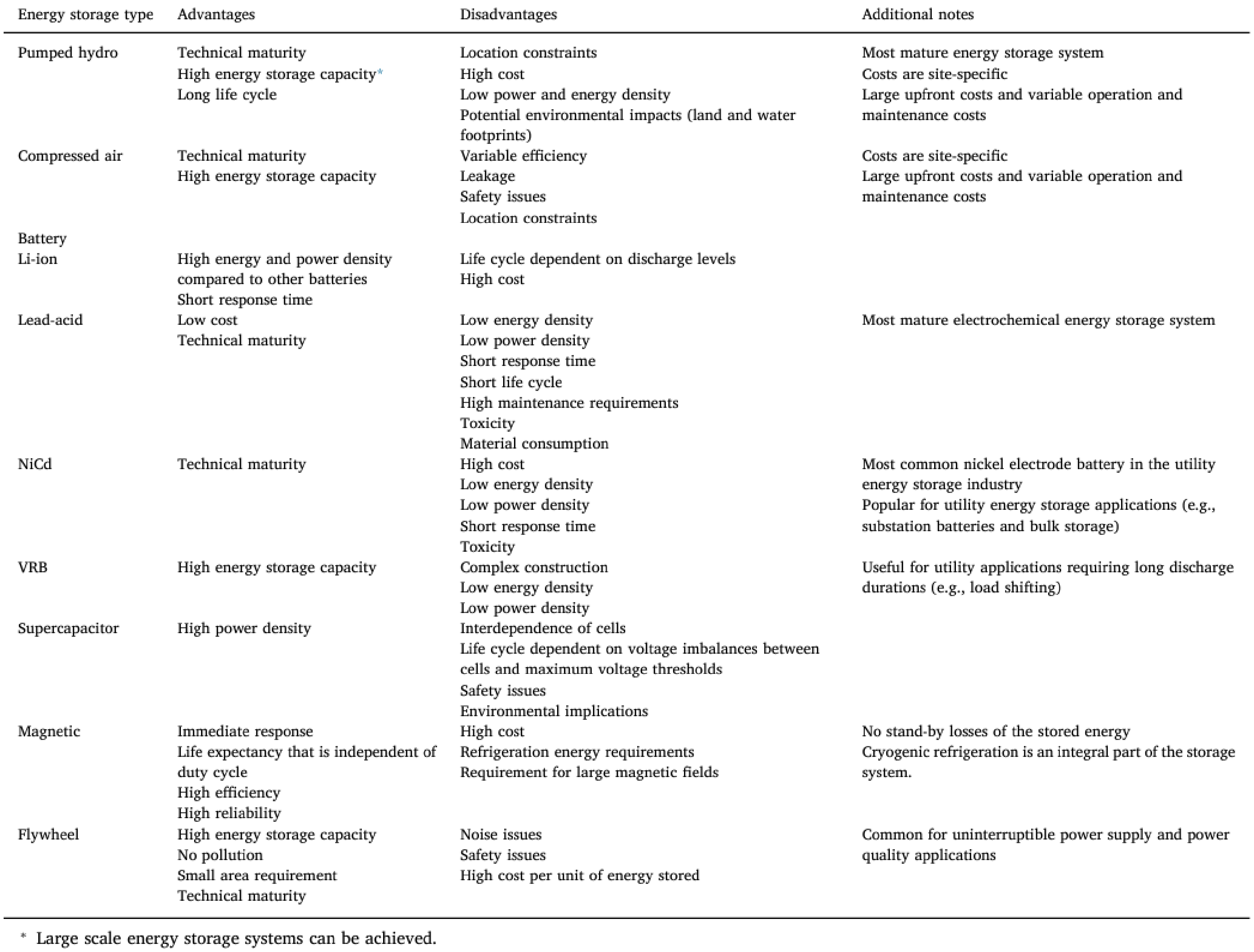
# APPENDIX

## APPENDIX: Advantages and Disadvantages of various energy storage technologies



| Energy storage type | Advantages | Disadvantages | Additional notes |
|---|---|---|---|
| Pumped hydro | Technical maturity<br>High energy storage capacity*<br>Long life cycle | Location constraints<br>High cost<br>Low power and energy density<br>Potential environmental impacts (land and water footprints) | Most mature energy storage system<br>Costs are site-specific<br>Large upfront costs and variable operation and maintenance costs |
| Compressed air | Technical maturity<br>High energy storage capacity | Variable efficiency<br>Leakage<br>Safety issues<br>Location constraints | Costs are site-specific<br>Large upfront costs and variable operation and maintenance costs |
| Battery | | | |
| Li-ion | High energy and power density compared to other batteries<br>Short response time | Life cycle dependent on discharge levels<br>High cost | |
| Lead-acid | Low cost<br>Technical maturity | Low energy density<br>Low power density<br>Short response time<br>Short life cycle<br>High maintenance requirements<br>Toxicity<br>Material consumption | Most mature electrochemical energy storage system |
| NiCd | Technical maturity | High cost<br>Low energy density<br>Low power density<br>Short response time<br>Toxicity | Most common nickel electrode battery in the utility energy storage industry<br>Popular for utility energy storage applications (e.g., substation batteries and bulk storage) |
| VRB | High energy storage capacity | Complex construction<br>Low energy density<br>Low power density | Useful for utility applications requiring long discharge durations (e.g., load shifting) |
| Supercapacitor | High power density | Interdependence of cells<br>Life cycle dependent on voltage imbalances between cells and maximum voltage thresholds<br>Safety issues<br>Environmental implications | |
| Magnetic | Immediate response<br>Life expectancy that is independent of duty cycle<br>High efficiency<br>High reliability | High cost<br>Refrigeration energy requirements<br>Requirement for large magnetic fields | No stand-by losses of the stored energy<br>Cryogenic refrigeration is an integral part of the storage system. |
| Flywheel | High energy storage capacity<br>No pollution<br>Small area requirement<br>Technical maturity | Noise issues<br>Safety issues<br>High cost per unit of energy stored | Common for uninterruptible power supply and power quality applications |

* Large scale energy storage systems can be achieved.