Energy Storage Mechanisms for an African Microgrid

by

Taariq Hendricks

Dissertation submitted in partial fulfilment of the requirements for the degree

Master of Engineering in Energy

Faculty of In the Engineering and the Built Environment

Cape Peninsula University of Technology

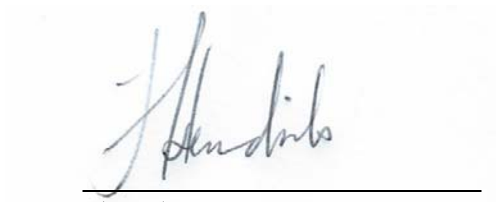
Supervisor: Dr M Adonis

Bellville

October 2020

Declaration

I, Taariq Hendricks, declare that the contents of this dissertation/thesis represent my unaided work and that the dissertation/thesis 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.



Signed

16 October 2020

Date

Abstract

Due to the intermittent nature of renewable energy resources, storage mechanisms were modelled to support the power supply system. The main functions of the energy storage mechanism were to supply consumers with stored energy during periods when energy production was not able to meet the demands of consumers and to improve power quality by acting as a buffer between supply and demand.

The energy stored was from periods when energy production exceeded energy consumption, i.e. off-peak hours, to supply consumers during periods where energy consumption exceeded the amount of energy produced i.e. peak hours. This report aimed to determine the ideal energy storage mechanism for an African microgrid, where the term "African microgrid" was defined as a microgrid which uses African resources to supply electrical energy to African communities. These resources included material resources and labour.

It was determined that the GDP of a country is proportionate to the electrification rate. The country with the lowest electrification rate was, therefore, considered to be powered by a microgrid which that made use of renewable energy and possible surrounding resources (such as biomass) to generate electricity. The country selected for this study as an African country, was Burundi.

The storage mechanisms modelled were to serve a community with an average energy consumption of 500 kWh per day. The storage mechanisms selected to be modelled were:

- Pumped Hydro Storage Systems.
- Battery Energy Storage Systems.
- Supercapacitor Energy Storage Systems.
- Flywheel Energy Storage.
- Thermal Energy Storage.

The energy storage systems were modelled using HOMER, with the following parameters modelled and compared: electrical specifications, energy storage specifications, emission volumes, and costs. The energy storage which had the most suitable results was then determined to be the best-suited energy storage mechanism for an African microgrid. The results of the models were then compared to each other, as well as to results from the literature.

Keywords: Energy Consumption, Renewable Energy Resources, African Microgrid, Energy Storage Mechanisms, HOMER

Acknowledgements

Thanking:

- Dr Adonis for continuous mentoring and guidance.
- Dr Raji for use of his computer resources.
- My family and friends for continuous encouragement and support.

Dedication

Dedicated to all my family and friends for their constant support.

Table of Contents

List of Figures

List of Tables

List of Equations

Acronyms

AC	Alternating Current
AGM	Absorbed Glass Mat
ATES	Aquifer Thermal Energy Storage
BESS	Battery Energy Storage System
BTES	Borehole Thermal Energy Storage
CAES	Compressed Air Energy Storage
CFL	Compact Fluorescent Lamp
CHP	Combined Heat and Power
CSP	Concentrated Solar Power
DC	Direct Current
DLC	Double-Layer Capacitor
EAPP	Eastern African Power Pool
EM-PHS	Energy Membrane Pumped Hydro Storage
ESS	Energy Storage Systems
Fe Air	Iron Air
FESS	Flywheel Energy Storage System
GDP	Gross Domestic Product
HDPE	High Density Polyethylene
HESS	Hydrogen Energy Storage System
HTF	Heat Transfer Fluid
LA	Lead Acid
LCOE	Levelised Cost of Energy
LEC	Levelised Electrical Cost
Li Ion	Lithium-ion
NaS	Sodium-sulphur

NiCad	Nickel-Cadmium
NiMH	Nickel Metal Hybrid
NPC	Net Present Cost
NPSH	Net Positive Suction Head
Pb Acid	Lead-Acid
PCM	Phase Change Material
PEM	Polymer Electrolyte Membrane
PHS	Pumped Hydro Storage
PV	Photovoltaic
SCES	Supercapacitor Energy Storage System
SVM	Support Vector Machine
SWERA	The Solar and Wind Energy Resource Assessment
TESS	Thermal Energy Storage System
TLC	Thermal Load Controller
UPH	Underground Pumped Hydro
USD	US Dollar
VLRA	Valve Regulated Lead Acid
Zn Air	Zinc Air

1. Introduction

1.1. Statement of Research Problem

The construction of informal settlements results in many people connecting to the national grid illegally or not at all. Rural areas, being placed far from a national electrical energy supplier, also results in many people not being able to connect to the national grid. The idea of a microgrid, therefore, seems a viable solution to the lack of electricity (Kyriakopoulos and Arabatzis, 2016)

The purpose of microgrids, which rely on renewable energy systems to generate electricity, is only to produce enough electricity to meet consumer's demands in certain seasons (such as solar PV systems in summer seasons). In seasons, where the weather is not favourable for the renewable energy technology system, a problem can arise where not enough energy is produced to meet the consumers' demand. Due to the fluctuating electrical energy consumption and supply, electrical energy storage is a vital component needed to meet the demands of consumers during peak consumption times (Kyriakopoulos and Arabatzis, 2016).

1.2. Background to the Research Problem

South Africa has higher electrification rates when compared to the rest of Sub-Saharan Africa. South Africa yields an electrification rate greater than 90%, whereas the rest of Sub-Saharan Africa yields an average electrification rate of 30% (Jamal, 2015). Electrifying areas where inhabitants occupy areas far from the national grid becomes increasingly difficult (Winkler et al., 2011).

The migration of people, moving from rural areas to urban areas, places a large strain on available resources such as land, electrical energy, and water. Furthermore, inadequate housing plans made by the government results in the construction of informal settlements (Turok, 2012).

Foreign investors are largely interested in funding South African rural areas independent of the national grid. The resulting scenario leans towards the utilisation of microgrids, supplying heat and electrical energy to consumers of outlying areas (Xu and Chowdhury, 2013).

Due to the global realisation of reducing the use of fossil fuels, and separating economic growth from environmental harm (Barbour et al., 2016), the use of renewable energy technology as a power source for smart microgrids is a greatly promoted idea. The purpose of smart microgrids is to compliment larger national grids, however, during periods when the load on the national grid is low, the microgrid can function independently and assume the role of an islanded grid (Korkas et al., 2016).

1.2.1. Area of Concern

Due to the global conscious effort to reduce the carbon footprint of human beings, a greater emphasis is placed on renewable energy such as wind energy, hydropower, and solar power. Since these sources of energy are replenishable and emit no harmful gases into the atmosphere, harnessing these sources of energy are deemed beneficial (Ramos et al., 2014).

Allowing these renewable sources to be harnessed for electricity is a viable option for communities placed far away from electrical energy producers.

Microgrid systems, powered by renewable energy technologies such as solar PV systems or wind power, are highly advantageous in that no greenhouse gases and other harmful emissions are released into the environment and no external fuels are required. There are, however, disadvantages, such as the nature of the power sources. Since renewable energy technology is greatly dependent on variable natural sources, it results in the variable natural sources being intermittent (Gao et al., 2015).

An energy storage device was, therefore, designed to store electrical energy generated from the microgrid systems (Gao et al., 2015). When conditions, such as the weather, were favourable, the electricity generated by renewable energy powered microgrids was to be stored in these storage devices.

1.3. Electrical Energy and Africa

1.3.1. Current Energy Generation in Africa and the impact of fossil fuels

North Africa, Sub-Saharan Africa, and Southern Africa use various sources of energy to produce electrical energy to meet consumer needs. Sources of energy such as gas, oil, biomass, and coal are used as they are abundant and indigenous to these areas, resulting in cost-effective methods of electricity generation (Belward et al., 2011). Whereas oil is primarily used in North Africa and coal is predominantly used in South Africa, the use of traditional biomass is prevalent in Sub-Saharan Africa to meet the energy demands of consumers (Karekezi and Kithyoma, 2003; Castellano et al., 2015).

The Sub-Saharan African consumers, however, have a lower electrification rate than that of North African countries. There are seven countries that can provide more than 50% of its population with electricity, while the rest of the Sub-Saharan African countries fall below the 50% mark.

African countries, dependent on fossil fuels to generate electricity, find greater difficulty in retrieving the resources required (fossil fuels) than developed countries, according to Belward et al. (2011). It is often difficult and expensive to transport fuel from major cities to outlying areas due to the distances and untarred or unmaintained roads. The increased cost of transporting fuel increases the cost of generating electricity which, as a result, increases the cost of electricity for the consumer.

The fluctuation in the prices of fossil fuels also increases the cost of electricity for consumers. According to Kirchner & Salami (2014), an example of this occurred between the years 1999 and 2012 when the price of oil increased by 400%.

Fossil fuel delivery times to different African regions (Belward et al., 2011) illustrates the time taken for fossil fuel to reach various regions in Africa, with areas illustrated in darker colours reaching up to 10 days.

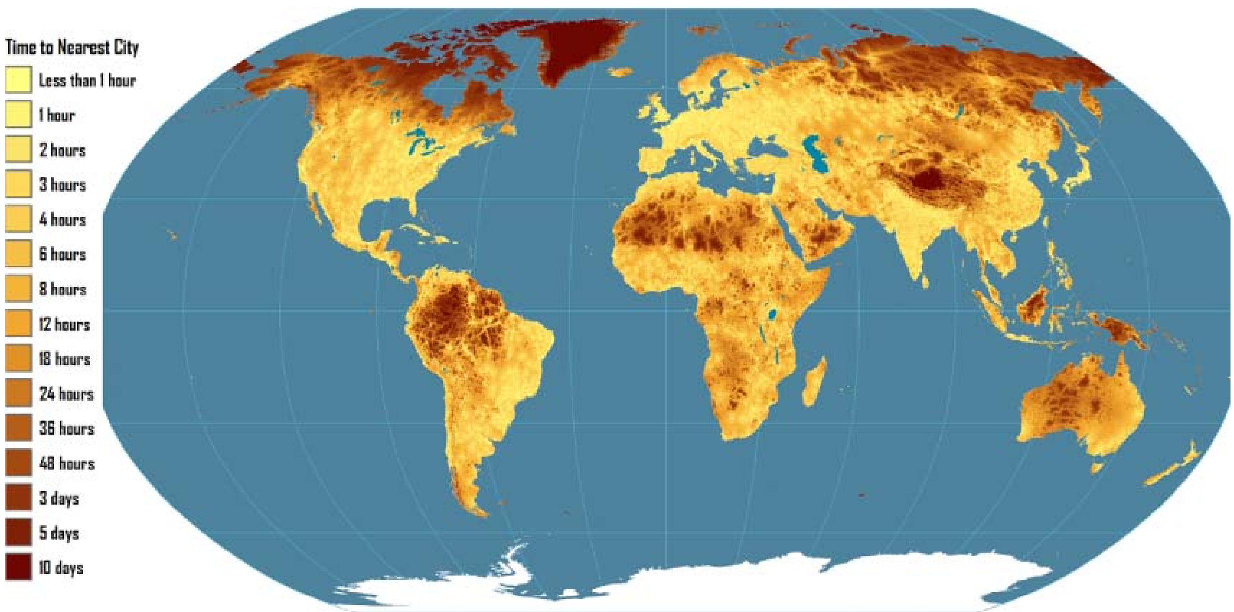


Figure 1: Fossil fuel delivery times to different African regions (Belward et al., 2011)

The vast majority of the African population inhabit rural areas and are unable to pay for electrical energy, therefore, these areas are not supplied with electrical energy. For cooking and heating purposes, rural communities make use of raw biomass, which is indigenous to the area and available from farming waste as the rural population generates income and sustains themselves through agriculture (Belward et al., 2011).

1.3.2. Urbanisation and Africa

Africa's electrical consumption per capita is far lower than the rest of the world (approximately eleven times less than Europe, despite having a larger population). This is due to the low electricity generation and inadequate infrastructure resulting from the lack of development and investment. As a result, this inhibits the people of rural parts of Africa from having access to electrical energy, which in turn affects the economic growth of the respective African countries (Rault et al., 2014).

Africa's urban population is expected to escalate with urbanisation, population growth and the increase in the industrial sector. To cater for the expected increase of urbanisation, an adequate, reliable electrical supply needs to be built to be able to cope with consumer demands (Rault et al., 2014).

1.3.3. Challenges caused by the increase of urbanisation

According to the African Development Bank Group (2012), the increase in urbanisation is a result of people seeking jobs and improved amenities to better their quality of living. There are, however, many challenges that follow when large groups of people move from rural areas to cities. Due to the influx of people moving to urban areas, many informal structures are set up by local civilians as the respective governments are unable to plan and budget for formal housing developments. This is not the case in all African countries, however. Northern Africa has a larger urban population, at 47.8%, than Sub-Saharan Africa, which is at 32.8%. The difference in urbanisation is attributed to superior government policies, which caters for improved productivity of people such as infrastructure and skills development (African Development Bank Group, 2012).

The increase of urbanisation impacts the environment negatively and puts a larger strain on resources such as food, water, and wood. To accommodate large groups of people inhabiting cities, large areas of forest are destroyed and ecosystems are disrupted (Gessner et al., 2016).

1.3.4. Political and cultural challenges Africa faces regarding Renewable Energy

Renewable energy projects struggle to begin because of insufficient policies that are put into place, or inadequately managed by government officials. These projects are decided upon between the government and consultants without the input of consumers. Renewable energy projects are often neglected or inadequately budgeted for, especially in African countries where civil war is rife and large amounts of the countries' capital is spent on military equipment (Uyigue and Archibong, 2010).

Due to the lack of expertise, African countries employ foreign aid to facilitate renewable energy projects. The employment of foreign, qualified staff increases the cost of energy generation, thereby increasing the selling price of energy. In parts of Africa where a large percentage of the population is low-income based, purchasing electrical energy becomes too costly (Uyigue and Archibong, 2010; Lambert et al., 2014).

Because of cultural and communication conflicts, many countries do not share experience across borders, which consequently inhibits the growth of less developed countries. Many countries' officials are not open to change and believe that the way things have been run in the past is adequate for the future. This is due to the government officials' lack of knowledge in the growth and benefits of renewable energy. Renewable energy harnessing is not encouraged by African governments to the population and the industrial sector due to fears that private investors would capitalise on the energy market in Africa and exploit African countries to dictate government policies to suit the private investor's interests (Uyigue and Archibong, 2010; Burke and Stephens, 2018).

Governments and the private sector focus on funding centralised, large-scale power stations, instead of investigating smaller, decentralised, renewable energy powered plants. Smaller, decentralised power plants have many advantages over centralised plants, such as closer placement of plants to consumers as well as reducing transmission costs. Larger, centralised power stations generate larger tariffs for governments, however, transmitting larger quantities of electricity over long distances results in a loss of power (Uyigue and Archibong, 2010; Lantero, 2014).

1.4. African Microgrid

One solution to increase the electrification rate for African people may be to invest in microgrids for communities located too far from electrical energy providers. For the microgrid to be beneficial, renewable energy technology should be utilised to supply communities with electricity. The term "African Microgrid" can be used to describe a microgrid which uses all forms of local African energy resources to supply electrical energy to African communities.

An initiative like an African microgrid holds many benefits (Whitlock, 2015):

- Improved quality of life of people.
- Empowerment of people through education.
- Job creation.
- Generating money for communities employing feed-in-tariffs.
- Increase of respective countries GDP.

Due to renewable energy sources being intermittent, storage devices are coupled to the microgrid to ensure energy is stored when electrical energy production is unable to meet the demands of the consumers. Energy storage devices have the following benefits, according to Barbour et al. (2016):

- Increased use of renewable energy technology.
- Reduced carbon footprint.
- Provided a reliable energy supply.
- Stabilised electricity prices.

- Improved the stability of the electrical supply system.
- Improved the flexibility of the supply system.
- Reduced cost of transmission system upgrades.

1.5. Selection of Location

HOMER was used to model a microgrid system using a solar PV system as an energy supply. The location selected was a country on the African continent, preferably in Sub-Saharan Africa where certain areas were lacking basic electrical energy infrastructure. Determining the areas required considering the countries annual energy consumption per capita and GDP per capita. Sub-Saharan African areas are home to 19% of the world's population, yet only 50% of the population had electricity (approximately 600 million people). Although the more developed Sub-Saharan countries such as South Africa, Namibia, Ghana, Cameroon, Côte d'Ivoire, Gabon, and Senegal, were able to serve more than half their respective populations with electricity, the rest of Sub-Saharan Africa reached electrification rates of 20%, according to 2011 statistics by the U.S Energy Information Administration (Castellano et al., 2015). Figure 2 illustrates various countries with their respective energy consumption per capita and GDP per capita.

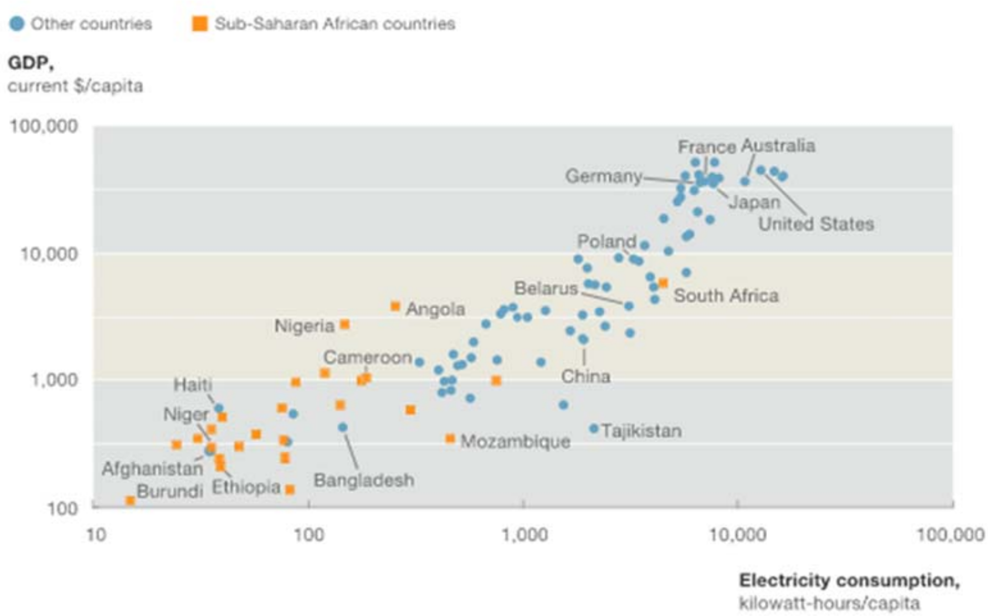


Figure 2: Respective GDP and Energy Consumption of countries (Castellano et al., 2015)

The countries with the lowest energy consumption also have the lowest GDP per capita. Therefore, it can be concluded that there is a correlation between the energy consumption and the GDP of a country (Castellano et al., 2015).

1.6. Electrical Generation Capacity of Burundi

For viable energy storage mechanisms to be determined and established in Burundi, it is necessary to determine the resources that Burundi has in abundance and the resources that are scarce.

In terms of hydropower potential, the Rusumo Falls hydropower plant, located on the Nile, can produce approximately 80 MW of power which is designated to Burundi, Rwanda, and Tanzania (Brown, 2016). Burundi has a 55 MW electricity capacity which serves 5% of the country's population, of which only 2% of the rural areas has access to (USAID, 2016).

The annual irradiance is approximately 2000 W/m^2, similar to the solar irradiance of the Mediterranean regions in Europe. Therefore, solar power energy generation is a viable solution to generate energy to remote parts of rural Burundi (Rakiza, 2012).

According to (Rakiza, 2012), two wind turbines have been erected, in Burundi, in the past two decades and there are no adequate feasibility studies to substantiate the generation of wind power. The wind velocity in Burundi reaches speeds of approximately 4.8 m/s according to the Solar and Wind Energy Resource Assessment (SWERA), by NASA, however, there may be areas with significant wind power potential due to the fluctuating altitudes. There is significant wind potential in Burundi which the Burundi government aims to establish (USAID, 2016).

Burundi has a vast potential to harness the biomass electricity generation due to large deposits of peat and sugar cane residue. Peat potential volumes are in the excess of 600 million tons. Feasibility studies determine that the use of peat for biomass energy generation is a viable option. The MOSO sugar company based in Burundi has a 4 MW biomass generation plant which makes use of sugar cane residue. It is, however, established that excess electricity generated by the plant does not feed into the national grid. Studies are underway exploring the possibility of feeding excess energy generated by the biomass plant into the national grid (Rakiza, 2012).

Transmission lines in Burundi, seen in Figure 3, are established to be well developed with high voltage lines of 70 and 110 kV and medium voltage lines of 10, 15, 30 and 35 kV. While being a member of the Eastern African Power Pool (EAPP), Burundi aims to establish a pool of energy to be distributed between the countries of Tanzania and Egypt (Rakiza, 2012).

Figure 3: Burundi Transmission Network (ArcGIS, 2017)

1.7. Grid-Types

1.7.1. Traditional Central Grids versus Microgrids

Central grids consist of a series of networks which connects homes, businesses and other energy consumers to the energy suppliers. A major disadvantage of these traditional grids is that when the energy supplier fails to produce energy, many consumers are affected (Lantero, 2014).

A microgrid, which may be connected to the grid, serves a smaller number of consumers than the traditional central grid, however, should a fault occur in the power generation or distribution process, fewer people will be affected. These advantages become ideal in areas where storms are prevalent and the microgrid can disconnect from the main grid, using its respective means of energy production to serve its designated consumers. Microgrids can produce energy by means of generators, renewable resources, and batteries (Lantero, 2014).

1.7.2. Micro, Mini and Nano Grids

The scale of the microgrids varies depending on the output power of the system. Microgrids consist of various or a single generation system, operating on a low voltage network, using wind turbines, solar power and fuel cells coupled to energy storage systems such as batteries, flywheels, or pumped hydro systems. Table 1 below illustrates the scale of the various grid types, the type of consumer typically associated with the respective grid-scale, and the use of distribution lines (Ryocroft, 2016).

Table 1: Differentiation of Grid-scales (Ryocroft, 2016)

Grid-scale	Power	Typical consumer	Distribution Lines
Mini	50 kW – 1 MW (up to 10 MW)	• Rural Areas • Residential Areas • Commercial and Industrial Areas • Universities • Medical Centres	Yes
Micro	1 – 50 kW	• Rural Areas • Residential Areas • Commercial and Industrial Areas • Universities • Medical Centres • Military Establishments	Yes
Nano	≤ 1 kW	• Single Customer • Single Building	No

1.7.3. Centralised versus Decentralised Energy

A system which makes use of centralised energy production often has one or many energy production facilities located within the same vicinity and are usually partially or completely state-owned. A decentralised system makes use of a larger number of smaller energy production systems, often varying in energy sources, to meet the demands of consumers. These facilities are often privately owned and work in conjunction with a larger state-owned energy production company (Green, 2014).

Decentralised systems have many advantages over centralised production plants, such as placing the smaller energy production facilities closer to consumers, decreasing distribution line lengths, and ultimately decreasing the cost of energy for the consumer (Green, 2014).

Increasing the amount of energy production companies ultimately allows for innovation, efficient use of resources, job creation, and cheaper energy costs for consumers. In contrast, centralised systems feel no need to improve systems and generally have a monopoly on the energy market, thereby increasing energy prices for consumers (Green, 2014). Due to the benefits of decentralised energy systems, the microgrid designed for Burundi was to be a decentralised system.

1.7.4. Islanded versus Grid-connected

Distribution grid systems (grid-tied systems) which often makes use of various sources such as renewable energy sources or other natural resources are often designed to operate in conjunction with a traditional power generation system, where the primary goal is to serve consumers in surrounding areas before contributing to a national, conventional grid.

It is found to be more favourable, by consumers, to have an islanded grid separated from a national utility grid for increased reliability of energy supply. It is also deemed a simpler option to have an islanded grid than a grid-tied system due to fewer design considerations and operation requirements (Moran, 2014).

There are, however, certain factors to be taken into consideration when designing a microgrid to be islanded. Should these factors not be taken into consideration, the microgrid may be deemed less reliable than the conventional national grid. These factors include (Moran, 2014):

- Load Management.
- Generation to Load Ratios.
- System Contingencies.
- Governor and frequency control.
- Voltage Control.
- Protection.
- Grounding.

According to Moran (2014), many distribution generation systems such as photovoltaic (PV), wind and fuel cells can operate without being connected to a national grid, which works in favour of consumers as consumers prefer using distributed generation systems that are independent of the grid due to grid unreliability. Since diesel engines, used in diesel generators, have an instantaneous response time to varying loads, including a diesel generator to the microgrid serving the consumers in Burundi may be beneficial.

1.8. Energy Audit

As previously discussed, there is a correlation between the energy consumed and the GDP of a country. Since a small minority of Burundi (approximately 5% of the population) has access to electricity, its GDP is one of the lowest in the world. The national average of energy consumption, per capita, is calculated to be 20 kWh per year (Bikalemesa, 2014).

An estimated load was determined by calculating the energy consumed per household to model the energy storage systems. The appliances, along with power drawn and the number of hours the appliance was in operation for, was required to calculate the electrical energy consumed per day. Table 2 illustrates possible appliances that consumers may own as well as energy consumption. The values and appliances are based on typical South African consumer appliances and operation times (City of Cape Town, 2014).

Table 2: List of Typical Major Appliances and Respective Energy Consumption (City of Cape Town, 2014)

Appliance	Power Consumed (W)	Hours of Operation (Hr)	Number of Appliances	Energy Consumed per day (kWh)	Energy Consumed per month (kWh)
CFL (Bulb)	18	8	7	1,01	30,24
Kettle	1 900	0,3	1	0,57	17,1
Gas Stove	0	2	1	0,00	0,00
Gas Geyser	0	1,7	1	0,00	0,00
Refrigerator	158	5	1	0,79	23,70
Iron	980	0,4	1	0,39	11,76
Washing Machine	3 000	0,75	1	2,25	67,50
Radio	12	3	1	0,04	1,08
Total				**5,05**	**151,50**

Because electric stoves and geysers were two appliances which spiked the energy consumption (with the power consumptions of 3 000 W and 2 600 W, respectively), gas stoves and gas geysers (which used no electricity) were included amongst the appliances and brought down the energy consumption drastically.

The energy consumption per household was calculated to be 5 kWh per day and 100 households were to be served by the microgrid, resulting in a total energy consumption of 500 kWh per day.

1.9. Aims and Objectives of Research

The purpose of this study is to determine the most appropriate energy storage system (ESS) to support a renewable energy microgrid in Burundi, based on locally available resources. The ESS considered to be modelled were: pumped hydro storage (PHS), battery energy storage systems (BESS), flywheel energy storage systems (FESS), supercapacitor energy storage systems (SCES) and thermal energy storage systems (TESS).

The objective of this study is to determine the optimum energy storage scheme to support the microgrid through measuring and comparing the following variables:

- Nominal capacity.
- Overall Efficiencies.
- The maximum charge and discharge current.
- Device Lifespan.
- Energy input and Energy output.
- Energy Losses.
- Cost-effectiveness based on techno-economic analysis of the energy storage system.

The study establishes the most suitable ESS for an African microgrid based on the characteristics of the ESS for the area being modelled. Electricity is generated using renewable energy technology. The most suitable ESS is required to use the resources indigenous to the area, reducing the importing cost of materials. The main purpose of the electrical storage device is to supply stored, excess electrical energy to consumers during peak hour energy demands so that energy supply systems can meet consumer demands.

1.10. Research Design and Methodology

To determine the most suitable ESS for an African microgrid, the method of energy generation needs to be determined, such as whether a renewable energy source or fossil fuel is used. Electrical storage systems vary depending on the energy source used.

An area in Burundi was selected and modelled. The average energy consumption was estimated and an energy load was therefore determined. Five scenarios were modelled, where five different energy storage systems were used to store energy produced from a co-fire biodiesel generator and PV system in HOMER. The results obtained from the HOMER models included the following per energy storage system:

- Electrical Summaries
- Cost Summaries
- Emission Summaries

The summaries of the respective energy storage systems were listed and compared to each other. The energy storage system with the most advantages was selected as the most suitable energy storage system for an African Microgrid.

To determine the most efficient method of energy storage, five energy storage systems were compared, and the advantages and disadvantages of each system were highlighted. The storage systems were modelled, using HOMER, with a base-load for a community relying on an islanded microgrid. The energy storage system was ideal for African microgrids which generate electricity via renewable energy technologies.

1.11. Delineation of Research

The thesis aims to develop a model for five best-suited energy storage systems. The size of the microgrid was to be determined and models were developed per energy storage technology using HOMER.

2. Literature Review

Due to a global realisation of reducing the world's carbon footprint, many countries have taken the initiative of introducing renewable energy sources of electrical energy generation into the grid to supply energy to consumers. Electrical energy storage mechanisms are vital for the use of microgrids where renewable energy was the main source of electrical energy generation (López González et al., 2015).

Many obstacles obstructed the supply of electrical energy to consumers located far from power generation facilities such as transmission lines, which have proven to be costly to maintain, as well as the magnitude of power loss in transmission lines over long distances. Communities located too far from power generation facilities made use of diesel generators to supply electrical energy demands due to its low capital cost, however, diesel generators had a high operating cost. The use of renewable energy technology was, therefore, a viable option due to its low operating cost. Furthermore, energy storage needed careful consideration due to the intermittent nature of renewable energy (Tucker and Negnevitsky, 2011).

Electrical energy storage systems comprise five main groups, namely, mechanical, electrochemical, chemical, electrical, and thermal systems (IEC, 2009) as illustrated in figure 4.

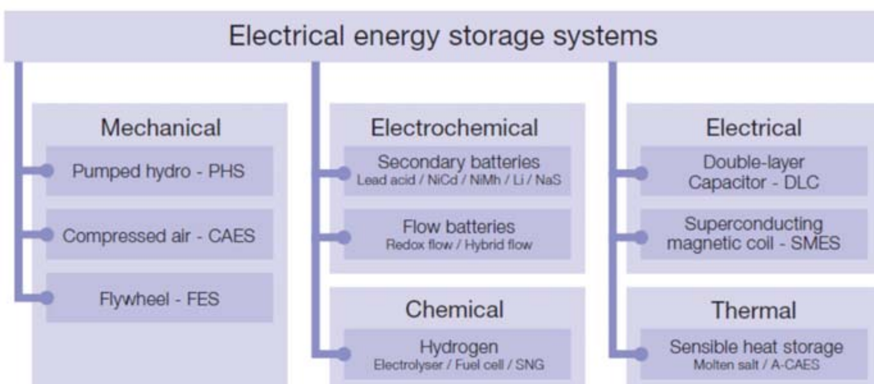


Figure 4: Electrical energy storage system classification (IEC, 2009)

One mechanism type from each of the five groups was researched and discussed in this study. Five devices which held the most benefits for the application of a storage mechanism in an African context were then selected to be modelled.

The devices selected were the following:

- Mechanical: Pumped Hydro Systems
- Electrochemical: Secondary Batteries
- Chemical: Hydrogen Fuel Cells
- Electrical: Double-Layer Capacitor
- Thermal: Thermal Energy Storage

When selecting a storage mechanism to store excess electrical energy for future use, the following considerations were taken into account:

- Duration the stored energy is to be available.
- Installed capacity.
- Discharge time.
- Technology life cycle.
- Installation, operating, maintenance, and decommissioning costs.
- Feasibility of the storage mechanism.
- Control and monitoring equipment.
- Landscape.
- Energy efficiency.

2.1. Mechanical: Pumped Hydro Storage (PHS) Systems

Pumped hydro storage (PHS) systems have been used commercially since the late 19th century and has been of interest as a storage mechanism due to the vast benefits that pumped hydro storage facilities hold (Yang, 2015).

A pumped hydro storage mechanism can store excess energy when excess energy is produced (off-peak hours) for times when the electrical energy demands increase (peak hours). The concept makes use of the difference in potential energy of a body of water placed at different heights. During off-peak hours, excess electricity is used to pump a volume of water to the “upper reservoir” which is placed at a greater height than the “lower reservoir.” The water is then stored in the upper reservoir until peak hours when electricity demand exceeds the power production capacity of the power generation plant. A second purpose of the pumped hydro system is for grid stabilisation (Yang, 2015).

During peak hours, the water stored at the upper reservoir is released. The potential energy of the body of water is then converted to kinetic energy, driving a hydro turbine which then generates electricity (Steffen and Weber, 2016; Yang, 2016). An illustration of a closed-loop pumped hydro system can be seen in Figure 5.

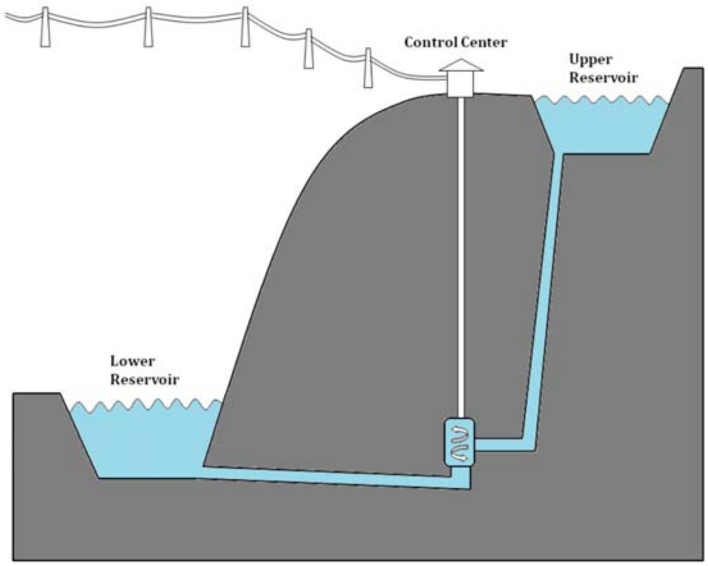


Figure 5: Pumped Hydro System (Yang, 2015)

There are two main typed of PHS; the closed-loop system, seen in Figure 5, and a hybrid system, which harnesses the energy of pumped water and a flowing river to generate electrical energy to meet the electrical demand (Yang, 2015).

2.1.1. PHS Benefits

To meet the demand of consumers, power generators are generally used during peak hours. However, due to fluctuating fuel prices, generators are often costlier, whereas PHS presented a cheaper solution for energy storage. Because cheaper baseload power is used to pump water to upper reservoirs, the levelised cost of energy (LCOE) is less than any other storage mechanism (Yang, 2015).

PHS systems can store large amounts of energy at lower costs than other methods of energy storage and are cheaper to maintain than other energy storage methods (Yang, 2016).

2.1.2. PHS Disadvantages

The mechanics of the system requires a difference in elevation of two reservoirs. Thus, the system may only be viable in areas with a suitable terrain and a sufficient amount of water (Yang, 2015).

Capital costs for the construction of PHS systems are great and often resulted in lead-times of decades in past projects. Since the capital costs are so great, the return on investment is only seen after decades of use (Yang, 2015).

There are ecological barriers which inhibit and often result in the cancellation of PHS systems. Because large volumes of water are required, dams are often erected to collect the required amount of water. Damming an area results in the displacement of people as well as disrupts the natural habitat of animals and fish by changing the landscape. The pumping of the water increases the water temperature, changes its oxygen content, and moves debris around in the water, which results in the death of fish (Yang, 2015).

Furthermore, possible floods caused by a rupture in the dam or an overflow of the dam could result in the mortality of people, plants, and animals in the surrounding areas (Yang, 2015).

2.1.3. PHS Case Studies

2.1.3.1. Case 1: Hydrokinetic Pump Hydro Storage

A study by Kusakana (2015) aims to prove the feasibility of an off-grid hydrokinetic system, for a rural area in South Africa, coupled to a series of batteries or a pump hydro storage facility to store excess electrical energy for peak hours. Furthermore, the study aims to determine the most suitable storage system.

The system model for the Hydrokinetic-PHS system, as found by the author, was (Kusakana, 2015):

$$\boldsymbol{E_{Load} = E_{HKT} - E_{M-P} + E_{T-G}} \quad (1)$$

Where:

- E_{Load} = Energy demand
- E_{HKT} = Energy produced by the hydrokinetic turbine
- E_{M-P} = Electrical energy required by the motor-pump assembly to move a column of water up an elevation
- E_{T-G} = Energy produced from a micro-hydro system

Kusakana (2015) simulates the model in HOMER, a programme used to build renewable energy systems. HOMER's storage calculation capabilities, however, is limited. As there is no pump hydro storage function in the program version used in the study. Kusakana, (2015) equates the system to a series of batteries to store the excess electricity. There is, however, the option of using PHS systems in the version used in this report i.e. HOMER 3.9. The following assumptions were made in the study:

- The rate at which the water flows from the lower reservoir to the upper reservoir can be compared to the rate at which the batteries charge.
- The volume of the reservoir can be compared to the battery capacity.
- The flow from the upper reservoir to the lower reservoir can be compared to the rate at which batteries supply current.

Kusakana (2015) modelled and simulated he two storage mechanisms to determine that PHS is economically feasible and can maintain a reliable power supply to consumers. The proposed system layout is shown in Figure 6.

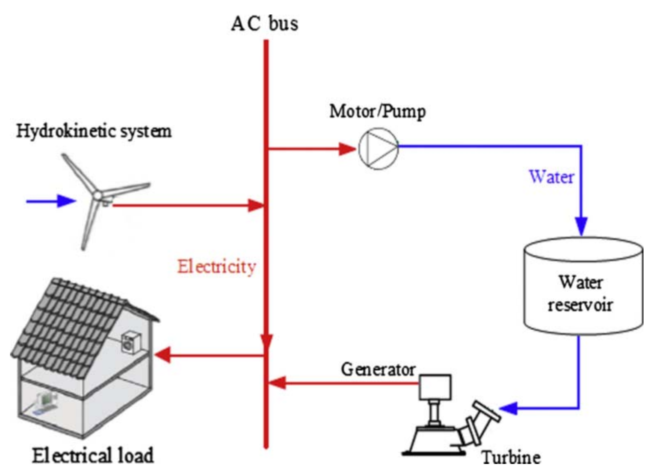


Figure 6: System layout for a hydrokinetic pump hydro storage system (Kusakana, 2015)

2.1.3.2. Case 2: Pump hydro storage versus Battery storage

A remote island in Hong Kong is powered by a microgrid system utilising renewable energy technology. Since renewable energy is intermittent, a storage mechanism is required to store energy during off-peak hours and supply energy to consumers during peak hours. A study by Ma et al. (2014) aims to compare the economic feasibility of batteries and PHS, namely, the life-cycle cost and the levelised cost for the storage system.

According to Ma et al. (2014), lithium-ion batteries are selected, out of eight battery technologies, as they are the best-suited batteries for the storage of renewable energy. Other batteries considered are nickel-cadmium and lead-acid batteries. As nickel-cadmium batteries hold lower efficiencies, higher capital costs, and a low voltage, it was not selected. Lead-acid batteries hold a short life span of up to eight years, and due to the risk of toxins spilling into the environment, this type of d battery was deemed unsafe for this study.

Different scenarios are set up in the study to find the most feasible storage mechanism. The scenarios are:

- Deep-cycle lead-acid batteries.
- Conventional batteries.
- Pump hydro storage and battery hybrid.
- Pump hydro.

Ma, Yang and Lu, (2014) set up the following conditions for the storage mechanisms:

- The power stored is to be generated from renewable energy technology (PV solar panels).
- Daily consumption of 250 kWh is considered, with a load peaking at 50 kW.
- The maximum available sun time is approximately 4 hours.

In conclusion, a hybrid pump hydro and battery storage system is the ideal electrical energy storage device.

2.1.3.3. Case 3: Wind power and Pump hydro

In the case of Island areas which are isolated and therefore challenging and costly to provide electricity for, an unreliable energy source poses many problems for inhabitants, especially when power is needed to desalinate seawater for use. Segurado et al. (2016) proposes that excess energy produced by wind can be stored and used for desalinating water.

According to Zhao et al. (2015), due to the unpredictable nature of wind energy, a storage mechanism is vital to store electrical energy for use during peak demand hours. When coupling a renewable energy source such as wind energy, (which delivers an unreliable energy supply) to a national grid, the energy delivered by the wind has the potential to destabilise the grid. Storage mechanisms are therefore frequently used to bring stability to national grids due to its ability to discharge the required amounts of energy when needed.

However, because PHS systems are slow in response to the varying wind patterns, they are not deemed ideal for the storage mechanisms for wind energy technology (Zhao et al., 2015).

2.2. Electrochemical: Secondary Batteries

A battery is a device which stores energy with the use of chemicals. Batteries consist of three main components, namely, an anode, a cathode, and the electrolyte that separates the cathode and anode. When the battery is connected to a device, a chemical reaction occurs in the battery known as a redox reaction (a reduction and oxidising reaction), wherein the cathode accepts electrons from the anode. The cathode is known as the oxidising agent, and the anode is the reducing agent which loses electrons. Because the excess electrons, which are negatively charged, aimed to move to the positively charged cathode, the electrons moved through a device to the cathode. The flow of electrons is known as the current (MIT, 2012). Figure 7 illustrates the cross-section of a typical lead-acid battery.

Various batteries have been developed, namely: Lead-acid (LA) batteries, Nickel-Cadmium

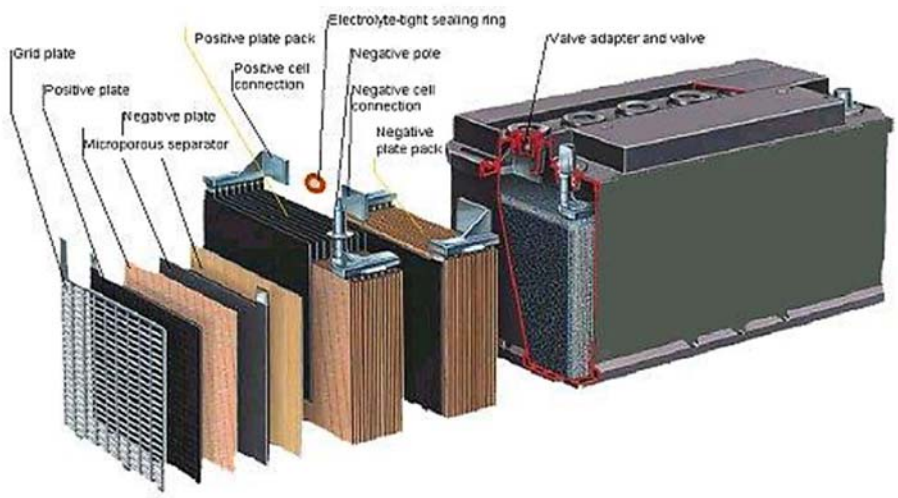


Figure 7: Lead Acid Battery cross-section (Pradhan et al., 2012)

(NiCad), Lithium-ion (Li Ion), Sodium Sulphur (NaS), and Nickel-Metal hybrid batteries (NiMH) (Zhao et al., 2015).

Batteries used in conjunction with renewable energy technology (such as solar, wind etc.) are known as deep-cycle batteries. The term deep-cycle refers to the discharge of current that the battery can deliver without causing harm to the battery. Deep-cycle batteries can discharge many deep, low current discharges with no harm, whereas starting batteries, used in cars, deliver short bursts of high current (Pradhan et al., 2012).

2.2.1. Battery Benefits

Batteries are widely used commercially due to benefits such as the rapid response time of discharging current which enhances the stability of a grid or system (Zhao et al., 2015). Losses caused by the internal resistance of batteries are low, which results in batteries having efficiencies ranging from 60-90%. Battery storage devices yield high power and great energy densities (Zhao et al., 2015).

2.2.2. Battery Disadvantages

Due to the chemicals used as electrolytes and other toxic materials used in the construction of batteries, proper disposal of batteries is important as well as costly. Batteries have a limited cycle time, with life cycles ranging from 3 to 15 years according to Zhao et al. (2015), and are therefore not used in conjunction with large-scale utilities.

Lithium-ion batteries yield high energy densities and are used for the storage of electrical energy of electric cars, however, due to the high capital cost, large-scale commercial use is considered impractical (Zhao et al., 2015).

2.2.3. Battery Case Studies

2.2.3.1. Case 1: PV solar systems and Batteries

Pradhan et al. (2012) aims to design an off-grid solar PV system which makes use of lead-acid batteries as a storage mechanism. The system is designed for domestic use rated at 24 V (volts) and 400 Ah (ampere-hours) and 6 kWh for a day at a total cost of 10 000 US Dollars (USD).

The capacities of batteries are rated in ampere-hours at a given voltage at a 20-hour rating. These ratings serve as a comparative purpose for consumers, however, are not meant to guarantee the performance of batteries. Manufacturers influence the quality of the product; therefore, battery performance is manufacturer dependent as well as dependent on the climate (Pradhan et al., 2012).

According to Pradhan et al. (2012), there are two main categories of lead-acid batteries, namely gel cell batteries and the absorbed glass mat battery (AGM). These batteries hold advantages such as the low levelised costs of energy (LCOE). Furthermore, they can be safely transported via air without the need for special protocols. This is largely due to the electrolyte being immobilised, whereas flooded batteries require special packaging when being transported. Although lacking in performance when compared to other batteries, lead-acid batteries require no maintenance.

There are many drawbacks to the use of batteries in this application, such as the performance and disposal costs. Battery performance depends on the usage of the battery; the more it is used, the more the performance deteriorates. For every amp-hour used from the battery, an additional 25% of electrical energy is required to recover the battery to its charged state (Pradhan et al., 2012).

However, batteries host benefits such as instantaneous discharging of electrical energy as well as not requiring pumps or motors (Pradhan et al., 2012). Furthermore, battery use is not location specific.

2.2.3.2. Case 2: Comparison of three types of batteries for a hybrid microgrid

With off-grid power generation technologies gaining interest, governments of various countries such as Germany and Japan incentivise renewable energy technology for domestic use, which in turn promotes the use of renewable energy technology for domestic consumers. According to Ciez and Whitacre (2016), the interest for off-grid renewable energy technology to generate electrical energy for remote regions has grown.

(Dwivedi et al., (2016) aims to develop a model which incorporates the deterioration of batteries, which plays a role in the selection of batteries. The batteries used for modelling are lead-acid batteries, a high-power density lithium-ion battery, and a high-energy density lithium-ion battery.

Ciez and Whitacre (2016) use a solar-diesel hybrid system coupled with batteries for the model. The model aims to find the optimal storage capacity required from batteries while minimising the use of fossil fuel (diesel) to meet the demands of the consumer. Additionally, the model aims to determine the configuration which yields the lowest levelised cost of energy. The specifications for the model are as follows:

- 7.5 kW solar PV.
- 2.5 kW diesel generation.
- 20.5 kWh daily energy demand.

Once the ideal storage capacity is determined for each battery type, the levelised cost of energy is energy.

The findings of the model indicate that lead-acid batteries yield the lowest capital cost at discount rates of 4% and lower, however, at higher discount rates the high energy density lithium-ion batteries yield lower levelised costs of energy (LCOE). Therefore, high power density lithium-ion batteries prove to be the most costly energy storage device of the three batteries (Ciez and Whitacre, 2016).

2.2.3.3. Case 3: Aqueous batteries on a grid-scale

Batteries such as lithium-ion batteries hold high efficiencies (up to 99%) in most cases and yields energy densities up to 100-200 Wh per kg (watt-hour). These batteries can also endure up to a thousand cycles before the performance of the battery fades. Sodium-based batteries operate at temperatures around 300 °C, have energy densities of 150 Wh per kg, and can endure 3 000 cycles before the performance of the battery declines. However, according to Posada et al. (2016), these batteries do not offer the safety that aqueous batteries offer. The most common form of aqueous batteries is lead-acid batteries.

Posada et al. (2016) summarises the cost, energy density, life-cycle, self-discharge %, and memory effect of each battery technology which are listed and compared in Table 3 below.

Table 3: Summary of battery technologies (Posada et al., 2016)

Technology	Cost (€/kWh)	Energy Density (Wh/kg)	Life (no. of Cycles)	Self-Discharge (% per month)	Memory Effect
Pb Acid	25-40	30-50	300-500	30	No
NiFe	50-60	30-50	2000+	20	No
NiCd	70-80	50	1500	28	Yes
NiMH	275-550	50-80	500-800	30	Yes
Li-ion	500-700	75	500-3000	10	Small
Na-ion	300-400	50-60	-	-	-
Zn Air	5-10	350-500	200-600	20	No
Fe Air	5-10	60-80	300	20	No

Posada et al. (2016) therefore concludes that for large-scale energy storage, to the order of a few hundred megawatts of electricity, apparatus needs to be cost-effective and long-lasting. Energy density, power density, and efficiency are unimportant factors to take into consideration when designing for large-scale applications. Factors which takes preference includes capital, maintenance costs, and safety. Making use of aqueous batteries eliminates the implementation of costly safety systems which aims to prevent hazards.

The study concludes that nickel-iron (NiFe) is ideal to use for large-scale applications, due to the resilient nature and endurance of the battery, as well as the safe features the batteries exhibit for the environment. Due to these features, NiFe batteries are costlier than lead-acid batteries.

2.3. Chemical: Hydrogen Fuel Cells

The basic structure of a fuel cell consists of an electrolyte placed between an anode and a cathode. The anode and cathode are then placed between two bipolar plates as seen in Figure 8. Hydrogen and oxygen, used as fuel, is supplied to the anode where the hydrogen is ionised. The positively charged hydrogen can pass through the electrolyte and cathode membrane, while the electrons, which are separated from the hydrogen, are funnelled through a circuit and used to do electrical work (US Department of Energy, 2006).

The protons (ionised hydrogen) which passes through the electrolyte and cathode membrane reacts with the oxygen supplied to the cell. Then, the electrons, which return from doing work, creates a reaction with the oxygen and positively charged hydrogen, which results in water being formed and heat generated (US Department of Energy, 2006).

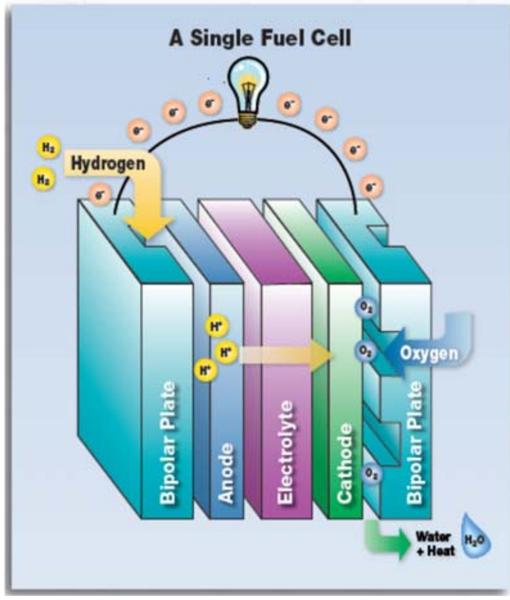


Figure 8: Fuel cell operation (US Department of Energy, 2006)

The mechanics of fuel cells are the same. Any variations in fuel cells are the result of variations in the electrolyte being used. Depending on the application, the most appropriate electrolyte needs to be selected. The electrolyte selection is determined by the output power required and the operating temperature, according to the US Department of Energy, (2006). Table 4 illustrates the fuel cell type with respective output power, operating temperature, efficiencies, and applications.

Table 4: Fuel Cell type and respective applications (US Department of Energy, 2006)

Fuel Cell Type	Operating Temperature	System Output	Efficiency	Applications
Alkaline (AFC)	90 – 100 °C	100 – 100 kW	60 – 70 % electric	• Military • Space
Phosphoric Acid (PAFC)	150 – 200 °C	50 kW – 1 MW (Module Typical)	80 – 85 % overall with CHP (36 – 42 % electric)	• Distributed Generation

Polymer Electrolyte Membrane or Proton Exchange Membrane (PEM)	50 – 100 °C	≤ 250 kW	50 – 60 % electric	• Back-up Power • Portable Power • Small Distributed generation • Transportation
Molten Carbonate (MCFC)	600 – 700 °C	≤ 1 MW (Module Typical)	85 % overall with CHP (60 % electric)	• Electric Utility • Large Distributed Generation
Solid Oxide (SOFC)	650 – 1000 °C	5 kW – 3 MW	85 % overall with CHP (60 % electric)	• Auxiliary Power • Electric Utility • Large Distributed Generation

The Polymer Electrolyte Membrane (PEM) fuel cell yields great promise for transportation and stationary power generation applications. The application possibilities are vast, from cars to communities unable to access the electrical grid (Department of Energy, 2011; Giorgi and Leccese, 2013). PEM fuel cells offer a high-power density and, due to the operating temperature of 80 °C, a variety of materials can be used in the production of these fuel cells.

2.3.1. Fuel Cell Benefits

Hydrogen energy storage systems (HESS) hold much promise for a large variety of applications, such as transportation and stationary systems. Since hydrogen can be stored for long periods and may be a possible replacement for fossil fuels in the transport industry, hydrogen energy storage systems are widely researched (López González et al., 2015).

The by-products of hydrogen fuel cells consist of only water and heat. This is beneficial for areas where water is scarce, and the excess heat may be used to generate more electricity or to provide heat for homes (US Department of Energy, 2006). Coupled with renewable energy generation systems, no pollutants or greenhouse gas emissions are emitted into the environment (Giorgi and Leccese, 2013).

One of the greatest attributes to hydrogen fuel cells is the efficiency that the storage device yields (approximately 60%) which is greater than conventional electrical energy power production plants (US Department of Energy, 2006).

2.3.2. Fuel Cell Disadvantages

Fuel cell technology is a specialised technology, in other words, a high cost-low volume production process. As a result, there is a lot of competition in terms of the financial feasibility of fuel cells for commercial use. Due to the specialised nature of the materials used to produce fuel cells, the cost of manufacturing these products increases the cost of the fuel cells (US Department of Energy, 2006).

Due to lack of information, the life cycle of the fuel cells and the way the fuel cells degrade over time is unknown (Giorgi and Leccese, 2013).

Large quantities of hydrogen fuel is not freely available for commercial electricity production and are, therefore, expensive, thereby increasing the price of electricity for consumers (Giorgi and Leccese, 2013).

PEM, which is considered the most promising hydrogen technology due to its vast applications, is prone to damage caused by carbon monoxide due to the low operating temperature. Carbon monoxide levels, therefore, have to be constantly monitored. The excess heat given off in PEM fuel cells is lower than that of other fuel cell technologies and is therefore not usable (Giorgi and Leccese, 2013).

2.3.2.1. Case 1: Solar PV and Battery-hydrogen fuel cell hybrid storage

The premise for the paper by Douglas (2016) aims to develop a model which utilises a solar PV system to charge a series of batteries for small power loads for long periods. The hydrogen fuel cell, which stores excess electricity generated from the solar PV system, aims to meet the demands of the consumers. It was found that the hydrogen fuel cell can supply energy for high power loads but short periods (Douglas, 2016).

The model simulated, by Douglas (2016) in MATLAB/Simulink. A block diagram can be seen in Figure 9.

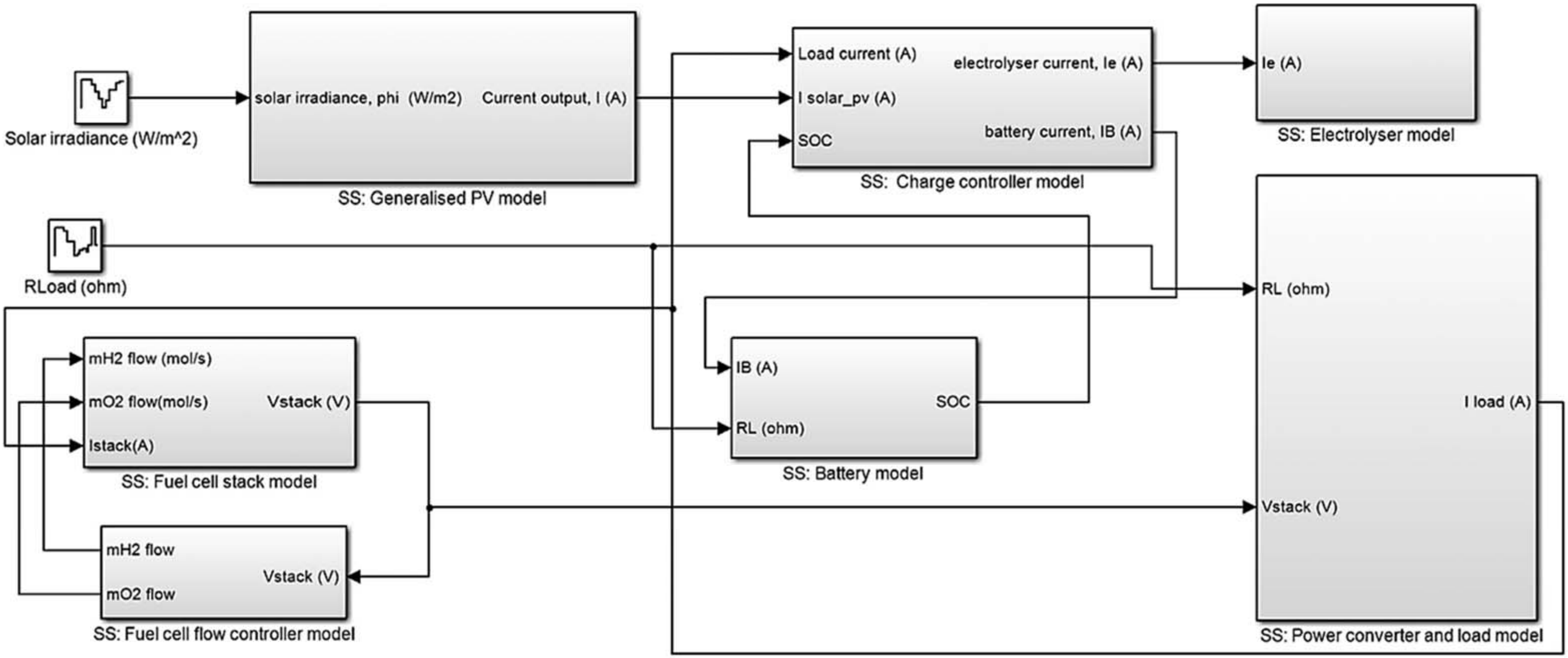


Figure 9: Block diagram of Solar PV and battery-fuel cell hybrid model (Douglas, 2016)

The study concludes that the hybrid storage mechanism is capable of providing energy for small power loads for long durations using the stored battery power, and large power load demands are met by hydrogen fuel cells for shorter periods. The hybrid energy storage system is found to be a successful method of energy storage as it provides a cost-effective, environmentally friendly storage solution (Douglas, 2016).

2.3.2.2. Case 2: Solar-Wind Hybrid system and Hydrogen fuel cell storage

The study by Tucker and Negnevitsky (2011) aims to meet the demands of an isolated community using a solar-wind system and a hydrogen fuel cell storage system to store electrical energy for times when the intermittent nature of renewable energy technology interferes with consumer's demands.

The load profile for the community is initially determined, which includes the peak hours, off-peak hours, and the time of the maximum demand. The second step taken is the selection of power generation devices. To select the appropriate wind turbine and PV solar panels, the wind speed and solar irradiation is determined for the area. The energy storage system is then selected. Tucker and Negnevitsky (2011) chose hydrogen fuel cells due to the quick response time of the storage system. Capital and operational costs, lifetime and power density and quality play an important role in the selection of energy storage devices.

2.3.2.3. Case 3: Grid-tied microgrid with hydrogen fuel cell stack

Zhang and Xiang (2014) aims to distribute the method of power generation by varying the technology used to generate electricity. The purpose of varying the generation is to increase the reliability of the grid and to supply electrical energy to remote areas. The excess energy generated from a solar PV system is stored using hydrogen fuel cells (Zhang and Xiang, 2014).

The solar PV system can produce a maximum power output of 85 kW with a temperature coefficient of 0.12, an ambient temperature of 25 °C, and solar irradiance of 1000 W/m^2 (Zhang and Xiang, 2014). The voltage is calculated using the following equation:

$$\boldsymbol{V_{OC} = \alpha(T_{STC} - T_A) + V_{Rated}} \tag{2}$$

Although being technically feasible, as the fuel cell stack can meet the electrical energy demand, the study concluded that the hydrogen fuel stack is not economically viable (Zhang and Xiang, 2014).

The increase of electrical energy prices attributable to the cost of hydrogen fuel cells is, therefore, not a viable option for rural African areas where the majority of the community earns below the low-income threshold.

2.4. Electrical: Double-Layer Capacitor

Electrical double-layer capacitors, which are also known as supercapacitors, gold capacitors or ultracapacitors are devices used to store charge (Stoller & Ruoff, 2010). The carbon pores, placed next to each other, form a double layer with spaces between the carbon pores to the order of 2-10 Å (0.2-1 nm). The space between the carbon pores, which effectively becomes the capacitor, is dependent on the electrolyte used and the size of the ions. When a current is passed through the electrodes, the nano-charge between the carbon pores is the stored charge (Stoller and Ruoff, 2010).

2.4.1. Double-Layer Capacitor Benefits

One of the benefits that supercapacitors hold over other forms of electrical energy storage devices, such as batteries and low-temperature fuel cells, is the power density per unit area. It is common for supercapacitors to exhibit power densities above 1000 W/kg (Yassine and Fabris, 2017), as illustrated in Figure 10. Supercapacitors also display longer lifespans than conventional batteries can improve power density when coupled to a battery (battery-supercapacitor hybrid) and can also improve the energy density of a capacitor (capacitor-supercapacitor hybrid) (Kötz and Carlen, 2000).

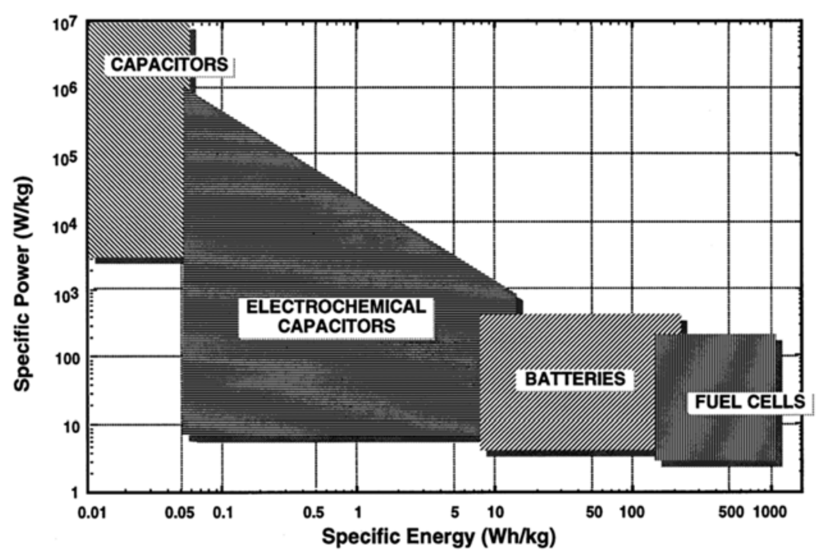


Figure 10: Specific energy and power of various storage devices (Kötz & Carlen, 2000)

Supercapacitors contain no harmful toxins which pose a risk to the environment and are simple to dispose of, resulting in an environmentally friendly storage mechanism. The maintenance costs of supercapacitors are considerably lower than other forms of storage devices as no maintenance is required throughout the lifetime of the double-layer capacitor. This results in an overall lower levelised cost of energy for the consumer. Common efficiencies for double-layer capacitors are known to yield above 95% (Kötz and Carlen, 2000).

Supercapacitors can perform in a great range of temperatures and yield greater efficiencies than batteries at low temperatures (Kötz and Carlen, 2000). These capacitors are widely used in renewable energy technology mechanisms, such as providing power to wind turbines during periods when wind energy is not adequate and to prevent momentary drops in power for solar PV panels. Double-layer capacitors are suitable for these applications due to the instantaneous response time of the device (Hauge et al., 2014).

2.4.2. Double-Layer Capacitor Disadvantages

Although double-layer capacitors (DLC) obtain a greater power density than batteries, batteries are better suited for supplying energy for longer periods (Hauge et al., 2014), which is required for the storage of energy in a microgrid. Kötz and Carlen (2000) explains the ratio of electrical energy stored to the available power is not encouraging. For the DLC to be technically feasible for a microgrid, the DLCs have to be oversized. Although DLCs are not constricted by polarity, AC applications for DLCs are unsuitable due to the high internal resistance of the device, which may result in failure caused by thermal deterioration. According to Shukla et al. (2012), DLCs are also known to exhibit high resistance, yield low energy, and is a costly form of electrical storage.

2.4.2.1. Case 1: Standalone solar PV with Supercapacitor energy storage

A study by Li et al. (2011) aims to design a solar PV system for a remote region using supercapacitor energy storage (SCES) instead of deep-cycle batteries, and to determine the feasibility of the SCES device. The reasoning behind the research was due to the inability of solar PV systems to maintain the minimum charge required to prolong battery life, known as a floating charge. As a result, deep-cycle batteries' lifespans are shortened. Stand-alone solar PV systems are also unable to fully charge batteries during seasons where solar irradiance is at a minimum.

Therefore, due to the advantages of supercapacitors, such as high power densities and long life cycles, supercapacitors are useful as storage devices in solar PV systems (Li et al., 2011).

2.4.2.2. Case 2: Solar PV system with a Battery-supercapacitor hybrid storage

The premise for the study by Chia et al. (2015) is to combine the deep-cycle the batteries, conventionally used with solar PV systems, and supercapacitors. The aim is to overlap the advantageous characteristics of both energy storage devices to yield the ideal storage device. The battery's high energy density is to combine with the high-power density of the supercapacitor to deliver a reliable source of energy. The supercapacitor aims to extend the life-cycle of the batteries by serving instantaneous peak power, which ordinarily degrades deep-cycle batteries. To accommodate for the instantaneous peak power that the solar PV system develops, many batteries are used. However, this is not a cost-effective and ideal utilisation of space, especially when the instantaneous peak power occurs for a few seconds. Prolonging the life-cycle of batteries can provide a more environmentally friendly and cost-effective source of energy storage, as fewer batteries need replacement and disposal in the future.

The study makes use of a load predictive management system, namely a Support Vector Machine (SVM), which is used to predict future power demands for solar PV systems. By implementing a predictive management system, efficiency is improved, and the cost of the system is reduced by approximately 10%. The cost reduction is due to the exclusion of components conventionally used to balance voltage levels in the hybrid storage system, namely the bi-directional DC-to-DC converter (Chia et al., 2015). The layout of the system can be seen in Figure 11.

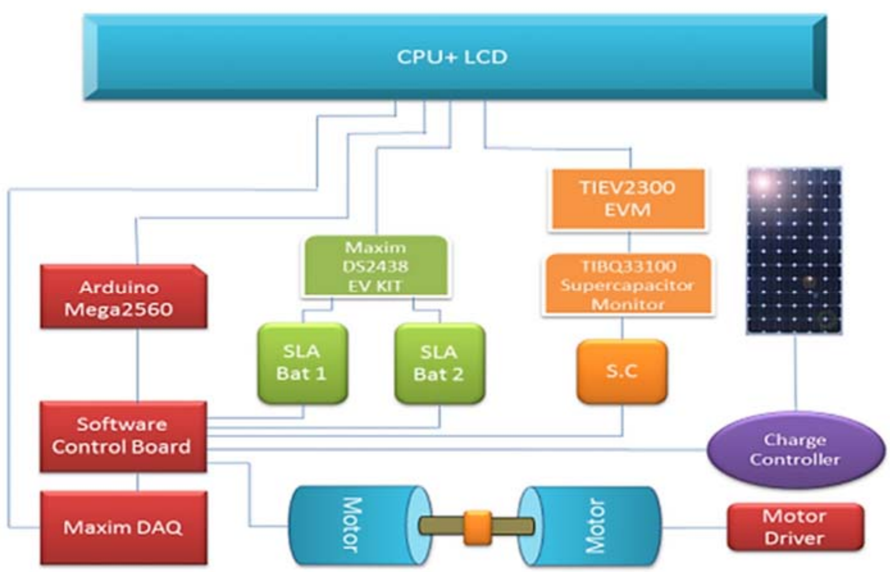


Figure 11: SVM layout for solar PV with battery-SCES hybrid (Chia et al., 2015)

Chia et al. (2015) concludes that due to the instantaneous response of the supercapacitor, the hybrid storage mechanism can deliver energy for peak power instantaneously. The life-cycle of the batteries is prolonged because the peak power, which otherwise damages deep-cycle batteries, is catered for.

2.4.2.3. Case 3: PV-Wind-Diesel hybrid coupled with a Battery-SCES hybrid

Tankari et al. (2010) aims to develop a PV-Wind-Diesel generator hybrid energy generation system which makes use of a battery and supercapacitor hybrid energy storage mechanism. Due to the nature of wind energy generation, the power produced varies significantly, which affects the quality of the power delivered. The solar PV systems can deliver energy at a higher quality power than wind energy on a cloudless day, however, when the weather is unfavourable for solar energy power generation, the power quality and quantity is decreased. The hybrid storage device is, therefore, expected to deliver energy with reliable quality.

The configuration, which can be seen in Figure 12, illustrates the PV-Wind-Diesel generator system. The wind generator and solar PV-hybrid system generates electrical energy using wind and solar energy, respectively. Because these sources of energy production are intermittent, a diesel generator is included to compensate for the required power, should the renewable energy technology fail to meet the power demand.

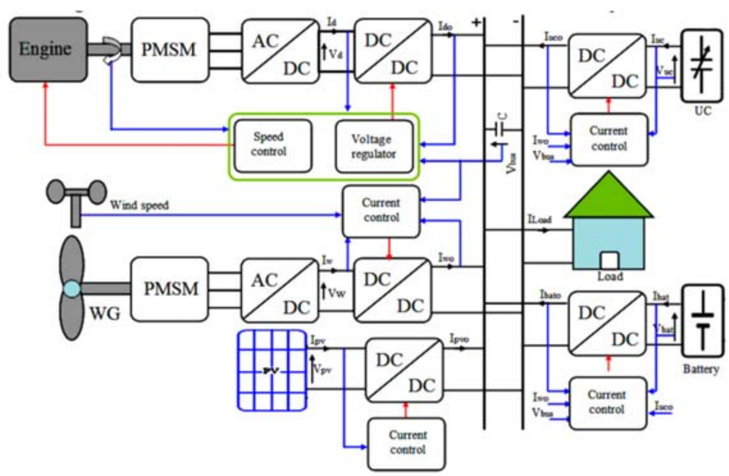


Figure 12: Layout of the hybrid systems (Tankari et al., 2010)

Tankari et al. (2010) reports that when size of storage devices is considered for renewable energy systems, inaccurate data is used to estimate life-cycles using hourly data for storage mechanisms. However, what is not taken into account is the intermittent power produced by renewable energy technology, such as peak power fluctuations and large cycle numbers, which greatly contributes to the deterioration of lead-acid batteries.

The hybrid storage simulations are done after determining the load characteristics of the hybrid energy production system. Once load characteristic data is received, simulations using only batteries are done, followed by supercapacitors and then the combination of the two storage devices. The hybrid storage device is to improve power quality by compensating for the power fluctuations after the diesel generator had compensated for the lack of power supply. When the diesel generator overcompensates by delivering more energy than the required amount, the excess energy gets stored in the storage device; when the diesel generator is unable to meet the required power demand, the storage device compensates for the necessary power (Tankari et al., 2010).

The study concludes that the batteries and supercapacitors can complement each other to provide a reliable power storage system (Tankari et al., 2010).

2.5. Thermal: Thermal Energy Storage

Thermal energy storage comprises two types of methods in which heat could be stored, namely latent heat storage which refers to the storage of heat in a medium which changes state or phase change process, i.e. from liquid to solid or from gas to liquid , and sensible heat storage, which does not include phase change material (Hahne, 2001). An example of latent heat storage includes cryogenic energy storage, which uses excess electricity to convert air or nitrogen to liquid form by cooling it to temperatures around -190 °C. When energy is needed, the air is heated to room temperature. The energy produced in the expansion of the air is equal to the sum of the energy used to freeze the air and additional losses. The air is then used to drive a gas turbine (Harrabin, 2012).

The second type of thermal energy storage is sensible heat storage which stores energy in a medium without inducing a phase change. Sensible heat storage can be classified into low-temperature storage and high-temperature storage. Low-temperature storage operates at temperatures below 100 °C, while high-temperature storage operates at temperatures which exceed 100 °C (Hahne, 2001).

Latent heat storage or phase change storage has many disadvantages when compared to sensible heat storage, such as a higher rate of corrosion of materials, as well as phase separation, which is the separation of a liquid or solid mixture to form two distinct mediums. Furthermore, the manufacturing cost of latent heat storage devices far exceeds that of sensible heat storage (Li, 2016).

According to Li (2016), mediums used to store energy have the following thermal properties:

- High energy density.
- A thermal conductivity greater than 0.3 W/mK
- Simple manufacturing methods and low capital and operation costs.
- Materials and mediums used should be harmless to the environment.

The most commonly used medium in sensible heat storage is water, due to its availability, non-toxic nature, benefits to the environment, and ability to be used at vast temperature ranges (Li, 2016).

Two of the most common water-based sensible heat storage devices are liquid aquifers and water tanks. Water tanks, which make use of the principle of stratification of water (layers of water) when it is heated, are commonly used in applications like solar-heated geysers. When water is heated, the density of the water decreases, which results in the layer formation of the water (stratification) with different temperatures. The colder water accumulates at the bottom of the tank, while warm water accumulates at the top of the tank. These systems often include an electrical element for periods of low solar irradiation. An illustration of the water tank can be seen in Figure 13.

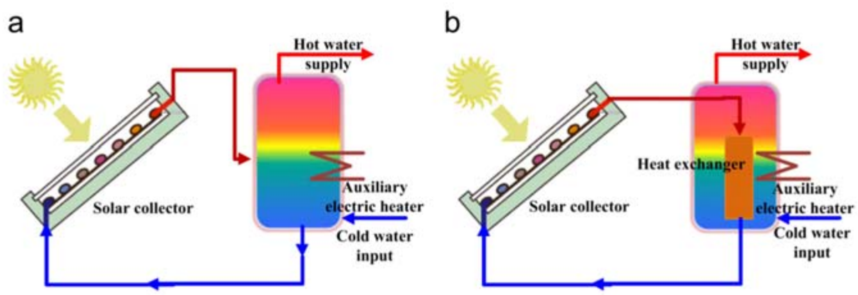


Figure 13: Water tank heat storage device (Li, 2016)

Aquifers, which can be seen in Figure 14, are the result of geological formations located underground, where a water table with available heat can be extracted, used and pumped back into the ground. These aquifers have a lower capital and operational cost than storage tanks and can store water for longer periods (Li, 2016).

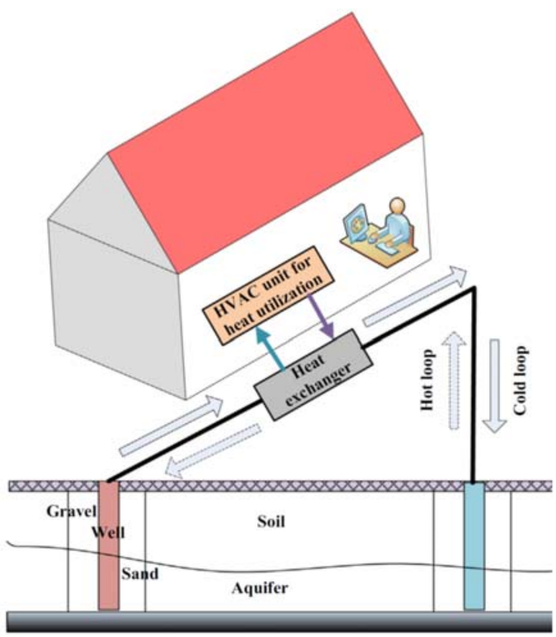


Figure 14: Illustration of aquifer system (Li, 2016)

2.5.1. Thermal Energy Storage Benefits

Thermal energy storage holds great benefits for combined heat and power (CHP) applications. The storage of heat energy, for peak-hour use, can reduce harmful emissions into the environment, energy consumption, as well as costs associated with energy storage. Because consumer demands are erratic, sensible heat storage can facilitate CHP systems by balancing energy demands with energy supply. The benefit of integrating thermal storage to a power generation system, especially one making use of CHP, is the ability of the storage system to reduce the operating cost of equipment used, such as boilers. The storage system can reduce the overall costs of a CHP system by 30% (Smith, Mago and Fumo, 2013).

According to Edwards et al. (2016), thermal energy storage holds advantages over other energy storage mechanisms such as:

- Thermal energy storage is not geologically dependent.
- Does not require large space for storage.
- Low capital and operational costs.

2.5.2. Thermal Energy Storage Disadvantages

A comparative study between latent heat storage and sensible heat storage by Padmaraju et al. (2008) concludes that sensible heat storage holds a lower energy density and exhibits non-isothermal behaviour in heat storage (temperature is not constant), which means that heat energy is lost.

One of the disadvantages of thermal energy storage is low efficiency when converting heat energy to electrical energy. Thermal energy storage is feasible when coupled with power generation plants utilising processes at high temperatures, such as nuclear energy and coal-powered stations (Edwards et al., 2016).

There are a vast number of mediums able to be used for thermal energy storage, however, due to the application, the medium used is limited. For the application of a microgrid, which uses a phase change medium such as molten salts, an element to supply heat may be needed as temperatures required to change the state of molten salts exceed 200 °C (Edwards et al., 2016). This is an important factor when considering microgrids that make use of renewable energy technology. Depending on the scale of the microgrid and the excess energy produced, thermal energy storage may not be a viable option for a microgrid. A feasibility study would, therefore, be required.

2.5.2.1. Case 1: Wind Energy and Thermal Energy Storage

A novel system developed by Okazaki et al. (2015) aims to generate heat energy using wind energy. The system incorporated a heat generator which converts the rotational energy from the wind turbine to thermal energy. The medium, which is heated by the thermal generator, transfers the energy to a storage tank and is used when consumer demand exceeds electrical energy production. The thermal energy is then used to heat water, converting it to steam, to drive a steam turbine. An illustration of the configuration can be seen in Figure 15.

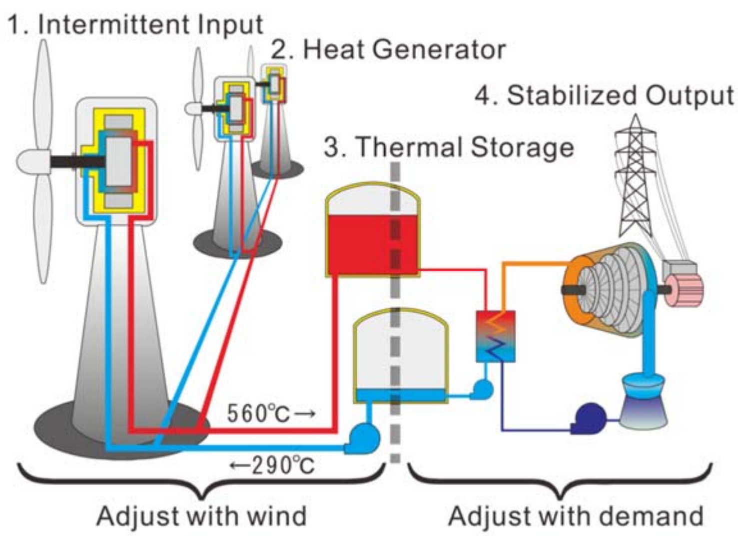


Figure 15: Wind to thermal energy configuration (Okazaki et al., 2015)

Okazaki et al. (2015) concludes that the wind-powered thermal energy conversion device is more economically viable than wind power with battery storage. These systems are placed within proximity to each other to avoid heat loss.

2.5.2.2. Case 2: Concentrated Solar Power with Thermal Energy Storage

A study by Hummon et al. (2013) aims to highlight the benefits of using thermal energy storage (TES) to store energy harnessed from a concentrated solar power (CSP) system. Hummon et al. (2013) predicts that coupling the thermal energy storage to a CSP system can yield the following benefits:

- Provide electrical energy at a low tariff for consumers.
- Stabilise a national grid.
- Provide energy to consumers when power demand is above power generation capabilities.

The system utilises a parabolic mirror used to receive and concentrate the solar energy to heat water. The heated water is then stored in a thermally insulated tank. When electricity is needed to meet consumer demands, the water is then converted into steam and used to drive a turbine, which is connected to an alternator, thereby generating electricity (Hummon et al., 2013).

The study concludes that the CSP-TES can meet consumer's energy demands by being able to meet peak demands in the morning and evening. Additionally, it is found that the CSP-TES system can reduce production costs by 15% when tested in two states, namely Colorado and Wyoming (Hummon et al., 2013).

2.6. Literature Review Summary

The literature review covered the five main groups of energy storage, namely:

- Mechanical: Pumped Hydro Systems
- Electrochemical: Secondary Batteries
- Chemical: Hydrogen Fuel Cells
- Electrical: Double-Layer Capacitor
- Thermal: Thermal Energy Storage

The mechanics of each system and the benefits and disadvantages of these storage systems were explored as well as working examples of these systems storing energy from various energy production sources. Table 5 summarises the energy storage technologies with respective benefits and disadvantages.

Table 5: Benefits and Disadvantages of Selected Storage Technologies

Storage Technology	Benefits	Disadvantages
Pumped Hydro Storage	• Low-cost form of energy storage • Low maintenance costs • Mature technology • A highly efficient form of energy storage	• Geographically dependent • High capital costs • Large space required • Erection of dams may cause people to be displaced • Rupture of dams may have dire consequences

Secondary Batteries	• Yields high power and energy densities • High efficiencies • Quick response times	• Cost of disposal is great • Short life-cycle • High capital costs
Hydrogen Fuel Cells	• Able to be stored for long periods • By-products are water and heat • Yields high efficiencies	• High capital costs • Lack of information on the degradation of fuel cells • Large quantities of hydrogen are scarce and therefore costly
Double-Layer Capacitor	• Yields high energy densities and efficiencies • Contains no harmful toxins, therefore disposal costs are low. • Able to operate in a vast temperature range	• Not suitable for energy supply over extended periods • Not suitable for AC applications
Thermal Energy Storage	• Mature technology • Low capital and operational costs • High energy density • Does not require a large space	• Low efficiencies • Mediums used are application-specific • Sensible heat storage yields lower energy density and exhibits non-isothermal behaviour

Pumped hydro storage, secondary batteries, flywheel technology, supercapacitor technology, and thermal energy storage systems were selected to be modelled for a microgrid in Africa. These storage technologies were the simplest to maintain and were the most advantageous for rural communities. As Burundi has an established pumped hydro facility, where the bulk of the utility grid is powered by Rusumo Falls hydropower plant and has the resources to harness energy from an underground thermal aquifer, thermal energy storage was a viable option as an ESS. Batteries were seen as an established energy storage mechanism; therefore, these systems were focussed on. However, other storage systems were also explored and modelled.

3. Background of Energy Storage Systems (ESS)

3.1. Introduction

Energy storage systems are a vital component to society's electronic evolution, with an emphasis on portable devices (Whittingham, 2012). These technologies have proven to be vital components in the systems of utility grids, especially grids which make use of renewable energy sources. As renewable energy sources such as wind and solar PV are intermittent, storage mechanisms are useful as they provide energy during periods of peak energy demand. According to Whittingham (2012), renewable energy sources and smart grid technology, coupled with energy storage devices may revolutionise the utility grid within the near future.

Another function that storage mechanisms provide is the stable integration of renewable sources into hybrid grids, which make use of renewable energy sources to supplement the baseload. The storage devices become a necessity when renewable energy technology meets 10% of the energy demand (Whittingham, 2012).

An example of a generic energy demand curve can be seen in Figure 16, below:

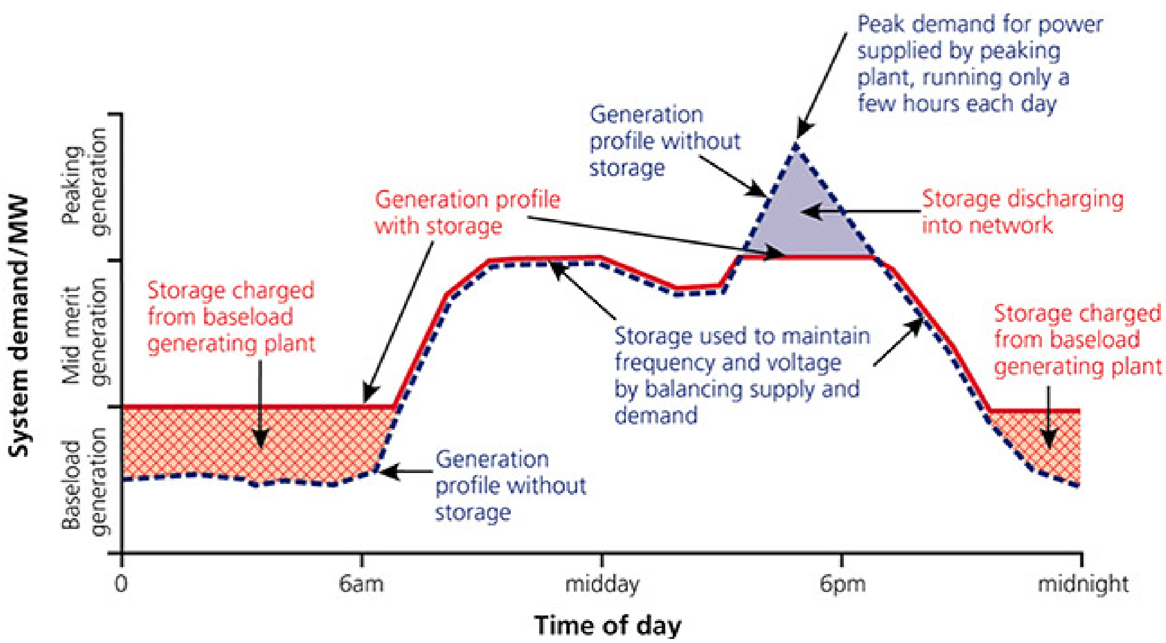


Figure 16: Generic energy demand curve (Whittingham, 2012)

Regarding the curve, the consumer's energy consumption patterns are constantly measured by energy suppliers, which allows for accurate energy production and planning. The data captured also allows for energy suppliers to plan maintenance intervals, which provides the consumers with the least amount of inconvenience.

Regarding Figure 16, the curve represents the energy consumption with peaks and troughs at various points. The peaks represent the peak energy demand periods at the respective times of the day, and the troughs represent periods of low energy demand or off-peak periods. These off-peak periods generally occur approximately between 10 pm and 6 am, thereafter the demand then increases for a few hours.

Figure 16 illustrates two scenarios. The first scenario with the dotted curve illustrates the load profile without the use of a storage mechanism. The electricity demand is met solely by the power generation plant, where the plant supplies energy to consumers during off-peak and peak hours. However, to meet consumer demand during the second peak hour period, the high demand is supplied by peaking the plant (Whittingham, 2012).

Power plants, which solely rely on a single source of energy to generate electricity, are at a disadvantage to areas where an inadequate energy supply system is in place. Due to the fluctuating pattern of the electricity demand, a peak demand which is not able to be met by a suitable baseload results in blackouts and losses in revenue. A suitable relationship between intermittent energy sources and a baseload lowers the risk of blackouts and creates a reliable source of energy (Matek and Gawell, 2015).

The second scenario as illustrated by the red curve makes use of storage mechanisms and requires that the power supply plant produces more power during off-peak periods than in the scenario where no storage mechanisms are used. The difference in the power produced by the power plant is the point where mid merit generation is produced and the original off-peak supply power. The difference in the power produced is stored in the energy storage system for use during peak hour demand periods. The second purpose of the storage mechanism is to maintain the frequency and voltage by balancing the energy demand and supply (Whittingham, 2012). At the second peak hour demand period, the power plant generates power to the threshold of mid merit generation. The excess power required to meet consumer demands is met by the storage mechanism, by discharging stored power into the grid.

Various energy storage mechanism technologies are discussed within this chapter, particularly the energy storage devices which are to be modelled, namely, pumped hydro storage, batteries, flywheel technology, supercapacitors, and thermal storage. This chapter focusses on the technologies available in the industry, what they are used for, and the reason behind certain storage mechanisms being more appropriate for certain applications.

3.2. Background of Pumped Hydro Storage Systems

Pumped hydro storage systems have been used to store energy for over a century with little intervention. It has proven to be a tough technology which works efficiently. Compared to other storage technologies such as batteries, fuel cells, flywheels and compressed air systems, pumped hydro is the only storage technology proven to be sustainable at large-scale use, in the order of Gigawatt-days (Pickard, 2012).

Pumped hydro storage systems consists of a lower reservoir connected to a tailrace, which is a channel that connects the lower reservoir to the pump-turbine assembly. The pump moves a column of water to the upper reservoir via a shaft, known as a penstock. The penstock is connected to the upper reservoir via a headrace. During periods when energy is required, the water is released from the upper reservoir, driving the hydro turbine and generating electricity. According to Pickard (2012), during off-peak periods electrical energy is used to drive turbines in reverse, converting the turbine to a pump. These energy storage facilities have efficiencies which range between 67% and 84%, seen in Table 6, which lists pumped hydro storage facilities in the United States of America.

Table 6: List of Pumped Hydro Storage plants in the USA (Pickard, 2012)

Plant Name	State	Power (GW)	Energy (GWdays)	Average Head (m)	Efficiency (%)
Bath County	VA	2.86	0.99	359	80
Ludington	MI	1.98	0.72	111	72
Raccoon Mountain	TN	1.53	1.31	273	77
Castaic	CA	1.28	0.50	326	67
Bad Creek	SC	1.07	1.00	350	-
Helms Pumped Storage	CA	1.05	7.67	490	74
Blenheim Gilboa	NY	1.00	0.50	335	75
Northfield Mountain	MA	0.94	0.44	227	75
Rocky Mountain Hydro	GA	0.85	0.24	197	84
Muddy Run	PA	0.80	0.46	108	71

However, due to the low energy density of pumped hydro storage, enormous quantities of water and space are needed to sustain energy demands. Due to the large spatial and water requirements, pumped hydro systems are considered region-specific technologies which are only feasible in areas where water and space are abundant.

Another challenge which faces the feasibility of pumped hydro storage systems is the availability of a location with a great vertical drop. For the storage system to be technically feasible, a large spacious area needs to be available, with copious amounts of water in an area where there is a large vertical distance (Pickard, 2012). Since areas which meet all these criteria are not that common, underground pumped storage systems were developed.

3.2.1. Underground Pumped Hydro Systems

With the growth of pumped hydro storage facilities starting in the 1950s, feasible locations are becoming limited. Pickard (2012) states that an idea was proposed during the late 1960s to place the lower reservoir underground. This idea was inspired by abandoned mine shafts. The concept, as seen in Figure 17, is similar in design to a conventional pumped hydro storage facility, except for the lower reservoir being placed hundreds of meters below the surface and an added air vent which runs from the lower reservoir to the ground, serving to equate the lower reservoir pressure to atmospheric pressure. An access shaft which leads from the surface to the power station is also required, for maintenance purposes.

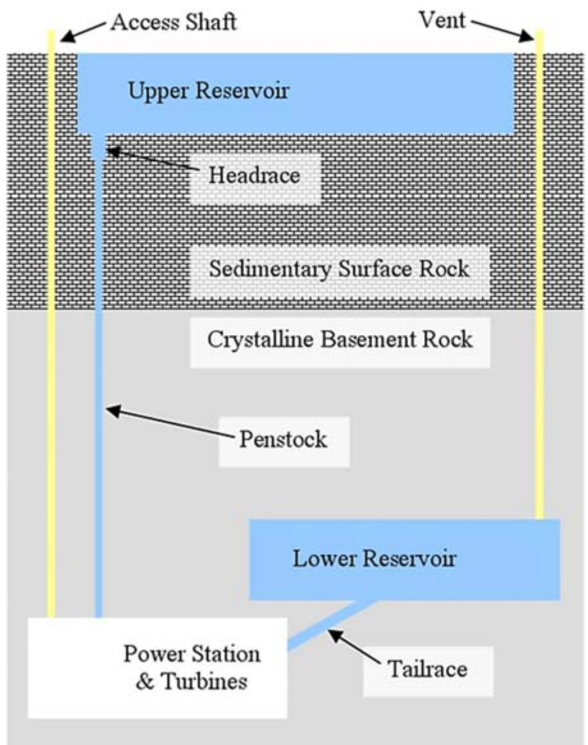


Figure 17: Schematic of an Underground Pumped Hydro Storage system (Pickard, 2012)

Pickard (2012) investigates the feasibility of this system where it is noted that excavation costs are affected by the depth, however, it is not a significant increase in cost, while storage potential energy can increase significantly with depth. There are, however, environmental concerns regarding the construction of pumped storage systems as ideal locations for PHS systems overlaps with natural reserves. Underground pumped hydro storage (UPH) systems, therefore, seems to be a viable solution.

3.2.2. Underground Pumped Hydro (UPH) Storage Challenges

One of the challenges facing UPH systems is the requirement of suitable rock. According to Pickard (2012), the ideal rock requirements includes igneous rock (rock formed by lava or magma). This type of rock should not be under lateral stress (stress occurring perpendicular to the normal). These suitable rock caverns should be within a

100 km range of the most densely populated areas, however, the locations with suitable rock formations need to be drilled for.

Hoisting the heavy equipment, located hundreds of meters below the surface, was an issue four decades ago, however, due to technological advancement approximately 470 tons can be hoisted (Pickard, 2012).

Excavating caverns to serve as the lower reservoir is the costliest stage of the construction of underground pumped hydro storage systems. The caverns are typically built at a volume of approximately 10 000 m^3. The pump-turbine configuration, which costs a fraction of the excavation costs while only able to achieve an effective head of 750 m. A solution to increase the effective head is to introduce a multiple stage pump system, thereby increasing the efficiency of the system. According to Pickard (2012), increasing the volume of the lower reservoir and introducing a multistage pump-turbine system is not a financially viable strategy. Two proposed scenarios which makes the system financially viable involve:

- **Scenario 1**: Increasing the depth of the lower reservoir (to double the original depth), reduce the reservoir volume by half the original volume and build many storage facilities.
- **Scenario 2**: Increasing the depth of the lower reservoir, leaving the original volume and build fewer storage facilities.

3.2.2.1. Historical fears around Pumped Hydro Systems

Due to the failure of three pumped hydro systems within the last 10 years, in which the dykes of the upper reservoir failed, there are public concerns around the use of pumped hydro storage systems, particularly those built within proximity to inhabitants. These dam failures include the Taum Sauk PHS System in Missouri, the Kingston fossil fuel plant in Tennessee, and a dam in western Hungary (Pickard, 2012). Upon closer inspection, two of the dykes which breached leaked hazardous materials while the upper reservoir leaked potable water. The third major disaster, which involves the breaching of a dyke, was caused by a failed sensor which allowed the pump to overfill the upper reservoir, which failed the dyke. These concerns are dealt with by using the compacted competent rock used from the excavation below the earth’s surface. The rock is sufficient enough to build a wall high enough to ensure no over spillage would occur and that it would be stronger than the previous three failed dykes (Pickard, 2012).

3.2.2.2. Underground Pumped Hydro Costs

According to Madlener and Specht (2013), who conducted an economic analysis of an underground pumped hydro storage facility in an abandoned coal mine in Ruhr, Germany, the associated costs with underground pumped hydro storage systems are largely incurred during the establishment of the underground cavity that serves as the lower reservoir. Feasibility studies for the use of natural caverns prove to be financially exhausting, due to the soft sedimentary rock below the surface. It is therefore not a viable option. Furthermore, building larger cavities for the storage of water below the surface is also seen as an expensive option. The only viable option is to make use of drifts (horizontal entries). As existing caverns and drifts are not adequate, the construction of circular drifts, with an approximate area of 48 m^2, costs approximately 200-420 €/m. Table 7 illustrates the extension of drifts with respective costs, where the cost per meter increases as the extension increases.

Table 7: Development Cost of Drift Extension (Madlener and Specht, 2013)

Drift Extension (m)	Storable amount of water (t)	Extension cost at 10 k€/m (M€)	Extension cost at 20 k€/m (M€)
2,000	96,000	20	40
5,000	240,000	50	100
10,000	480,000	100	200
15,000	720,000	150	300
20,000	960,000	200	400
30,0000	1,440,000	300	600

Other costs included are the owner's cost, the cost of the upper reservoir, engineering procurement, the cost of the powerhouse (i.e. pump-turbine and generator), powerhouse excavation costs, tunnels, and the cost of the drifts (lower basin) which totalled 253 €/kWh for a 1000 m head system. A breakdown of the associated costs can be seen in Figure 18.

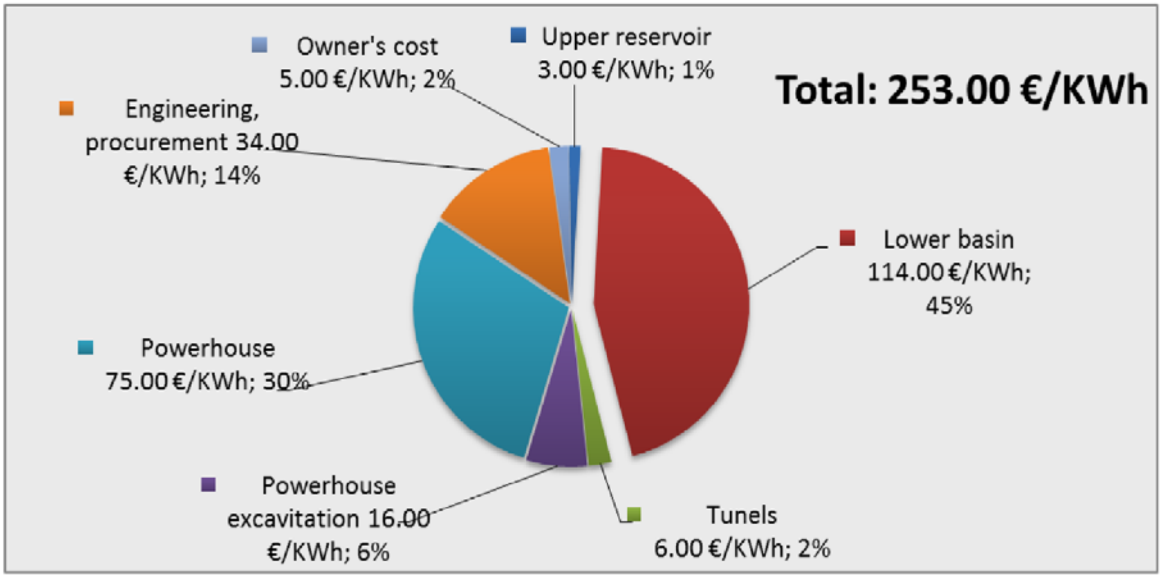


Figure 18: Breakdown of UPHS Construction Costs (Madlener and Specht, 2013)

When compared to a conventional pumped hydro storage facility, the specific construction costs are approximately 178 €/ kWh.

Madlener and Specht (2013) conclude that underground pumped hydro storage options are expensive and require major investment, where specific capacity costs range from 1 300 €/kW for a 5-hour design period and 2 000 €/ kW for an 8 hour design period. These costs are necessary for long term plans to generate a greater dependence on renewable energy sources or for communities depending on microgrids. As costly as these storage mechanisms are, they are cheaper than storage mechanisms such as hydrogen fuel cells, with a specific capacity cost of 2 350 €/kW, which are not as well suited for larger storage purposes.

3.2.3. A Novel Pumped Hydro Storage Alternative

A simpler alternative proposed by Olsen *et al.* (2015) introduces a novel idea which allows areas with insufficient height differences for conventional pumped hydro storage facilities or areas which lack ideal rock deposits below the earth's surface (i.e. igneous rock) for underground pumped hydro storage. The system, named the energy membrane pumped hydro storage system (EM-PHS), makes use of a membrane placed just below the soil as a reservoir.

Like conventional PHS and UPHS, the concept of energy membrane pumped hydro storage systems makes use of potential energy storage of water, although at considerably lower heights. The system consists of a piping system which leads from a water source, such as the sea or river, through a filter, to a pump-turbine assembly. The pump-turbine assembly is connected to the membrane (where the water is stored) via a connecting pipe. The membrane is then covered with soil. During periods of low energy demand, water is pumped into the membrane and stored. When energy consumption increases during peak hours, the weight of the soil, at the respective height, yields potential energy and is used to pump water through the turbine. A schematic illustrating of the system concept can be seen in Figure 19.

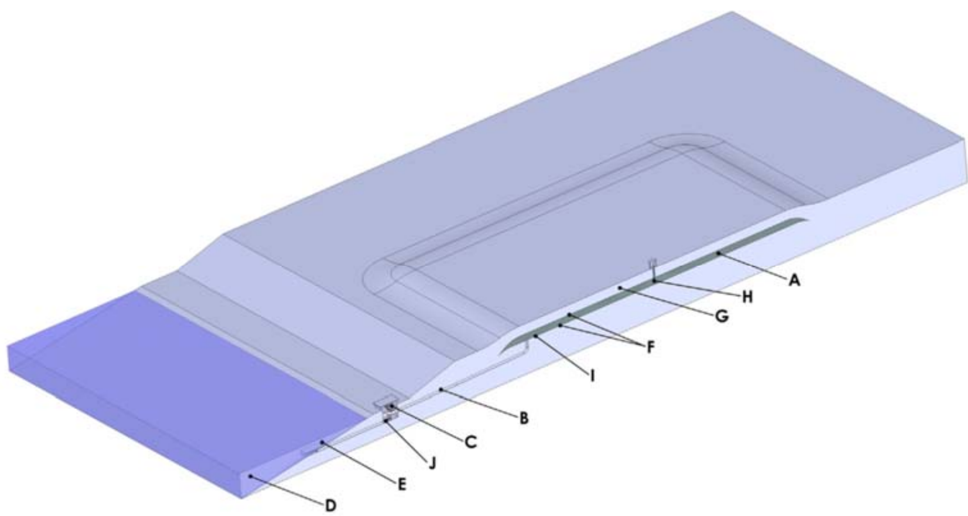


Figure 19: Cross-section of a 50 m × 50 m EM-PHS (Olsen et al., 2015)

Where the labels indicate (Olsen et al., 2015):

A. Cavity
B. Connecting pipe
C. Pump-turbine assembly
D. Water source
E. Filter
F. Lower membrane
G. Topsoil
H. Level meter
I. Pressure gauge
J. Flow Meter

The energy stored can be calculated using the following equation:

$$E_{Stored} = g.\rho_{soil}.H_{Soil}.Area.H_{Lift} \quad (3)$$

Where: ρ_{soil}= Density of the soil

H_{Soil}= Height of the soil

H_{Lift}= Maximum lift height of the membrane

3.2.3.1. Advantages and Disadvantages of the EM-PHS System

The energy membrane pumped hydro storage system holds many advantages over conventional pumped hydro systems such as avoiding large risks associated with the construction of upper reservoirs for conventional pumped hydro. The use of sea-water in pumped hydro storage poses an even greater risk, especially for agricultural use, for should the upper reservoir be breached, the risk of water contamination greatly increases. The energy membrane does not require the possibility of a community to be displacement for construction. Ideal locations for these systems include rivers and coastlines, where water access is abundant.

However, due to the nature of the system, the constant inflation and deflation of the membrane may cause strain, as was discovered by (Olsen et al., 2015). After 10 cycles, it was noticed that the membrane had torn due to strain along the welding edges of the membrane. Alterations to the shape of the membrane proved to be successful, however, constant maintenance is required as the risk of the membrane tearing, due to the strain, would be high.

Conventional pumped hydro storage plants also hold the advantage of greater volumes of energy storage due to the considerable height differences between the upper and lower reservoirs.

3.2.3.2. Energy Membrane Pumped Hydro Storage Costs

A full-scale energy membrane pumped hydro storage facility, proposed by Olsen et al. (2015), with membrane dimensions of 500 m × 500 m, is capable of supplying 30 MW of power. The total construction cost of the EM-PHS system is calculated at € 33.4 million, with the sales price of € 0.09 per kWh. A full-scale EM-PHS is calculated to have the following specifications:

Table 8: Full-scale Specifications of EM-PHS (Olsen et al., 2015)

Specifications	
Dimensions	500 m × 500 m
Pump-Turbine Size	30 MW
Theoretical Efficiency	80 %
Operating Hours per Day	8
Operation Days per Year	280

Max Energy Storage Capacity	200 MWh
Capital Cost	€ 1 111/ kW

With a capital cost per kW of € 1 111 and the cost per kWh of € 208, as seen in Table 8, EM-PHS systems are more financially feasible than underground pumped hydro storage systems. A comparison of the capital cost per kW and the unit of energy storage can be seen in Table 9, below:

Table 9: Cost comparison of three types of PHS (Poonpun and Jewell, 2008; Madlener and Specht, 2013; Olsen et al., 2015)

Pumped Hydro Technology	Cost per kW	Cost per kWh
Conventional PHS	**902**	**135. 30**
Underground PHS	2000	253. 00
Energy Membrane PHS	1111	208. 00

The costs, listed in table 9, are for the pumped hydro technologies operating on an 8-hour cycle. The comparison of pumped hydro storage technologies is compared with the same operating hours as costs decrease exponentially as operating time increases (Poonpun and Jewell, 2008).

Observing the table above, conventional pumped hydro storage systems have a lower cost per kW and cost per kWh, where EM-PHS is the second cheapest pumped hydro technology and underground pumped hydro storage is the most expensive form. However, due to the flexible nature of EM-PHS, it is the most flexible technology in terms of possible landscape restrictions when compared to conventional and underground PHS.

3.3. Background of Battery Storage

Lead Acid cell technology has been under constant refinement for over a century due to drawbacks such as constant maintenance requirements. During the 1960s, constant improvements lead to the design of the valve-regulated lead-acid batteries (VRLA). These improvements were not able to increase the lifespan of lead-acid batteries yet rectified issues such as the constant need for maintenance and lower electrolyte content, which allowed lead-acid batteries to be transported easily (Hittinger et al., 2015).

Due to the lack of energy in many parts of the world, solar PV systems are used to supply electrical energy where sunlight is abundant. In large parts of Africa, where communities are situated too far from power generating stations, renewable energy systems are a viable cheaper solution for these communities. However, due to the erratic nature of solar PV systems, energy storage for PV systems are essential. Solar PV systems, which provides

DC-current for low energy consumption, can be seen in Figure 20, below. This can sustain a low energy consumption household with the energy consumption as seen in Table 10.

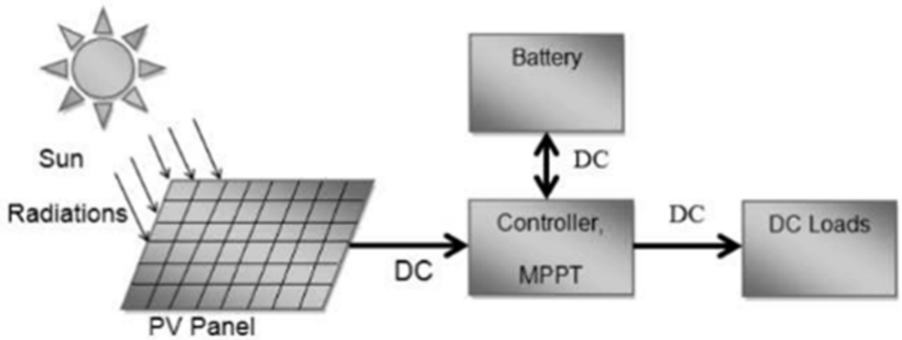


Figure 20: Solar PV microgrid system with battery storage (Bokanga and Kahn, 2014)

Table 10: Energy consumption of a rural household (Bokanga and Kahn, 2014)

Appliances	Power (W)	Hours used per day	Energy Consumption (Wh)
Lights (LED)	18	7	126
Television	5	12	60
Refrigerator	30	18	540
Fan	6	7	42
Radio	6	4	24
Total	**65**		**792**

Bokanga and Kahn (2014) designed a system that meets the daily energy consumption of 792 Wh. It was designed to store excess electricity using lead-acid batteries, due to its popularity and economic feasibility. The power distribution system meets the South African National Standards, where a 6 mm^2 wire is designed for the power generation and 2.5 mm^2 wire is used for power distribution purposes.

According to Medve and Kolcun (2011), other advantages of batteries is the ability to grant energy consumers large quantities of energy for short periods while being charged slowly of long periods. Batteries are popular due to their immediate response times and the ability to move energy due to batteries being portable.

3.3.1. Battery Storage Mechanics

Essentially, the lifetime of batteries spans between 3 to 5 years, depending on battery types and factors such as battery temperatures and discharge rates. As mentioned previously, batteries used for solar PV systems are known as deep-cycle batteries, which allow batteries to supply small amounts of current over extended periods.

The capacity of the battery measured is in Amp-hours (Ah), however, to compare batteries, manufacturers rate batteries at 20-hour rates. The battery capacity, divided by the 20-hour rate, results in the current supplied by the battery for 20 hours (Medve and Kolcun, 2011).

To return batteries to the original state of charge, which are percentage points of a battery's capacity (similar to the fuel gauge mechanism in a car); for every 1 Ah used, the battery requires 1.25 Ah to return the original state of charge. Batteries used in solar PV installations have various discharge times resulting in erratic charge times (season-dependent). Normally these factors negatively affect the lifespan of the batteries, which requires batteries to be reliable under fluctuating discharge conditions (Medve and Kolcun, 2011).

3.3.2. Battery Energy Storage used in Solar PV Installations

For selecting the ideal battery for solar PV installation, the following parameters need to be consulted (Medve and Kolcun, 2011):

- Life Cycle.
- Self-discharge rate (the rate at which capacity is lost due to stagnation).
- Current capacity (Ah).
- Specific power (per unit weight and volume).
- Maintenance schedules.
- Cost per kWh.

According to Jaiswal (2017), these parameters can be broken up into two groups, namely: Primary Battery Parameters and Secondary Battery Parameters. The parameters can be broken up as seen in Table 11:

Table 11: Battery Parameters (Jaiswal, 2017)

Primary Battery Parameters	**Secondary Battery Parameters**
• *Life Cycle* • *Cost* • *Safety* • *Nominal Cell Voltage (determines battery cost)* • *Maintenance Schedules* • *Current Capacity*	• Energy Density • Rate Capability

Conventionally, lead-acid batteries are a popular choice for the storage of electrical energy due to its economic viability, low self-discharge rates, and low maintenance costs. However, due to the short lifespan of lead-acid batteries, approximately 70% of a 20-year system's lifespan cost is attributed to the replacement of batteries (Jaiswal, 2017).

Although lead-acid batteries are seen as the most economically viable option for storing energy harnessed from solar PV systems, there are other batteries such as Nickel-Cadmium (NiCd), Nickel-Metal Hydride (NiMH), and Lithium-ion (Li Ion). These are all technically feasible storage devices which hold various advantages over lead-acid batteries (Tan, Li and Wang, 2013). The advantages of these batteries are listed in Table 12, below.

Table 12: NiCad, NiMH and Li Ion battery advantages over Lead-acid Batteries (Tan, Li and Wang, 2013)

Battery Technology	Advantages over Lead Acid Batteries
Nickel-Cadmium (NiCad)	• Greater lifespan • Fewer maintenance requirements • Greater energy density
Nickel-Metal Hydride (NiMH)	• Environmentally Friendly • Similar lifespan as Lead Acid batteries • Greater capacity (25%-40%)
Lithium-ion (Li Ion)	• The greatest energy density of all the aforementioned batteries

3.3.3. Lithium-ion batteries for a Microgrid

Jaiswal (2017) states that a solar PV solution for a low income-based home is regarded as an ideal solution in an environment where solar energy is abundant, such as Africa and India. These solar PV systems are cheaper to operate than current kerosene and paraffin applications and are approximately 10 times cheaper than grid electricity. However, the replacement of batteries, which occurs every 3-5 years, holds the bulk of the lifetime running cost of the system. Because of the short lifespan of lead-acid batteries, it is not financially viable for a low-income based community, where Burundi has a GNI (Gross National Income) per capita of 280 USD (World Bank, 2016). Because lead-acid technology is characterised as a mature technology with a saturated research base, the chance of lead-acid batteries decreasing in price is minimal. The use of lithium-ion batteries may be a viable solution for solar PV systems.

There are seven main types of lithium-ion batteries, which can be categorised into two groups. The first group uses conventional graphite anodes while the second group uses lithium titanium oxide anodes. A comparison of the two lithium-ion anode groups can be seen in Table 13, below.

Although lithium-ion batteries hold a lifespan advantage over lead-acid batteries, a further step can be taken to discuss the ideal type of lithium-ion battery for a solar PV system. Because there are various typed of lithium-ion batteries, it yields another advantage over lead-acid batteries as various chemistries for lithium-ion batteries can be selected to suit the user's application, whereas there is only one type of lead-acid battery (Jaiswal, 2017).

Table 13: Comparison of Lithium-ion Anode Groups (Jaiswal, 2017)

Lithium-ion Anode Groups	Advantages	Disadvantages
Graphite Anode	• Greater energy density • Greater cell voltage • More cost-effective	• Lower cycle life • Lower rate capability • Less safe
Lithium Titanium Oxide	• Safer than graphite anode • Greater rate capability • Better performance at lower temperatures • Greater lifespan	• Less cost-effective • Lower cell voltage • Lower energy density

3.4. Lithium-ion Technology Costs for a Microgrid

A financial analysis for a solar PV system used by a prosumer (consumers who can supply excess energy to the grid) can be seen in Table 14, below, which also provides the economic analysis for the use of a lithium-ion battery.

Table 14: Specifications of a Lithium-ion Battery (Jarnut, Wermi and Wa, 2017)

Specifications	
Energy Capacity (kWh)	6.34
Depth of Discharge	80 %
Cycle Life	200
Cost of Investment (€)	3 882
LCOE (€/kWh)	0.16

3.5. Novel Battery Technologies

3.5.1. Molten Salts Batteries

In the pursuit of developing battery technology with higher energy densities and power densities with a lower development cost, molten salt batteries have been developed and used in the industry since the 1980s.

Sodium-sulphur (NaS) batteries have been in use since the 1980s in approximately 20 projects spanning from Japan and many other countries. The sodium-sulphur battery technology was developed in pursuit of storage technology with a power density and energy density greater than current technologies. The sodium-sulphur battery gained popularity due to the energy density being four times greater than the conventional lead-acid battery, longer life cycle, greater efficiencies, and a greater depth of discharge (Tan, Li and Wang, 2013).

Sodium-sulphur batteries are manufactured at lower costs than batteries, such as lithium-ion, due to the abundance of raw materials, which makes this technology more appealing. However, there are safety issues regarding this technology. To retain the molten phase of the salts, the batteries need to be operated at temperatures ranging between 300 °C and 350 °C, which affects the efficiency of the technology. Due to the corrosive nature of the molten salts, there are concerns with regards to the environmental impact of a failure. These failures can be resolved with correct enclosures manufactured from chromium and molybdenum vessels, as well as rerouting molten salts should there be a leak (Sabihuddin, Kiprakis and Mueller, 2015).

3.5.2. Liquid Metal Battery Technology

Liquid Metal batteries were developed approximately a century ago, with much investment by governments due to the Cold War and the pursuit for technological dominance. The technological advancement of liquid battery technology was then abandoned due to the search for higher energy density storage devices. Due to the growth of renewable energy sources, liquid battery technology has gained popularity once more (Kim et al., 2013).

The liquid battery comprises all-liquid internals, which differs from the conventional battery that uses solid materials for the cathode and anode. The materials used for the cathode and anode, separated by molten salt, should meet three requirements to be selected. Firstly, the temperatures of the metals must have a melting point of less than 1000 °C and boiling temperatures of greater than 25 °C. Furthermore, the cathode and anode material must have greater conductivity than molten salt, and the materials should be radioactively stable (Kim et al., 2013). Typical elements selected for the use of cathodes and anodes can be seen in Table 15, below.

Table 15: List of Suitable Elements for Cathodes and Anodes for Liquid Metal Batteries (Kim et al., 2013)

Anode	**Cathode**
Lithium	Aluminium
Sodium	Zinc
Magnesium	Gallium
Potassium	Cadmium
Calcium	Indium
Rubidium	Tin
Strontium	Antimony
Caesium	Tellurium
Barium	Mercury
	Thallium
	Lead
	Bismuth

Figure 21, below, contains a schematic of a liquid battery during discharge (A) and periods of recharging (B). During discharge states, electrons flow from the anode to the cathode; when electrons are passed, the anode materials become positively charged and are attracted to the cathode material. When the battery has been completely discharged, the three liquids in the battery consists of anode material, the molten salt, and an alloy made of elements from the cathode and anode. The materials, seen in the figure below, stay separated due to the difference in material densities (Kim et al., 2013).

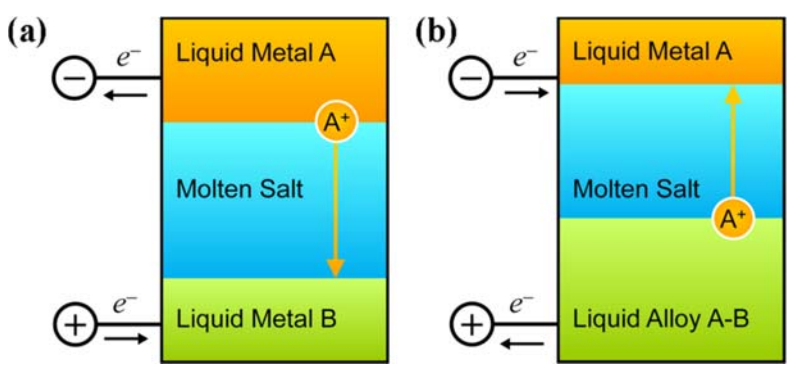


Figure 21: Schematic of a Liquid Metal Battery (Kim et al., 2013)

Due to the materials being abundant, material costs may be cheap, thereby reducing the manufacturing costs. Another advantage that this technology holds for manufacturing costs would be the natural segregation of the liquids, due to differentiating densities. The manufacturing costs of these batteries are, therefore, lower than conventional batteries. Due to the constant creation and breakdown of the materials used for the cathode and anode, the cycle remains unobstructed by the breakdown of electrode mechanisms which inhibit conventional batteries, which allows for the batteries to yield unlimited cycle lives (Kim et al., 2013).

Due to the disadvantages, these technologies may only be suitable for applications where the batteries are to remain stationary. The disadvantages of these batteries include (Kim et al., 2013):

- High operating temperatures (above 200 °C).
- Low specific energy densities (below 200 Wh/kg; would require a large stationary area to accommodate the batteries).
- May contain highly corrosive materials.
- High self-discharge rates.
- Batteries may be sensitive to motion.

Liquid metal battery applications are ideally suited to grid-scale energy storage, which ranges from 100 MWh to 1 GWh.

These storage mechanisms are economically viable for either energy storage (yield a low cost/kWh) or power storage (yield a low cost/kW). Thus, the advantages of the liquid battery makes the technology economically viable for both situations due to the technology’s charge-discharge rate (Kim et al., 2013).

For the battery option to be financially viable, it has to be more economically attractive than existing methods of energy storage. According to Kim et al. (2013), at an approximation of 10 000 cycles with an efficiency of 80%, it costs approximately 400 USD per kWh. Various materials are cheaper and yield lower costs than 400 USD per kWh.

3.6. Battery Technology Summary

The batteries reviewed were the lead-acid and lithium-ion batteries. Lead-acid batteries were regarded as the conventional battery used in energy storage, and lithium-ion was considered a battery yielding superior battery life, however at greater costs. These batteries were compared to emerging battery technologies, such as liquid metal batteries and sodium-sulphur batteries, which makes use of molten salts. Table 16 illustrates the specifications of each battery, highlighting the battery yielding the advantage per metric.

Table 16: Comparison of Reviewed Battery Technologies (Kim et al., 2013; Sabihuddin, Kiprakis and Mueller, 2015)

Metric	**Lead Acid**	**Lithium-ion**	**Sodium-sulphur**	**Liquid Metal**
Specific Energy (Wh/kg)	10 - 20	30 - 300	100 - 240	
Specific Power (W/kg)	25 - 415	8 -2 000	14.29 - 260	
Efficiency (%)	63 - 90	70 - 100	65 - 92	80
Lifespan (Years)	3 - 20	2 - 20	5 - 20	Indefinite
Cycle Life	100 – 2 000	250 – 10 000	1 000 – 4 500	10 000 ≥
Self-Discharge Rate (%/day)	0.033 – 1.10	0.03 - 0.33	0 - 20	
Potential Scale (MW)	50	3	0.01 - 80	100 – 1 000
Capital Cost (Energy: (USD/kWh)	50 – 1 100	200 - 4000	150 - 900	400
Capital Cost (Power: USD/kW)	175 - 900	175 - 4000	150 – 3 300	

Lead-acid batteries had a substantial financial advantage over other battery technologies as well as a proven record, therefore, the choice with the least risk. From the table above, lithium-ion batteries had many advantages over other battery technologies and seemed the most feasible battery storage mechanism, however, with more research and investment newer technologies such as liquid metal and sodium-sulphur battery technologies may become more financially viable for grid-scale use in the future.

3.7. Thermal Energy Storage

Thermal energy storage technology is a mature technology which has been used throughout history, since civilisations have lived in underground caverns rocks. Depending on seasonal needs, where heat would penetrate underground caverns during late periods of the night, keeping inhabitants warm when temperatures have dropped (IRENA, 2013).

Current thermal energy technology operates at temperature ranges between -40 °C and 400 °C. This technology can be broken down into three main divisions, namely: sensible heat, latent heat, and thermochemical.

3.7.1. Sensible Heat Storage

Sensible heat systems make use of energy storage in mediums such as water, to heat and potentially cool buildings. The medium, stored in well-insulated tanks to avoid heat losses, is used to absorb heat energy and disperse the energy when required. The amount of heat stored depends on the materials used, as different materials have various specific heat capacities, measured in J/kg.K (Dwivedi et al., 2016) . A list of various materials commonly used as storage mediums can be seen in Table 17, below.

Table 17: Commonly Used Mediums for Sensible Heat Storage (Dwivedi et al., 2016)

Medium	Operating Temperature (°C)	Density (kg/m^3)	Specific Heat Capacity (J/kg.K)
Rock	20	2560	879
Brick	20	1600	840
Concrete	20	1900-2300	880
Water	0-100	1000	4190
Caloriea HT43	12-260	887	2200
Engine Oil	160	888	1880
Organic Ethanol	≤ 78	790	2400
Organic Propanol	≤ 97	800	2500
Organic Butanol	≤ 118	809	2400
Organic Isobutanol	≤ 100	808	3000
Organic Isopentanol	≤ 148	831	2200
Organic Octane	≤ 126	704	2400

Popular sensible heat storage technologies are underground energy storage systems, which can be further subdivided into the following groups (Nordell, 2000):

- Aquifer Thermal Energy Storage
- Borehole Thermal Storage
- Rock Cavern Thermal Energy Storage

3.7.1.1. Aquifer Thermal Energy Storage

Aquifer thermal energy storage makes use of natural groundwater residing below the surface as the medium to store energy (Nordell, 2000). Thermal energy extraction occurs via wells drilled below the surface to the aquifer. These wells can serve two purposes, such as supplying heat during winter periods using warm water from the warm aquifer while a second well supplies cold water from the cold section of the aquifer. The second purpose is to extract heat from buildings. Aquifer thermal energy storage technology is ideal for long term and short term applications while being economically feasible (Nordell, 2000).

There are drawbacks to the aquifer technology, such as the dispute over water-use, where different parties have different opinions over the usage of the water. Parties dispute that the water should be used for consumption while other parties see the need for harnessing energy from the water. Because the water lies below the earth's surface, the water may contain contaminants which cause the water to be acidic (Nordell, 2000). Furthermore, these systems are site-specific and are only able to be installed where aquifers exist.

3.7.1.2. Borehole Thermal Energy Storage

A borehole thermal storage system is typically a heat exchanger placed below the earth's surface. This storage system typically comprises of a 110 mm diameter drill-well, placed 100-150 m below the earth's surfaced. The drill-well, occupied by an HDPE U-bend pipe, is used to transport water, with high thermal conducting material used as grouting, in the gap of the U-bend pipe. Coldwater is then funnelled through one end of the pipe and received as heated water at the other end of the pipe (Nordell, et al., 2007).

The borehole energy storage systems have the following advantages and disadvantages (Hesaraki et al., 2015):

Advantages

- Used for both heating and cooling applications.
- Vertical boreholes are less sensitive to outside climates as ground temperature is constant.
- Horizontal boreholes require less excavation and therefore have lower installation costs.
- Borehole thermal storage systems are ideal for any size application.

Disadvantages

- Unsuitable for locations where groundwater flows as it affects the temperature.
- Capital costs are quite significant.
- The system requires three years to reach maximum potential.

Typical specifications for a residential borehole thermal storage system can be seen in Table 18 below, and a residential system is illustrated in Figure 22, below.

Table 18: Specifications of a Typical Borehole Thermal Energy Storage System for Residential Use (Nordell, Grein and Kharseh, 2007; Hesaraki et al., 2015)

Specifications	
Storage Medium	Rock
Storage Capacity (kWh/m³)	15 - 30
Drilling Depth (m)	30 - 200
Borehole Diameter (mm)	110
Extracted energy (kWh)	25 000
Capital Cost (€)	10 000
Payback Period (Years)	10 - 15

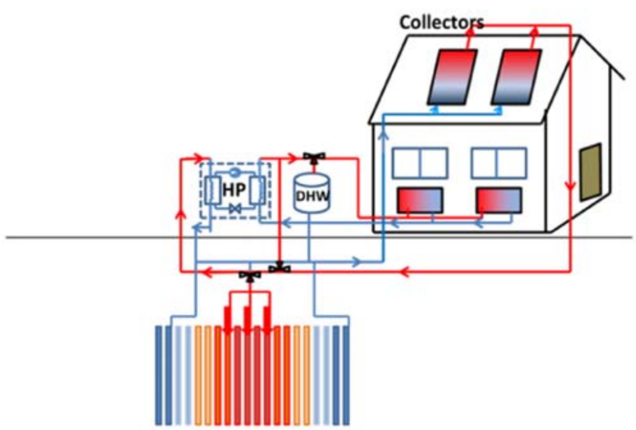


Figure 22: Borehole Thermal Energy Storage System coupled to Solar Collectors (Hesaraki et al., 2015)

3.7.1.3. Cavern Thermal Energy Storage

Rock cavern thermal energy storage technology makes use of abandoned rock formations to store heated water. The system consists of a pump and two water pipes, where one pipe reaches the surface of the storage tank while the second pipe reaches the bottom of the cavern. The purpose of the two pipes is to induce and maintain a stratification of the temperature within the cavern, where warm water is injected during periods of low energy demand and cold water would be extracted from the bottom of the cavern (Nordell et al., 2007).

An example of these systems is a 115 000 m^3 cavern in Sweden which operates at a temperature of 90 °C and can store 5 500 MWh of energy between seasons. This storage method, however, is not as popular as borehole thermal energy (BTES) and aquifer thermal energy storage (ATES) due to the high capital costs (Nordell et al., 2007).

3.7.2. Latent Heat Energy Storage

Latent energy storage refers to phase-changing materials as mediums to store energy. The medium, generally in a solid-state, absorbs energy in the solid-state until the temperature increases to the point where the material changes phases, which allows the medium to absorb more energy. Once the complete transformation of the medium from solid to liquid occurs, the temperature remains constant until the material increases in temperature again, in which case the heat energy is treated as sensible heat as no phase change occurs (Dwivedi, Tiwari and Tiwari, 2016). The equation derived to calculate the stored energy of a medium can be seen below:

$$\boldsymbol{Q = m\left[\left(C_p \times (T_m - T_i)\right) + L + \left(C_p \times \left(T_f - T_m\right)\right)\right]} \quad (4)$$

Where: m = Mass (kg)

Cp = Specific heat capacity at constant pressure (J/kg.K)

T_m = Middle temperature (K)

T_i = Initial temperature (K)

T_f = Final Temperature (K)

L = Enthalpy of fusion of material (J)

3.7.2.1. Phase Change Material

Phase change material is commonly used in applications such as concentrated solar power (CSP), where current mediums used in the parabolic trough collectors is synthetic oil. however, there are drawbacks with using synthetic oil as a heat transfer fluid (HTF), such as the limited temperature range. To achieve greater system efficiencies, higher temperature ranges are required. Possible mediums to use as heat transfer fluids fall under the category of phase change materials (PCM) such as molten salts. However, due to the high freezing point of molten salts (234 °C), additives such as anti-freeze need to be added to inhibit the salts from solidifying, which raises costs.

Another possible solution is to use ice. Ice has a melting temperature of 0 °C and therefore does not need additives like anti-freeze (Seitz, Johnson and Hübner, 2017).

Typical phase change material with respective properties can be seen in Table 19 below:

Table 19: Typical PCM used with Respective Properties (IRENA, 2013)

Phase Change Material	**Melting Temperature (°C)**	**Melting Enthalpy (kJ/kg)**	**Density (kg/m³)**
Ice	0	333	920
Sodium-acetated Trihydrate	58	250	1300
Paraffin	-5	150-240	770
Erythritol	118	340	1300

The materials selected are designed to meet thermo-physical, kinetic, and chemical criteria. The criteria for materials to be selected are listed in Table 20.

Table 20: Rubric of PCM (Medveď, Kvakovský and Sklenárová, 2010)

Thermo-physical	**Kinetic**	**Chemical**
Desirable temperature range	The high crystal growth rate	Chemically stable
High thermal conductivity	High nucleation rates	Ability to completely freeze or melt
Small volume and pressure changes at the melting point		No degradation after multiple freezes, melt cycles
High specific heat values		Non-corrosive and non-toxic
Consistent melting of materials		Non-flammable and non-explosive
The high energy density (per unit volume), to use less space		

Latent heat energy storage holds the advantage of greater energy densities per volume than sensible energy storage, where ice has an energy density of 100 kWh/m^3 compared to 25 kWh/m^3 for sensible energy storage mediums. The reason for the difference in energy density is the melting point of the phase change material, which allows the material to absorb more energy (IRENA, 2013).

Although latent heat energy storage yield high energy storage densities, it is not a preferred method of energy storage due to its disadvantages, such as phase segregation, irregular melting, and volume change (Medveď, Kvakovský and Sklenárová, 2010).

3.7.2.2. Latent Heat Energy Storage Plants

Pelay et al. (2017) proposes three solutions to deliver a reliable, consistent energy source despite the intermittent nature of solar energy. These solutions are hybrid CSP-Biomass or fossil fuel systems or utilising energy storage technologies such as thermal energy storage.

The system makes use of large mirrors which focusses the solar energy to a receptor, generally located atop a tower, where the receptor heats the heat transfer fluid. The heat transfer fluid is led to a boiler where water is heated to superheated steam at high pressures, which is then used to drive a turbine. The heat transfer fluid, used during periods of high energy demand, is stored in thermally insulated containers. An illustration of a typical CSP plant with a latent thermal energy storage system can be seen in Figure 23.

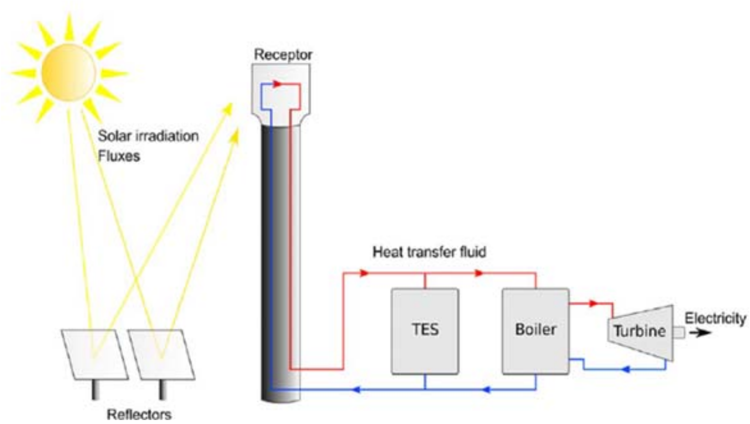


Figure 23: Typical CSP Plant with Thermal Energy Storage (Pelay et al., 2017)

3.7.2.3. Cost Analysis of Thermal Energy Storage

Nandi et al., (2012) performed a cost analysis of a thermal energy storage system which considers multiple thermal energy storage systems, including phase change materials as a medium. The modelled system includes a 50 MW concentrated solar plant which operates for 6 hours to meet the peak energy demand of consumers. The levelised cost of energy (LCOE) is dependent on three factors, namely: material cost, labour cost, and operation and maintenance (O&M) of the plant. The levelised cost of energy is the labour and materials costs, multiplied by the change rate, with the addition of the operation and maintenance cost, divided by the net energy output.

The variables considered for the net energy is heat loss, indirect energy (energy used in the manufacturing and pump energy. The results can be seen in Table 21, below.

Table 21: Comparison of Thermal Storage Systems (Nandi et al., 2012)

	Castable Ceramics	Concrete	Two-Tank System	Thermocline	PCM
Storage Cost (M$)	27.77	26.57	35.05	19.65	30.60
LEC ($/MWh)	33.47	32.29	40.23	25.28	35.88
Heat Loss (MWhs)	45.27	96.33	17.49	17.57	42.63
Indirect Energy (MWhs)	40.37	17.615	16.32	6.90	44.49
Pump Energy (kWh)	658.57	658.57	1721.89	2459.85	790.28
Total Energy (MWhs)	**86.30**	**114.60**	**35.53**	**26.93**	**87.90**

From Table 21, a thermocline system, which is a sensible heat storage method, operates similarly to a rock cavern thermal energy storage system, where the high-temperature medium and the cold temperature medium is separated by a temperature gradient in a single tank. Steam, which drives steam turbines, is pumped through these heat exchangers (Nandi et al., 2012). These systems are more economically feasible than phase change materials (PCM) systems as seen in Table 19, where the LEC of the thermocline system is lower than other thermal heat energy storage systems, including the use of phase-change material.

3.7.3. Thermo-Chemical Heat Storage

Thermo-chemical heat storage mechanisms store energy utilising chemical reactions, where all chemical reactions are reversible as energy recovery is dependent on the reversibility of the chemical reaction (Nandi, Bandyopadhyay and Banerjee, 2012). This form of heat storage is appealing due to benefits such as the large energy density, usually above 300 kWh/m^3 (IRENA, 2013), which makes it ideal for applications where space allocated to storage systems are limited (Abedin, 2010). Thermo-chemical systems are ideal for long term energy storage, where theoretically, energy can be stored indefinitely if temperature conditions remain near ambient temperature conditions. Energy losses can be expected to reach near zero, which makes this storage method ideal for seasonal storage applications (Abedin, 2010).

3.7.3.1. Thermo-Chemical Heat Storage Mechanics

The thermo-chemical storage system has two processes, namely: a charging process and a discharge process. During the charging period, which makes use of an endothermic reaction (heat required), excess energy is converted to heat energy and supplied to a chemical (C), which splits the chemical (C) and form reactants (A) and (B), which is then stored separately in ambient temperatures, resulting in little to no heat loss (Abedin, 2010). The chemical reaction can be seen as:

Heat + C → A + B

During the discharge process, where energy is needed, the two reactants (A) and (B) are brought together, which results in an exothermic reaction (heat released). The heat energy is harnessed and chemical (C) is stored and reused when needed (Abedin, 2010). The chemical reaction is then reversed for the charging cycle:

A + B → Heat + C

An illustration of the charging and discharging cycles can be seen in Figure 24, below.

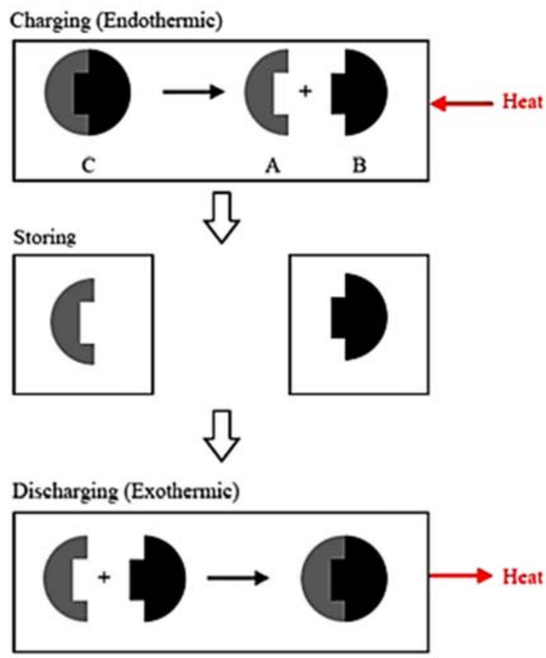


Figure 24: Charge and Discharge Cycles of Thermo-Chemical Storage System (Mahlia et al., 2014)

Typical materials used for thermo-chemical heat storage can be seen in Table 22, below, where the materials used must meet the following requirements: low cost, ability to undergo multiple charge and discharge cycles, readily available material, non-toxic, non-flammable, and the ability to undergo complete chemical reactions (Mahlia et al., 2014).

Table 22: Typical Thermo-Chemicals with Respective Properties (Mahlia et al., 2014)

Material	Formula (C)	Reactant A: Reactant B:	Energy Density (GJ/m^3)	Charge Temperature (°C)
Magnesium Sulphate	$MgSO_4\ 7H_2O$	A: $MgSO_4$ B: $7H_2O$	2.8	122
Iron Carbonate	$FeCO_3$	A: FeO B: CO_2	2.6	180
Iron Hydroxide	$Fe(OH)_2$	A: FeO B: H_2O	2.2	150

According to Nandi et al., (2012), further research is required for large-scale thermo-chemical energy storage, however, it promises many benefits should it be hybridised with other forms of storage technologies as well as other industries (such as glass and steel manufacturers, which give off heat as a by-product).

3.7.4. Thermal Energy Storage Summary

Thermal energy was grouped into 3 divisions, namely sensible heat energy storage, latent heat energy storage, and thermo-chemical heat storage. The three divisions were examined, and the technologies were defined in the subdivisions.

Sensible heat storage technologies, which makes use of a medium in a single phase, predominantly utilised underground thermal energy storage devices. Underground heat energy storage devices explored were aquifers, borehole, and rock cavern thermal energy storage systems.

Aquifers were a cost-effective, long term solution to energy storage which supplied heat energy during cold seasons and extracted heat from a dwelling during warmer periods of the year. However, aquifers were seen as a site-specific technology only installed in areas where aquifers were available. There were also disputes for the usage of water where certain parties felt the water should be used for consumption (Nordell, 2000).

Borehole energy technology was the most promising technology for larger-scale applications than domestic use. Borehole systems made use of a u-shaped pipe, placed below the earth's surface (either horizontally or vertically), which operated as an underground heat exchanger. Borehole technologies had the advantages of cooling and heating areas and were suitable for any application size, however, the technology was not feasible in areas near underground running water. The system yielded high capital costs and it took the system three years to reach its maximum potential (Hesaraki et al., 2015).

Rock cavern heat storage systems made use of existing underground rock caverns to store water, where warm water was layered at the top of the well, while the cold water occupied the bottom of the cavern. The storage of the water at multiple temperatures induced a stratification. These systems, however, were not ideal for large-scale applications due to high capital costs. However, large power quantities could be extracted from this system (Nordell, Grein and Kharseh, 2007).

Latent heat energy storage technology made use of phase-changing material and stored larger amounts of energy than sensible heat energy technology due to yielding higher energy densities. Although these systems were suitable for any applications, there were larger capital costs for latent heat energy technology than sensible heat energy technology.

The third division of thermal heat energy storage discussed was the use of thermochemical technologies, in which excess heat applied to a medium caused the medium to separate into two separate reactants. The reactants were then stored separately and used when required. When the reactants were reunited, the original, stable component was formed again, releasing large amounts of energy. Of the three groups of thermal energy storage mentioned, thermo-chemical technology yielded the largest energy density. However, the technology was not used in large-scale application due to the technology being relatively new and costly (Aydin, Casey and Riffat, 2015). Further research was, therefore, required to make use of thermo-chemical technology for grid applications (IRENA, 2013).

A summary of thermal energy technologies can be seen in Table 23, below.

Table 23: Summary of Thermal Energy Storage (Abedin, 2010)

Parameters	**Thermal Energy Group**		
	Sensible	Latent	Thermo-Chemical
Temperature Range (°C)	50 - 400	20 - 40 (Paraffin) 30 - 80 (Salts)	20 - 200
Energy Density (GJ/m³)	0.2	0.3 - 0.5	0.4 - 3
Lifespan	Long Period	Limited (depending on cycling)	Indefinite (dependent on degradation of reactants)
Research Status	Commercially Available	Commercially Available	Not available
Advantages	• Low Cost • Reliable • Simple application • Materials readily available	• Medium storage density • Smaller space requirements • Transport of energy possible	• High energy density • Minimal heat loss • Long storage period • Long-distance transport possible

			• Compact energy storage (due to energy density)
Disadvantages	• Large amounts of heat loss over time • Large spatial requirements	• Low heat conductivity • Possible corrosiveness of materials • Large amounts of insulation needed	• Technically complex • High capital cost • New and much-needed research required for improvements

Sensible heat energy storage had the lowest costs and was regarded as reliable and simple with readily available materials. It was the ideal solution amongst the three thermal energy groups. However, a concern was the requirement for large space. Thermo-chemical was not ideal due to the high capital cost, possible corrosive nature of materials, and complexity of the technologies. Latent heat storage technology was seen as the middle ground of the two technologies and was considered the most viable solution.

4. System Design

4.1. Pumped Hydro Energy Storage Analysis

Pumped hydro storage systems are one of the most mature storage technologies, which hold the advantage of years of technological advancement. Other advantages of PHS is the high efficiency, quick reaction time, and low maintenance cost (Ayanrohunmu and Ilupeju, 2015). However, there are a few drawbacks to this technology, such as it only being viable in certain regions, risk of displacing communities, and high capital costs.

Utilising pumped hydro storage presents a challenge as the storage of energy requires more power than what the storage mechanism provides i.e. the water pumped to the upper reservoir requires more energy than what the water provided to the turbine needs. The difference in these powers is due to friction in the pipes, bends and pump efficiencies (Ayanrohunmu and Ilupeju, 2015).

Mathematical modelling of pumped hydro storage systems, discussed by Ayanrohunmu and Ilupeju (2015), is used to describe the dynamics of the system, confined to the proposed parameters of the design.

Modelling these storage mechanisms is a vital process as it provides information for the optimal storage system size and storage type. Other conditions to consider are the economic benefits (Berrada and Loudiyi, 2015).

The storage systems selected to be modelled were pumped hydro storage systems, secondary batteries, flywheel energy storage systems, supercapacitor storage systems, and thermal energy storage systems.

4.2. Modelling Methods

According to Berrada and Loudiyi (2015), the following considerations are taken into account when energy production is decided on: the allocation of energy, which takes into account the dynamics of the energy resources. These include energy abundance versus energy demand as well as the cost of energy. Once these uncertainties are modelled, energy storage systems are selected and modelled with the variables considered. Variables which are challenging to account for numerically is assumed (Berrada and Loudiyi, 2015).

4.2.1. Modelling Assumptions

Typical assumptions for the modelling are listed as follows (Berrada and Loudiyi, 2015):

- All energy is supplied from a single energy supplier.
- Energy storage demand is observed within 24 hours, on an hour-to-hour basis.
- Optimisation models are modelled a day in advance as it is the most accurate method of power demand determination.
- Energy demand is assumed to be infinite, although realistically, energy demand is predicted by energy suppliers.
- Energy transmission capacity is assumed to be infinite
- Energy production, per hour, is assumed to be constant.
- Capabilities of storage mechanism (although storage mechanisms differ with regards to supply time, all storage mechanisms is assumed to supply energy instantaneously).

4.2.2. Storage System Parameters

Input requirements for the model include hourly power production, characteristics of storage mechanisms, and hourly tariffs, assuming tariffs varies from hour to hour (Berrada and Loudiyi, 2015).

The parameters used by (Berrada and Loudiyi, 2015) are used to define:

- Energy generation.
- Energy storage.
- Power limits.
- Storage capacity limits.
- Discharge limits.

These constraints are expressed, mathematically, as:

Energy Generation:

$$\boldsymbol{E_{Generated}(t) = E_{Stored}(t) + E_{supplied}} \quad (5)$$

The energy generation constraint indicates that the energy generated, as a function of time, is equivalent to the energy stored and the energy supplied to the grid/microgrid.

Energy Storage Equation:

$$\boldsymbol{S_{Level}\,(t) = \big(S_{Level}\,(t-1)\times(1-d)\big) + (E_{Stored}(t)\times\eta) - E_{Discharged}(t)} \quad (6)$$

Where: $S_{Level}(t)$ = Storage Level (MWh)

d = Discharge rate (%)

$E_{Stored}(t)$ = Stored Energy (MWh)

η = Storage System Efficiency

$E_{Discharged}(t)$= Discharged Energy (MWh)

Power Limits:

The constraints of the storage system are expressed as follows:

$$\boldsymbol{E_{Discharged}(t) \leq SP_{Limit}} \quad (7)$$

Where: SP_{Limit} = Storage Power Limit (MW)

This implies that the energy discharged, as a function of time, is less than or equal to the power limit of the storage system.

$$\boldsymbol{E_{Stored}(t) \leq SP_{Limit}} \quad (8)$$

Implies that the energy stored, as a function of time, is less than or equal to the stored power limit of the storage system.

Capacity Limits:

Storage capacity limits are expressed as follows:

$$\boldsymbol{S_{Level}(t) \leq SE_{Limit}} \quad (9)$$

Where: SE_{Limit} = Storage Energy Limit (MWh)

The equation indicates that the amount of energy stored is less than or equal to the storage energy limit of the storage device.

4.3. PHS Modelling Methodology

The following method is used to model the pumped hydro storage system for an African microgrid. The modelling system focused solely on the design of the energy storage device. The method of modelling are structured as seen below:

- PHS assumptions.
- PHS parameters.
- Analysis of a typical pumped hydro storage plant, in mathematical terms and expressions.

- Modelling with the use of HOMER.
- Results and discussion of results.
- Recommendations and Conclusion.

4.3.1. PHS Assumptions

To get a general sense of the size of the storage mechanism, the storage mechanism being modelled caters for approximately 100 consumers (households).

To model the PHS systems, the following assumptions are made:

- Electricity generation is produced from a single supply point.
- Electricity production is constant throughout the year.
- Pumps that move a column of water from the lower reservoir to an upper reservoir which is powered solely by excess energy from the microgrid.
- Modelling is based on the daily, average, South African household energy demand.

4.3.2. PHS Parameters

The following are parameters related to storage mechanisms as set by Berrada and Loudiyi (2015):

- Energy generation.
- Energy storage.
- Power limits.
- Storage capacity limits.
- Discharge limits.

Mathematical expressions for these parameters were previously discussed.

4.3.3. Analysis of PHS

A typical pumped hydro system includes the following components: pumps, a lower and higher reservoir, a piping network, and a hydro turbine. The system is broken down into four main phases for simplicity, namely:

- The feeding phase, where water is pumped from the lower reservoir to the upper reservoir.
- The storage phase, where the water is stored at the upper reservoir.
- The released phase, where water is released from the upper reservoir to the turbine,

- Power generation phase, in which power is generated via the turbine.

The breakdown of the PHS into phases allows for a simple analysis of the PHS. The analysis of these phases facilitates the calculation of power, energy, pressures, and losses throughout the system.

4.3.3.1. The Feeding Phase

During the feeding phase, water is pumped from the lower reservoir to the upper reservoir. Essentially converting the excess electrical energy to kinetic energy during periods of low energy demand.

The components used during this phase consists of the pump, lower reservoir, and the piping network to the upper reservoir.

4.3.3.2. Pumps

The purpose of the pump is to move a body of water from the lower reservoir to the upper reservoir. There are, however, various factors to consider when selecting an appropriate pump such as pump speed, system pressure, fluid characteristics, pump cost and size, operational temperature, efficiency, life expectancy, and net positive suction head (NPSH) (Ayanrohunmu and Ilupeju, 2015).

Common categories of pumps comprise positive displacement pumps, centrifugal pumps (which increase the pressure of the fluid), and axial flow pumps (ideal for delivering fluid at larger flow rates). The ideal pump for the pumped hydro storage system is the centrifugal pump.

One of the parameters to carefully consider is the net positive suction head, which is affected by the losses between the intake pipe and the head. Obtaining a net positive suction head is possible when the pressure (P) everywhere inside the pump is greater than the vapour pressure (P_{Vap}). The result of a positive NPSH reduces the risk of cavitation, which decreases the lifespan of the pump by damaging the impeller blades (Cengel and Cimbala, 2014). Factors which affects the static pressure and reduces the friction losses in the piping include:

- Decreasing the vertical distance between the pump and the source.
- Reducing the intake pipe diameter.
- Reduce pipe lengths.
- Avoid unnecessary bends in the intake pipe design.

The equation for NPSH (net positive suction head) is calculated via the following (Cengel and Cimbala, 2014):

$$NPSH = \left(\frac{P}{\rho g} + \frac{v^2}{2g}\right) - \frac{P_{Vap}}{\rho g} \quad (10)$$

Where: P = Pressure (kPa)

ρ = Density (kg/m^3)

v = Velocity (m/s)

P_{Vap} = Vapour Pressure (kPa)

g = Gravity (m/s^2)

4.3.3.3. Lower Reservoir

The lower reservoir contains the water to be pumped via the piping network to the upper reservoir. An ideal lower reservoir used as a water source is a river, in which case the initial volume of water available is assumed to be infinite. Assuming a river is used in the design of the PHS, freshwater is the medium in which the energy is stored. Freshwater, at the selected temperature of 20 °C, has the following properties according to Cengel and Cimbala (2014):

- Density (ρ) = 998.0 kg/m^3
- Dynamic Viscosity (μ) = 1.002 $\times 10^{-3}$ kg/m. s

4.3.3.4. Piping Network

The piping network is made of concrete and is used to transport the water from the lower reservoir to the upper reservoir. The design procedure of these pipes is important as the piping network affects the decision of the pump.

One of the piping factors which affects the pump selection is the pipe length. The pipe length is determined by the height of the reservoir and, therefore, the distance. The appropriate height of the upper reservoir is determined during the calculation phase of the released water phase. Additionally, the materials used for the piping network o affects the overall system, as pipes with rougher finishes increase the friction between the water and the pipes, resulting in a greater pressure required from the pump to deliver water to the upper reservoir.

Determining the appropriate pipe diameter also affects the pressure of the water. To design for the impact of friction over the length of the pipe, taking the pipe diameter and pipe materials into account, the following equations are used:

$$\boldsymbol{h_{Friction}} = \frac{4flv^2}{2gd} \quad (11)$$

Where: f = Friction coefficient of the concrete pipe

l = Length of the pipe (m)

v = Velocity of the fluid (m/s)

d = Pipe diameter (m)

Other factors which contribute to head losses in the piping network are bends, valves, and the entrance and exits for the fluid to the reservoirs. These losses, considered as minor losses, are calculated as follows:

$$\boldsymbol{h_{minor}} = \frac{v^2}{2g} \times \boldsymbol{K} \quad (12)$$

Where: K = Constant which specifically relates to relevant component i.e. valve, bends.

4.3.3.5. Storage Phase

At the point of the storage phase, which mainly consists of the upper reservoir, the mass of water pumped from the lower reservoir is stored. At this point, the mass of water has the greatest amount of potential energy needed.

Calculating the volume of the reservoir requires the difference in energy by the consumers during peak demand hours. The energy supplied by the PHS is calculated as follows:

$$\boldsymbol{Energy\ Required} = \frac{[(\boldsymbol{Energy\ stored\ by\ PHS})]}{\eta_{Turbine}} - \boldsymbol{h_{losses}} \quad (13)$$

The energy stored can be calculated by rearranging the above equation as follows:

$$\boldsymbol{Energy\ Required} = \left(\frac{Energy\ stored\ by\ PHS}{\eta_{Turbine}}\right) - h_{losses}$$

Where: energy stored by PHS = mgh (J)

$$mgh = \left(\frac{Energy\ Required}{\eta_{Turbine}}\right) - h_{losses}$$

Assuming the height of the PHS is known, which is dependent on the layout of the land, the mass of water and therefore the volume of water required is calculated as follows:

$$m = \frac{\left(\frac{Energy\ Required}{\eta_{Turbine}}\right) - h_{losses}}{gh}$$

$$\therefore \qquad V = \frac{m}{\rho}$$

4.3.3.6. Released Phase

When electrical energy is needed to meet the demands of consumers, stored energy, in the form of the water in the upper reservoir, is released. The water travels via the pipeline towards the hydro turbine, which is connected to an alternator to generate electricity. Once the water is released, the energy effectively converts from potential energy to kinetic energy.

4.3.3.7. Power Generation Phase

Upon reaching the bottom of the line, the water, being at the maximum velocity, is used to drive the hydro turbine, generating electricity. The hydro turbine is placed near the lower reservoir, driving water back to the lower reservoir once the energy is harvested.

4.4. System Design and Calculations

The assumptions made for the system are related to the energy required, based on the South African energy consumption curve, as seen in Figure 16. It is assumed that there are 100 households to supply electricity for during peak hour demand. It is also assumed that each household would consume approximately 5 kWh of energy per day.

Energy consumption would, therefore, equate to:

$$Energy\ consumed = 5\ kWh \times 100$$

$$Energy\ consumed = 500\ kWh$$

To calculate the mass of the water needed to produce the energy required, the energy needs to be converted from kilowatt-hours to kJ, where 1 kWh is equivalent to 3600 kJ.

$$Potential\ Energy\ Required = mgh = 500\ kWh \times\ 3600 \frac{kJ}{kWh}$$

$$Potential\ Energy\ Required = mgh = 1.8\ \times\ 10^6\ kJ$$

$$m = \frac{1.8 \times 10^6 \, kJ}{gh}$$

Assuming the height of the second reservoir to be 10 m above the pump and the turbine, the mass of the water required (at a height of 10 m) to provide 500 kWh of energy would therefore be:

$$m = 18.3 \times 10^6 \, kg$$

The assumption is that fresh water is used at approximately 20 °C. The water has the following properties according to (Cengel and Cimbala, 2014):

- $\rho = 998.0 \text{ kg/m}^3$
- $\mu = 1.002 \times 10^{-3} \text{ kg/m. s}$

The theoretical volume of water required to deliver the energy is calculated as follows:

$$\boldsymbol{\rho = \frac{m}{V}} \qquad (14)$$

$$V = \frac{m}{\rho}$$

$$V = \frac{18.3 \times 10^6 \, m^3}{998.0 \, \frac{kg}{m^3}}$$

$$V = 18.37 \times 10^3 \, m^3$$

A schematic of the PHS can be seen in Figure 25, below.

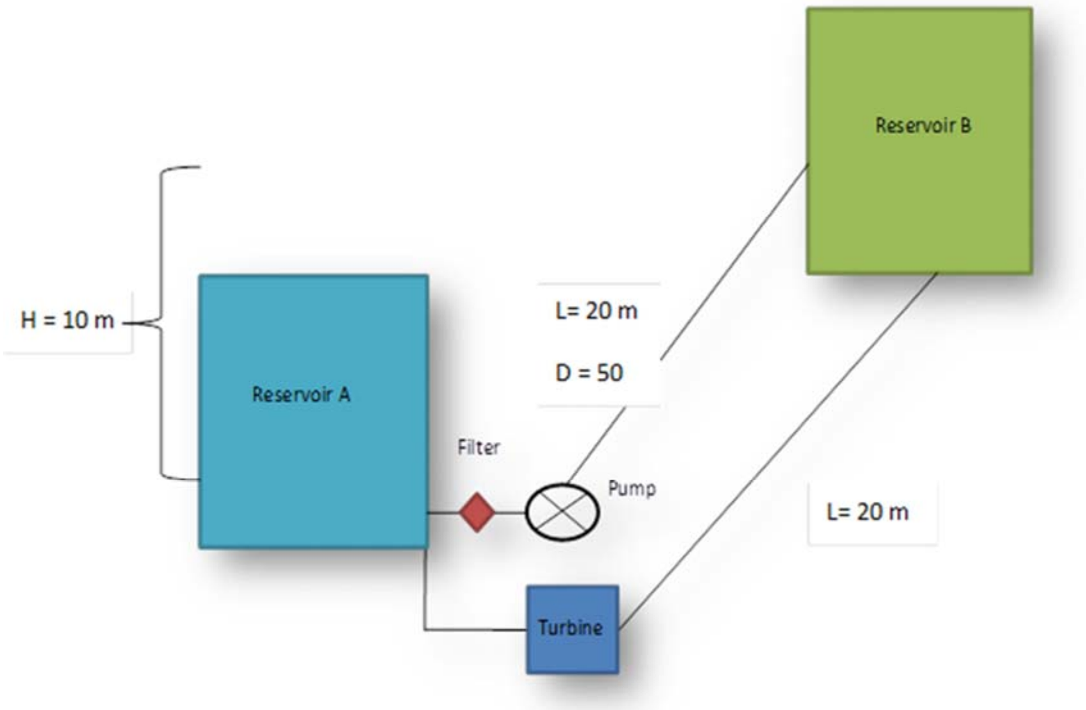


Figure 25: Schematic of PHS

The head losses in the pipe consisted of the following:

- Exit Losses.
- Entry Losses.
- Pipe Friction Losses.
- Losses caused by the filter.

However, before the head losses are calculated, the flow in the pipe and the velocity of the water is determined.

Reservoir B, the upper reservoir, is filled during periods of low demand. According to figure 25 periods of low energy consumption last approximately eight hours before the energy demand begins to increase. As a factor of safety, the pump supplies Reservoir B with 18.37 m^3 of water within an hour.

$$\therefore \boldsymbol{Q} = \frac{\mathbf{18.37}\, \boldsymbol{m^3}}{\mathbf{1}\, \boldsymbol{hour}} \qquad (15)$$

$$Q = 18.37 \frac{m^3}{hr}$$

$$Q = 5.102 \times 10^{-3}\, m^3 \frac{}{s}$$

A single smooth concrete pipe with a diameter of 50 mm is used, due to the pipe being exposed to the elements.

$$Q = v.A$$

$$v = \frac{Q}{A}$$

$$v = \frac{5.102 \times 10^{-3} \frac{m^3}{s}}{\left(\frac{\pi}{4} \times 0.05^2\right)}$$

$$v = 2.598 \frac{m}{s}$$

With the velocity calculated, the nature of the flow in the pipes is calculated, using the Reynold's number as follows:

$$\boldsymbol{Re = \frac{\rho v d}{\mu}}$$

$$Re = \frac{\left(998.0 \frac{kg}{m^3}\right)\left(2.598 \frac{m}{s}\right)(0.05\ m)}{\left(1.002 \times 10^{-3}\ N \frac{s}{m^2}\right)}$$

$$Re = 1.29 \times 10^5$$

$$Re = 1.29 \times 10^5 > 4000$$

The flow is, therefore, described as turbulent.

With the Reynold's number calculated, the friction factor *f* can be calculated to determine the head loss due to friction in the pipe.

$$\boldsymbol{h_{loss} = \frac{4flv^2}{2gd}}$$

Where *f* is the friction factor of the concrete pipe, determined using the Moody chart. Determining the friction factor required Reynold's number and the relative roughness of the pipe. The corresponding value on the Moody chart was the friction factor *f*. The relative roughness was determined as follows:

$$\boldsymbol{Relative\ roughness = \frac{\varepsilon}{d}} \quad (16)$$

$$Relative\ roughness = \frac{0.025}{50}$$

$$Relative\ roughness = 5 \times 10^{-4}$$

The corresponding friction factor, from the Moody chart, is taken as:

$$f = 0.017$$

$$\therefore h_{loss} = \frac{4(0.017)(20\ m)\left(2.598\frac{m}{s}\right)^2}{2g(0.05\ m)}$$

$$h_{loss} = 9.36\ m$$

It is assumed that a one-way valve is used, as in k = 2.5, Cengel and Cimbala, (2014). The head loss due to the valve is calculated as follows:

$$\boldsymbol{h_{loss}} = \frac{\boldsymbol{k.v^2}}{\boldsymbol{2gd}} \qquad (17)$$

$$h_{loss} = \frac{(2.5)\left(2.598\frac{m}{s}\right)^2}{2g(0.05\ m)}$$

$$h_{loss} = 17.2\ m$$

The entry and exit loss have the following relationship (Cengel and Cimbala, 2014):

$$Exit\ loss = 2 \times Entry\ loss$$

Where the losses due to the entry into Reservoir B can be calculated as follows:

$$h_{loss} = \frac{(0.5).v^2}{2gd}$$

$$h_{loss} = \frac{(0.5)\left(2.598\frac{m}{s}\right)^2}{2g(0.05\ m)}$$

$$h_{loss} = 0.172\ m$$

$$\therefore Exit\ h_{loss} = 0.344\ m$$

The total head loss in the pipe was:

$$h_{loss(Total)} = 9.39\ m + 17.20\ m + 0.17\ m + 0.34\ m$$

$$h_{loss(Total)} = 27.11\ \mathrm{m}$$

The head loss calculations are important in determining the appropriate pump to be used for the system. The system requires a pump that can overcome the head losses due to friction.

To compensate for the total head loss, additional energy is required by the system. The additional energy required by the system is calculated as follows:

$$Additional\ energy\ required = \rho g h_{loss}$$

$$\rho g h_{loss} = 998.0 \times 9.81 \times 27.11$$

$$Additional\ energy\ required = 265.42\ kJ$$

To compensate for the total head loss, at the same height, the additional volume of water required is calculated as follows:

$$mgh = 265.42\ kJ$$

$$m = \frac{265.42\ kJ}{gh}$$

$$m = 2\ 705.57\ kg$$

$$v_{additional} = \frac{2\ 705.57\ kg}{998.0}$$

$$v_{additional} = 2.71\ m^3$$

The additional water required to compensate for the drop in pressure due to friction is 2.71 m^3.

4.5. Analysis of Thermal Energy Storage

Thermal energy storage technology is divided into three categories, namely: sensible heat storage, latent heat storage, and thermo-chemical heat storage. It was previously discussed that sensible heat storage has the lowest cost, is reliable, simple, and the materials are readily available. However, there is a large spatial requirement and sensible heat storage technology has the lowest energy density of the three divisions. Thermo-chemical heat storage technologies yield the largest energy density; however, the technology is not developed enough to be designed for large-scale use as the materials are corrosive and the technology requires large capital investment. As previously discussed, latent heat storage systems are the ideal solution for an African microgrid, due to its greater energy density compared to sensible heat storage technologies.

4.6. Latent Heat Storage Assumptions

As previously designed for the PHS and battery storage devices, the latent heat storage device has the same design criteria, namely:

- The energy stored is to be received only from the microgrid.
- All energy stored in storage mediums, contained in tanks, have zero heat loss.
- Energy production per hour must be assumed to be constant.
- Energy losses in pipelines can be assumed to be zero.

4.7. Latent Heat Storage Parameters

- Serve 100 households with a total energy consumption of 500 kWh per day.
- The storage system is to be able to store 8 hours' worth of energy to meet peak-hour energy demands.

4.8. Latent Heat Storage System Design

The system is to make use of the following components:

- Concentrated solar PV system
- Large tower
- Parabolic mirrors
- Insulated storage tank
- Water storage tank
- Steam turbine
- Condenser
- Alternator
- Piping Network

A schematic of the design can be seen in Figure 26 below.

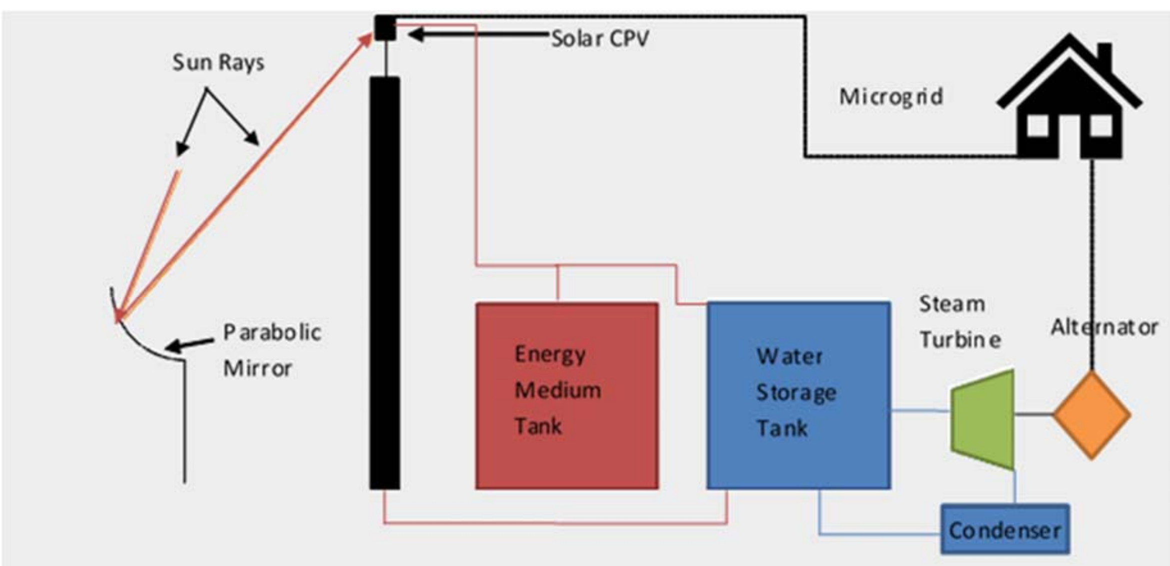


Figure 26: Schematic of Latent Heat Storage System

The parabolic mirror, namely heliostats, reflects and concentrates the sun's rays onto the molten salt central receiver, where the energy produced is directed to the microgrid, serving the consumer (General Electric, 2016). The excess energy is directed to the medium which is the phase change material. The phase change material is stored in the energy medium tank, designed to be thermally insulated, thus allowing no heat loss.

During periods of peak demand, the energy medium is pumped to the water storage tank, heating the water to superheated steam which is directed to the steam turbine. The steam turbine is connected to the alternator via a shaft to generate electricity and serve the consumers.

4.8.1. Molten Salts and Water

Molten salt consists of 60% Sodium Nitrate ($NaNO_3$) and 40% Potassium Nitrate (KNO_3). Assuming that this is used as an energy storage medium, the following properties of molten salts are used for the calculations (Pfleger *et al.*, 2015; McMullen, 2016):

- Melting Temperature: 230 °C
- Operating Temperature: 150 – 565 °C
- Volumetric Heat Capacity: 3 000 kJ/m^3
- Specific Heat Capacity: 1 560 J/kg. °C
- Density: 1 680 kg/m^3
- Enthalpy of Fusion: 120 kJ/kg

As previously assumed, in the design of the PHS and battery storage devices, the average energy consumption per household was 5 kWh per day. This energy is typically used for lighting, cooking and heating. There is a total of 100 households to be catered for, which brings the total energy consumption to 500kWh per day. The purpose of the thermal energy storage system is to store energy from the energy production system for periods of high energy demand or during seasons where power generation, via renewable energy, becomes insufficient due to unfavourable weather conditions. The storage systems are meant to provide energy for a minimum period of 8 hours.

The energy equation for a latent heat energy system (Equation 4), as previously mentioned in Chapter 3, is used to determine the amount of molten salt and water required for the system.

$$\boldsymbol{Q = m\left[\left(C_p \times (T_m - T_i)\right) + L + \left(C_p \times \left(T_f - T_m\right)\right)\right]}$$

Where: m = Mass (kg)

Cp = Specific heat capacity at constant pressure (J/kg.K)

T_m = Middle temperature (K)

T_i = Initial temperature (K)

T_f = Final Temperature (K)

L = Enthalpy of fusion of material (kJ/kg)

It was assumed that the initial temperature is standard room temperature (approximately 24 °C or 297 K), the middle temperature is set to be the melting temperature (230 °C or 503 K), and the final temperature is the maximum operating temperature 565 °C (808 K).

$$1\ kW.hour = 3\ 600\ kJ$$

$$\therefore 500\ kW.hour = 1.8\ \times 10^{6}\ kJ$$

$$1.8 \times 10^{6} kJ = m\ \left[\left(1.56 \frac{J}{kgK} \times\ (503\ K - 297\ K)\right) + 120\ kJ + \left(1.56 \frac{J}{kgK} \times\ (808\ K - 503\ K)\right)\right]$$

$$1.8 \times 10^{6} kJ = m\ \left[\left(321.36 \frac{kJ}{kg}\right) + 120 \frac{kJ}{kg} + \left(475.80 \frac{kJ}{kg}\right)\right]$$

$$\therefore m = \frac{1.8 \times 10^{6} kj}{917.16 \frac{kj}{kg}}$$

$$m = \frac{1.8 \times 10^{6}\ kJ}{917.16 \frac{kJ}{kg}}$$

$$\therefore m_{molten\ salt} = 1\ 962.58\ kg$$

However, due to similarities, in the production of steam, between a thermoelectric power station and the latent heat facility which makes use of the molten salts; it is assumed the overall efficiency of the systems are the same, approximately 32% to 42% depending on whether supercritical power plants are used (Zactruba and Scudder, 2010). Due to the efficiency, the volume of molten salts required to generate the amount of steam needed would increase by a factor of:

$$m_{molten\ salt} = \frac{m}{efficiency}$$

As there is no reheat cycle and the plant make no use of superheated steam, an efficiency of 32% is assumed.

$$m_{molten\ salt} = \frac{1\ 962.52\ kg}{.32}$$

$$m_{molten\ salt} = 6\ 132.88\ kg$$

This calculates the equivalent water needed to be converted to steam at temperatures greater than 373 K and pressures greater than atmospheric pressure. Assuming that the steam turbine has an efficiency of 83% (Zahrani, et al., 2016) and an approximate water consumption of 49-120 litres of water per kWh (Macknick et al., 2012), the volume of water required for the system is calculated as follows:

$$V_{water} = Rate\ of\ Consumption \times \left(\frac{Energy}{\eta_{turbine}}\right)$$

Where the rate of consumption was taken to be the median of the values from (Macknick *et al.*, 2012):

$$\text{Rate of Consumption} = 49\ \frac{\text{l}}{kW.hour} + \left(\frac{120-49}{2}\right)\frac{l}{kW.hour}$$

$$\text{Rate of Consumption} = 84.5\frac{l}{kW.hour}$$

$$V_{water} = Rate\ of\ Consumption \times \left(\frac{Energy}{\eta_{turbine}}\right)$$

$$V_{water} = 84.5\ \frac{l}{kW.hour} \times \left(\frac{500\ kw.hour}{0.83}\right)$$

$$V_{water} = 50.903\ m^3$$

4.8.2. Steam Turbine

The steam turbine selected for the latent heat storage application, mentioned in the calculation, is an SST-040 by Siemens which is a single-stage turbine (no reheat stage), ideal for decentralised solar plants, small CHP plants, and waste-heat recovery systems. The steam turbine yields many benefits such as simple and quick maintenance solutions, failure safe, rapid start-up times, low operation and installation cost, as well as being able to fit any process. The specifications of the turbine can be seen below:

Table 24: Specifications of Siemens SST-040 Steam Turbine (Siemens, 2017)

Specifications	**Values**
Power Output	75 - 300 kW
Inlet Steam Pressure	2 - 40 Bar
Inlet Steam Temperature	Dry Saturated Steam ≤ 400 °C
Exhaust Pressure	7 Bar
Dimensions	1.5 × 2.5 × 2 m (W × L × H)
Weight	4 500 kg

This latent heat storage calculation was done to determine the theoretical mass of molten salts and the volume of water required to sustain a community of 100 households with energy for approximately 8 hours. It was calculated that 6 132.88 kg of molten salts and a volume of 50.90 m^3 of water was required to serve a community of 100 households, using 5 kWh of energy per day. Due to modelling limitations of the HOMER program, there were no options for thermal energy storage systems. An alternative method was therefore used to model thermal energy storage systems.

5. System Modelling

As shown in Figure 2, African countries with the lowest energy consumption and GDP are Niger, Ethiopia, and Burundi. The country selected for modelling purposes was Burundi as it has the lowest GDP and energy consumption. A microgrid and storage system is ideal for areas located too far for the grid to deliver energy. Furthermore, the installation of this infrastructure has socio-economic benefits as these projects aim to empower residents by creating jobs and educating people.

A solar PV system was used to generate electrical energy for a community in Burundi. However, it can be noted that the power supply is not the focus of this report and that emphasis lies on the storage mechanism used to serve the community. Nonetheless, various energy supply systems are incorporated.

HOMER was used to model various energy storage systems. These systems were extensively modelled with various energy sources varying from islanded microgrids, which made use of renewable energy sources such as solar PV systems, cofire diesel generators and resources indigenous to Burundi.

The systems were modelled at two locations in Burundi to accommodate various energy storage systems. Various scenarios were modelled, including hybrid energy storage, where the scenarios modelled are addressed below.

5.1. Modelling Scenarios

The modelling scenarios are included in the table below.

Table 25: Modelling Scenarios

Scenario Number	Location	Power Source	Energy Storage System	Electrical Bus
1	Kirundo	Solar PV + Diesel Generator + Biomass	Pumped Hydro Storage	DC
2	Ruyigi	Solar PV + Diesel Generator + Biomass	Battery	DC

3	Ruyigi	Solar PV + Diesel Generator + Biomass	Supercapacitor	DC
4	Ruyigi	Solar PV + Diesel Generator + Biomass	Flywheel	DC
5	Ruyigi	Solar PV + Diesel Generator + Biomass	Thermal Energy Storage	DC

The location selected in HOMER was set at Burundi, with coordinates of 3°22,4 S, 29°55,1 E (Ruyigi) and 2.5848° S, 30.0961° E (Kirundo). The community load included approximately 5 kWh per household for 8 hours. The solar PV system was used to generate electrical energy during the day and store excess energy via the energy storage systems. The energy storage systems were designed to serve the community during peak hour energy demand periods.

Energy storage systems which relied on a water source, such as pumped hydro systems, were located in Kirundo which was situated near a water source. The second location, Ruyigi, was not near a water source and made use of battery and flywheel technology to store energy.

6. Results and Discussion

6.1. Scenario 1: Modelling of a Pumped Hydro Storage (PHS) System

6.1.1. PHS System Components (Scenario 1)

This scenario made use of a microgrid being supplied by biomass, a solar PV system, and PHS as a storage mechanism. The schematic is illustrated in Figure 27 below. The fixed parameters remained 500 kWh in order to be supplied to a community.

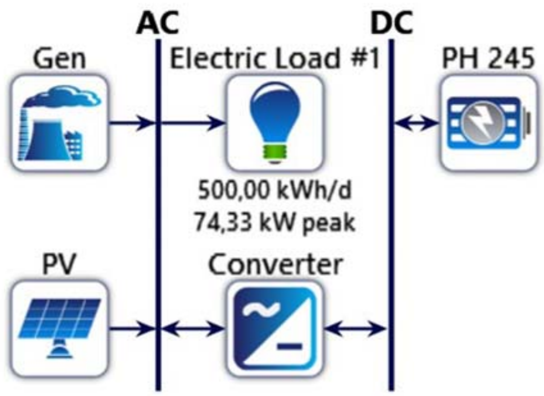


Figure 27: Schematic of Microgrid (Scenario 1)

The system consisted of the following apparatus:

- PHS System 245 kWh (× 2).
- Solar PV System..
- System Converter.
- Biogas Cofire Generator.

The PHS system had the specifications highlighted in scenario 1. The graph illustrating the state of charge can be seen in Figure 28. The monthly total power output of the system is illustrated in figure 29 and the graph illustrating the solar PV output is seen in figure 30. The specifications of the system components are shown in the tables below:

PHS System

PHS system specifications such as nominal voltage, current and efficiency shown in table 26.

Table 26: PHS System Specifications

2 × 245 kWh PHS System	
Nominal Voltage (V)	240

Maximum Charge Current (A)	91.6
Maximum Discharge Current (A)	91.6
Water Capacity (L)	1000
Discharge Period (Hours)	12
Effective Head (m)	100
Efficiency (%)	90
Discharge Flow Rate (m^3/s)	0.023
Power Generated (kW)	20.44
Number of Systems Used	2

Solar PV System

Solar PV system specifications illustrated in table 27.

Table 27: Specifications of Solar PV system

Generic Flat Plate PV system	
Rated Capacity (kW)	44
Average Output (kW)	7.3
Daily Average Output (kW)	178
Capacity Factor (%)	16.9
Total Annual Energy Production (kWh/year)	65 119
PV Penetration (%)	35.7
Annual Operating Hours (hours/year)	4 380
Levelised Cost of Energy (USD/kWh)	0,123

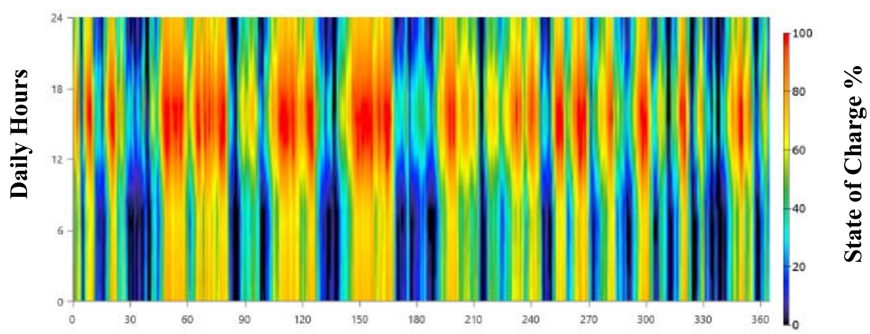


Figure 28: State of Charge of PHS (Scenario 1)

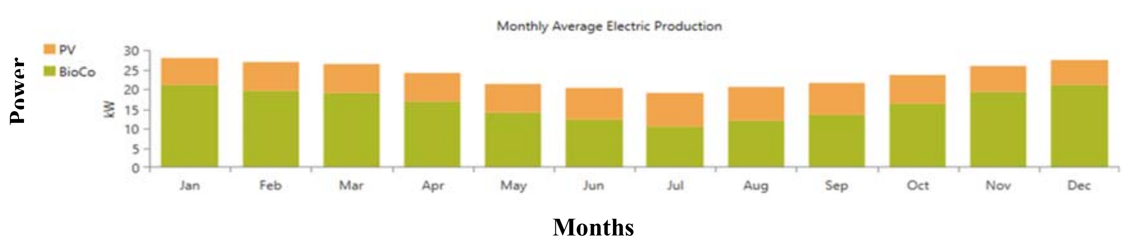


Figure 29: Monthly Power Output of Solar PV and Generator (Scenario 1)

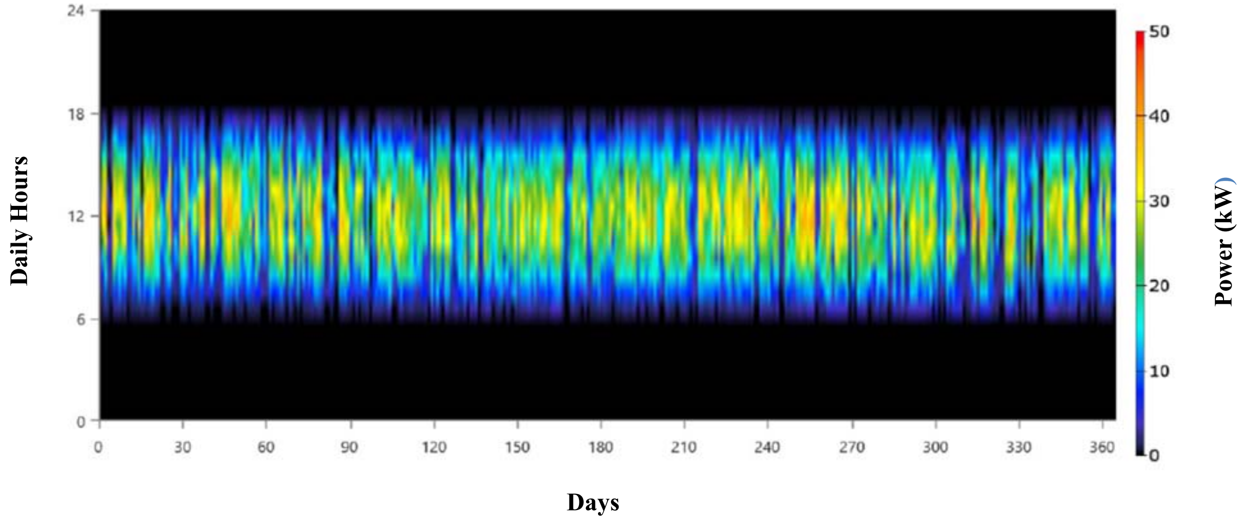


Figure 30: Solar PV Annual Power Output (kW) Graph (Scenario 1)

System Converter

The converter's specifications, required for the system, is shown below in table 28.

Table 28: Specifications of System Converter (Scenario 1)

System Converter	Inverter	Rectifier
Capacity (kW)	30.5	29.0
Average Output (kW)	6.5	8.46
Minimum Output (kW)	0	0
Maximum Output (kW)	27.7	30.5
Capacity factor (%)	21.3	27.7
Annual Operating Hours (hours/year)	5 351	3 355
Energy Out (kWh/year)	57 091	74 108
Energy In (kWh/year)	60 096	82 342
Losses (kWh/year)	3 005	8 234

Generator

The specifications for the biogas cofire generator as shown below in table 29.

Table 29: Specifications of Biogas Cofire Generator

Biogas Cofire Generator	
Annual Operating Hours (hours/year)	2 241
Lifespan (Years)	6.69
Generation Cost ($/hour)	4.95

Energy Production (kWh/year)	142 631
Average Electrical Output (kW)	63.60
Minimum Electrical Output (kW)	25.00
Maximum Electrical Output (kW)	100
Fuel Consumption (L)	9 463
Specific Fuel Consumption (L/kWh)	0.066
Fuel Energy Input (kWh/year)	443 428
Average Electrical Efficiency (%)	32.20
Biomass Feedstock Consumption (ton/year)	328

6.1.2. Electrical Energy Summary

From the initial report, the following results were obtained:

Table 30: Electrical Summary (Scenario 1)

Electrical Summary	
Annual Flat Plate PV Production (kWh/year)	65 119
Biogas Cofire Generator (kWh/year)	142 631
Primary Load (Consumption) (kWh/year)	182 500
Excess Electricity (kWh/year)	0
Unmet Electrical Load (kWh/year)	0
Capacity Shortage (kWh/year)	0

The result data from the PHS model can be seen in Table 31 below:

Table 31: Results of PHS model (Scenario 1)

Quantity	**Value**
Energy In (kWh/year)	74 108
Energy Out (kWh/year)	60 096
Storage Depletion (kWh/year)	76.70
Losses (kWh/year)	14 088
Nominal Capacity kWh	508
Expected Lifespan (Years)	25
Annual Throughput (kWh/year)	66 774

6.1.3. Emission Summary

The following emissions, listed in Table 32, was the result of using a cofire generator for periods when the solar PV system was not able to meet consumer demands. The generator was also used to supply the excess energy required to pump water to the upper reservoir, to make up for the losses experienced due to pipe and entry losses.

Table 32: Summary of Emissions (Scenario 1)

Pollutant	Quantity (kg/year)
Carbon Dioxide	65 832
Carbon Monoxide	754
Unburned Hydrocarbons	30.5
Particulate Matter	3.02
Sulphur Dioxide	54.3
Nitrogen Oxides	60.3

6.1.4. Costs

A summary of the Net Present Cost (NPC) of the system and Annualised Costs (AC) are presented in Tables 33 and 34.

Table 33: NPC of PHS System (Scenario 1)

Component	**Capital (USD)**	**Replacement (USD)**	**O & M (USD)**	**Fuel (USD)**	**Salvage (USD)**	**Total (USD)**
Generic Solar PV Plate	132 148	0	7 670	0	0	139 819
100 kW Biogas Cofire Generator	40 000	81 843	78 046	82 393	-5 063	277 219
Generic PHS 245 (× 2)	44 000	0	34 826	0	0	56 826
System Converter	9 159	5 879	0	0	-1 458	13 580
Total	**203 308**	**87 722**	**120 542**	**82 393**	**-6 521**	**487 444**

Table 34: Annualised Costs of PHS System (Scenario 1)

Component	**Capital (USD)**	**Replacement (USD)**	**O & M (USD)**	**Fuel (USD)**	**Salvage (USD)**	**Total (USD)**
Generic Solar PV Plate	7 589	0	440.49	0	0	8 029
100 kW Biogas Cofire Generator	2 297	4 700	4 482	4 732	-290.74	15 920
Generic PHS 245 (× 2)	2526	0	2 000	0	0	3 263
System Converter	526.00	337.62	0.00	0	-83.74	779.88
Total	**11 676**	**5 038**	**6 922**	**4 732**	**-374.48**	**27 993**

The total net present cost of the system required approximately 487 444 USD. The levelised cost of energy was calculated to be USD 0.153/kWh.

6.2. Scenario 2: Modelling of a Battery Energy Storage System (BESS)

6.2.1. Battery Model

The location of the battery model was set in a location further away from a water source, namely Ruyigi. A schematic of the system model can be seen in Figure 31.

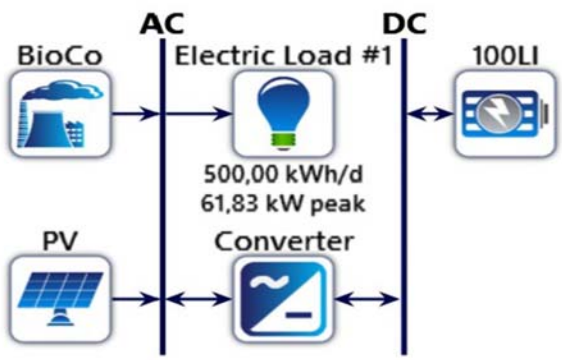


Figure 31: Schematic of Microgrid (Scenario 2)

6.2.2. System Components

The system comprised of the following components:

- Solar PV System.
- 100 kW Cofire Generator.
- System Converter
- 5×100 kWh Li-ion Battery Pack.

Solar PV System

Solar PV system specifications for the battery model illustrated in table 35.

Table 35: Specifications for PV Plate (Scenario 2)

Generic Flat Plate PV system	
Rated Capacity (kW)	36.5
Average Output (kW)	6.0
Daily Average Output (kW)	144
Capacity Factor (%)	16.4

Total Annual Energy Production (kWh/year)	52 486
Annual Operating Hours (kWh/year)	4 380

Additionally, the PV penetration throughout the year can be seen in Figure 32.

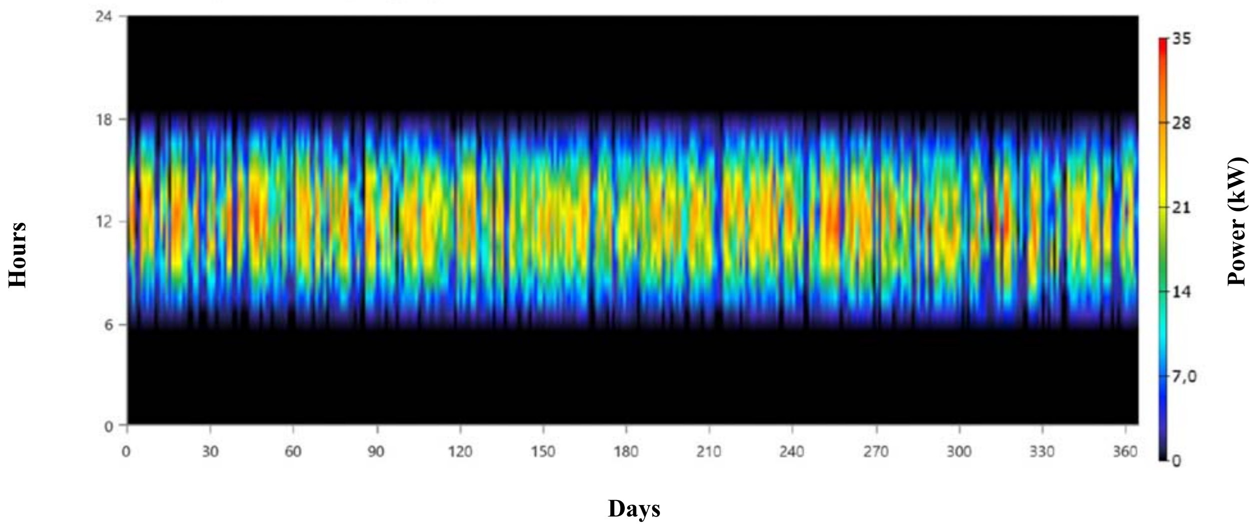


Figure 32: Graph of Daily PV Penetration (Scenario 2)

Generator

The specifications for the biogas cofire generator as shown below in table 36.

Table 36: Specifications of Biogas Cofire Generator (Scenario 2)

Biogas Cofire Generator	
Annual Operating Hours (hours/year)	7 444
Lifespan (Years)	2.02
Generation Cost ($/hour)	5.23
Energy Production (kWh/year)	194 899
Average Electrical Output (kW)	26.2
Minimum Electrical Output (kW)	25.0
Maximum Electrical Output(kW)	55.5
Fuel Consumption (L)	14 031
Specific Fuel Consumption (L/kWh)	0.072
Fuel Energy Input (kWh/year)	735 684
Average Electrical Efficiency	22.2
Biomass Feedstock Consumption	559

The monthly average energy production is illustrated in figure 33.

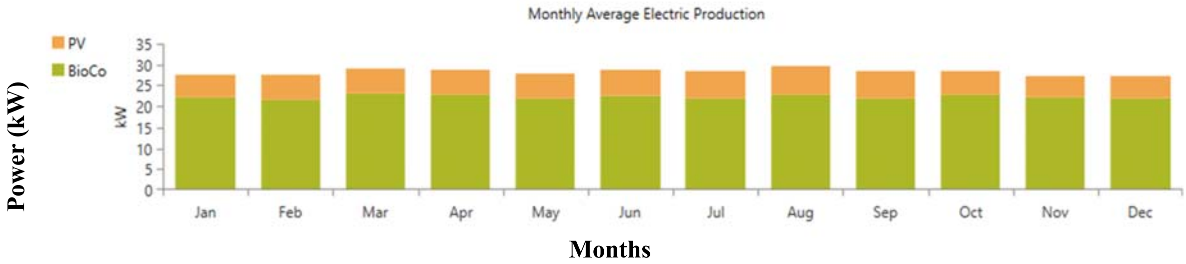


Figure 33: Monthly Average Energy Production (Scenario 2)

System Converter

The converter's specifications, required for the BESS, is shown below in table 37.

Table 37: Specifications of System Converter (Scenario 2)

System Converter	**Inverter**	**Rectifier**
Capacity (kW)	6.30	5.98
Average Output (kW)	1.52	1.78
Minimum Output (kW)	0	0
Maximum Output (kW)	6.30	9.30
Capacity factor (%)	24.2	28.2
Annual Operating Hours (hours/year)	2 708	2 977
Energy Out (kWh/year)	13 340	15 571
Energy In (kWh/year)	14 042	17 301
Losses (kWh/year)	702	1 730

Battery Energy Storage System

The battery energy storage system specifications such as nominal voltage, current and efficiency shown in table 38.

Table 38: Specifications of Battery Energy Storage System

100 kWh Li-Ion Battery	
Nominal Voltage (V)	600
Nominal Capacity (kWh)	100
Nominal capacity (Ah)	167
Efficiency (%)	90
Maximum Charge Current (A)	167
Maximum Discharge Current (A)	500
Expected Life (Years)	15
Energy In (kWh/year)	15 571

Energy Out (kWh/year)	14 042
Storage Depletion (kWh/year)	29.60
Losses (kWh/year)	1 559
Annual Throughput (kWh/year)	14 802
Capital Cost (USD)	350 000

A graph illustrating the daily state of charge of the battery can be seen below.

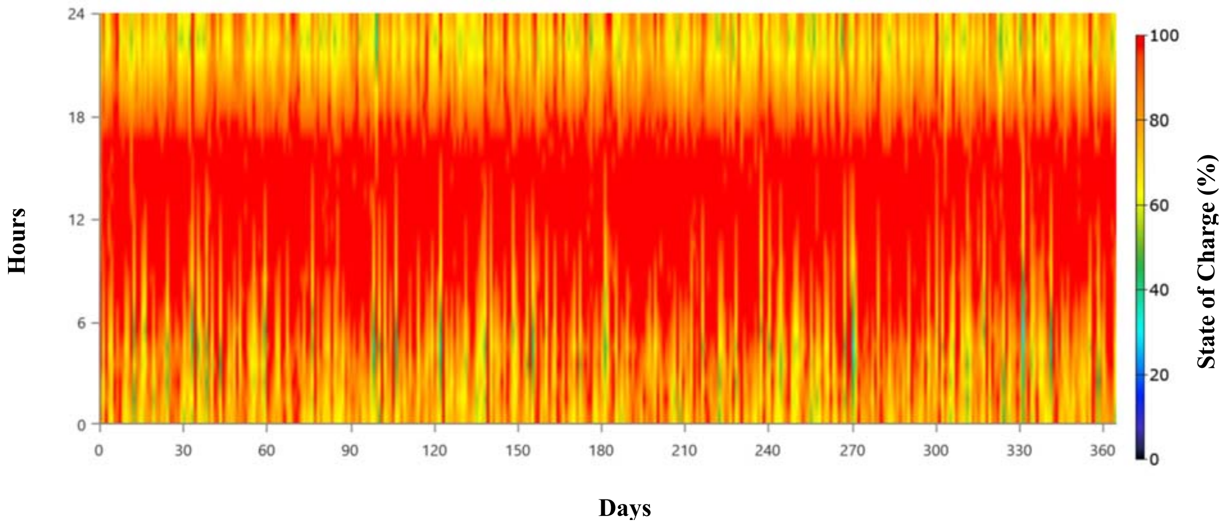


Figure 34: Graph Illustrating Daily Battery State of Charge

6.2.3. Electrical Summary

The electrical production energy of the system for the battery energy storage system is shown in table 39

Table 39: Electrical Energy Summary (Scenario 2)

Electrical Summary	
Annual Flat Plate PV Production (kWh/year)	52 486
100 kW Generator with Biogas Cofire (kWh/year)	194 899
Primary Load (Consumption) (kWh/year)	182 500
Excess Electricity (kWh/year)	60 924
Unmet Electrical Load (kWh/year)	0
Capacity Shortage (kWh/year)	0

6.2.4. Emission Summary

A summary of the emissions for the system is listed in table 40.

Table 40: List of Pollutants for PV-Battery System

Pollutant	**Quantity (kg/year)**
Carbon Dioxide	35 129
Carbon Monoxide	1 248
Unburned Hydrocarbons	50.50
Particulate Matter	4.99
Sulphur Dioxide	89.90
Nitrogen Oxides	99.80

6.2.5. Costs

A summary of the costs of the system, attained from the model report, can be seen in Table 41 and Table 42, respectively.

Table 41: NPC of Solar PV-Battery System

Component	**Capital (USD)**	**Replacement (USD)**	**O & M (USD)**	**Fuel (USD)**	**Salvage (USD)**	**Total (USD)**
Generic Solar PV Plate	109 594	0	4 670	0	0	114264
100 kW Biogas Cofire Generator	40 000	24 2598	190 319	179 357	-5 530	646744
100 kWh Li-Ion batteries (× 5)	350 000	23 365	127,85	0	-4 349.30	369173,85
System Converter	1 889	788,24	0,00	0	-146.72	2530,52
Total	**501 483**	**266 751,24**	**195 116,85**	**179 357**	**-9 923**	**1 132 712,37**

Table 42: Annualised Cost of Solar PV-Battery System

Component	**Capital (USD)**	**Replacement (USD)**	**O & M (USD)**	**Fuel (USD)**	**Salvage (USD)**	**Total (USD)**
Generic Solar PV Plate	8 573	0	365,31	0	0	8938,31
100 kW Biogas Cofire Generator	3 129	18 978	14 888	14 031	-432,58	50 593,42
100 kWh Li-Ion batteries (× 5)	27 380	365,58	10	0	-68,05	27 687,53

System Converter	147,78	67,66	0	0	-11,48	203,96
Total	**392 29,78**	**194 11,24**	**15 263,31**	**14 031**	**-512,11**	**87 423,22**

The net present cost for the solar PV with the use of a battery as an energy a storage mechanism was calculated at approximately 1 132 712,37 USD, with a LCOE of 0.359/kWh USD

6.3. Scenario 3: Supercapacitor Energy Storage (SCES)

The supercapacitor model was set in a location which was not near any water, namely in Ruyigi. A schematic of the system model can be seen in Figure 35:

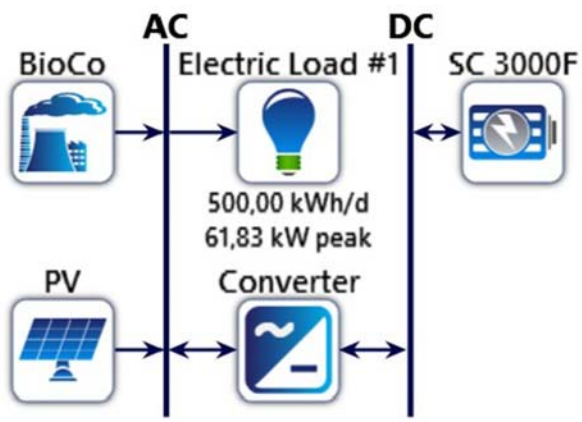


Figure 35: Schematic of Supercapacitor Storage System (Scenario 3)

6.3.1. System Components

The system comprised of the following components:

- Solar PV System.
- System Converter.
- 134 000×3000 Farad Capacitor.

Solar PV System

Solar PV system specifications for the supercapacitor storage model illustrated in table 43.

Table 43: Specifications for PV Plate (Scenario 3)

Generic Flat Plate PV system	
Rated Capacity (kW)	523
Average Output (kW)	85.3
Daily Average Output (kWh/day)	2 046
Capacity Factor (%)	16.3
Total Annual Energy Production (kWh/year)	746 914
Maximum Power Output (kW)	499
Annual Operation hours (kWh/year)	4 380

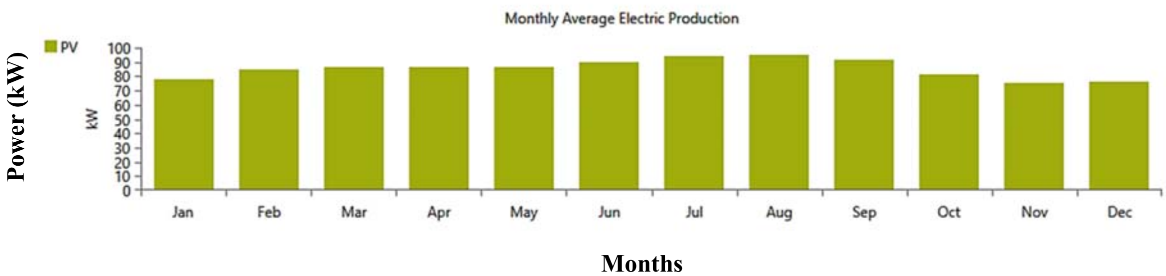


Figure 36: Monthly Average Energy Production (Scenario 3)

System Converter

The converter's specifications, required for the SCES, is shown below in table 44.

Table 44: Specifications of System Converter (Scenario 3)

System Converter	Inverter	Rectifier
Capacity (kW)	71.6	68
Average Output (kW)	8.35	10.3
Minimum Output (kW)	0	0
Maximum Output (kW)	61.8	71.6
Capacity factor (%)	11.7	14.4
Annual Operating Hours	4 204	1 697
Energy Out (kWh/year)	73 143	90 369
Energy In (kWh/year)	76 992	100 410
Losses (kWh/year)	3 850	10 041

Supercapacitor Energy Storage System

Supercapacitor energy storage system specifications such as nominal voltage, current and efficiency shown in table 45.

Table 45: Specifications of Supercapacitor Storage System

3000 Farad Supercapacitor	
Nominal Voltage (V)	3
Nominal Capacity (kWh)	100
Maximum Charge Current (A)	2.2×10^3
Maximum Discharge Current (A)	2.2×10^3
Energy In (kWh/year)	90 369
Energy Out (kWh/year)	76 992
Storage Depletion (kWh/year)	193
Losses (kWh/year)	13 571
Annual Throughput (kWh/year)	83 510
Nominal Capacity (kWh)	240
Usable Nominal Capacity (kWh)	240
Lifetime throughput (kWh)	2 505 296
Expected Life (Years)	30

$$\boldsymbol{Energy\ Stored_{Capacitor} = \frac{1}{2} \times C \times V^2} \quad (18)$$

$$Energy\ Stored_{Capacitor} = \frac{1}{2} \times 3000 \times 3^2$$

$$Energy\ Stored_{Capacitor} = 3.5\ W.hour$$

The number of capacitors required was therefore:

$$Number\ of\ Capacitors = \frac{Energy\ Required}{Max\ energy\ stored\ per\ Capacitor}$$

$$Number\ of\ Capacitors = \frac{500 \times 10^3\ W.hour}{3.5\ W.hour}$$

$$Number\ of\ Capacitors = \ 134\ 000$$

A graph illustrating the daily state of charge of the battery can be seen in Figure 37 below.

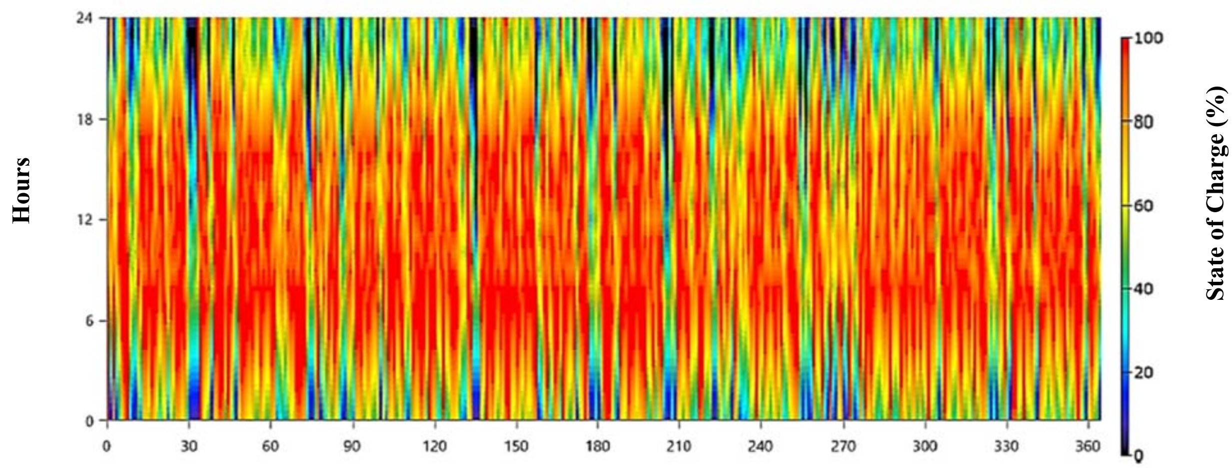


Figure 37: Graph Illustrating Daily Capacitor State of Charge

6.3.2. Electrical Summary

The electrical energy produced by the SCES system is shown in table 46.

Table 46: Electrical Energy Summary

Electrical Summary	
Generic Plat Plate PV (kWh/year)	746 914
Primary Load (Consumption) (kWh/year)	174 719
Excess Electricity (kWh/year)	544 927
Unmet Electrical Load (kWh/year)	7 781
Capacity Shortage (kWh/year)	9 089

6.3.3. Emission Summary

A list of the emissions as well as the annual mass produced by the system can be seen in Table 47 below.

Table 47: List of Pollutants for PV-Supercapacitor System

Pollutant	**Quantity (kg/year)**
Carbon Dioxide	0
Carbon Monoxide	0
Unburned Hydrocarbons	0
Particulate Matter	0

Sulphur Dioxide	0
Nitrogen Oxides	0

6.3.4. Costs

A summary of the costs of the system, attained from the model report, can be seen in Table 48 and 49, respectively.

Table 48: NPC of Supercapacitor Storage System

Component	**Capital (USD)**	**Replacement (USD)**	**O & M (USD)**	**Fuel (USD)**	**Salvage (USD)**	**Total (USD)**
Generic Solar PV Plate	1.57 M	0	66 832	0	0	1.64 M
3000 F Supercapacitor	6.69 M	0	0	0	-259 786	6.43 M
System Converter	21 473	8 960	0	0	-1 668	28 765
Total	**8.28 M**	**8 960**	**66 832**	**0**	**-261 454**	**8.09 M**

Table 49: Annualised Cost of Supercapacitor Storage System

Component	**Capital (USD)**	**Replacement (USD)**	**O & M (USD)**	**Fuel (USD)**	**Salvage (USD)**	**Total (USD)**
Generic Solar PV Plate	122 692	0	5 228	0	0	127 920
3000 F Supercapacitor	523 322	0	0	0	-20 322	502 999
System Converter	1680	700.90	0	0	-130.46	2 250
Total	**647 693**	**700.9**	**5228**	**0**	**-20 453**	**633 169**

The net present cost for the solar PV with the use of a battery as an energy a storage mechanism was calculated at approximately 8 094 030.93 USD, with a levelised cost of energy of 3.62 USD/kWh.

6.4. Scenario 4: Flywheel Energy Storage (FESS)

As previously stated, the average energy consumption of the households selected was assumed to be approximately 5 kWh per day, of which100 households were to be served by the energy storage mechanism. The location of the flywheel model was not near any water, namely in Ruyigi. A schematic of the system model can be seen in Figure 38 below.

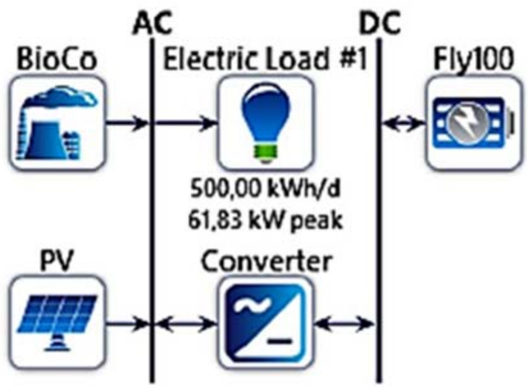


Figure 38: Schematic of Flywheel Storage System (Scenario 4)

6.4.1. System Components

The system comprised of the following components:

- Solar PV System.
- System Converter.
- 20×25 kWh Flywheel.

The component specifications can be seen in the following tables.

Solar PV System

Solar PV system specifications for the flywheel energy storage model illustrated in table 50.

Table 50: Specifications for PV Plate (Scenario 4)

Generic Flat Plate PV system	
Rated Capacity (kW)	208
Average Output (kW)	33.90
Daily Average Output (kWh/day)	814
Capacity Factor (%)	16.3
Total Annual Energy Production (kWh/year)	297 083
Annual Operating hours (kWh/year)	4 380

The monthly annual energy production by the solar PV system is shown in figure 39.

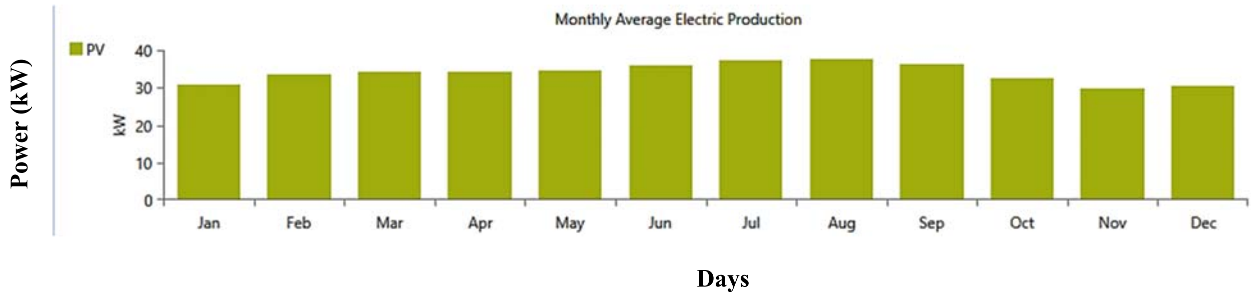


Figure 39: Monthly Average Energy Production (Scenario 4)

System Converter

The converter's specifications, required for the FESS, is shown below in table 51.

Table 51: Specifications of System Converter (Scenario 4)

System Converter	**Inverter**	**Rectifier**
Capacity (kW)	69.60	66.10
Average Output (kW)	9.91	12.20
Minimum Output (kW)	0	0
Maximum Output (kW)	61.80	69.60
Capacity factor (%)	14.20	17.50
Annual Operating Hours (hours/year)	4 928	2 457
Energy Out (kWh/year)	86 770	106 804
Energy In (kWh/year)	91 337	118 671
Losses (kWh/year)	4 567	11 867

Flywheel Energy Storage System

Flywheel energy storage system specifications such as nominal voltage, current and efficiency shown in table 52.

Table 52: Results and Specifications of the modelled Flywheel Storage System

100 kW Flywheel	
Nominal Voltage (V)	825
Nominal Capacity (kWh)	25
Nominal Capacity (Ah)	30.3
Maximum Power (A)	100
Maximum Charge Current (A)	121
Maximum Discharge Current (A)	121
Efficiency (%)	85
Energy In (kWh/year)	106 804
Energy Out (kWh/year)	91 337
Storage Depletion (kWh/year)	600

Losses (kWh/year)	16 067
Annual Throughput (kWh/year)	99 069
Lifetime Throughput (kWh/year)	1 981 371
Expected Life (Years)	20

A graph illustrating the daily state of charge of the battery can be seen in Figure 40 below.

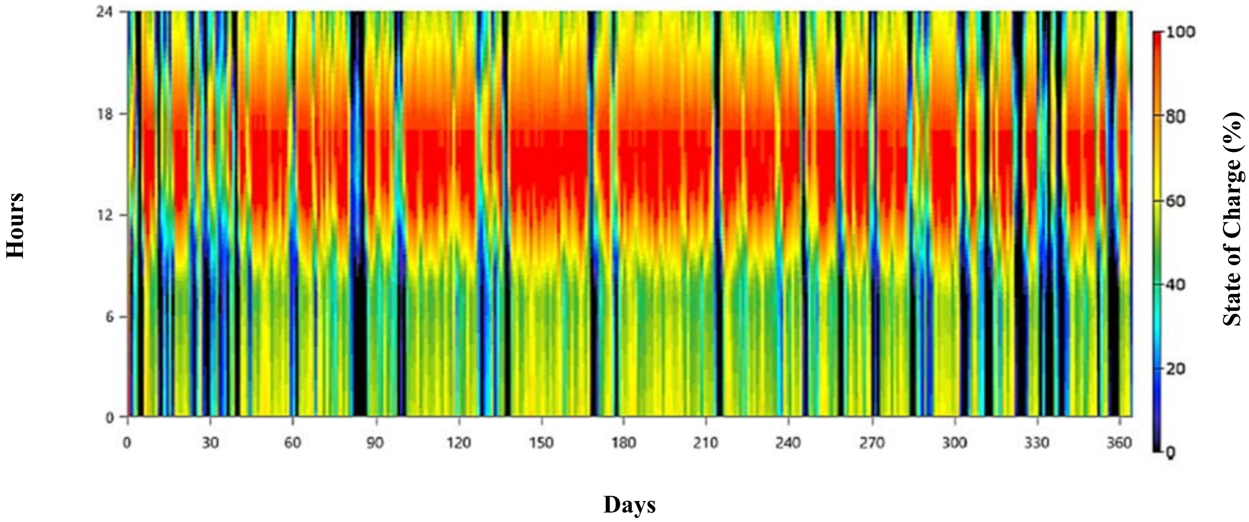


Figure 40: Graph Illustrating Daily Flywheel State of Charge

6.4.2. Electrical Summary

The electrical energy production for the FESS system is shown in table 53.

Table 53: Electrical Energy Summary (Scenario 4)

Electrical Summary	
Annual Flat Plate PV Production (kWh/year)	96.1
100 kW Generator with Biogas Cofire (kWh/year)	216 591
Primary Load (Consumption) (kWh/year)	182 500
Excess Electricity (kWh/year)	0
Unmet Electrical Load (kWh/year)	0
Capacity Shortage (kWh/year)	0

6.4.3. Emission Summary

The total emissions of the FESS system are shown in table 40.

Table 54: List of Pollutants for a PV-Biogas-Flywheel Storage System

Pollutant	**Quantity (kg/year)**
Carbon Dioxide	0
Carbon Monoxide	0
Unburned Hydrocarbons	0
Particulate Matter	0
Sulphur Dioxide	0
Nitrogen Oxides	0

A summary of the costs of the system, attained from the model report, can be seen in Table 55 and 56 respectively.

Table 56: NPC of PV-Biogas-Flywheel Storage System

Component	**Capital (USD)**	**Replacement (USD)**	**O & M (USD)**	**Fuel (USD)**	**Salvage (USD)**	**Total (USD)**
Generic Solar PV Plate	623 378	0	26 563	0	0	649 941
100 kW Flywheel	360 000	74 833	0	0	-41 940	392 893
System Converter	20 871	8 703	0	0	-1 621	27 959
Total	**1.0 M**	**83 542**	**26 563**	**0**	**-4 3561**	**1.07 M**

Table 55: Annualised Cost of Flywheel Storage System

Component	**Capital (USD)**	**Replacement (USD)**	**O & M (USD)**	**Fuel (USD)**	**Salvage (USD)**	**Total (USD)**
Generic Solar PV Plate	48 765	0	2 078	0	0	50 843
100 kW Flywheel	28 162	5 854	0	0	-3 281	30 735
System Converter	1 633	681.27	0	0	-126.81	2 187
Total	**78 559**	**6 535**	**2 078**	**0**	**-3 408**	**83 765**

The net present cost for the solar PV and biogas utilising flywheel storage technology as an energy storage mechanism was calculated at approximately 1 070 793.28 USD, with an LCOE of 0.48USD/kWh.

6.5. Scenario 5: Thermal Energy Storage (TESS)

The thermal energy storage model was set in a location near a water source, namely Kirundo. A schematic of the system model can be seen in Figure 41.

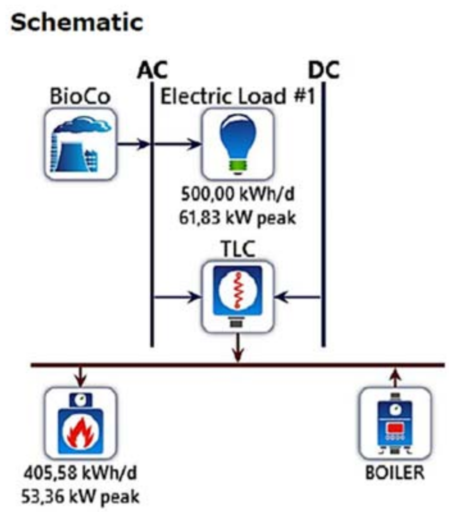


Figure 41: Schematic of Thermal Energy Storage System (Scenario 5)

The system made use of a hybrid generation system which included a PV solar system coupled with a boiler, fuelled by biomass, to convert water to steam in order to drive a steam-powered turbine. The turbine was coupled to an alternator to generate electricity. The system included a thermal load controller (TLC) which harnessed and stored the heat energy.

6.5.1. System Components

The system comprised of the following components:

- Thermal Load Controller.
- 100 kW Cofire Generator.
- Boiler.

Thermal Load Controller

The specifications of the thermal load controller are illustrated in table 57.

Table 57: Specifications for Thermal Load Controller (Scenario 5)

Generic Thermal Load Controller	
Operating Hours	5 580 hours/year

Average Output	6.91 kW
Maximum Output	24.6 kW
Minimum Output	0 kW

100 kW Biogas Cofire Generator

The specifications for the TESS biogas cofire generator as shown below in table 58.

Table 58: Specifications of Biogas Cofire Generator (Scenario 5)

Biogas Cofire Generator	
Annual Operating Hours (hours/year)	8 760
Lifespan (Years)	1.71
Generation Cost ($/hour)	5.23
Energy Production (kWh/year)	243 044
Average Electrical Output (kW)	27.7
Minimum Electrical Output (kW)	25.0
Maximum Electrical Output (kW)	61.80
Fuel Consumption (L)	17 204
Specific Fuel Consumption (L/kWh)	0.0708
Fuel Energy Input (kWh/year)	902 063
Average Electrical Efficiency (%)	26.9
Biomass Feedstock Consumption (ton/year)	685

The monthly average energy production of the system is illustrated in figure 42.

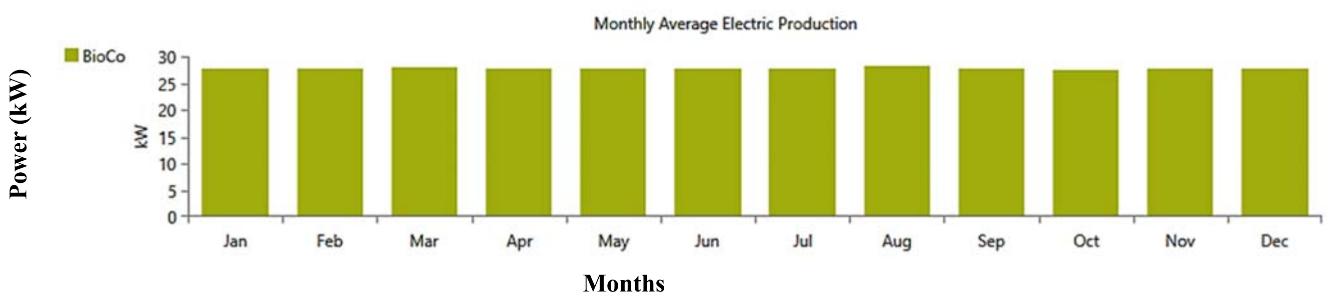


Figure 42: Monthly Average Energy Production (Scenario 5)

System Boiler

The specifications of the system's boiler are shown in table 59.

Table 59: Specifications of System Boiler (Scenario 5)

System Boiler	**Inverter**
Annual Operating hours (hours/year)	6 573
Annual Energy Production (kWh/year)	113 684
Mean Output (kW)	13
Minimum Output (kW)	0.022
Maximum Output (kW	45

Annual Fuel Consumption (L/year)	14 211
Specific Fuel Consumption (L/kWh)	0.125
Fuel Energy Input (kWh/year)	133 746
Average Efficiency (%)	85

Thermal Storage System

The specifications of the thermal storage system are shown in table 60.

Table 60: Specifications of Thermal Energy Storage System

Thermal Storage System	
System Boiler (kWh/year)	113 684
Excess Electricity (kWh/year)	60 544
Total Energy Production (kWh/year)	174 228
Thermal Load (kWh/year)	148 037
Excess Thermal Energy (kWh/year)	26 191

6.5.2. Electrical Summary

An electrical summary of the thermal energy storage system can be seen in Table 61 below.

Table 61: Electrical Energy Summary (Scenario 5)

Electrical Summary	
100 kW Generator with Biogas Cofire (kWh/year)	243 044
Primary Load (Consumption) (kWh/year)	182 500
Excess Electricity (kWh/year)	60 544
Unmet Electrical Load (kWh/year)	0
Capacity Shortage (kWh/year)	0

6.5.3. Emission Summary

A list of the emissions, as well as the annual mass, as produced by the system is presented in Table 62.

Table 62: List of Pollutants for PV-Biogas-Flywheel System

Pollutant	**Quantity (kg/year)**
Carbon Dioxide	43 073
Carbon Monoxide	1 531

Unburned Hydrocarbons	61.9
Particulate Matter	6.12
Sulphur Dioxide	110
Nitrogen Oxides	122

6.5.4. Costs

A summary of the costs of the system, attained from the model report, can be seen below in Tables 63 and 64, respectively.

Table 63: NPC of a Thermal Energy Storage System

Component	**Capital (USD)**	**Replacement (USD)**	**O & M (USD)**	**Fuel (USD)**	**Salvage (USD)**	**Total (USD)**
100 kW Biogas Cofire Generator	40 000	286 926	223 964	219 920	-3 728	767 082
Thermal Load Controller	200	62,36	0	0	-34,95	227,41
Generic Boiler	0	0	0	181 670	0	181 670
Total	**40 200**	**286 988**	**223 964**	**401 590**	**-3 763**	**948 980**

Table 64: Annualised Cost of a Thermal Energy Storage System

Component	**Capital (USD)**	**Replacement (USD)**	**O & M (USD)**	**Fuel (USD)**	**Salvage (USD)**	**Total (USD)**
100 kW Biogas Cofire Generator	3 129	22 445	17 520	17 204	-292	60 006,37
Thermal Load Controller	16	4,88	0	0	-2,73	17,8
Generic Boiler	0	0	0	14211	0	14211
Total	**3 145**	**22 450**	**17 520**	**31 415**	**-294**	**74 235**

Therefore, the net present cost for the solar PV and biogas, with the use of flywheel storage technology as an energy a storage mechanism, was calculated at approximately 948 979USD, with a levelised cost of energy of USD 0.31 USD/kWh.

7. Discussion of Results

The models, simulated using HOMER, made use of the following information:

- Location (Kirundo or Ruyigi in Burundi).
- Power consumption.
- System design.
- System parameters.

The results obtained from the HOMER models included the most economically feasible solution (arrangement of components) to meet the demand requirements. This purpose of this chapter is to analyse the results obtained from the HOMER models and compare the results. The results are compared to literature and models from previous studies. Also included are discussions on possible variations in results.

7.1. Analysis of Power Production Systems

The power production system comprised of a solar PV System which harnessed the 2000 kWh/m^2 solar irradiance as well as a cofire generator that made use of the annual 600-million-ton peat and sugar cane deposits that constitutes Burundi's resources. A comparison of the generic flat plate system for each energy storage system can be seen below.

Table 65: Comparison of Solar PV Results

Generic Flat Plate PV System					
	PHS	**Battery**	**Supercapacitor**	**Flywheel**	**Thermal**
Rated Capacity (kW)	44	36,5	523	208	0
Average Output (kW)	7,3	6	85,3	33.90	0
Daily Average Output (kWh)	178	144	2 046	814	0
Capacity Factor (%)	16,9	16,4	16,3	16,3	0
Total Annual Energy Production (kWh/year)	65 119	52 486	746 914	297 083	0
Annual Operating Hours	4 380	4 380	4 380	4 380	0

As the microgrid which made use of a supercapacitor and flywheel storage technologies solely utilised PV solar energy to produce electricity, it was found that the supercapacitor energy storage system had the highest rated capacity, average output, daily average output, as well as total annual energy production, as seen in Table 65 above.

The cells highlighted in Table 66 indicates the energy storage system which had the highest-rated value for the corresponding variable. The pumped hydro system had the greatest number of highlighted cells, indicating that the PHS system made the greatest use of biogas cofire generator and a boiler.

Table 66: Comparison of Biogas Generator Results

Biogas Cofire 100 kW Generator	**PHS**	**Battery**	**Supercapacitor**	**Flywheel**	**Thermal**
Annual Operating Hours (hours/year)	2 241	7 444	0	0	8 760
Lifespan (Years)	6.69	2.02	0	0	1.71
Generation Cost($/hour)	4.95	5.23	0	0	5.23
Energy Production (kWh/year)	142 631	194 899	0	0	243 044
Average Electrical Output (kW)	63.6	26.2	0	0	27.7
Minimum Electrical Output (kW)	25.0	25.0	0	0	25.0
Maximum Electrical Output (kW)	100	55.5	0	0	61.80
Fuel Consumption (L)	9 463	14 031	0	0	17 204
Specific Fuel Consumption (L/kWh)	0.066	0.072	0	0	0.0708
Fuel Energy Input (kWh/year)	443 428	735 684	0	0	902 063
Average Electrical Efficiency (%)	32.2	22.2	0	0	26.9
Biomass Feedstock Consumption (ton/year)	328	559	0	0	685

The highlighted values indicates the values which were most beneficial for the variable in question. The supercapacitor and flywheel energy storage system made no use of a generator; their systems were solely dependent on solar energy to generate electricity. Thermal energy storage had the greatest number of operating hours per year, while the PHS system had the longest lifespan, the lowest power generation costs (per hour), the highest mean electrical output and maximum electrical output, the lowest fuel consumption (which ultimately affects the LCOE), and the greatest efficiency. Furthermore, the PHS had the lowest specific fuel consumption. The thermal energy storage system had the greatest annual energy production as well as the greatest fuel energy input. Due to the fuel consumption (biomass feedstock consumption) of the thermal energy storage system exceeding the available biomass feedstock (600 million tons per year), the cofire generator used diesel as a fuel, which in turn increased the cost of energy production.

Table 67: Comparison of the System Boiler

System Boiler	**PHS**	**Battery**	**Supercapacitor**	**Flywheel**	**Thermal**
Hours of Operation (*hours/year*)	0	0	0	0	6 573
Annual Energy Production (*kWh/year*)	0	0	0	0	113 684
Mean Output (kW)	0	0	0	0	13
Minimum Output (kW)	0	0	0	0	0.022
Maximum Output (kW)	0	0	0	0	45
Annual Fuel Consumption (*L/year*)	0	0	0	0	14 211
Specific Fuel Consumption (*L/kWh*)	0	0	0	0	0.125
Fuel Energy Input (*kWh/year*)	0	0	0	0	133 746
Average Efficiency (%)	0	0	0	0	85

The thermal energy storage system was the only system which made use of a system boiler to supplement the energy produced by the biogas generator. The results of the boiler can be seen above, in Table 67. The total energy produced by the system boiler and biogas generator was therefore 356 728 kWh per year.

7.2. Energy Storage Systems

The results of the energy storage systems, received from HOMER, included the nominal voltage, maximum charge, efficiency, life expectancy, energy in and out, losses, and annual throughput.

Table 68: Comparison of Energy Storage Devices

	PHS System	**Lithium-ion Battery**	**Supercapacitor**	**Flywheel**	**Thermal**
Nominal Voltage (V)	240	600	3	825	*N/A*
Nominal Capacity (kWh)	508	100	100	25	*N/A*
Nominal capacity (Ah)	N/A	167	*N/A*	30,3	*N/A*

Efficiency (%)	90	90	85	85	85
Maximum Charge Current (A)	91,6	167	2.2×10^3	121	*N/A*
Maximum Discharge Current (A)	91,6	500	2.2×10^3	121	*N/A*
Expected Life (Years)	25	15	30	20	*N/A*
Number of Units	2	5	134×10^3	20	1
Energy In (kWh/year)	74 108	15 571	90 369	106 804	174 228
Energy Out (kWh/year)	60 036	14 042	76 992	91 337	148 037
Storage Depletion (kWh/year)	76,7	29.60	193	600	*N/A*
Losses (kWh/year)	14 088	1 559	13 571	16 067	26 191
Annual Throughput (kWh/year)	66 774	14 802	83 510	99 069	174 228

From Table 68 above, flywheel technology had the greatest nominal voltage. The PHS system and lithium-ion batteries had the greatest efficiencies, at 90%, however, the efficiencies of the remaining energy storage systems were lacking 5%.

The supercapacitor energy storage system had the greatest charge current, with a magnitude greater than the other storage systems. However, due to the low input and output of energy, supercapacitors were deemed unfeasible for a project of the proposed scale.

Thermal energy storage had the greatest advantages in terms of technical data due to only one system being needed. However, it was scaled to meet the demands of the consumers. Furthermore, the thermal energy storage system had the greatest input and output of energy as well as the greatest annual energy throughput.

7.3. Emissions

Energy storage systems which made use of a cofire generator, in their energy production systems were compared to energy storage systems which only used clean energy in their power production. The systems which made use of cofire generators emitted harmful emissions, while the systems which made sole use of solar PV systems had no harmful emissions. The comparison of these systems is seen in table 69. The storage system with the least harmful pollutants was deemed the cleanest energy storage system. The results derived from HOMER was the most feasible scenarios per energy storage system and power generation system. The amount of biomass and fossil fuels used to produce energy was proportional to the pollutants released into the environment.

Table 69: Comparison of Emissions of Storage Systems

Pollutant	***PHS System***	***Lithium-ion Battery***	**Supercapacitor**	**Flywheel**	**Thermal**
Carbon Dioxide (kg/year)	65 832	35 129	0	0	43 073
Carbon Monoxide (kg/year)	754	1248	0	0	1 531
Unburned Hydrocarbons (kg/year)	30,5	50,5	0	0	61,9
Particulate Matter (kg/year)	3,02	4,99	0	0	6,12
Sulphur Dioxide (kg/year)	12,3	89,9	0	0	110
Nitrogen Oxides (kg/year)	60,3	99,8	0	0	122

The system utilising a supercapacitor storage system and flywheel energy storage technology produced the least amount of carbon dioxide since no cofire generators were used in the system. However, of the microgrid systems which made use of the cofire generator, the pumped hydro storage system yielded the least carbon monoxide, unburnt hydrocarbons, particulate matter, sulphur dioxide, and nitrogen oxides. The microgrid, which made use of a thermal energy storage system and required the most input energy (in the form of fuels), produced the largest amounts of pollutants.

7.4. Costs

The costs derived from HOMER were based on values of generic systems applied to the program. The validity of the cost values derived from the models were, therefore, dependent on the accuracy of the program. In Table 70 below, respective costs associated with the respective microgrids can be seen.

Table 70: Comparison of Cost per Energy Storage System

	PHS System	**Lithium-ion Battery**	**Supercapacitor**	**Flywheel**	**Thermal**
Capital Costs ($)	203 308	221 483	8.28 M	1,07 M	1,0 M
Operation and Maintenance ($)	120 542	195 014	66 832	26 563	223 964
Replacement Cost ($)	87 722	248 060	8 960	83 542	286 988
Total Net Present Cost ($)	487 444,00	1 132 712,37	8,09 M	1,07 M	948 979,00
Annualised Cost ($)	27 993,00	87 423,32	633 163	83 765	74 235,00
Levelised Cost of Energy ($/kWh)	0,15	0,36	3,62	0,48	0,31

It was found that the microgrid with the lowest net present cost (NPC) was the PHS system which also had the lowest total NPC, annualised cost, and the lowest cost of energy. The microgrid which made use of lithium-ion batteries resulted in the system with the greatest net present cost and levelised cost of energy. The lithium-ion battery system was, therefore, concluded to cost consumers the most per unit of energy.

7.5. States of Charge of Storage Mechanisms

As previously mentioned, the state of charge of batteries related to the capacity of batteries (the amount of energy the battery was able to store in amp-hour) where 1.25 amp-hours was required to charge a battery for every 1 amp-hour used.

The states of charge for the storage mechanisms was an important factor to consider when selecting an appropriate energy storage mechanism for a microgrid. The lower the state of charge of the energy storage mechanism, the more energy was required to return the energy storage mechanism to its full capacity. HOMER provided the states of charge, in percentages, in the form of a graph. The graph illustrated the percentages per day for a year, seen in the figures in Chapter 7.

The pumped hydro state of charge graph had a median variation between 40% and 100%, whereas the state of charge of the PHS system was 100% before 6 am, dropped to 40% between 8 am and 5 pm, and then peaked at 100% between 9 pm and 5 am. There were certain days (anomalies) in which the state of charge reached values between 0% and 40%. These values may be attributed to days when consumer consumption was greater than the mean consumption or the energy production system was producing less energy than usual, causing greater reliance on the energy storage system.

The lithium-ion battery state of charge had a low discrepancy in the variation of the state of charge, such that the state of charge percentages varied between 60% and 100%. The state of charge values was at 60% at approximately 6 pm and 6 am and was at 100% between 6 pm and 6 am. The characteristics of the battery's state of charge was opposite to that of the PHS system.

The generic supercapacitor had large discrepancies in its state of charge values, in which the state of charge varied between 0% and 100%. The state of charge of the supercapacitor was at 100% between the hours of 6 am and approximately 6 pm, and then was at 0% at approximately 8 pm and 5 am. It was therefore found that the supercapacitor had very extreme states of charge when compared to other energy storage systems.

The flywheel energy storage system had a state of charge which also had large discrepancies, where the state of charge aired between 0% and 100%. The periods when the highest states of charge occurred was approximately between 12 pm and 6 pm. The periods with the lowest states of charge, approximately 0% - 20%, occurred between 8 pm and 12 pm. There were instances where the state of charge was at 0% - 20% for several days.

The state of charge graph for the thermal load controller was different to the graphs for the other energy storage systems, where the output power of the thermal load controller was illustrated per day of the year for a year. The output power of the thermal load controller varied between 0 kW and approximately 18 kW. Close to 0 kW of thermal power was drawn from the thermal load controller between 7 am and 11 pm. The thermal load controller provided power to consumers between the hours of 12 am and 6 am.

Table 71 illustrates the respective states of charge (SOC) of these energy storage mechanisms.

Table 71: Storage Systems and Associated

Time	States of Charge										
	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
1:00	SC	-	Flywheel	-			Battery				PHS
2:00	SC		Flywheel				Battery				PHS
3:00	SC		Flywheel				Battery				PHS
4:00	SC		Flywheel				Battery				PHS
5:00	SC		Flywheel				Battery				PHS
6:00			Flywheel				Battery				PHS, SC
7:00			Flywheel				Battery	PHS			PHS, SC
8:00			Flywheel		PHS						Battery, SC
9:00			Flywheel		PHS						Battery, SC
10:00			Flywheel		PHS						Battery, SC
11:00			Flywheel		PHS						Battery, SC
12:00					PHS						Battery, Flywheel, SC
13:00					PHS						Battery, Flywheel, SC
14:00					PHS						Battery, Flywheel, SC
15:00					PHS						Battery, Flywheel, SC
16:00					PHS						Battery, Flywheel, SC
17:00					PHS						Battery, Flywheel, SC
18:00							Battery	PHS			Flywheel, SC
19:00	SC						Battery	PHS			
20:00	SC		Flywheel				Battery	PHS			
21:00	SC		Flywheel				Battery				PHS
22:00	SC		Flywheel				Battery				PHS
23:00	SC		Flywheel				Battery				PHS
0:00	SC		Flywheel				Battery				PHS

7.6. Comparison of Results to Literature

7.6.1. Comparison of Modelled PHS to Literature Model

A study by Iqbal, (2009) explores the feasibility of using a pumped hydro storage system instead of a hydrogen fuel cell system, due to its greater efficiency. The pumped hydro storage system stores energy from a wind-diesel generator hybrid system which supplies energy to 600 consumers in Newfoundland, Canada.

A comparison of the specifications and results obtained can be seen in Tables 72 and 73 below.

Table 72: Comparison of PHS Model and Literature Specifications

Specifications	**Model**	**Literature**
Water Capacity (L)	1000	4000
Discharge Period (Hours)	12	3.14
Effective Head (m)	100	63
Efficiency (%)	90	70
Flow Rate (m^3/s)	0.023	0.347
Daily Power (kW)	20.44	150

Table 73: Comparison of PHS Model and Literature Results

Quantities	**Model**	**Literature**
Energy In (kWh/year)	74 108	73 233
Energy Out (kWh/year)	60 096	62 302
Storage Depletion (kWh/year)	76.70	52
Losses (kWh/year)	14 088	10 985
Nominal Capacity (kWh/year)	508	675
Expected Lifespan (Years)	25	6.25
Annual Throughput (kWh/year)	66 774	67 575

The power produced by the literature was greater than that of the model however, the power demand of the two communities was different, therefore resulting in a lower nominal capacity for the modelled system. The results of the energy storage system showed slight differences in comparison to the PHS system results in which the literature PHS system had a lower input of energy but greater energy output, lower storage depletion, fewer losses, a greater annual throughput. However, the literature's model had a shorter lifespan.

7.6.2. Comparison of a Modelled Battery Energy Storage System to Literature Model

A study by Peerapong and Limmeechokchai (2017) proposes utilising solar PV systems in conjunction with diesel generators to supply energy to consumers on islands, in Thailand. Due to the fluctuating diesel prices and increasing fuel transportation costs, relying solely on diesel generators is not economically sustainable. For a microgrid system using a solar PV system to supply communities on the islands with electricity, the use of battery energy storage was considered for the model.

A comparison of the specifications and the results of the battery models can be seen in Table 74 below.

Table 74: Comparison of Battery Model to Literature Model

	Model	**Literature**
Nominal Voltage (V)	600	12
Nominal Capacity (kWh)	100	6.91
Nominal Capacity (Ah)	167	1 156
Efficiency (%)	90	80
Maximum Charge Current (A)	167	279
Maximum Discharge Current (A)	500	279
Expected Life (Years)	15	20
Energy In (kWh/year)	15 571	2 784 357
Energy Out (kWh/year)	14 042	2 442 939
LCOE ($/kWh)	0.36	0.37

A large difference between the energy output and input was noted, however, this was due to the larger consumer population being catered for. The model in this report catered for 100 households with approximately 500 people, whereas the population of the islands consisted of 64,786 people. The batteries used in the literature was a string of lead-acid batteries, whereas the model in this report utilised a lithium-ion battery (which at the same scale as the literature model would have cost more). Furthermore, levelised cost of energy of the model was similar to that of the literature's model.

7.6.3. Comparison of a Supercapacitor Energy Storage System to Literature Model

Supercapacitors were often compared to batteries in literature, with supercapacitors yielding greater efficiencies, greater power densities, no harmful toxins, and low maintenance costs. However, due to the higher capital cost and the ability of batteries to supply energy for longer periods, supercapacitors were often modelled in conjunction with batteries to form a hybrid energy storage system (HESS). The supercapacitors were able to reduce the total percentage costs of batteries by up to 40% and 70%, in certain cases, with just above 60% of the supercapacitor utilised. (Kötz and Carlen, 2000; Jing et al., 2017).

7.6.4. Comparison of a Flywheel Energy Storage System to Literature Model

A study conducted by Ramli, Hiendro and Twaha, (2015) made use of microgrid, which harnessed solar energy to meet consumer demands. This study was considered for Makkah, Saudi Arabia. The system made use of flywheel energy storage technology due to the geography of Makkah, being inland, and the lack of access to enough water to explore other forms of storage technology. The study also aimed to determine the energy storage system which would result in a lower LCOE: a flywheel energy storage system or a flywheel-battery hybrid system.

The energy stored in flywheel energy storage systems were dependent on mass with an angular velocity. The energy in a flywheel was stored by accelerating the mass, and when energy was required, it was transferred to another body (such as a generator) which resulted in the slowing down of the flywheel to a complete stop (Ramli, Hiendro and Twaha, 2015). The energy stored in the rotor was determined with the following equation:

$$\boldsymbol{E = \frac{1}{2}.J.\omega} \qquad (19)$$

Where: ω = Angular Velocity (rad/s)

J = Moment of Inertia ($kg.m^2$)

$$\boldsymbol{J = kmr^2} \qquad (20)$$

Where: m = Mass (kg)

R = Radius (m)

K = Constant (Dependent on rotor shape)

A comparison of the modelled flywheel and the flywheel specifications and results can be seen in Table 75.

Table 75: Comparison of Modelled Flywheel Results to Literature Results

	Model	Literature
Discharge Capacity (kW)	100	250 000
Capital Cost ($)	300 000/unit	400 000/unit
Replacement Cost ($)	200 000/unit	200 000/unit

Efficiency	85 %	≥ 90 %
Energy In (kWh/year)	112 650	10 323 232
Energy Out (kWh/year)	95 768	8 323 816
Expected Life (Years)	20	20
LCOE ($/kWh)	0.19	0.37

The system used in the literature was larger than the system used in the model, however, the storage system used in the literature had a greater efficiency than the model's flywheel system. The modelled system, however, had a lower LCOE.

7.6.5. Comparison of a Thermal Energy Storage System to Literature Model

A study by Hameer and Van Niekerk (2015) aims to compare a thermodynamic energy storage model to that of electrochemical mechanisms (batteries and fuel cells) and mechanical energy storage (pumped hydro storage and compressed air energy storage). The CSP, which made use of a parabolic trough system, coupled to thermal energy storage had a combined power output of 97 MW and made use of molten salts as a heat transfer medium, whereas the HOMER model made use of a solar PV-biomass hybrid generation system, a boiler and thermal load controller.

A comparison of the results of the HOMER model and literature model can be seen in Table 76.

Table 76: Comparison of Thermal Energy Storage Model and Literature Model

Thermal Storage System	**Model**	**Literature**
Heat Transfer Fluid (HTF)	Water	Molten Salt
Efficiency (%)	85	86
Total Energy Input (GWh/year)	0.174	233
Energy Output (GWh/year)	0.148	200
LCOE ($/kWh)	0.31	0.216

The plant modelled in the literature was greater than the one modelled in HOMER, however, the LCOE made a direct comparison possible, wherein the LCOE of the literature model was lower than that of the HOMER model. According to (Hameer and Van Niekerk, 2015), the use of molten salts as a heat transfer fluid (HTF) in a parabolic trough lowers the total cost significantly. Therefore, it was concluded by (Hameer and Van Niekerk, 2015) that thermal energy storage had the lowest LCOE compared to PHS, Compressed air energy storage (CAES), and batteries.

7.7. Comparison to Literature Costs

Results obtained from the HOMER models were compared to that of Lazard, (2016), which summarises the levelised cost of energy storage systems, where the levelised cost is calculated in $/MWh. Table 77 summarises the costs associated with the total LCOE per energy storage system.

Table 77: Costs Associated to Literature Energy Storage Systems (Wei et al., 2009; Lazard, 2016)

	PHS	**Li-Ion Battery**	**Supercapacitor**	**Flywheel**	**Thermal**
Capital ($/MWh)	67	143	N/A	115	404
Operation and Maintenance ($/MWh)	8	26	0	25	49
Charging ($/MWh)	52	138	N/A	137	81
Taxes ($/MWh)	1	19	N/A	1	67
Other ($/MWh)	13	46	N/A	36	106
Total ($/MWh)	152	372	7440	332	707

The values seen in the Lazard (2016) Levelised Cost of Energy Storage Systems, table 77, had a significant discrepancy compared to that of the HOMER models. The variation in values was due to extra charges that the Lazard tables included, which the HOMER results did not, such as taxes, charging and discharging costs, as well as other costs. The values HOMER used for the capital and component costs varied to that of the values incorporated by (Lazard, 2016).

Supercapacitors were compared to batteries and were thought to replace batteries in the future. Although supercapacitor systems yield far more superior properties to that of batteries, such as greater power densities, low maintenance costs, and low toxicity levels of the materials used in production, supercapacitor storage systems were calculated to be 20 times more expensive than batteries. (Wei et al., 2009).

8. Conclusion

8.1. Overview

This study provided a solution to the electrification of two rural areas in Burundi, namely Kirundo and Ruyigi. The area with the lowest GDP was selected (which was directly proportional to the electrification rates of a country). The study was based on the assumption that increasing the electrification rates may increase the GDP of the country. Areas placed too far from power producers were difficult to provide electricity for, due to transmission systems being technically and economically unfeasible. Rural areas made use of a microgrid system that was able to run independently from the national grid. The systems relied on indigenous natural resources as much as possible to operate the microgrid, which added to the term "African Microgrid." Resources such as fossil fuels, for diesel generators, were relied on a little as possible due to fluctuating fuel prices and increasing transportation costs.

The microgrid system, which provided energy for the consumers, made use of renewable energy and natural resources. However, due to the intermittent nature of renewable energy, energy storage systems were used to balance the power delivery and store energy when renewable energy sources were unable to meet the consumer demands.

Five systems were modelled and compared. These systems included the pumped hydro storage, battery energy storage, supercapacitor energy storage, flywheel energy storage systems, and thermal energy storage.

8.2. Findings

The energy storage systems were modelled using HOMER, which found the most technical and economically feasible solution for the load and storage system. The results found in HOMER related to the power production system, energy storage systems, emissions, states of charge, and costs.

The analysis of the power production system, which made use of solar PV and a biogas cofire system, revealed that the solar PV system with the highest-rated power output, average output, daily average output, and the highest annual energy output was the solar PV system that made use of PHS. The biogas cofire generator which made use of the PHS had the longest lifespan, lowest power generation cost, lowest fuel and feedstock consumption, specific fuel consumption, and efficiency. In conclusion, the storage system which made the greatest use of solar PV to provide energy for consumers was the PHS system. The thermal energy storage system, which made use of a system boiler and thermal load controller, had the highest annual operating hours and annual energy production. The system which utilised flywheel energy storage technology had the highest minimum and maximum electrical output. The PHS system, therefore, yielded the greatest amount of benefits in terms of power production.

The PHS system and battery energy storage system had the highest nominal capacity and highest efficiency. The supercapacitor yielded the highest maximum current and expected life, as well as the lowest storage depletion and losses. The flywheel energy storage system yielded the greatest nominal voltage, while thermal energy storage systems required the least amount of systems, with only one system required. Thermal energy storage systems required the greatest input of energy, which required the most fuel, however, yielded the greatest energy output and energy throughput. Therefore, as an energy storage system, supercapacitors yielded the most benefits.

The pollutants measured in the model was carbon dioxide, carbon monoxide, unburnt hydrocarbons, particulate matter, sulphur dioxide, and nitrogen oxides. It was found that the energy storage system with the least carbon dioxide emissions was lithium-ion batteries. PHS systems had the lowest emissions, due to having the lowest reliance on the cofire gas generator.

The system costs derived from the HOMER models revealed that PHS systems had the lowest replacement costs, annualised costs, and LCOE. The low levelised cost and the annualised cost of the PHS system was attributed to the low NPC and expected lifespan ratio. Flywheel energy storage technology yielded the lowest maintenance and lowest net present cost, while thermal energy storage systems yielded the lowest required capital costs. The results of the supercapacitor contradicted that of the literature which stated that supercapacitors required little to no maintenance. It was, in fact, found that in the HOMER model supercapacitors had the highest operations and maintenance costs. When the cost results were compared to the tables in Lazard, (2016), if was found that the results coincided with that of the results modelled in this report, with slight discrepancies. These discrepancies were attributed to the varying capital and maintenance costs used by the HOMER program, as well as the additional costs included in the Lazard tables, such as taxes and charging costs. Costs for supercapacitors, however, were not able to be compared due to supercapacitors not being used at the scale of a microgrid. However, according to Lazard, (2016) was predicted that the costs for supercapacitors were twenty times more than that of batteries. In terms of costs, PHS systems had the greatest advantage.

The results, therefore, concluded that the PHS system had the most advantages for an African Microgrid and therefore considered the most viable form of energy storage for an African Microgrid. PHS systems were determined to be a site-specific technology in which water and a land layout with height difference were needed; however, as seen in Chapter 3 there are alternative methods to make PHS systems work.

8.3. Future Work

Due to flooding hazards tied to the use of pumped hydro storage systems, energy membrane systems could be used at a larger scale i.e. a microgrid. These systems have proven to be more cost-effective, particularly in terms of capital costs, and are safer to use than a conventional pumped hydro system. A detailed comparison of an energy membrane storage system and conventional PHS is recommended in the context of African resources.

As seen by the results, supercapacitors yield many advantages as a storage mechanism yet are not invested in due to high costs. Supercapacitors may be advantageous at a microgrid scale due to its high-power density and its low maintenance requirements. It was concluded that supercapacitors used in conjunction with batteries will result in a reliable energy storage mechanism with a high energy density. Modelling of this hybrid energy storage system and a techno-economic comparison between the hybrid energy storage system and conventional battery system could be done to determine whether the battery-supercapacitor energy storage system is a viable ESS at a microgrid scale.

For the abovementioned systems, the MATLAB program would be an ideal tool for modelling.

Much research has been made in the advancement of storage mechanisms, particularly those in rural areas, however, further research into the viability of energy storage mechanisms could be made in the context of Africa and African resources.

9. References

- Abedin, A. H. (2010) ‘Thermochemical energy storage systems: Modelling, analysis and design’, *Mechanical Engineering*, M. Sc(July), p. 146. doi: 10.1016/B978-0-12-803440-8/00017-8.
- African Development Bank Group (2012) *Urbanisation in Africa*. Available at: http://www.afdb.org/en/blogs/afdb-championing-inclusive-growth-across-africa/post/urbanization-in-africa-10143/ (Accessed: 15 June 2016).
- ArcGIS (2017) *ArcGIS*. Available at: https://www.arcgis.com/home/webmap/viewer.html?layers=22ef33ce499d4abbafa7fb53ec4dc4c5 (Accessed: 17 June 2017).
- Ayanrohunmu, S. and Ilupeju, O. (2015) *Design, Modelling and Optimisation of an Isolated Small Hydropower Plant Using Pumped Storage Hydorpower and Control Techniques*. University of KwaZulu-Natal.
- Aydin, D., Casey, S. P. and Riffat, S. (2015) ‘The latest advancements on thermochemical heat storage systems’, *Renewable and Sustainable Energy Reviews*. Elsevier, 41, pp. 356–367. doi: 10.1016/j.rser.2014.08.054.
- Barbour, E., Wilson, I.A.G., Radcliffe, J., Ding, Y. & Li, Y. (2016) ‘A review of pumped hydro energy storage development in significant international electricity markets’, *Renewable and Sustainable Energy Reviews*. Elsevier, 61, pp. 421–432. doi: 10.1016/j.rser.2016.04.019.
- Belward, A., Bisselink, B., Bódis, K., Brink, A., Dallemand, J., Roo, A. De, Huld, T., Kayitakire, F., Mayaux, P., Ossenbrink, H., Pinedo, I., Sint, H., Thielen, J., Szabó, S., Tromboni, U., Willemen, L. & Monforti, F. (2011) ‘Renewable energies in Africa’, *JRC Scientific and Technical Reports*, pp. 1–62. doi: 10.2788/1881.
- Berrada, A. and Loudiyi, K. (2015) ‘Optimal Modeling of Energy Storage System’, *International Journal of Modeling and Optimization*, 5(1), pp. 71–77. doi: 10.7763/IJMO.2015.V5.439.
- Bikalemesa, J. M. (2014) *Energy Sector Profile in Burundi*, *Fortune of Africa*. Available at: http://fortuneofafrica.com/burundi/energy-sector-profile-in-burundi/ (Accessed: 4 October 2017).
- Bokanga, G. M. and Kahn, M. T. E. (2014) ‘Design of a low voltage DC microgrid system for rural electrification in South Africa’, 25(2), pp. 9–14.

- Brown, C. (2016) *World Energy Resources: Hydropower*. Available at: https://books.google.com/books?id=WLC7CdLOZosC&pgis=1 (Accessed: 2 October 2017).
- Burke, M. J. and Stephens, J. C. (2018) 'Energy Research & Social Science Political power and renewable energy futures : A critical review', *Energy Research & Social Science*, 35(November 2017), pp. 78–93.
- Castellano, A., Kendall, A., Nikomarov, M. & Swemmer, T. (2015) *Powering Africa*. Available at: https://www.mckinsey.com/industries/electric-power-and-natural-gas/our-insights/powering-africa (Accessed: 3 July 2017).
- Cengel, Y. A. and Cimbala, J. M. (2014) *Fluid Mechanics: Fundamentals and Applications*. Third Edit. Singapore: McGraw-Hill.
- Chia, Y.Y., Lee, L.H., Shafiabady, N. & Isa, D. (2015) 'A load predictive energy management system for supercapacitor-battery hybrid energy storage system in solar application using the Support Vector Machine', *Applied Energy*. Elsevier Ltd, 137, pp. 588–602. doi: 10.1016/j.apenergy.2014.09.026.
- Ciez, R. E. and Whitacre, J. F. (2016) 'Comparative techno-economic analysis of hybrid micro-grid systems utilizing different battery types', *Energy Conversion and Management*. Elsevier Ltd, 112, pp. 435–444. doi: 10.1016/j.enconman.2016.01.014.
- City of Cape Town (2014) *Energy in your home*, *SMART LIVING handbook*. Cape Town. Available at: https://www.capetown.gov.za/en/EnvironmentalResourceManagement/EnergyEfficiency/Documents/SLH energy audit pp 44-47.pdf (Accessed: 27 April 2016).
- Department of Energy (2011) 'Integrated Resource Plan for Electricity 2010-2030', (March), p. 78. doi: 10.1016/j.wneu.2010.05.012.
- Douglas, T. (2016) 'Dynamic modelling and simulation of a solar-PV hybrid battery and hydrogen energy storage system', *Journal of Energy Storage*. Elsevier Ltd, 7, pp. 104–114. doi: 10.1016/j.est.2016.06.001.
- Dwivedi, V. K., Tiwari, P. and Tiwari, S. (2016) 'Importance of phase change material (PCM) in solar thermal applications: A review', *International Conference on Emerging Trends in Electrical, Electronics and Sustainable Energy Systems, ICETEESES 2016*, pp. 42–45. doi: 10.1109/ICETEESES.2016.7581349.
- Edwards, J., Bindra, H. and Sabharwall, P. (2016) 'Exergy analysis of thermal energy storage options with nuclear power plants', *Annals of Nuclear Energy*. Elsevier Ltd,

96, pp. 104–111. doi: 10.1016/j.anucene.2016.06.005.

- Gao, Y., Xu, A., Zhang, L., Wang, G., Bai, D. & Zhao, Y. (2015) ‘Study on micro-grid power storage converter’, *International Journal of Grid and Distributed Computing*, 8(3), pp. 337–350. doi: 10.14257/ijgdc.2015.8.3.31.
- General Electric (2016) *Molten Salt Central Receiver (MSCR)*. Switzerland. Available at: https://www.gerenewableenergy.com/content/dam/gepower-renewables/global/en_US/downloads/brochures/solar-molten-salt-central-receiver-mscr-gea32276.pdf.
- Gessner, U., Knauer, K., Machwitz, M., Dech, S. & Kuenzer, C. (2016) ‘Impacts of socio-economic development and urbanization on natural resources - case studies from Africa’, *2016 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*. IEEE, pp. 7283–7284. doi: 10.1109/IGARSS.2016.7730899.
- Giorgi, L. and Leccese, F. (2013) ‘Fuel Cells: Technologies and Applications’, *The Open Fuel Cells Journal*, 6, pp. 1–20.
- Green, D. (2014) *Centralised to decentralised energy: What does it mean?*, *REneweconomy*. Available at: http://reneweconomy.com.au/centralised-decentralised-energy-mean-34072/ (Accessed: 3 October 2017).
- Hahne, E. (2001) ‘Storage of Sensible Heat’, *Encyclopedia of Life support systems*, I, pp. 1–8.
- Hameer, S. and Van Niekerk, J. L. (2015) ‘a Thermodynamic Model for Comparing Thermal Energy Storage System To Electrochemical , Chemical , and Mechanical Energy’, in *Third Southern African Solar Energy Conference*. Nelspruit, pp. 123–128.
- Harrabin, R. (2012) *Liquid air ‘offers energy storage hope’*. Available at: http://www.bbc.com/news/science-environment-19785689.
- Hauge, H. H., Presser, V. and Burheim, O. (2014) ‘In-situ and ex-situ measurements of thermal conductivity of supercapacitors’, *Energy*. Elsevier Ltd, 78, pp. 373–383. doi: 10.1016/j.energy.2014.10.022.
- Hesaraki, A., Holmberg, S. and Haghighat, F. (2015) ‘Seasonal thermal energy storage with heat pumps and low temperatures in building projects—A comparative review’, *Renewable and Sustainable Energy Reviews*. Elsevier, 43(March), pp. 1199–1213. doi: 10.1016/j.rser.2014.12.002.
- Hittinger, E., Wiley, T., Kluza, J. & Whitacre, J. (2015) ‘Evaluating the value of batteries in microgrid electricity systems using an improved Energy Systems Model’,

Energy Conversion and Management. Elsevier Ltd, 89, pp. 458–472. doi: 10.1016/j.enconman.2014.10.011.

- Hummon, M., Denholm, P., Jorgenson, J. & Mehos, M. (2013) 'Modelling Concentrating Solar Power with Thermal Energy Storage for Integration Studies', *The 3rd International Workshop on Integration of Solar Power into Power Systems*, (October).
- IEC (2009) 'Executive summary', *Electrical Energy Storage White Paper*, 39, pp. 11–12. doi: 10.1016/j.icrp.2009.12.007.
- Iqbal, T. (2009) 'Feasibility Study of Pumped Hydro Energy Storage for Ramea', *The Harris Centre - Memorial University*, p. 23. Available at: https://www.mun.ca/harriscentre/reports/arf/2009/ARF_Iqbal_RameaHybrid.pdf.
- IRENA (2013) 'Thermal Energy Storage. Technology Brief', (January), p. 24. Available at: www.irena.org/Publications.
- Jaiswal, A. (2017) 'Lithium-ion battery based renewable energy solution for off-grid electricity: A techno-economic analysis', *Renewable and Sustainable Energy Reviews*. Elsevier Ltd, 72(August 2016), pp. 922–934. doi: 10.1016/j.rser.2017.01.049.
- Jarnut, M., Wermi, S. and Wa, B. (2017) 'Comparative analysis of selected energy storage technologies for prosumer- owned microgrids', 74(April 2016), pp. 925–937.
- Jing, W., Lai, C.H., Wong, W.S.H. & Wong, M.L.D. (2017) 'Dynamic power allocation of battery-supercapacitor hybrid energy storage for standalone PV microgrid applications', *Sustainable Energy Technologies and Assessments*, 22, pp. 55–64. doi: 10.1016/j.seta.2017.07.001.
- Karekezi, S. and Kithyoma, W. (2003) 'Renewable energy development', *workshop on African Energy Experts on Operationalizing the NEPAD Energy Initiative, June*, pp. 2–4.
- Kim, H., Boysen, D.A., Newhouse, J.M., Spatocco, B.L., Chung, B., Burke, P.J., Bradwell, D.J., Jiang, K., Tomaszowska, A.A., Wang, K., Wei, W., Ortiz, L.A., Barriga, S.A., Poizeau, S.M. & Sadoway, D.R. (2013) 'Liquid Metal Batteries : Past , Present , and Future'. doi: 10.1021/cr300205k.
- Kirchner, R. and Salami, A. (2014) 'Promoting a low cost energy future in Africa', *African Journal of Environmental Science and Technology*, 8(2), pp. 91–98. doi: 10.5897/AJEST2013.1619.

- Korkas, C.D., Baldi, S., Michailidis, I. & Kosmatopoulos, E.B. (2016) 'Occupancy-based demand response and thermal comfort optimization in microgrids with renewable energy sources and energy storage', *Applied Energy*, 163, pp. 93–104. doi: 10.1016/j.apenergy.2015.10.140.
- Kötz, R. and Carlen, M. (2000) 'Principles and applications of electrochemical capacitors', *Electrochim. Acta*, 45(15–16), pp. 2483–2498. doi: DOI: 10.1016/S0013-4686(00)00354-6.
- Kusakana, K. (2015) 'Feasibility analysis of river off-grid hydrokinetic systems with pumped hydro storage in rural applications', *Energy Conversion and Management*. Elsevier Ltd, 96, pp. 352–362. doi: 10.1016/j.enconman.2015.02.089.
- Kyriakopoulos, G. L. and Arabatzis, G. (2016) 'Electrical energy storage systems in electricity generation: Energy policies, innovative technologies, and regulatory regimes', *Renewable and Sustainable Energy Reviews*. Elsevier, 56, pp. 1044–1067. doi: 10.1016/j.rser.2015.12.046.
- Lambert, J.G., Hall, C.A.S., Balogh, S., Gupta, A. & Arnold, M. (2014) 'Energy , EROI and quality of life', *Energy Policy*. Elsevier, 64, pp. 153–167. doi: 10.1016/j.enpol.2013.07.001.
- Lantero, A. (2014) *How Microgrids Work*, *U.S Department of Energy*. Washington, DC. Available at: http://energy.gov/articles/how-microgrids-work (Accessed: 2 October 2017).
- Lazard (2016) 'Lazard's levelised cost of storage v2.0', *Climate Policy*, 6(6), pp. 600–606. doi: 10.1080/14693062.2006.9685626.
- Li, G. (2016) 'Sensible heat thermal storage energy and exergy performance evaluations', *Renewable and Sustainable Energy Reviews*. Elsevier, 53, pp. 897–923. doi: 10.1016/j.rser.2015.09.006.
- Li, J., Chen, Y. and Liu, Y. (2011) 'Research on a stand-alone photovoltaic system with a supercapacitor as the energy storage device', *Energy Procedia*, 16(PART C), pp. 1693–1700. doi: 10.1016/j.egypro.2012.01.262.
- López González, E., Isorna Llerena, F., Silva Pérez, M., Rosa Iglesias, F. & Guerra Macho, J. (2015) 'Energy evaluation of a solar hydrogen storage facility: Comparison with other electrical energy storage technologies', *International Journal of Hydrogen Energy*, 40(15), pp. 5518–5525. doi: 10.1016/j.ijhydene.2015.01.181.
- Ma, T., Yang, H. and Lu, L. (2014) 'Feasibility study and economic analysis of

pumped hydro storage and battery storage for a renewable energy powered island', *Energy Conversion and Management*. Elsevier Ltd, 79, pp. 387–397. doi: 10.1016/j.enconman.2013.12.047.

- Macknick, J., Newmark, R., Heath, G. & Hallett, K.C. (2012) 'Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature', *Environmental Research Letters*, 7(4), p. 045802. doi: 10.1088/1748-9326/7/4/045802.
- Madlener, R. and Specht, J. M. (2013) 'An Exploratory Economic Analysis of Underground Pumped-Storage Hydro Power Plants in Abandoned Coal Mines Reinhard Madlener and Jan Martin Specht February 2013 Institute for Future Energy Consumer Needs and Behavior (FCN)', (2). Available at: https://www.rwth-aachen.de/global/show_document.asp?id=aaaaaaaaaagvvyq.
- Mahlia, T.M.I., Saktisahdan, T.J., Jannifar, A., Hasan, M.H. & Matseelar, H.S.C. (2014) 'A review of available methods and development on energy storage; Technology update', *Renewable and Sustainable Energy Reviews*. Elsevier, 33, pp. 532–545. doi: 10.1016/j.rser.2014.01.068.
- Matek, B. and Gawell, K. (2015) 'The Benefits of Baseload Renewables: A Misunderstood Energy Technology', *The Electricity Journal*. Elsevier Inc., 28(2), pp. 101–112. doi: 10.1016/j.tej.2015.02.001.
- McMullen, P. (2016) *Using Molten Salts as a Heat Transfer Fluid and Thermal-Storage Medium*, *Process Heating*. Available at: http://www.process-heating.com/articles/91918-using-molten-salts-as-a-heat-transfer-fluid-and-thermal-storage-medium (Accessed: 12 July 2017).
- Medve, D. and Kolcun, M. (2011) 'Importance of Batteries for Photovoltaic Systems', (september), pp. 40–44.
- Medveď, D., Kvakovský, M. and Sklenárová, V. (2010) 'Latent Heat Storage Systems', *Intensive Programme "Renewable Energy Sources"*, i(May). Available at: http://home.zcu.cz/~tesarova/IP/Proceedings/Proc_2010/Files/001 IP2010_Medved.pdf.
- MIT (2012) *How does a battery work?* Available at: http://engineering.mit.edu/ask/how-does-battery-work (Accessed: 22 June 2016).
- Moran, B. (2014) 'Distributed Generation Operation : Grid-connected vs. Islanded'.
- Nandi, B. R., Bandyopadhyay, S. and Banerjee, R. (2012) 'Analysis of high

temperature thermal energy storage for solar power plant', *IEEE - ICSET, Nepal*, 5, pp. 438–444.

- Nordell, B. (2000) 'Large-scale thermal energy storage', *Proceedings of Winter Cities*, (February), pp. 1–10. Available at: https://pure.ltu.se/portal/files/1172884/Large-scale_TES__WC2000.pdf.
- Nordell, B., Grein, M. and Kharseh, M. (2007) 'Large-scale Utilisation of Renewable Energy Requires Energy Storage', *Int. Conf. for Renewable Energies and Sustainable Development (ICRESD_07)*, pp. 21–24. Available at: http://large.stanford.edu/courses/2013/ph240/lim1/docs/grein.pdf.
- Okazaki, T., Shirai, Y. and Nakamura, T. (2015) 'Concept study of wind power utilizing direct thermal energy conversion and thermal energy storage', *Renewable Energy*. Elsevier Ltd, 83, pp. 332–338. doi: 10.1016/j.renene.2015.04.027.
- Olsen, J., Paasch, K., Lassen, B. & Veje, C.T. (2015) 'A new principle for underground pumped hydroelectric storage', *Journal of Energy Storage*. Elsevier Inc., 2, pp. 54–63. doi: 10.1016/j.est.2015.06.003.
- Padmaraju, S. A. V., Viginesh, M. and Nallusamy, N. (2008) 'Comparative study of sensible and latent heat storage systems integrated with solar water heating unit', *Renewable Energy & Power Quality Journal*, (6), pp. 1–6.
- Peerapong, P. and Limmeechokchai, B. (2017) 'Optimal electricity development by increasing solar resources in diesel-based micro grid of island society in Thailand', *Energy Reports*. Elsevier Ltd, 3, pp. 1–13. doi: 10.1016/j.egyr.2016.11.001.
- Pelay, U., Luo, L., Fan, Y., Stitou, D. & Rood, M. (2017) 'Thermal energy storage systems for concentrated solar power plants', *Renewable and Sustainable Energy Reviews*. Elsevier Ltd, 79(March 2016), pp. 82–100. doi: 10.1016/j.rser.2017.03.139.
- Pfleger, N., Bauer, T., Martin, C., Eck, M. & Wörner, A. (2015) 'Thermal energy storage - overview and specific insight into nitrate salts for sensible and latent heat storage', *Beilstein Journal of Nanotechnology*, 6(1), pp. 1487–1497. doi: 10.3762/bjnano.6.154.
- Pickard, W. F. (2012) 'The history, present state, and future prospects of underground pumped hydro for massive energy storage', *Proceedings of the IEEE*, 100(2), pp. 473–483. doi: 10.1109/JPROC.2011.2126030.
- Poonpun, P. and Jewell, W. (2008) 'Analysis of the cost per kWh to store electricity', *2008 IEEE Power and Energy Society General Meeting - Conversion and Delivery of*

Electrical Energy in the 21st Century, 23(2), pp. 1–1. doi: 10.1109/PES.2008.4596555.

- Posada, J.O.G., Rennie, A.J.R., Villar, S.P., Martins, V.L., Marinaccio, J., Barnes, A., Glover, C.F., Worsley, D.A. & Hall, P.J. (2016) ‘Aqueous batteries as grid scale energy storage solutions’, *Renewable and Sustainable Energy Reviews*. doi: 10.1016/j.rser.2016.02.024.
- Pradhan, A., Ali, S. M. and Behera, P. (2012) ‘Utilisation of Battery Bank in case of Solar PV System and Classification of Various Storage Batteries’, 2(12), pp. 1–5.
- Rakiza, C. M. (2012) *Investment opportunities in renewable energy Burundi Investment opportunities in renewable energy Burundi*. Available at: http://www.bi.undp.org/content/dam/burundi/docs/publications/Investment opportunities in renewable energy Burundi.pdf (Accessed: 2 October 2017).
- Ramli, M. A. M., Hiendro, A. and Twaha, S. (2015) ‘Economic analysis of PV/diesel hybrid system with flywheel energy storage’, *Renewable Energy*. Elsevier Ltd, 78, pp. 398–405. doi: 10.1016/j.renene.2015.01.026.
- Ramos, H. M., Amaral, M. P. and Covas, D. I. C. (2014) ‘Pumped-Storage Solution towards Energy Efficiency and Sustainability : Portugal Contribution and Real Case Studies’, (September), pp. 1099–1111.
- Rault, C., Arouri, M.E.H., Youssef, A. Ben & M’Henni, H. (2014) ‘Energy use and economic growth in Africa: A panel Granger-causality investigation’, *Economics Bulletin*, 34(2), pp. 1247–1258.
- Ryocroft, M. (2016) *The development of renewable energy based mini-, micro- and nano-grids*, *EE Publishers*. Available at: http://www.ee.co.za/article/development-renewable-energy-based-mini-micro-nano-grids.html (Accessed: 2 October 2017).
- Sabihuddin, S., Kiprakis, A. E. and Mueller, M. (2015) ‘A numerical and graphical review of energy storage technologies’, *Energies*, 8(1), pp. 172–216. doi: 10.3390/en8010172.
- Segurado, R., Madeira, J.F.A., Costa, M., Duić, N. & Carvalho, M.G. (2016) ‘Optimization of a wind powered desalination and pumped hydro storage system’, *Applied Energy*, 177, pp. 487–499. doi: 10.1016/j.apenergy.2016.05.125.
- Seitz, M., Johnson, M. and Hübner, S. (2017) ‘Economic impact of latent heat thermal energy storage systems within direct steam generating solar thermal power plants with parabolic troughs’, *Energy Conversion and Management*. Elsevier Ltd, 143, pp. 286–

294. doi: 10.1016/j.enconman.2017.03.084.

- Shukla, A.K., Banerjee, A., Ravikumar, M.K. & Jalajakshi, A. (2012) ‘Electrochemical capacitors: Technical challenges and prognosis for future markets’, *Electrochimica Acta*. Elsevier Ltd, 84, pp. 165–173. doi: 10.1016/j.electacta.2012.03.059.
- Siemens (2017) *Siemens Steam Turbine SST-600*. Available at: https://www.energy.siemens.com/hq/en/fossil-power-generation/steam-turbines/sst-040.htm#content=Description (Accessed: 19 July 2017).
- Smith, A. D., Mago, P. J. and Fumo, N. (2013) ‘Benefits of thermal energy storage option combined with CHP system for different commercial building types’, *Sustainable Energy Technologies and Assessments*, 1(1), pp. 3–12. doi: 10.1016/j.seta.2012.11.001.
- Steffen, B. and Weber, C. (2016) ‘Optimal operation of pumped-hydro storage plants with continuous time-varying power prices’, *European Journal of Operational Research*. Elsevier B.V., 252(1), pp. 308–321. doi: 10.1016/j.ejor.2016.01.005.
- Stoller, M. D. and Ruoff, R. S. (2010) ‘Best practice methods for determining an electrode material{’}s performance for ultracapacitors’, *Energy Environ. Sci.*, 3(9), pp. 1294–1301. doi: 10.1039/C0EE00074D.
- Tan, X., Li, Q. and Wang, H. (2013) ‘Advances and trends of energy storage technology in Microgrid’, *International Journal of Electrical Power and Energy Systems*. Elsevier Ltd, 44(1), pp. 179–191. doi: 10.1016/j.ijepes.2012.07.015.
- Tankari, M.A., Camara, M.B., Dakyo, B. & Nichita, C. (2010) ‘Power fluctuations attenuation in wind-PV-diesel hybrid system - Ultracapacitors and batteries’, *International Review of Electrical Engineering*, 5(5), pp. 2063–2071.
- Tucker, S. and Negnevitsky, M. (2011) ‘Renewable energy micro-grid power system for isolated communities’, *Universities Power Engineering Conference (AUPEC), 2011 21st Australasian*, pp. 1–7.
- Turok, I. (2012) *Urbanisation and Development in South Africa : Economic Imperatives , Spatial Distortions and Strategic Responses*.
- US Department of Energy (2006) ‘Hydrogen Fuel Cells Fact Sheet’. Available at: http://www.hydrogen.energy.gov/pdfs/doe_fuelcell_factsheet.pdf.
- USAID (2016) *Burundi: Power Africa Fact Sheet*, *U.S. Agency for International Development*. Available at: https://www.usaid.gov/powerafrica/burundi (Accessed: 2

October 2017).

- Uyigue, E. and Archibong, E. O. (2010) 'Scaling-up renewable energy technologies in Africa', *Journal of Engineering and Technology Research Vol.*, 2(8), pp. 130–138.
- Wei, H.W.H., Xin, W.X.W., Jiahuan, G.J.G., Jianhua, Z.J.Z. & Jingyan, Y.J.Y. (2009) 'Discussion on application of super capacitor energy storage system in microgrid', *International Conference on Sustainable Power Generation and Supply*, pp. 1–4. doi: 10.1109/SUPERGEN.2009.5348079.
- Whitlock, R. (2015) *7 Benefits of Microgrids*, *Interesting Engineering*. Available at: https://interestingengineering.com/7-benefits-of-microgrids (Accessed: 13 April 2018).
- Whittingham, M. S. (2012) 'History, Evolution, and Future Status of Energy Storage', *Proc. IEEE*, 100(Special Centennial Issue), pp. 1518–1534. doi: 10.1109/JPROC.2012.2190170.
- Winkler, H., Simões, A.F., Rovere, E.L. la, Alam, M., Rahman, A. & Mwakasonda, S. (2011) 'Access and Affordability of Electricity in Developing Countries', *World Development*, 39(6), pp. 1037–1050. doi: 10.1016/j.worlddev.2010.02.021.
- World Bank (2016) *Burundi Data*. Available at: https://data.worldbank.org/country/burundi (Accessed: 13 April 2018).
- Xu, Z. and Chowdhury, S. (2013) 'A Review of Rural Electrification through Micro-grid Approach : South African context', *48th International Universities' Power Engineering Conference (UPEC)*, pp. 1–6.
- Yang, C.-J. (2016) *Pumped Hydroelectric Storage*. Edited by T. M. Letcher. North Caolina: Elsevier. doi: 10.1016/B978-0-12-803440-8.00002-6.
- Yassine, M. and Fabris, D. (2017) 'Performance of Commercially'. doi: 10.3390/en10091340.
- Zactruba, J. and Scudder, R. (2010) *Compare the Efficiency of Different Power Plants*, *Bright Hub Engineering*. Available at: http://www.brighthubengineering.com/power-plants/72369-compare-the-efficiency-of-different-power-plants/ (Accessed: 13 July 2017).
- Zahrani, A. Al, Bindayel, A. and Rished, A. Al (2016) 'Comparative Analysis of Different CSP Plant Configurations in Saudi Arabia', in Perdichizz, A., Franchini, G., and Ravelli, S. (eds). Riyadh: IEEE Conference Publications, pp. 1–7. doi: 10.1109/SASG.2016.7849679.

- Zhang, L. and Xiang, J. (2014) 'The performance of a grid-tied microgrid with hydrogen storage and a hydrogen fuel cell stack', *Energy Conversion and Management*. Elsevier Ltd, 87, pp. 421–427. doi: 10.1016/j.enconman.2014.07.045.
- Zhao, H., Wu, Q., Hu, S., Xu, H. & Rasmussen, C.N. (2015) 'Review of energy storage system for wind power integration support', *Applied Energy*. Elsevier Ltd, 137, pp. 545–553. doi: 10.1016/j.apenergy.2014.04.103.