Cape Peninsula University of Technology

Design and model development of a baseload power plant in 100% renewable energy system

by

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DECLARATION

I, Niksha Reddy, declare that the contents of this thesis represent my own unaided work and that the 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.

N. Reddy — 9/11/2023

Signed — **Date**

ABSTRACT

Kendal Power Station is one of the baseload power stations using coal-fired power plants for electricity supply to the Mpumalanga province in South Africa which is managed by Eskom. However, the power station has become the epicenter of air pollution in this region due to malfunctioning emission infrastructure at the facility. This forced the South African government to take legal action against Eskom because the power station was found to violate the emission standards set out by the Department of Forestry, fisheries and the Environment, particularly emissions such as sulphur dioxide, nitrogen oxide, particulate matter particles and carbon dioxide. These emissions negatively affect the health of citizens in Mpumalanga province and nearby communities, leading to chronic respiratory illnesses, stroke, heart attacks, birth defects and premature death. To eliminate these emissions, this research therefore designed and modeled the development of a baseload power station using 100% renewable energy resources. The renewable energy resources comprise of hybrid model of solar PV panels, wind turbines and a pumped hydro storage system.

Thus, a 4116MW renewable sources baseload power plant was designed for Mpumalanga province. A model was developed and simulated to determine the feasibility of the system. This capacity is equivalent to the nameplate generation capacity of the Kendal power station. The methodology involved included identifying a location close to the Kendal power station according to a certain criterion that is specific to the construction of a solar PV, wind turbine, and pumped hydro storage system. The Loskop dam was selected as the lower reservoir for the pumped hydro storage system. The area around the Loskop dam was the selected location for the installation of the wind turbine and solar PV system. After the design of the system, the HOMER Pro software was used for simulation, this allowed the model to be simulated using multiple parameters to decide on a system that would meet the objectives of this research.

The most optimal system that met the objectives of the research consists of a combination of components such as 68 Enercon E-126 wind turbines, a capacity of 24181500kW LONGi Solar LR6-72P panels, a converter capacity of 4220000kW and a three-string battery equivalent to the pumped hydro storage system with the capacity of 98 784 000 Ah. This system was able to meet the load capacity with the lowest LCOE and zero unmet electrical loads, proving the reliability of the system. The NPC of the system was R571 000 000 000 and the LCOE was R0.889 per kWh, which is lower than the current LCOE in South Africa.

The generated emissions from the system were determined to be 0 kg/year which will positively impact the health of citizens. This research can be applied in the design and development of hybrid renewable energy plants in South Africa. It can also be used by decision-makers to determine the feasibility of hybrid renewable energy systems.

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ACRONYMS AND ABBREVIATIONS

HRES	Hybrid Renewable energy systems
GHG	Greenhouse gas
PV	Photovoltaic
PSH	Pumped Hydro Storage
CO2	Carbon dioxide
PM	Particulate Matter
IRENA	International Renewable Energy Agency
HOMER	Hybrid Optimization Model for Electric Renewables
LCOE	Levelized Cost of Electricity
NPC	Net Present Cost
MW	Megawatt
kW	Kilowatt
SDG	Sustainable Development Goals
HV	High Voltage
LV	Low Voltage
MV	Medium Voltage
HAWT	Horizontal Axis Wind Turbine
VAWT	Vertical Axis Wind Turbine
GHI	Global Horizontal Irradiance
NASA	National Aeronautics and Space Administration
POWER	Prediction of Worldwide Energy Resources

CHAPTER ONE: INTRODUCTION

1.1. Introduction

This research focuses on the design and model of the development of a hybrid renewable energy system that will be used to replace the baseload generation capacity of the Kendal power station.

Centre for Environmental Rights (2020), The Kendal power station, located in Mpumalanga province, is a coal-fired facility. It was discovered that twelve of the fifteen operational power stations are also situated in Mpumalanga. Centre for Environmental Rights (2020), adults and children have lung and cardiovascular-related health issues. The Kendal power station failed to operate within the specified limits, endangering the lives of citizens.

The design of the HRES focuses on reducing the emissions generated by the Kendal power station. After an assessment of the geographical area in Mpumalanga, an area that is feasible for theinstallation of solar PV panels, wind turbines and a pumped hydro storage system will be used as the location for the HRES. The HOMER Pro software was used to simulate and analyze the economic, technical and environmental aspects of the HRES. The focus will be on the stability and reliability of the HRES to match the level of stability offered by a coal-fired power station. This was achieved by ensuring that the intermittency of the renewable energy sources was addressed and that there was no unmet generation capacity.

1.2. Problem Statement

Electricity is a necessity for survival. Access to reliable electricity contributes to the efficiency of the economy by allowing multinational companies and small business enterprises to operate. This creates employment for citizens offering an income and contributes to the economy of a country, giving investors and stakeholders the confidence to invest in a country. Electricity allows educational institutions to operate, developing citizens and expanding their knowledge.

In South Africa, electricity is predominantly generated by coal-fired power stations which are situated in the Highveld area in the Mpumalanga province. Dr. H. Andrew Gray (2019) highlights that the area has the worst air quality index in the country, primarily due to the air pollution caused by the power stations located in the area affecting the health of many citizens who reside in the vicinity of these stations.

Wernecke, Langerman, Garland and Feigh (2022) supported the decision of the high court to order the Department of Forest, Fisheries and the Environment to address the high amounts of air pollution in the Highveld area. It was suggested that plants should be decommissioned until they are maintained in a manner that will not contribute to increased air pollution in the area as a short-term solution.

1.3. Background of the Problem

For use in the thermal process, coal is pulverized and fed into a boiler for combustion. The heat produced from combustion is transferred to water flowing inside the pipes of the boiler to produce steam. The steam produced rotates a turbine connected to a generator producing electricity.Electricity is then transmitted and distributed at different voltage levels to industrial, residential and commercial regions.

However, as much as coal-fired power stations provide electricity, they also emit several harmful gases into the atmosphere causing a high rate of air pollution in installed provenience and South Africa at large. The combustion of coal produces sulphur dioxide, nitrogen oxide and particulate matter. Thesecontaminants are released into the atmosphere, affecting the quality of air and contributing togreenhouse gas emissions.

Center for Environmental Rights (2017) performed research on the health impacts of coal-fired power stations in South Africa, the conclusion was that the emissions from coal-fired power stations in Mpumalanga independently accounted for a total estimate of 1409 deaths in the year 2017. Center for Environmental Rights (2017) found that many citizens in the province of Mpumalanga have respiratory-related illnesses and it was medically proven that the cause of these illnesses is related to the coal-fired power stations inthe area.

Ramagoma, Mbavhalelo Justice (2018) focused on interviewing residents in the vicinity. Most of the residents experience high amounts of coal ash in their homes. This coal ash travels through the air thatthe residents use for breathing. The majority of children and adults in the area have respiratory-related illnesses and rely on a respiratory pump or oxygen tanks in the worst-case scenarios.

The last air emissions report for the Kendal power stations was completed in May 2022. This report was found on the Eskom website and indicates the emissions report from April 2021 to May 2022. After analysis of the report Table 1.3.1 below indicates the quantity of air pollutants emitted by the Kendal power station created by Eskom (2022).

Table 1.3.1: Indication of the amount of air pollutants that was found in the May 2022 air emissions report compiled by Eskom. [25]

Unit	PM (tons)	SO^2 (tons)	NO (tons)
April 2021	300.5	8605	3482
May 2021	395.28	8001	3402
June 2021	1169.19	9673	4124
July 2021	706.47	10388	4458
August 2021	1176.57	11656	4931
September 2021	835.17	9823	4095
October 2021	1219.22	7966	3334
November 2021	581.39	8233	3210
December 2021	365.05	8763	3486
January 2022	540.03	10707	4095
February 2022	842.69	11157	4421
March 2022	584.9	11425	4710

The report indicated that two units at the Kendal power station did not undergo proper maintenance to ensure that emissions could be reduced. All of the units at the power station violated the minimum acceptable emission standards as set out by the Department of Environmental Affairs. The minimum acceptable emission standards published in terms of section 21 of the National Environmental Management: Air Quality Act for coal-fired power stations are presented in Table 1.3.2. The time frame for the values below is daily.

Table 1.3.2: Indication of the MES set out by the National Environmental Management: Air Quality Act for coal-fired power stations. This section was found in the Eskom Air Quality Improvement Plan 2020. [25]

Gas	Amount (mg/NM^3)	Amount (tons)
Particulate Matter (PM)	75	0,000075
Sulphur dioxide (SO_2)	3500	0,0035
Oxides of Nitrogen (NO_x)	1100	0,0011

These findings indicate a direct relation between the deteriorating health of the citizens in nearby communities and the emissions from the Kendal Power Station.

1.4. Research Questions

- How will a hybrid renewable energy system that consists of a solar PV, wind turbine and hydro pumped storage power plant contribute to the stable and reliable supply of the baseload energy required?
- What can be done to reduce the cost of a hybrid renewable energy system to attract focus as these types of electricity generation are always assumed to be more expensive?
- How will an HRES affect pollution and the health of the community?

1.5. Aim and Objectives

The air pollution caused by coal-fired power stations has negatively affected the health of citizens in the surrounding communities.

This research aims to design and model a hybrid renewable energy system, equivalentto the generation capacity of the Kendal power station, to minimize or eliminate the emissions generated by the power station. A hybrid renewable energy system was chosen to combat the air pollution caused by coal-fired power stations. Since South Africa has a high solar and wind potential, such renewable energy systems will diversify the energy mix and decrease the amount of pollution created by coal-fired power stations by increasing reliance on renewable energy systems.

The objective of this research is as follows:

1.5.1. Identify the components that will be used to generate electricity from renewable resources. The components selected for this research are wind turbines, solar PV and pumped hydro storage systems.

1.5.2. Identify an area close to the Kendal power station that is a suitable location for the hybrid renewable energy system. This will be completed by assessing the area on Google Earth according to the required criteria.

1.5.3. Determine the size and quantity of the components required for the HRES.

1.5.4. Use simulation software to determine the viability of the HRES.

1.5.5. Analyze the HRES to ensure that it can generate a negligible amount or zero emissions and provide cost-effective electricity to the end user.

1.6. Research Design and Methodology

This research analyzed the data and design methods to provide a solution to a practical problem.

A literature review was completed to assess redundancy in the design proposed for the research.

The location of the hybrid renewable energy system was determined. This was selected depending on the proximity to the Kendal power station and the potential of constructing a hydro-pumped storage system. The availability of renewable resources such as solar and wind potential was assessed. The solar and potential was determined by evaluating the solar irradiance and average wind speed of the area respectively. The potential of the pumped hydro storage system was determined by assessing the elevation from the selected dams to the proposed area for the upper reservoir.

The capacity of the Kendal power station was assessed and a hybrid renewable energy system, consisting of wind turbines, solar PV panels and a pumped hydro storage system was simulated using the HOMER Pro software. The financial, environmental and technical aspects of the system was assessed to determine the effectiveness of the HRES.

1.7. Delimitation

This research is limited to the Mpumalanga province in South Africa. The HRES was designed taking into consideration the baseload capacity of the Kendal power generating plant only.The economic assessment of this research was limited to the analyses of the levelized cost of electricity (LCOE) and Net present cost (NPC) of the plant. The research will not include the design and optimal sizing of pumps and turbines for the hybrid renewable energy plant.

1.8. Significance of Research

The significance of this research is to provide municipalities and power generation companies with a design that has the potential to be implemented in the real world, proving that renewable energy resources can successfully generate a large capacity of electricity. This research will most importantly indicate how power stations can transition towards a zero-emission power generation strategy consequently improving the lifestyle and health of citizenslocated close to coal-fired power stations. Lastly, this research also indicates that the implementation of renewable energy resources for energy diversification will decrease the costof electricity for the end user.

1.9. Summary

This chapter forms the basis of the research project. The research project is introduced which gives a brief explanation of the problem statement and the methodology that is used to perform the research. The problem statement is then defined and information regarding the background of how the problem statement was formulated is mentioned. Research questions that will be highlighted in the project are then stated.

The research design and methodology highlighted the hybrid renewable energy system design and the software that will be used to simulate the design. The delimitations of this research are mentioned and how this research has the potential to impact the real-life decisions of energy professionals.

CHAPTER TWO: LITERATURE REVIEW

2.1. Introduction

The literature review covers the rationality behind the implementation of renewable energy systems in South Africa. Most importantly, before the implementation of HRES, the site should be able to have the minimum availability of renewable resources to ensure the feasibility of the system. This has been achieved by reviewing past literature that proves the availability of renewable resources in South Africa for energy. After identifying these resources as singular components, the feasibility of creating a hybrid system with multiple renewable resources was assessed. Lastly, literature on pumped hydro storage in South Africa was identified and assessed to ensure feasibility.

2.2. Rationality Behind Renewable Energy in South Africa

Traditional methods of electricity generation using non-renewable energy sources prove to have a harmful effect on the health of the population and the environment. One of the methods to reduce these negative outcomes from coal-fired power stations is to use renewable and sustainable resources for electricity generation. It is proven that electricity can be generated using renewable energy sources such as hydro, solar, biogas and wind energy. The use of these sources for electricity generation has advanced tremendously over the years, thus increasing the efficiency and reliability of these systems.

The United Nations is an intergovernmental organization that focuses on promoting and implementing goals to benefit a country. These goals are referred to as sustainable development goals and are specific to a country's needs. The purpose of sustainable development goals is to assist in transforming the world to promote the well-being of every individual on the planet. The United Nations in South Africa (2023) has set out seventeen Sustainable Development Goals (SDGs). The only goals that will be discussed in this chapter are the ones in direct relation to this research project.

The United Nations in South Africa (2023), Sustainable Development Goal number three refers to good health and well-being. The United Nations in South Africa (2023) target 3.9 highlights that by the year 2030, the number of deaths caused by hazardous chemicals and pollution such as air, water and soil should be drastically decreased.

The United Nations in South Africa (2023), Sustainable Development Goal number thirteen refers to Climate Action. The United Nations in South Africa (2023), target 13.1 highlights improving adaptive and resilient nature towards climate-related hazards. This can be achieved by building the capacity to be productive to change the circumstances that create climate-related hazards. The United Nations in South Africa (2023), target 133.2 discusses creating climate change measures in policies,regulations, and planning. This will be a step towards acting to climate change. For example, the proposition of not constructing more coal-fired power stations and moving towards a moresustainable source for electricity generation.

The United Nations in South Africa (2023), Sustainable Development Goal number seven highlights access to clean and affordable energy. The targets set out under this goal promotes to include more renewable energy resources into South Africa's energy mix. Universal access to clean and affordable energy. Expanding infrastructure to supply clean and sustainable energy. To increase energy efficiencyand promote investment towards clean energy. All these targets are to be achieved by the year 2030.

The United Nations in South Africa (2023), Sustainable Development Goal Eleven promotes sustainable cities and communities. The United Nations in South Africa (2023), target 11.6 highlights reducing the per capita negative effects of cities on the environment by focusing on air quality and waste management.

Shikwambana, Mhangara and Mbatha (2020) investigated the trends of pollutants emitted from coal-fired power stations over 39 years between the years 1980-2019. Since coal-fired power stations are situated in the provinces of Limpopo, Mpumalanga and Gauteng in South Africa, the air quality of these areas was analyzed. It was found that the amount of SO_2, NO_x and SO_4 emitted by the coal-fired power stations had drastically increased over this period due to aging infrastructure and an increase in demand. This has led to a negative impact on the health of citizens.

Gasparotto and Martinello (2021) reviewed research relating to the impacts of coal-fired power stations on human health and the environment. The emission from coal causes respiratory and cardiovascular disease, systemic inflammation, and neurodegeneration in humans. Apart from humans, flora and fauna are negatively impacted by the emissions. The study suggested that coal-fired power stations should be used with measures to protect the environment and human health. However, according to prior research, the Kendal power station has violated the acceptable emission values for numerous years.

Udeagha and Ngepah (2023) related public-private partnership investment in South Africa to CO_2 emissions. They found that by using different comparison models from previous research, currently, PPPI in South Africa relates to a higher CO_2 emission. This is due to PPPI regarding energy being mainstreamed towards non-renewable energy investments. Suggesting that this canbe changed using policies by promoting the investment in renewable energy. Also, by implicating carbon taxes on industries that are high producers of CO_2 emissions. Concluding that by changing policies and energy planning a decrease in CO emissions is possible. Irene *et al.*, (2023) discussed that the intervention of the government in creating policies, regulations, planning and systems towards sustainable energy is important for a positive outcome.

Mugambiwa, Shingirai, Rapholo and Selelo (2023) highlighted the effectiveness of decentralized energy systems in addressing sustainable development goal 7. According to the research paper decentralized energy systems are one of the best options to achieve SDG 7 as decentralized energy systems require little to no non-renewable resources for electricity generation. Mugambiwa, Shingirai & Rapholo, Selelo (2023) found that even though the world is making progress in terms of achieving SDG 7, developing countries are still faced with challenges. These challenges include the rising cost of electricity access, lack of electricity access in small communities and villages and the maintenance of microgrids, hence, highlighting that decentralized renewable energy systems are the way forward to achieve SDG 7 in South Africa and developing countries.

Ramona Hägele, Gabriela I. Iacobuţă & James Tops (2023) discussed how countries are addressing the Just Energy transition and achieving the sustainable development goal. This research paper focuses on Germany and South Africa. This research is performed by interviews and literature reviews. It was found that both Germany and South Africa experience challenges in trying to achieve sustainable development goals despite different socioeconomic backgrounds. Germany a far more financially and politically stable country in comparison with South Africa requires more frameworks and policies regarding the achievement of sustainable development goals about clean energy. South Africa requires more stakeholder involvement and the implementation of more rigid frameworks.

Past research on the need for renewable energy in South Africa mostly relates to similar factors. These factors include citizen wellness, climate change and environmental pollution. The literature proves that even though research has been performed to prove that coal-fired power stations in South Africa have a negative impact on the health of citizens, contribute negatively to climate change and is one of the highest producers of harmful emissions in the country, very little has been done to mitigate the negative aspects surrounding coal-fired power stations in South Africa. This has also been difficult due to the massive shortage of generation capacity and the inability of the operational coal-fired power stations to meet energy demand.

2.3. Optimal Renewable Resources in South Africa

Various renewable resources can be used to harness energy. However, this depends on the location and the capacity of energy that can be generated from renewable resources. Literature was assessed to identify the potential of renewable energy generation inSouth Africa.

South Africa is bordered by the Indian and Atlantic Ocean. Various coastal areas can be used to harness energy from the ocean. The generation of electricity using tidal energyas an option in South Africa is explored by Mtukushe and Ojo (2021). They concluded that theuse of tidal energy for electricity generated increases the reliability of a power generation system using renewable energy resources.

Uhunamure & Shale (2021) performed a strength, weakness, opportunities, and threats approach to the transition from non-renewable to renewable energy in South Africa. The strengths found included the geographic position of South Africa, which made solar and wind energy a favorable renewable resource for energy. The vast flora and fauna species allowedfor the utilization of biomass energy. Since, South Africa is viewed as a politically stable country, this will attract investors. There are policies developed by the government indicating a high interest in moving towards sustainable energy generation. The establishment of renewable energy centers by educational institutions in the country. Ensuring that there are skilled individuals in the energy sector.

The weaknesses identified is that the process to obtain documentation and approval from the government for renewable projects are lengthy and time-consuming. The lack of awareness and knowledge regarding the procedures and policies for IPP and households. The high initial investment cost usually distracts individuals and the government from investments.

The opportunities that were identified relate to the ability to increase the generation capacityof the country and to effectively contribute towards climate change, directly influencing the health of citizens.

The threats that were identified relate to the access of land for the construction of these power plants. The corruption in the country makes international investors reluctant. Most of the literature reviewed for this topic identifies the same renewable resources that can be harnessed in South Africa. These resources are solar, wind, biomass, and hydro. However, they are not harnessed to their full potential, possibly due to threats and weaknesses that are detailed by Uhunamure & Shale (2021).

2.4. Hybrid Renewable Energy Systems in South Africa

Renewable resources for energy production face the disadvantage of intermittency. This has increased the reluctance of investors and minimized the efforts towards clean and sustainable energy generation. However, research has discovered that the usage of multiple renewable energy resources and an energy storage system will increase the reliability of the clean energy system and solve the problem of intermittency. Below is a literature review on hybrid renewable energy systems in South Africa.

Ghayoor, Swanson and Sibanda (2021) designed and modeled a residential-based hybrid renewable energy system for residential use in Durban, South Africa. The system consists of a wind turbine, solar PV panel and battery storage with a grid connection. The HRES designis connected to the grid, the purpose of the design is to reduce the user's dependency on thegrid and not fully replace energy consumption from the grid. After the simulation, the conclusion was that the HRES was unable to supply power to meet the load demand regularly. It wasalso found that battery storage proved to be expensive, and it was cheaper to dump excess electricity generated by the HRES compared to storing the energy.

Miriam, Abdulla and Riyadh (2018) designed, simulated, and compared the viability of three off-grid hybrid renewable energy resources for the Gwakwani village in South Africa. The three HRES that was analyzed was a solar PV with a diesel generator system, a solar PV with a batterystorage system and a solar PV system with a diesel generator and battery storage.

The three HRES was assessed according to the criteria below:

- Ability to meet energy demands.
- Cost of the system
- Number of emissions generated by the system.

The HOMER Pro software tool was used to simulate and analyze the system. It was concluded that the solar PV and diesel generator systems proved to be more cost-effective, emit the least gases and was able to meet energy demands.

Motjoadi, Kilimi and Bokoro (2022) designed and simulated a grid-tied hybrid renewable energy system for the Lebowakgomo township in Limpopo. The purpose of this design was to provide electricity during electricity disruptions in the township. A grid-tied solar PV, wind turbine and battery storage hybrid system was designed. The system was then simulated using the HOMER software. It was concluded that the HRES system was able to meet the load demand and decrease LCOE. It was suggested that a grid-tied solar PV and wind turbine system would be more economical compared to off-grid systems.

Gilbert and Longe (2020) simulated a HRES consisting of wind turbines, a diesel generator, solarPV, solar CSP and a battery storage system to electrify a rural community of the Rand West municipality. The HOMER software was used to simulate the system. The HOMER software found that the most cost-effective solution was the Solar PV, Solar CSP, and Diesel generatorand battery storage configuration for the HRES. However, this system produced the most emissions compared to other configurations and was the only system to fully accommodate the load demand.

Prior literature indicates that various research has been conducted regarding small-scale hybrid renewable energy systems in South Africa. Most of the research leads to the system's ability to reduce the LCOE while others found that the system is more feasible if it is tied to the existing national grid. Importantly, most storage devices that are considered are batteries with almost none referring to a HRES that includes a pumped hydro storage plant.
Most systems include wind and solar in the design due to their availability in South Africa.

2.5. Pumped Hydro Storage

After reading prior literature regarding hybrid renewable energy systems, it came to light that very little research was completed regarding utility-scale hydro-pumped storage. Most literature explores storage such as batteries, fuel cells and hydrogen. Hence, the literature below was foundrelating pumped hydro as a method of storage for HRES in South Africa.
Kusakana (2019) developed a HRES to reduce the electricity cost of South African farms, mostly with readily available components such as a windmill and borehole water.A Pico turbine was chosen for this design. The grid system will only be used when the demand for electricity increases to a point where the HRES is not equipped to generate enough electricity. Figure 2.5.1 is a configuration of the proposed system as proposed by Kusakana (2019).

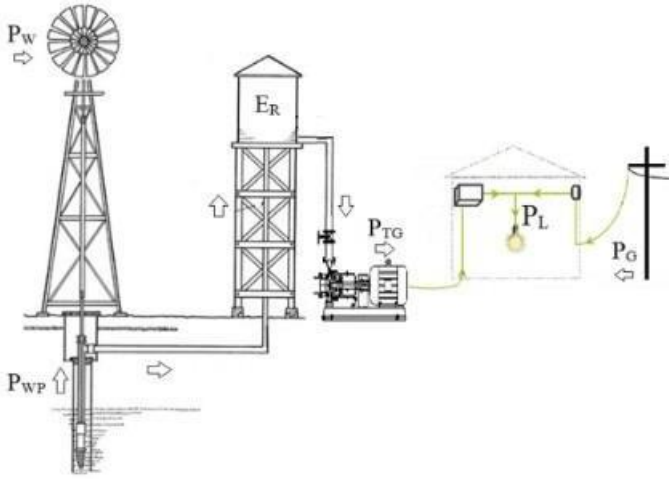

Figure 2.5.1: The configuration of the pumped hydro storage system indicating the different components. [39]

- Pw: The output power from wind speed
- Pwp: Hydraulic energy
- Er: Potential energy of water stored in the tank
- Ptg: The electrical power generated from the pico hydro system.
- Pg: Power from the grid

The HRES system was simulated on MATLAB, and it was found that the system was able to reduce the cost of electricity by 63.3%.

Shirinda, Kusakana & Koko (2019) designed and performed a techno-economic feasibility studyof an off-grid HRES. The purpose of the system was to mitigate the disruptions of grid-supplied electricity so that the agricultural industry is not negatively affected. The HRES consists of solar PV panels and pumped hydro storage. Previously, Kusakana (2019) explored the feasibility of a grid tied HRES with pumped hydro storage using borehole water. Borehole water is also used in this research project, however, the complete HRES is off grid. The HOMER software was used to perform a techno-economic analysis of the system. It was concluded that the system could meet the load demand, however, during a high radiation period, the excess energy generated cannot be successfully utilized and therefore lost. This aspect was to be addressed in future research.

Ayodele *et al.* (2021) designed a HRES and simulated the HRES with different storage devices. The storage devices assessed was pumped hydro storage, hydrogen and lithium-ion batteries. The HRES was designed for a rural clinic in the Eastern Cape which also included a solar PV and wind system. It was concluded that all the storage systems were feasible for the HRES. However, the most cost-effective system included the lithium-ion battery and the leastcost-effective system was the pumped hydro storage.

Dongen and Bekker (2020), assessed sites for potential pumped hydro storage in South Africa, arguing that there is still potential for pumped hydro storage systems in South Africa and that research should be conducted for the implementation of these systems. This research highlights the advantages of implementing such storage systems in South Africa, such as the improvement of grid flexibility and service of peak demand. It was also highlighted that future renewable energy projects in South Africa do not include storage such as pumped hydro and only battery storage is included. Three previous pumped hydro storage projects in South Africa were planned, however, the implementation of these projects was not successful. One of the projects to take note of was the Lima (Tubatse) project which included the De Hoop damin Mpumalanga which is one of the site surveys performed in this research. The Rhenosterkop dam is in the same vicinity, hence, there is great feasibility in the implementation of the pumped hydro storage system.

The literature reviewed for this section was limited to South African applications only. It can be concluded that limited research has been performed regarding utility-scale pumped hydro storage systems from the year 2018. However, the implementation of pumped hydro storage systems in South Africa is still feasible with many projects that have not been implemented.

2.6. Summary of the Literature Review

Prior literature was assessed in this chapter regarding HRES in South Africa and the urgency to implement these systems. South Africa has many reasons to implement the use of renewableenergy resources due to the high carbon emissions in the country, the adverse effect that coal-fired power stations have on the citizens of the country, and the slow movement towards

achieving the United Nations sustainable development goals by the year 2030. Most importantly, South Africa has an abundance of solar, wind, hydro and biomass energy to ensure the success of renewable energy systems in South Africa. However, the main disadvantage that comes with renewable energy resources is the intermittency. Multiple researchers have published papers proving that utilizing many renewable resources in a single system with an energy storage device, whether the system is grid-tied or off-grid addresses the intermittency of a renewable energy system. The papers reviewed for this research included renewable resources like wind and solar that are relevant to the research with different storagedevices. Many of them are lithium-ion batteries, hydrogen and fuel cells. To assess the feasibility of pumped hydro storage systems papers was reviewed and it was found that thesesystems are still viable and appropriate in the South African geographic context.

It was concluded that no previous research regarding the development of hybrid renewable energy systems in Mpumalanga had been performed.

CHAPTER THREE: DESIGN

3.1. Introduction

This chapter explains the operation of the hybrid renewable energy system. The components that are considered for the HRES are also introduced in this chapter.

3.2. Operation

The hybrid renewable energy system consists of wind turbines, solar PV panels and a pumped hydro storage system. A control station is used to monitor the load demand and the supply of electricity from the solar and wind systems. When the load demand was above a certain value and the supply of electrical energy from the wind and solar PV systems is insufficient, the pumped hydro storage system will then operate in the generating mode. This will allow for a valve to open, releasing water from the upper reservoir to the lower Loskop dam, in turn rotating a turbine connected to a generator to generate electricity. When the load demand is below a certain value and the solar PV and wind turbines generate excess electrical energy, the control station will then operate the pumped hydro storage system in pumping mode. Water was pumped from the lower Loskop Dam to the upper reservoir for future generation usage. Orenstein (2023) illustrates Figure 3.2.1 as a diagram of the hybrid renewable energy system designed for this research.

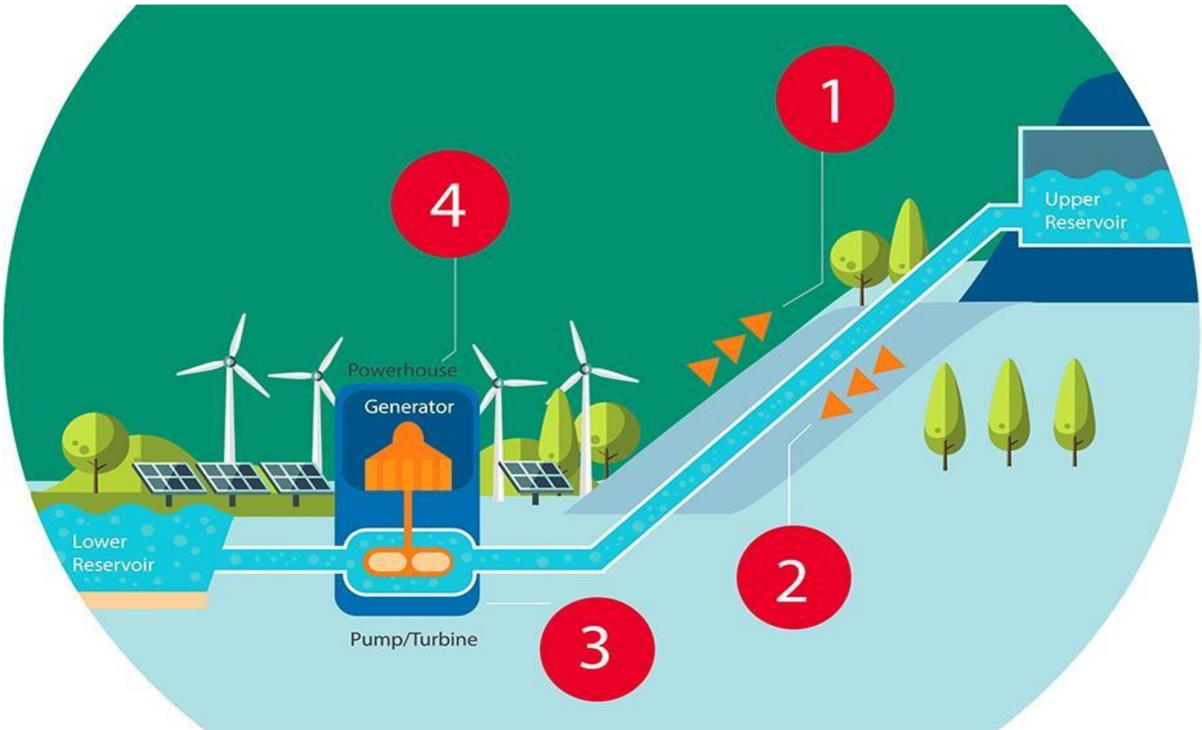

Figure 3.2.1: Diagram of the proposed hybrid renewable energy system consisting of solarPV panels, wind turbines, control station and a pumped hydro storage system. [63]

3.3. Components

Many forms of renewable energy resources are becoming more prominent in the world as a source of electricity generation. The most renowned forms of renewable energyare wind, solar, geothermal, hydro and biomass energy, each of them with a different principleof operation and requirements to operate. These forms of energy can operate as a stand-alone system and as a hybrid system that will incorporate many different types of renewable and non-renewable energy resources and systems to generate electricity. This research focused on a hybrid renewable energy system that consists of wind, solar and hydro storage for the generation of electricity. The information below describes the different components that was required for the HRES.

3.3.1. Solar PV and thermal panels

Solar panels utilize radiation or heat from the sun to generate electricity or heat fluids.

A typical model consists of a current source, the current source operates when solar radiation is sensed by the cell. A single diode was used as a blocking diode to allow for current to flow in one direction only. There was a double diode model available that made use of two diodes in parallel. The second diode acts as a bypass diode to allow for an alternate path for current flow in the event of a damaged diode. This increases the accuracy of a solar PV panel. Two resistors referred to the series resistance and shunt resistance. These resistors are present to compensate for imperfections in a cell. A series resistor is used to reduce the fill factor, which was defined by the division of the maximum output power of a cell to the actual power output. A shunt resistor was used to allow for the flow of leakage current caused by manufacturing defects of the solar PV cell. Shaik, Lingala and Veeraboina (2023), illustrate the model of a single solar cell as indicated in Figure 3.3.1.1.

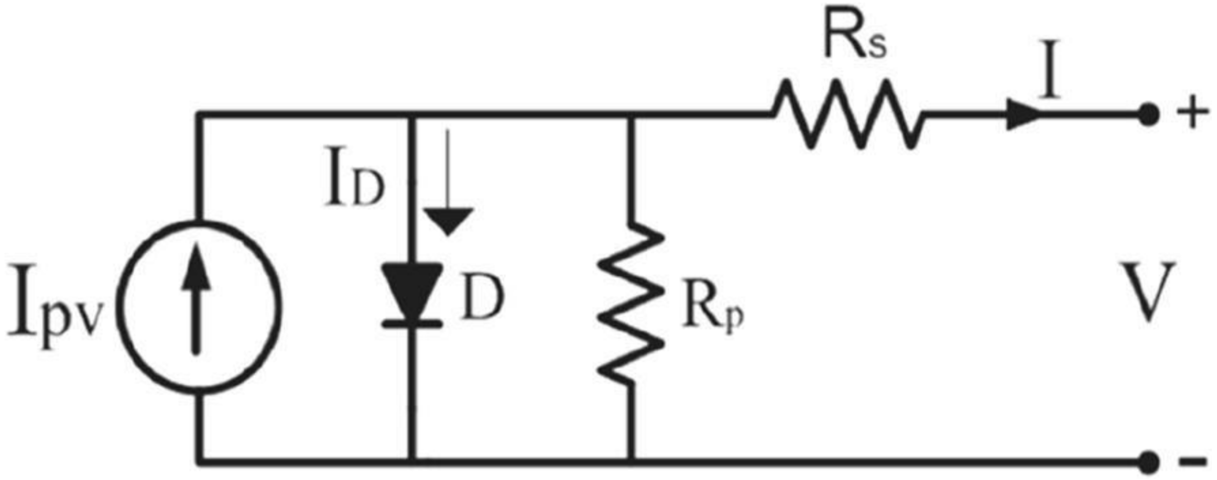

Figure 3.3.1.1: A single diode model of a solar PV cell. [47]

Two types of solar panels are available in the market. These are solar photovoltaic and solar thermal.

3.3.1.1. Solar PV Panels

Solar photovoltaic panels are manufactured using semiconductors to form solar cells to convert heat energy into DC electrical energy. Semiconductors are constructed from materials that have conductive and insulation properties. The main types of solar cells that are used in the construction of photovoltaic solar cells are monocrystalline or polycrystalline. A monocrystalline solar cell is manufactured from a single crystal of silicon, whereas a polycrystalline solar cellis manufactured from multiple fragments of silicon. Karakilic, Karafil & Nac (2022) indicate the difference in efficiency, current and voltage of a standard 100W monocrystalline and polycrystalline solar PV panel, these differences are presented in Table 3.3.1.1.1.

Table 3.3.1.1.1: Specifications of a monocrystalline and polycrystalline 100W panel.

Properties	Monocrystalline PV Panel	Polycrystalline PV Panel
Maximum panel power	100 W	100 W
Maximum power voltage	18.54 V	18.35 V
Maximum power current	5.39 A	5.45 A
Open circuit voltage	21.56 V	22.52 V
Short circuit current	6.09 A	5.78 A
Panel efficiency	16.27%	17.5%
Number of cells	36	36
Operating temperature	40 °C - +85 °C	40 °C - +85 °C

The power output from a monocrystalline and polycrystalline solar panel differs due to the properties of the materials used to construct the panels. Indicate that the figures below represent the current, voltage and power curves for a monocrystalline and polycrystalline solar PV panel atlow and high irradiance. (Takyi, Adunyah and Agyei-Agyemang, 2021)

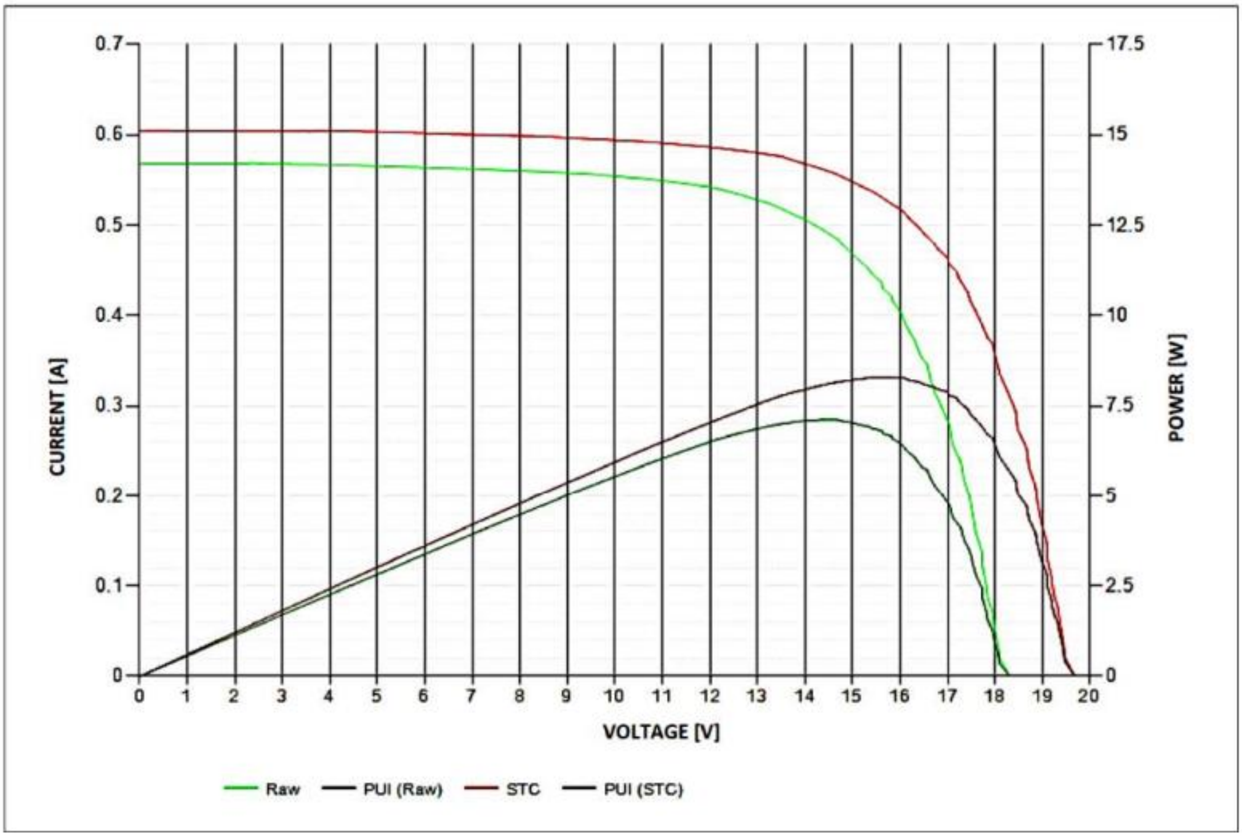

Figure 3.3.1.1.1: The current, voltage and power curve of a monocrystalline solar PV panel at low irradiance. [21]

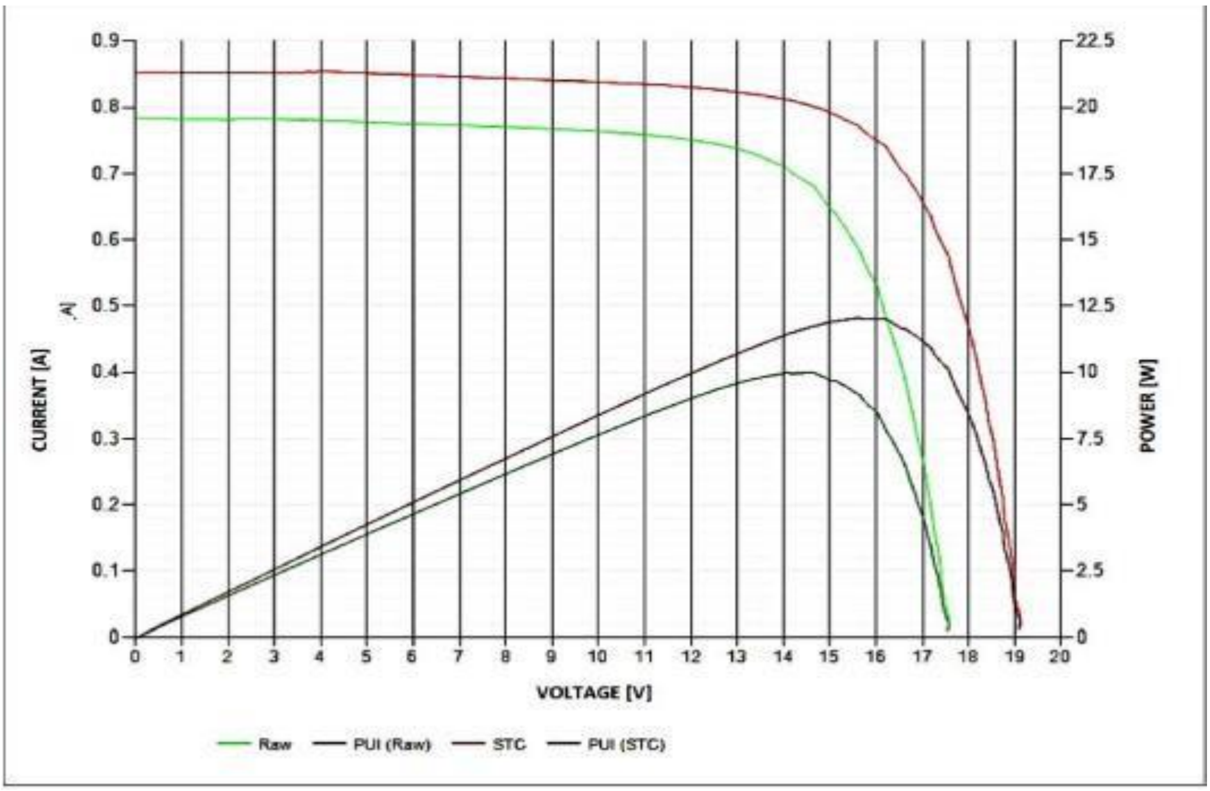

Figure 3.3.1.1.2: The current, voltage and power curve of a polycrystalline solar PV panel at low irradiance. [21]

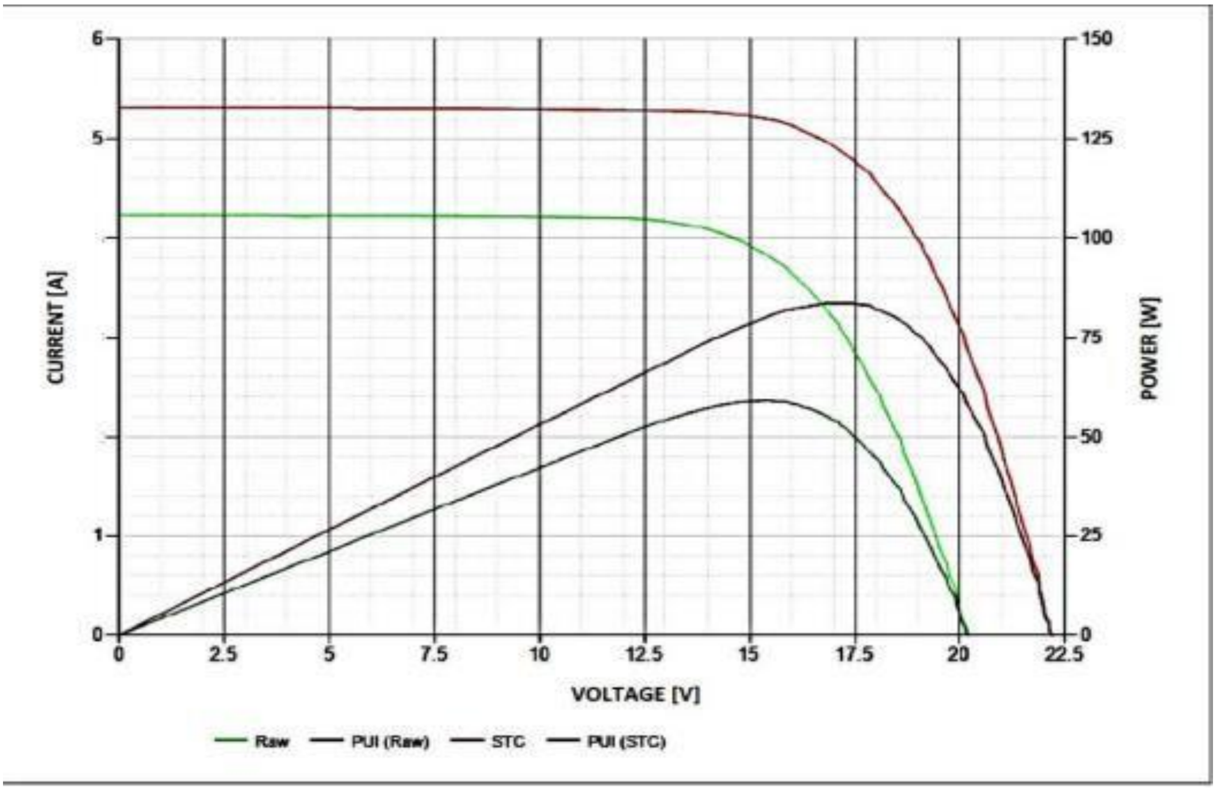

Figure 3.3.1.1.3: The current, voltage and power curve of a monocrystalline solar PV panel at high irradiance. [21]

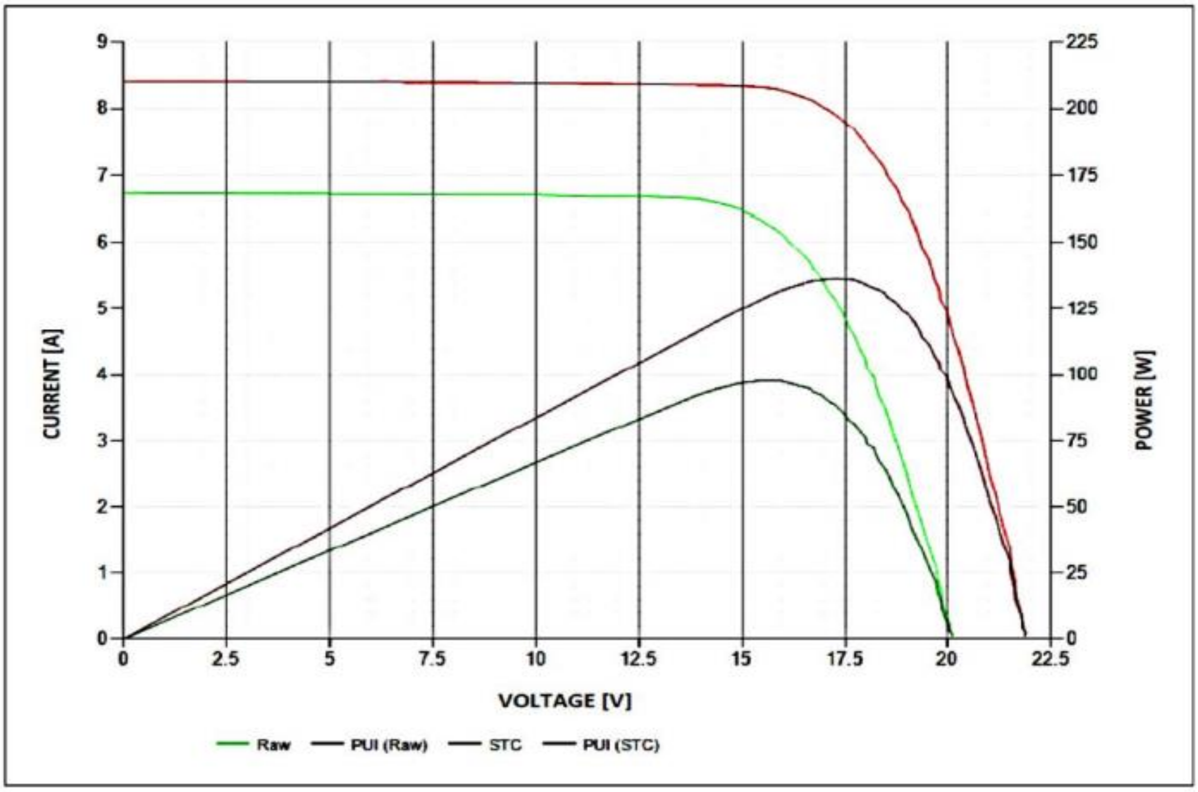

Figure 3.3.1.1.4: The current, voltage and power curve of a polycrystalline solar PV panel at high irradiance. [21]

Figures 3.3.1.1.1, 3.3.1.1.2, 3.3.1.1.3 and 3.3.1.1.3 indicate that the efficiency of a polycrystalline solar panel was higher at low and high irradiance conditions in comparison to the monocrystalline panel. The graphs indicate that under standard test conditions, as depicted by the red line, the current generated from a solar PV cell was proportional to the power output. It was evident that the polycrystalline solar PV panel was capable of achieving a higher power output compared to the monocrystalline solar PV panel under equal test conditions.

3.3.1.2. Solar thermal panels

Solar thermal panels are used for heating purposes. These panels circulate water which then transfers heat from the sun to the pipes containing the liquid on the panel. Sustainable Energy Authority of Ireland (2017) illustrated a roof-mounted solar thermal panel, figure 3.3.1.2.1 is an indication of a solar thermal panel.

Figure 3.3.1.2.1: A solar thermal panel mounted on a roof. [50]

This research project requires an electrical output, hence, solar PV panels was utilized for this research.

3.3.2.Inverter

Electricity from the national grid in South Africa ranges from 220 Vac – 230 Vac at a frequency of 50 Hz- 60Hz. The output of a solar PV panel is DC, hence inverters are required to convert the DC output to an AC output. The principle of operation of an inverter is as follows, firstly DC electricity is converted to AC electricity by using switches such as Metal Oxide Silicon Field Effect Transistors (MOSFETS) or Insulated-gate bipolar transistors (IGBT). These electronic switches DC electricity on and off creating an AC waveform. Due to the high-frequency switching, the AC waveform becomes distorted, this distortion is removed using filters. The voltage is then regulated to the required output. Figure 3.3.2.1 was presented by Jean Marie Takouleu (2021).

Figure 3.3.2.1: Inverters that are used in solar PV power plants. [27]

3.3.3.Mounting Rack

Solar PV panels can be mounted in two ways, directly on the ground or on the surface of the water on a dam or reservoir using a mounting rack. These racks are designed to sustain all types of weather and the environment. Mounting racks are constructed using two types of materials, either aluminum or steel due to their durability. Since a large hybrid plant was designedand the limited surface area of the dams in the district, the solar PV panels will be mounted onthe ground for this research. Kumar *et al.* (2020) specified the requirements for installing ground-mounting solar PV racks, these requirements are as follows:

- Preparation of a foundation for the stability of the mounting
- The installation of a crossbeam and support post for the solar panels to be mounted on.

The inverter store (2019) illustrates a solar PV ground mounting track as presented in the figure

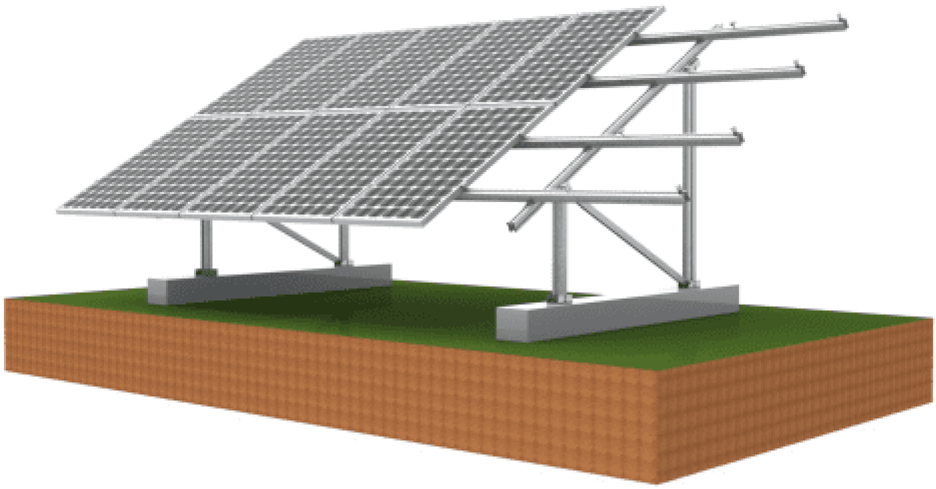

Figure 3.3.3.1. Indicates presented a ground-mounted solar PV rack with a fixed axis. [56]

3.3.4. Electrical Cables

Electrical cables was used for the connections between the solar panels, inverter and control unit.

An electrical cable consists of an electric conductor, insulation, auxiliary elements and an outer sheath.

Electrical cables can be categorized as High Voltage (HV), Medium Voltage (MV) and Low Voltage (LV). The type of cable used depends on the application, for this research project, high-voltage and medium-voltage electrical cables are advised for use. The difference in these cables lies in the materials that are used to manufacture them.

High-voltage electrical cables will be used to transmit and distribute the generated electricity to the load.

Cables that are referred to as solar cables are specially designed for the connection of solar PV panels to the DC-AC inverter. O. H. Abdalla and A. A.A. Mostafa (2019) highlighted that the cables used in a solar PV power plant should comply with the IEC Standard 60227 series for LV (below 1 kV) and IEC Standard 60502 series for HV installations. Eland Cables (2023) manufactures cables that comply with the IEC60502 standard as presented in Figure 3.3.4.1.

Figure 3.3.4.1: The N2XSEY XLPE PVC - 6/10 (12)kcable supplied by Eland cables that complies with IEC60227 and are suitable for solar PV plants. [17]

Eland cables (2023), suggest that cables such as the EVA LSZH Torsion Resistant 1.8/3kV Turbine Cable are suitable for onshore and offshore wind turbine installations.

Figure 3.3.4.2: Electrical cable that conforms to IEC 60502, 60228 for cables that can be used in wind turbine power plants. [17]

Rashmi, Shivashankar, G. S., & Poornima. (2017) suggest the use of Aluminum Conductor Composite Core cables for transmission and distribution in electrical power systems. The many advantages that are associated with these cables is that there is a reduction in power losses during transmission, a reduction in disturbances, and an increase in current carrying capacity. CTC Global Corporation (2023) manufactures Aluminum Conductor Composite Core cables, this is presented in Figure 3.3.4.3.

Figure 3.3.4.3: Electrical cables that are suggested for transmission and distribution in electrical power systems. [9]

3.3.5. Wind Turbine

Wind turbines are used to convert kinetic energy to AC electrical energy. Wind turbines have large blades that are mounted on a high tower and connected to a rotor. The rotor is connected to a generator which is housed in the nacelle. When there are high enough wind speeds, the blades rotate which consequently rotates the rotor connected to the generator, leading the generator to create AC electrical energy. The generated AC electrical energy is then fed to a transformer that increases the electrical voltage for transmission. However, each wind turbine is designed to operate at a maximum and minimum wind speed which is referred to as the cut-inand cut-out wind speed. Figure 3.3.5.1 indicates the main components of a wind turbine system. (Boshra, Ghada and Mostafa, 2016)

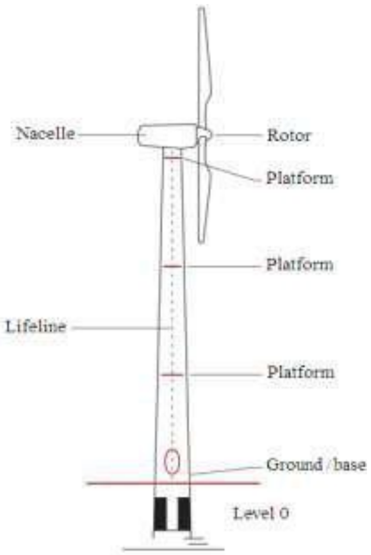

Figure 3.3.5.1: Figure of a wind turbine indicating the blades, nacelle which houses the generator, rotor hub, tower and foundation. [3]

Wind turbines can be classified into multiple categories such as horizontal axis wind turbines (HAWT), vertical axis wind turbines (VAWT), small-scale and large-scale wind turbines, onshore and offshore wind turbines and many other variations.

The category of wind turbines discussed in this chapter will focus on HAWT and VAWT. The main difference is in the axis of rotation with reference to the ground. A HAWT rotates on a horizontal axis with reference to the ground and a VAWT rotates on a vertical axis with reference to the ground.

The characteristics of a HAWT wind turbine are that it consists of a horizontal rotor shaft that is parallel to the ground. The nacelle and rotor are positioned on a tower so that the turbine can face the wind direction for optimum performance. The distinct characteristic of that the rotor blades are designed to support aerodynamic lift for rotation. The assembly is depicted in Figure 3.3.5.1.

The characteristics of a vertical wind turbine are described as a structure in which the main rotor shaft and blades are vertical and perpendicular to the ground. A vertical-axis wind turbine can be categorized into three types. These types are drag based also referredto as Savonius. Lift which is referred to as Darrieus and a combination of lift and drag is referred to as H-rotor.

The Savonius VAWT operates using the drag principle and are identified by the distinct S-shaped blades. Drag is referred to as the force that acts in the opposite direction of motion. These types of VAWTs can self-start at low wind speeds and produce low torque.These VAWTs are suitable for low wind speed applications.

The Darrieus VAWT operates on the lift principle and are identified by the distinct helical shape blades. Lift is the force created by the difference in air pressure. These types of wind turbines operate at high wind speeds, however, they produce low torque. Hence, they aresuitable for applications that require a low torque output.

The H-rotor wind turbine operates on both the lift and drag principle. The construction consists of a vertical rotor shaft with horizontal blades. When wind flows over the blades, the force of the wind rotates the turbine. The rotor shaft is connected to a generator which creates an electrical output. The H-rotor wind turbine operates with low to moderate wind speeds. These turbines are best suited for small-scale applications. Figure 3.3.5.2 indicates the difference in construction between the three types of VAWT which is adapted from Castellani *et al.* (2019).

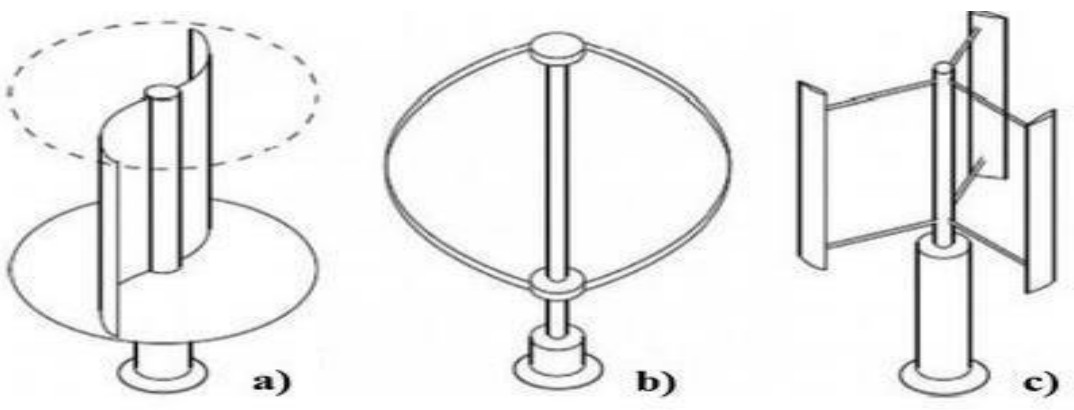

Figure 3.3.5.2: The difference in construction between the a) Savonius, b) Darrieus and c) H- rotor VAWT. [11]

3.3.6.Pumped hydro storage

Pumped hydro storage is an energy storage system. This system consisted of two reservoirs at different elevations. When there is a high electricity demand, water flows from the upper to the lower reservoir rotating a turbine connected to a generator. Excess electricity that is generated from other energy resources will pump water from the lower reservoir to the upper reservoir for storage until the demand increases, allowing sufficient water flow from the upper to the lower reservoir for electricity generation. There are two types of pumped hydro storage systems, they are closed-loop and open-loop systems. The US Department of Energy (2023) indicates the difference in componentsand construction of a pumped hydro storage system as presented in figure 3.3.6.1.

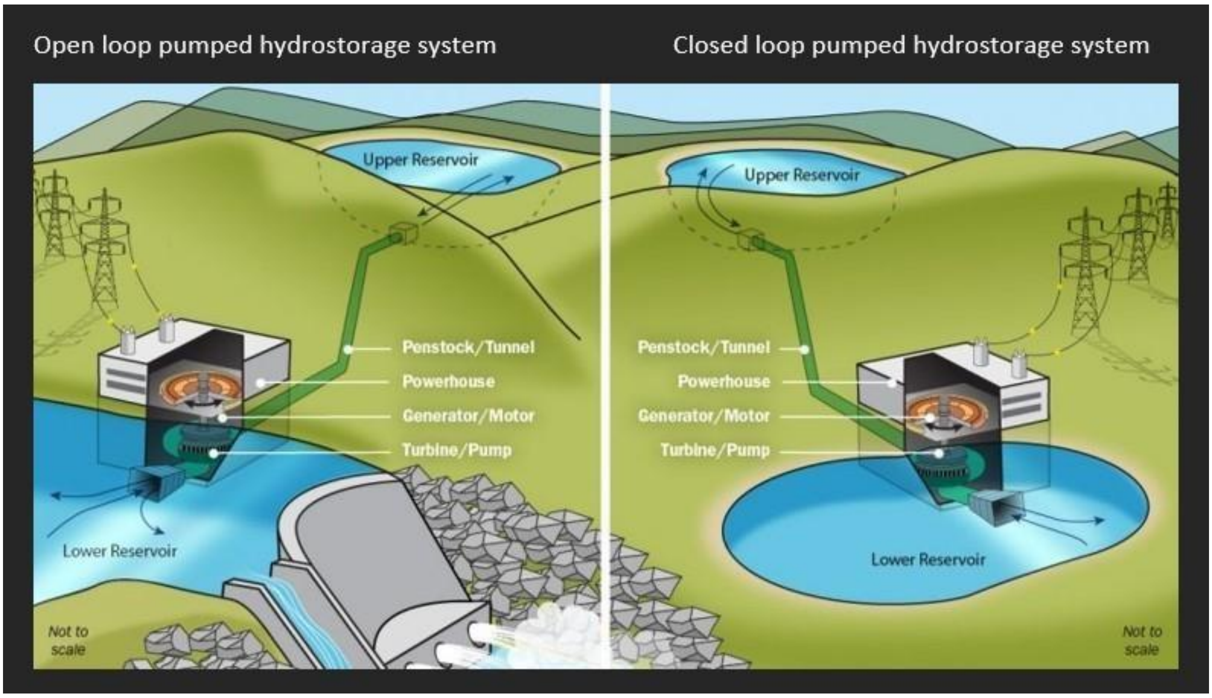

Figure 3.3.6.1: Indication of the difference in the construction between a closed and open loop pumped hydro storage system. [55]

3.3.6.1. Closed-loop pumped storage hydropower

In a closed-loop pumped storage hydropower system, the upper and lower reservoirs are both constructed according to the required water storage capacity for electrical generation. The same water is circulated between the reservoirs and water has to be manually refilled when lost by natural methods such as evaporation because these systems are not connected to any natural water sources. A closed-loop system will generally have a higher construction and operating cost.

3.3.6.2. Open loop pumped storage hydropower

In an open loop pumped storage hydropower system water from the lower reservoir is usually from a dam or river. These systems are connected to natural water resources. The construction and operation costs are generally lower than closed-loop systems. This is because only the upper reservoir requires construction according to a specific capacity. Water does not need to be manually topped off.

This research project used an open loop pumped hydro storage system to reduce costs due to the availability of dams in the selected areas.

3.3.7. Penstock and Tunnels

3.3.7.1. Penstock

A penstock is a pipe that operates at high pressure. They can operate bidirectionally and move water from the lower to the upper reservoir and vice versa. A penstock is usually used in large pumped hydro storage systems. Penstocks can be constructed underground or on thesurface of the ground. They are usually constructed from steel and concrete. A penstock is used in pumped hydro storage systems when there is a large elevation difference between the lower and upper reservoir. Water is regulated using valves and gates through the penstocks.

3.3.7.2. Tunnels

A tunnel is used to transport water from the lower to the upper reservoir and vice versa. However, tunnels can only be constructed underground unlike penstocks. Tunnels are also used in small-scale pumped hydro storage systems with a low elevation.

3.3.8. Pumps

Pumps are used to move water from the lower to the upper reservoir when there is excess electricity generated. Two types of pumps can be used in a pumped hydro storage system, axial flow or centrifugal pumps.

3.3.8.1. Axial Flow pump

An axial flow pump consists of a propeller connected to a shaft. The shaft is then connected to a motor that causes the propeller to rotate. The propeller causes the flow to move parallel to the shaft. In a pumped storage hydropower plant, an axial flow pump is used in a system where the elevation difference is low and the system operates between low to moderate pressure.

3.3.8.2. Centrifugal pump

A centrifugal pump consists of a shaft drive impeller. Liquid flows through the impeller blades and is discharged at a high pressure. Centrifugal pumps are used in pumped hydro storage systems with high elevation differences between the lower and upper reservoirs.

3.3.9. Turbines

Turbines are connected to generators. When water is released from the upper reservoir, the flow causes the turbine to rotate which directly rotates the generator creating electricity.
According to multiple articles, Francis turbines are best suited for hydroelectric applications. A Francis turbine consists of blades connected to a rotor that is connected to a shaft. The shaft is attached to the generator. When water flows from the upper to the lower reservoir via the penstock it causes the blades of the turbine to rotate. The rotation of the blades causes the shaft to rotate which then turns the shaft connected to a generator creating electricity.
The Francis turbine is best suited for applications with high heads.

Nikolaos, P.C., Marios, F. and Dimitris, K. (2023), recommend the use of variable speed pump-turbine systems for increased efficiency in pumped hydro storage systems with high heads. This allows the systems to effectively react to fluctuations in power generation and consumption.

3.3.10. Generator

A generator was used to convert mechanical energy from a turbine to electrical energy. The electrical energy produced is then stepped up and down using a transformer for transmission to be used by a load. A hydroelectric facility uses a synchronous generator. The flow of water is used to rotate a turbine. The turbine is connected to a rotor which is connected to a shaft. A rotor has electromagnets which are around the shaft. As the rotor turns the magnets pass by the stator which is fixed. A stator is a set of conductive coils.

According to Faraday's law of electromagnetism induction, an electrical current is induced inthe coils as the magnetic field of the magnets changes as they rotate.

3.3.11. Powerhouse

A powerhouse is a structure in a hydroelectric facility that is located close to a water resource. The generators and pumps are located in the powerhouse. A control room for the hydroelectric pumps is also located in the powerhouse. The powerhouse was used to monitor and control the hybrid renewable energy system by an operator.

3.3.12. Summary

This chapter highlights the components that will be used in the design of the HRES.
The ideal type of component is highlighted in each subchapter and the reason behind the selected component is expressed. The operation of each component is explained and the role that each component/equipment will play in the HRES.

CHAPTER FOUR: LOCATION SURVEY

4.1. Introduction

The Kendal power station is part of the Nkangala district in Mpumalanga. One of the objectives of this research was to reduce the air pollution caused by the Kendal power station. Hence, a location in the Nkangala district was chosen for the hybrid renewable energy system.
The locations that are used in the survey depend on the water resources available as this was vital for the pumped storage hydro plant. Using water resources as a reference point allowed for a cost reduction and will also mitigate water shortages when required by the system. Areas was marked for the proposed hybrid renewable energy system and the exact coordinates and location was determined using Google Earth. The solar PV power potential and wind power potential was determined using the global solar and wind atlas. The location was selected according to the required geographical and resource criteria.

4.1.1. Geographical and Resource criteria for the pumped hydro storage power plant

The geographical resource criteria for the construction of a pumped hydro storage system have many requirements depending on the type of construction. Since an open loop pumped hydro storage system will be used in this research project, the criteria below was considered according to Alnaqbi *et al.,* (2022) :

- The system requires easy access to water, hence, an area close to a reservoir or dam was considered.
- According to Alnaqbi *et al.* (2022), the requirement is a large slope between the upper and lower reservoirs to allow for theefficient operation of the system. A height difference of approximately 300 meters between the lower and upper reservoirs was recommended.
- There should be a large area of land for the construction and installation of the necessaryinfrastructure required for the plant.

4.1.2. Geographical and Resource criteria for the solar PV plant

The geographical and resource criteria for a solar plant was vital to the performance of the system. Hence, to support the optimal performance of the HRES the criteria below was considered for the solar PV system National Renewable Energy Laboratory (2013):

- The area was required to receive sufficient solar irradiance. According to a report by the National Renewable Energy Laboratory (2013), the minimum solar irradiance that was required was 3000Wh/m^2/day.
- There should be sufficient land space available for the installation of panels.
- The area should have a stable supply of solar radiation with low cloud coverage.

4.1.3. Geographical and resource criteria for the wind turbine plant

The geographical and resource criteria for a wind turbine system was vital to the performance of the system. Hence, to support the optimal performance of the HRES, the criteria below was considered for the wind turbine system as stipulated by the US Energy Information Administration(2023) :

- The US Energy Information Administration(2023) advises that an area should be able to provide an annual average wind speed of 5.8m/s.
- The ground area should not be obstructed and have open terrain.

4.2. Dams in the Nkangala district

The Nkangala district in Mpumalanga has three main dams. The Middelburg dam, Loskop dam and Rhenosterkop dam.

4.2.1. Middelburg dam

The Middelburg Dam is located on the Klein Olifants River. The dam was commissioned in 1978. According to Wikipedia (2023), the height of the dam is 36 meters and the length is 625 meters, the total capacity ofthe Middelburg dam is 484 350 000 m^3.

Brent Lindeque (2016) shows a full Middelburg dam after rainfall as presented in Figure 4.2.1.1.

Figure 4.2.1.1: Aerial view of the Middelburg Dam. [7]

The land area around Middelburg is near the R104 in Mpumalanga. From a visual inspection on Google Earth (2023) and the difference in elevation from the dam to the upper areas there is a limit in terms of mountainous areas near the dam. The coordinates chosen for the solar PV system was 25°47'14.53"S 29°34'56.25"E as indicated by Google Earth (2023). Using the Global Solar Atlas (2023) these coordinates had the potential PV output of 1838 GWh per year with a global tilted irradiation of 2292.2kWh/m^2 per annum. The coordinates chosen for the wind system was 25°48'15.11"S 29°35'0.53"E, Google Earth (2023) was used to select the co-ordinates. Using the Global Wind Atlas (2023) these coordinates had the potential to output a mean power density of 304 W/m^2 at a wind speed of 6.84 m/s. Figure 4.2.1.2 that was adapted from Google Earth (2023) was the proposed location of the wind and solar system and the marking of the upper and lower reservoirs for the pumped storage hydro plant

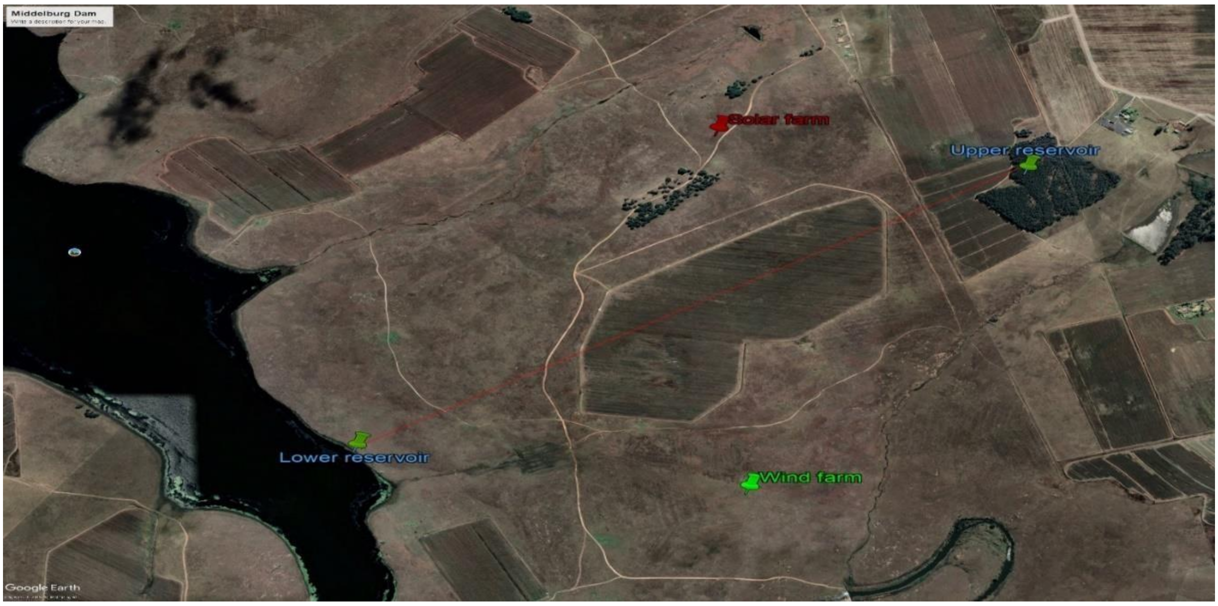

Figure 4.2.1.2: Indication of the location of the proposed HRES system near the Middelburg Dam. This figure indicates the wind and solar PV system and the upper and lower reservoirs for the pumped hydro storage system

One of the requirements for an efficient pumped hydro storage power plant was that the elevation between the upper and lower reservoir be as large as possible. Figure 4.2.1.3 is an elevation profile obtained from Google Earth (2023). This elevation profile allows for the analysis of the distance between the reservoirs and to calculate the elevation head between the upper and lower reservoirs.

Figure 4.2.1.3: Elevation profile of the Middelburg Dam

The elevation profile in Figure 4.2.3.1 indicates that the distance between the upper and lower reservoirs was 2.65km which was calculated using the tools from Google Earth (2023). The lower reservoir is at an elevation of 1512m and the upper reservoir is at an elevation of 1580m, this was selected using Google Earth (2023). Hence, the height difference between the upper and lower reservoirs is 68m which was calculated using the difference between the reservoir elevations from Google Earth (2023).

4.2.2. Loskop dam

The Loskop Dam was commissioned in 1939 and renovated in 1979. This dam is used for irrigation purposes and is classified as an arch-gravity dam. The height of the dam is 49 meters and the length is 105 meters. The Loskop dam has a runoff and runs in from the Olifantsrivier. The total capacity of the dam is 361 500 000m^3 according to Wikipedia (2022).

Figure 4.2.2.1: The Loskop Dam [32]

The Loskop Dam is close to the N11 highway and two resorts. However, the dam has a large ground surface area with high mountains nearby. This made it a highly suitable area for the hybrid renewable energy system. Figure 4.2.2.2 was adapted from Google Earth, it has markers indicating the proposed location of the HRES. (Adapted from Google Earth, 2023) The coordinates of the solar PV system was determined as 25°30'17.16"S 29°19'57.23"E. (Google Earth) This area has the potential to create a total output of 1.850 GWh photovoltaic power per year and a global tilted irradiation of 2291.9 kWh/m^2 per year. (Global Solar Atlas, 2023) The coordinates of the wind system was selected to be 25°28'26.54"S 29°21'43.43"E. (Google Earth) This coordinate has to potential mean power output of 256 W/m^2 at a wind speed of 6.2m/s. (Global Wind Atlas)

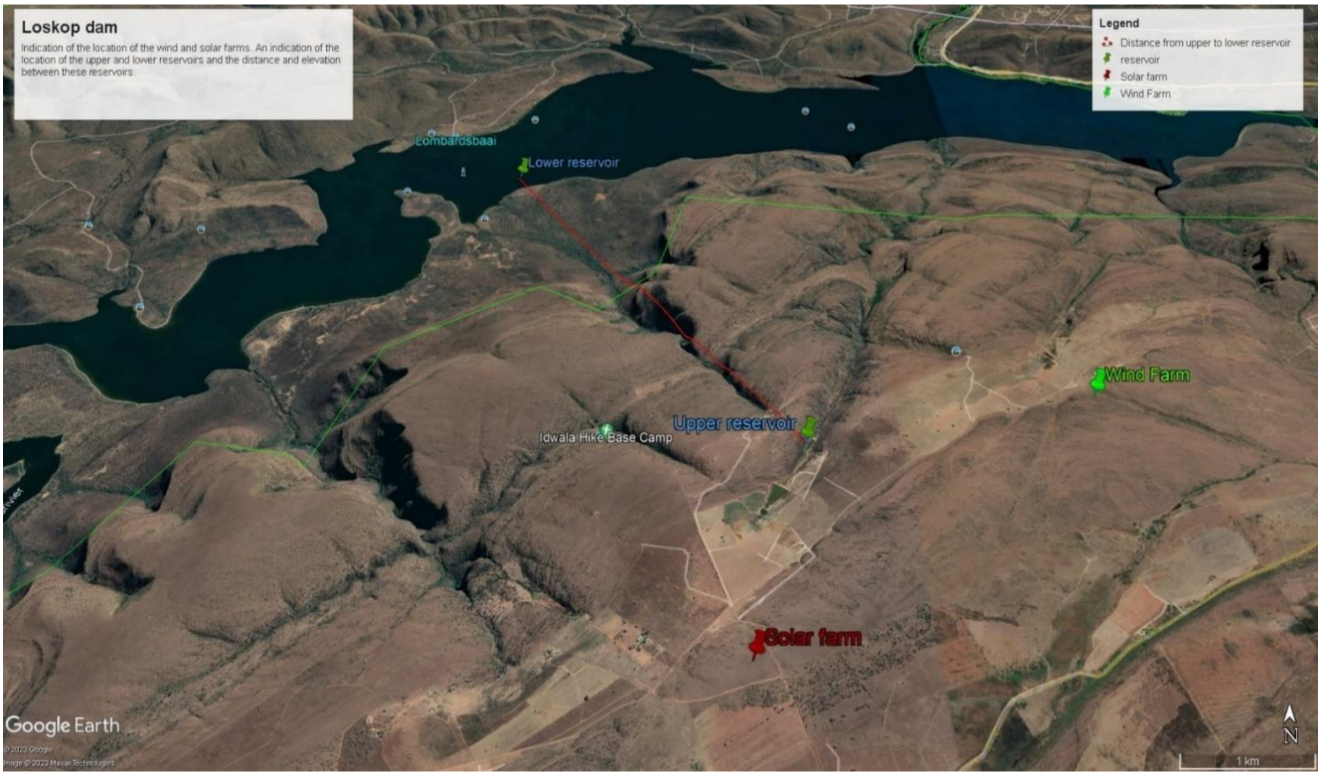

Figure 4.2.2.2: An indication of the location of the proposed HRES system near the Loskop Dam. This figure indicates the wind and solar PV system and the upper and lower reservoirs for the pumped hydro storage system.

Figure 4.2.2.3 is an elevation profile that details the distance between the upper and lower reservoirs and the elevation of these reservoirs. This information was used to determine the feasibility of the pumped hydro storage plant at the Loskop Dam. The elevation of the upper reservoir was found to be 1457m and the lower reservoir is 999m indicating a height difference of 458m. (Google Earth, 2023)

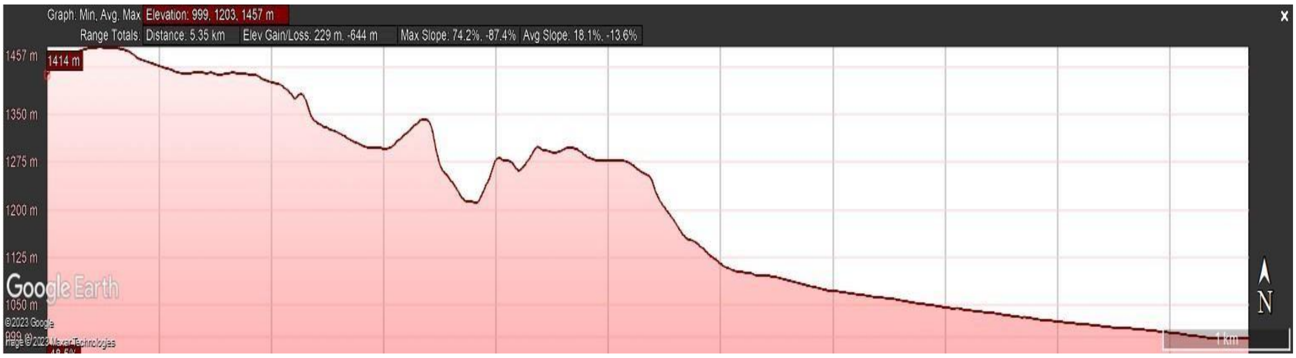

Figure 4.2.2.3: Elevation profile of the Loskop dam indicating the distance between the dam and the different elevations

4.2.3. Rhenosterkop dam

The Rhenosterkop Dam is an arch-gravity dam that was commissioned in 1984. This dam serves as a water source for industrial and domestic purposes. The height of the dam is 36 metres and the length of the dam is 515 metres. The total capacity of the dam is 206 000 000 m^3. (Wikipedia, 2023)

The Rhensterkop Dam is located close to many industrial and residential areas with limited mountains or hills nearby. Figure 4.2.3.1 indicate the proposed locations for the solar PV, and windsystem and the location of the upper and lower reservoirs for the HRES. (Adapted from GoogleEarth, 2023) The co-ordinates of the proposed solar PV system was determined to be 25° 4'29.53"S 28°50'28.22"E. (Google Earth)This area had the potential solar PV output of 1.822 GWh per and a global tilted radiation of 2303.6 kWh/m^2 per year. (Global Solar Atlas) The co-ordinates of the proposed wind system was determined to be 25° 4'19.52"S 28°52'12.58"E. (Google Earth) This area has the potential of a mean power density of 559 W/m^2 at a mean wind speed of 7.73 m/s. (Global Wind Atlas)

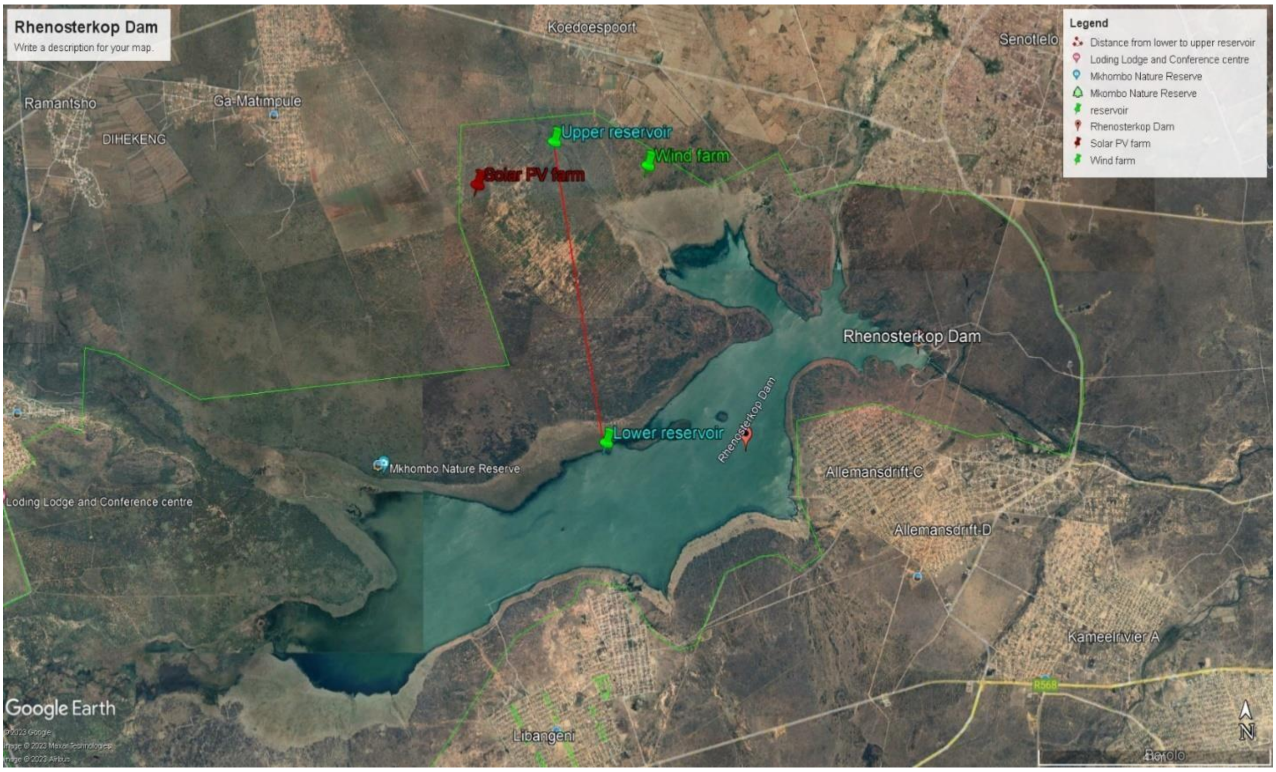

Figure 4.2.3.1: Indication of the proposed solar and wind system and the location of the upper and lower reservoirs for the pumped hydro storage power plant.

Figure 4.2.3.2 indicates the elevation profile from the lower to upper reservoir at the Rhenosterkop dam. The distance between the upper and lower reservoirs is 5.03km. The lower reservoir is at an elevation of 940 meters above sea level. The elevation of the upper reservoir is 955 meters above sea level. Hence, the head was calculated to be 15 meters between the upper and lower reservoir. (Google Earth, 2023)

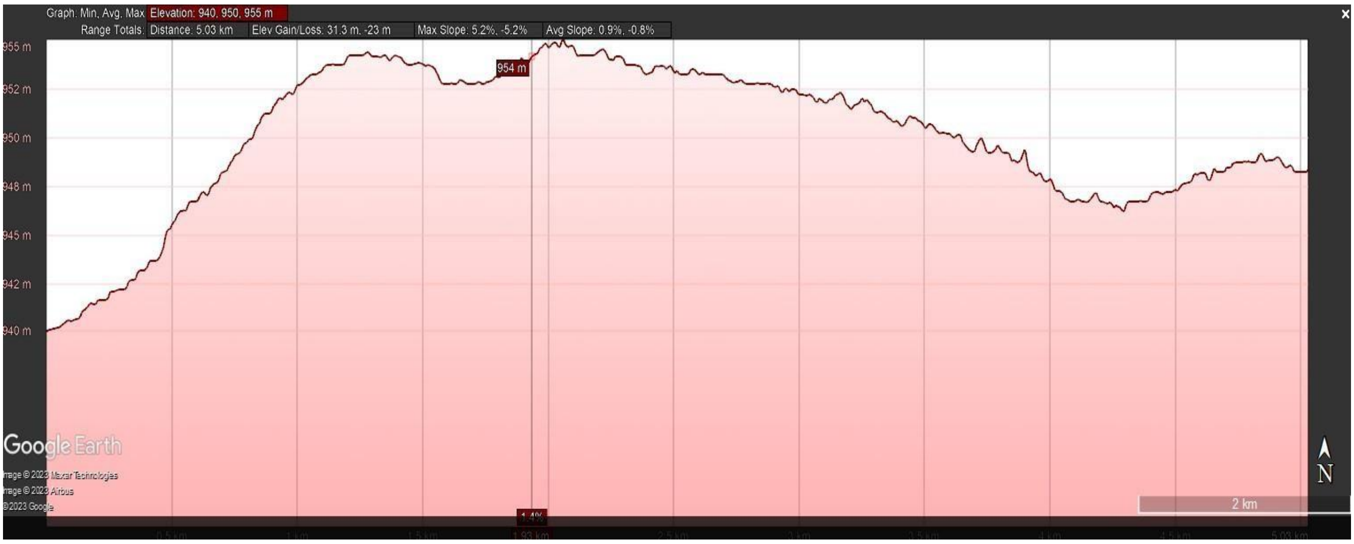

Figure 4.2.3.2: Elevation profile between the upper and lower reservoirs to indicate their distance apart and elevation above sea level

4.3. Comparison of the dam features

Table 4.3.1 is a list of specifications required to determine the most suitable area as thelocation of the hybrid renewable energy plant.

Table 4.3.1: Indicates the different parameters of each dam, the potential solar and wind power output and the proposed upper and lower reservoir details.

	Middelburg Dam	Loskop Dam	Rhenosterskop Dam
The difference in height between upper and lower reservoirs	68 m	458 m	15 m
Capacity	484 350 000 m^3	361 500 000m^3	206 000 000 m^3
Height of dam	36 m	45 m	36 m
Solar potential	1.838 GWh/year	1.850 GWh/year	1.822 GWh/year
Tilted radiation	2292.2 kWh/m^2/year	2291.9 kWh/m^2/year	2303.6 kWh/m^2/year
Mean Wind speed	6.84 m/s	6.20 m/s	7.73m/s
Mean wind power density	3.4 W/m^2	256 W/m^2	559W/m^2
Mountains or hills nearby	No	Yes	No

According to Alnaqbi et. Al (2022) the requirements of the pumped hydro storage plant, the upper and lower reservoir should have a height difference of approximately 300m or higher for an efficient system. According to Table 4.3.1, the only dam with such a large difference was the Loskop Dam. This dam also had an average wind speed of 6.2m/s which is higher than the annual average of 5.8 m/s recommended by the US Energy Information Administration (2023). The global solar tilted irradiation is at 2291.9kWh/m^2/year which was above the minimum requirement of 3000Wh/m^2/day as indicated by the National Renewable Energy Laboratory (2013). The area was also away from residential and industrial areas, therefore the installation of this plant will not cause inconvenience. This made the Loskop Dam an ideal location for the hybrid renewable energy system.

CHAPTER FIVE: MODEL DEVELOPMENT

5.1. Introduction

This chapter provides insight into the simulation software used for this research. This includes the methods used by the software to analyze and optimize the hybrid renewable energy system. The mathematical models used by the simulation software to determine the power output of the system are presented in this chapter.

5.2. Mathematical model

A system model is a mathematical, physical, or logical representation of a system. A model is necessary as it aids in analyzing, sizing optimizing, and communicating information about the system. For this research, a mathematical model will be used to analyze the power output of the different components in the hybrid renewable energy system. The HRES was designed to incorporate solar PV panels, wind turbines, pumped hydro storage, and a converter. The mathematical models used by the HOMER software to model each component are represented below.

5.2.1. Mathematical model of a solar PV array

HOMER Pro (n.d) models a solar PV panel based on the global solar radiation incident that is reflectedon the panel, irrespective of the voltage and the temperature of the PV array. The power outputof the solar PV panel is calculated according to equation 5.2.1.1.

$$P_{PV} = f_{PV}\ x\ Y_{PV}\ x\ \frac{I_T}{I_S} \qquad (5.2.1.1)$$

$P_{PV} = Power\ output\ of\ the\ PV\ panel$

$f_{PV} = PV\ derating\ factor$

$Y_{PV} = rated\ capacity\ of\ the\ PV\ array\ in\ kW$

$I_T = the\ global\ solar\ radiation\ (beam\ plus\ diffuse)\ incident\ on\ the\ surface\ of\ the$

$PV\ array\ (kW/m2)$

$T_S = 1\ kW/m2$

5.2.2.Mathematical model of a wind turbine

HOMER Pro (n.d) determines the mathematical model of a wind turbine by first determining wind speedat the hub height using logarithmic law and power law. This research will use the power law.

Once this is completed, HOMER Pro (n.d) determines the power output using the air density. Equation 5.2.2.1 is the mathematical model used by HOMER to calculate the wind speed at a hub height.

$$U_{hub} = \ U_{anem}\ x\ (\frac{Z_{hub}}{Z_{anem}})^{\propto} \qquad (5.2.2.1)$$

$U_{hub} = wind\ speed\ at\ the\ hub\ height\ of\ the\ wind\ turbine\ in\ m/s$

$U_{anem} = wind\ speed\ at\ the\ anemometer\ height\ in\ m$/s

$Z_{hub} = hub\ height\ of\ the\ wind\ turbine\ in\ m$

$Z_{anem} = anemometer\ height\ in\ m$

$\alpha = power\ law\ exponent$

HOMER Pro (n.d) calculates the power of the wind turbine at standard density and is calculated using equation 5.2.2.1.

$$P_{WTG} = \left(\frac{\rho}{\rho_0}\right) x\ P_{WTG,STP}$$

$P_{WTG} = power\ output\ of\ the\ wind\ turbine\ in\ kW$

$\rho = the\ actual\ air\ density\ in\ kg/m^3$

$\rho_0 = the\ air\ density\ at\ standard\ temperature\ and\ pressure$ (1.225~~kg/~~m³)

$P_{WTG,STP} = \ the\ wind\ turbine\ power\ output\ at\ standard\ temperature\ and\ pressure\ in\ kW$

5.2.3. Converter

The converter is a component that is used to convert AC-DC and/or DC-AC. An inverter is used to convert DC to AC power and a rectifier is used to convert AC to DC power. HOMER sizes a converter based on the power output from the AC and DC components which will affect the efficiency of the converter. Alluraiah and Vijayapriya (2022) presented the mathematical model for the converter efficiency as per equations 5.2.3.1.

$$\eta_{conv} = \frac{P_{out}}{P_{in}} \quad (5.2.3.1)$$

$\eta_{conv} = \ Converter\ efficiency$

$P_{out} = Power\ output\ from\ the\ converter$

$P_{in} = Power\ to\ the\ converter$

5.2.4. Pumped hydro storage

HOMER Pro (n.d) calculates the mathematical model for designing and analyzing a pumped hydro storage according to equation 5.2.4.1.

$$E = 9.81\, x\, \rho_{water}\, x\, V_{res}\, x\, h_{head}\, x\, \eta \quad (5.2.4.1)$$

$E = Energy\ stored\ in\ joules$

$\rho_{water} = density\ of\ water = 1000 kg/m^3$

$V_{res} = Volume\ of\ the\ reservoir\ in\ m^3 h_{head} = head\ height\ in\ m$

$\eta = efficiency\ of\ the\ energy\ conversion$

The power that is generated can be calculated using equation 5.2.4.2 presented by HOMER Pro (n.d).

$$P = \frac{9.81\, x\, \rho_{water}\, x\, h_{head}\, x\, \eta\, x\ F}{1000} \quad (5.2.4.2)$$

$P =\ Power\ generated\ in\ kW$

$F = Flow\ rate\ in\ m^3/s$

5.3. HOMER software

The design and development of a system involves simulation. Simulations assist in analyzing and optimizing the designed system. With energy systems, there are multiple system simulation software available. This research simulates the designed energy system using the HOMER (Hybrid optimization of multiple energy resources) software, Pro version 3.15.3, developed by the United States, National Renewable Energy Laboratory (2023). This software was developed to assist in the design of micropower systems. HOMER models the physical behavior of a power system and the life cycle cost of the power system. The HOMER software analyses a system using three principles, simulation, optimization, and sensitivity analysis.

5.3.1. Simulation process

The simulation process of the HOMER software allows you to model the designed power system. This process requires selecting the energy inputs that will be configured on the AC or DC bus, depending on the principle of operation. A converter, to convert from AC-DC or/and vice versa. The load represents energy consumption. An energy storage device is most commonly included in designs to address the intermittency of renewable energy resources. The system can also be connected to a grid.

The HOMER software also assists with the sizing of the system, this can be done using two methods, the HOMER optimizer or the search space method. The HOMER optimizer method sizes the components of the system based on the cost. The search space method allows the user to determine the size of the system and multiple values can be entered.

HOMER then considers the feasibility of the designed system based on cost and the ability of the system to meet the load demand.

5.3.2. Optimization process

The optimization process of the HOMER system determines the optimal system configuration. This is achieved by altering the energy resources that are used for the system depending on the ability to meet the load demand and the cost of generating electricity using the resource. The sizing of the system components are also manipulated. These factors are affected when the HOMER optimizer function is used to optimize the system.

Another method, referred to as search space is when the user is allowed to limit the HOMER software to optimize the system based on a user-defined criterion. The user is allowed to provide data such as the size of the PV array, the number of wind turbines, the number of batteries, and the size of the converter.

5.3.3. Sensitivity Analysis

The user was allowed to enter several sensitivity variables and HOMER performed a system optimization separately for each sensitivity value. This was usually used as a tool to assist during uncertainty. For example, when a user designs a hybrid system consisting of a diesel generator stakeholders would like to know the effects of the increasing cost of fuel on the LCOE of the system. This would be difficult for the user to create a new model for each price, hence, multiple prices can be entered for fuels and the most optimal system will be determined.

The HOMER software was chosen for this research due to its ability to model hybrid renewable and non-renewable energy systems.

5.4. Simulation requirements

The components required for simulation by the HOMER Pro software are introduced in this section. The manufacturer and specifications of the solar PV panels, the wind turbines, the converter, the load profile, and the pumped hydro storage are decided. The cost associated with each component is determined.

5.4.1.Load specifications

The Kendal power station is a baseload station designed to supply the required capacity over a 24-hour time frame. This power plant does not respond to peak load demand. The HOMER software only accepts load profiles in kW, the peak load demand was determined to be 4116000kW. The daily electricity generation was 98784000kWh/day. To simulate a baseload on HOMER Pro the random variability parameters had to be set to zero.

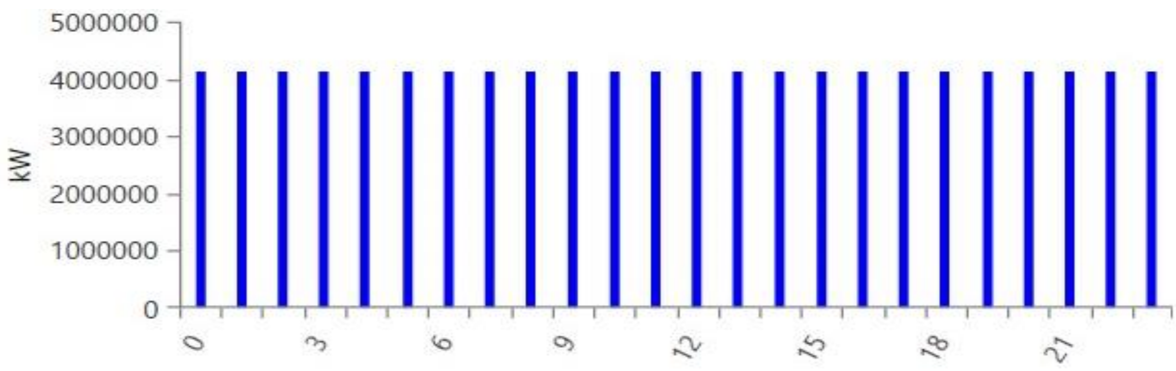

Figure 5.4.1.1: Daily load profile of the Kendal power station used for this research.

5.4.2.Solar PV panel

The solar catalogue on the HOMER software has a variety of panels with different specifications. The solar PV panel selected for this design is the LONGi Solar LR6-72P, this panel was selected due to its high-efficiency rating. Table 5.4.2.1 shows the specifications of the panel.

Table 5.4.2.1: Specifications of the solar PV panel

LONGi Solar LR6-72P	
Specification	**Values**
Capacity	0.37 kW
Derating factor	80 %
Lifetime	25 years
Efficiency	19.1 %

5.4.3.Wind turbine

The wind turbine selected for the system is the Enercon E-126. Table 5.4.3.1 shows the specifications of the wind turbine. The Enercon E-126 wind turbine was selected due to its high-capacity rating of the turbine. The turbine is also most suitable for utility-scale applications compared to turbines that are available in the HOMER Pro software catalogue.

Table 5.4.3.1: Specifications of the wind turbine

Enercon E-126	
Specification	**Values**
Capacity	7.5 kW
Hub height	135 m
Lifetime	20 years
Cut out wind speed	28-34 m/s

5.4.4.Pumped hydro storage

The built-in 245kWh pumped hydro storage module on the HOMER Pro software is developed using a reservoir capacity of 1000m^3, an effective head of 100m, an efficiency of 90% and a discharge period of 13 hours. These specifications was used to calculate parameters to create an idealized battery model for the pumped hydro storage system.

The parameters was found to be equal to the ones that Canales and Beluco (2014) designed to model a pumped hydro storage using HOMER.

This research used the methods outlined by Canales and Beluco (2014) to model the designed pumped hydro storage system on HOMER.

Canales and Beluco (2014), described the first step as listing the characteristics of the pumped hydro storage reservoir, which includes, the size of the reservoir, the effective head, the efficiency, and the flow rate.

Since the size of the reservoir and flow rate are unknown, these parameters was determined using equation 5.4.4.1 as indicated by Canales and Beluco (2014).

$$E_s = \frac{9.81 \ x \ \eta \ x \ h \ x \ Vd}{3600} \qquad (5.4.4.1)$$

$E_s = Total\ energy\ stored\ in\ kWh$

$\eta = Efficiency\ of\ energy\ conversion$

$h = Effective\ head$

$Vol = Volume\ of\ the\ reservoir\ in\ m^3$

The pumped hydro storage capacity was designed according to the baseload capacity of the pumped hydro storage system. This was done to increase the reliability and functionality of the system. Fourteen hours is the period for the reservoir to be in generating mode. Therefore, E_s was calculated to be 98784000 kWh. The efficiency of the pumped hydro storage is determined to be 85% considering system losses. As discussed in the previous chapter, the effective head was determined to be 458m.

$$98784000 = \frac{9.81\ x\ 0.85\ x\ 458\ x\ Vol}{3600}$$

$$Vol = 93118441.24m^3$$

The capacity of the Loskop dam is 361 500 000 $m^{3,}$ this is sufficient water supply to the upper reservoir of the pumped hydro storage system which is a volume of 93118441.24 m^3.

The second step of the method involves selecting a battery voltage and calculating the constant capacity, C_B, this value represents the capacity of the pumped hydro storage system. C_B is calculated using equation 5.4.4.2 as indicated by Canales and Beluco (2014).

$$E_S = \frac{V\ x\ C_B}{1000} \qquad (5.4.4.2)$$

$V = Voltage\ selected\ by\ user\ in\ Volts$

$C_B = Cpacity\ in\ A.h$

The voltage of the battery was selected to be 1000V, hence C_B is calculated

$$98784000 = \frac{1000\ x\ C_B}{1000}$$

$$C_B = 98784000\ A.h$$

The third step involves calculating the maximum charge current according to equation 5.4.4.3 as indicated by Canales and Beluco (2014).

$$P_{bat} = \frac{V\ x\ I}{100} \qquad (5.4.4.3)$$

$P_{bat} = Power\ of\ the\ battery$

$V = Selected\ battery\ voltage$

$I = The\ maximum\ charge\ current$

$$4116000 \frac{1000\ x\ I}{100}$$

$$I = 411600$$

The fourth step involves creating the battery and on the HOMER Pro software with certain parameters. The round-trip efficiency of the battery should be set to 100% and the minimum state of charge should be set to 0%. The fifth step involves creating the converter on the HOMER Pro software. Table 5.4.4.1 represents the characteristics of the pumped hydro storage system.

Table 5.4.4.1: Characteristics of the pumped hydro storage system

Pumped Hydro Storage	
Specification	Values
Capacity	93118441.24 m3.
Effective head height	458 m
Discharge period	24 hours

Table 5.4.4.2 represents the parameters of the battery that is used to model the pumped hydro storage system on HOMER Pro.

Table 5.4.4.2: Parameters of the battery

Pumped Hydro Storage	
Specification	**Values**
Capacity (CB)	98784000 Ah
Power of the battery (Pbat)	4116 000 kW
Round trip efficiency	100%
Minimum state of charge	0%
Maximum charge current	411600 Ah

5.4.5. Converter

The HOMER Pro software does not have a converter in the catalogue with a size sufficient to accommodate the capacity of the HRES. However, HOMER Pro did compensate with a converter that is referred to as the Generic large, free converter which has a 9999999kW that can be scaled according to the size of the system. For this system the converter was scaled to using search space, starting with a capacity of 422000kW and ending with 4660000kW.

5.4.6. Cost

The capital, operation, and maintenance cost was from the publication by IRENA (2022), Renewable power generation costs in 2021. The cost of the solar PV, wind, and pumped hydro storage system was taken from this report because this information is not readily available in the South African currency. The cost given by IRENA (2022) was then converted into South African Rand using the exchange rate in May 2023. This document highlighted the capital cost of solar PV to be USD 570/kW, and the operation and maintenance cost was determined to be USD 14.15/kW. The capital cost of onshore wind was determined to be USD 926/kW and the operation and maintenance cost was determined to be USD 33/kW. The replacement cost of the solar PV panels was R3000 per 0.37kW panel at Brands SA (2023) and the replacement cost of a 5kW wind turbine excluding tower and installation cost was determined to be R32880 which was extracted from Tesup (2023). The capital cost of a pumped hydro storage was determined to be USD 450/kW if an existing dam was to be used. The replacement cost of the pumped hydro storage was estimated to be 50% of the capital cost and the operation and maintenance cost was 1% of the capital cost as stipulated by the Renewable power generation cost publication. The cost of the converter was difficult to find due to the size, however, to be as accurate as possible the cost of a 250kW hybrid inverter was found from Afrimart (2023), which was approximately R904 120. The operation and maintenance cost of the converter was from de Kock and Rix (2022) which was determined to be R6700 per annum for a 15kW capacity. The cost was calculated in relation to the capacity of the converter. The cost of each component was calculated according to the required capacity for simulation. This information is presented in tables under the HOMER optimization chapter.

5.5. Schematic

Figure 5.5.1 indicates the schematic diagram of the HRES as modeled on the HOMERPro software. There are two buses, an AC and a DC bus, and the relevant components are connected on these lines. The wind turbine is connected to the AC, and the solar PV panels are connected to the DC bus. The converter is connected on both buses because of the conversion between AC-DC and DC-AC. The pumped hydro storage is connected to the DC bus because it is modeled as a battery. This was specified by the method presented by Canales and Beluco (2014).

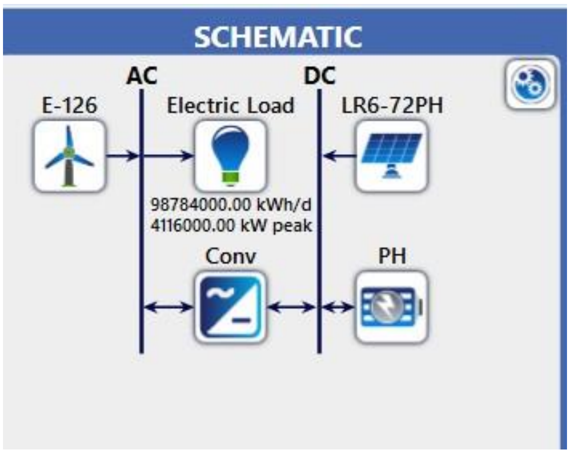

Figure 5.5.1: Schematic diagram indicating the connection of the components for the HRES.

5.6. Simulation process

The previous sub-chapter covered that the HOMER software can size the system using two approaches. The first approach is using the HOMER Optimizer function. The second approach is using the search space function which allows the user to define the sizing of the system. The HOMER Pro optimizer function was used to determine the most optimal system for this research project.

5.6.1.HOMER Optimization

The modeling of the HRES using the HOMER optimization method was discussed in an earlier subchapter. The parameters that was used during the HOMER optimization method are presented in the tables below for the solar PV and wind turbine system. The cost, quantity and capacity was determined for one component and the HOMER system determined the quantity and capacity to meet the load demand based on the lowest cost option.
The monthly average wind speed and Global Horizontal Irradiance (GHI) data was obtained from the HOMER Pro Micro Analysis Tool. This tool downloads the data from The National Aeronautics and Space Administration (NASA) Prediction of Worldwide Energy Resources (POWER), the monthly averages was taken over 22 years from July 1983 to June 2005.

Table 5.6.1.1: Parameters used for the solar PV module

Parameters	Values
Capacity	0.37 kW
Capital cost	R 3950.94
Replacement cost	R 3000
O&M cost/year	R 98.08
Derating factor	80%
Lifespan	25 years

Table 5.6.1.2: Parameters used for the wind turbine panel

Parameters	Values
Capacity	7.5MW
Quantity	1
Capital cost	R 130 105 546
Replacement cost	R 49 320 000
O&M cost/year	R 4 636 590
Lifespan	20 years
Hub height	135

Table 5.6.1.3: Parameters used for the converter

Parameters	Values
Capacity	1 kW
Capital cost	R 2168.24
Replacement cost	R 1808.24
O&M cost/year	R 446.67
Lifespan	15 years
Inverter and Rectifier efficiency	95 %

Table 5.6.1.4: Parameters used for the pumped hydro storage

Parameters	Values
Capacity	98784000 Ah
Quantity	1
Capital cost	R 36,407,121,030.00
Replacement cost	R 18,203,560,520.00
O&M cost/year	R 364,071,210.3
Lifespan	50 years

Table 5.6.1.5: The monthly average solar global horizontal irradiance(GHI) data.

Month	GHI (kWh/m^2/day)
January	6.820
February	6.370
March	5.730
April	5.030
May	4.560
June	4.140
July	4.470
August	5.110
September	5.860
October	6.180
November	6.400
December	6.730

Table 5.6.1.6: The monthly average wind speed data.

Month	GHI (m/s)
January	3.940
February	3.930
March	3.740
April	3.730
May	3.900
June	4.220
July	4.120
August	4.550
September	4.990
October	5.010
November	4.580
December	4.070

5.6.2.Constraints

The constraints that was set on the HOMER Pro software are related to renewable energy resources. The renewable energy fraction was set at 100%, this implies that only renewable resources will be considered for this design. The operating reserve was set to 80% to ensure the reliability of the system.

5.6.3. Search Space

The search space option was used for the converter and pumped hydro storage system only. The pumped hydro storage system consists of a string of three batteries. The converter was simulated using multiple sizes which included 4200000kW, 4330000kW, 4400000kW, 4500000kW and 4600000kW. The optimal size of the converter was selected from the stipulated values.

5.7. **Results**

The results from the simulation of the model during the optimizer process were presented based on three outcomes, technical, economic and environmental. The HOMER Optimizer process presented three systems. The first system consists of solar PVpanels, a converter and pumped hydro storage. The second system consists of wind turbines,solar PV, pumped hydro storage and a converter. The third system consists of wind turbines, converters and pumped hydro storage. Table 5.7.1 indicates the results obtained from the HOMER Pro optimization process. These results are separated into three optimizer results. All figures represented in this chapter are from the Homer Pro microgrid analysis tool.

Table 5.7.1: Overview of the results obtained from HOMER Pro.

Result	Capacity of Solar PV (kW)	Number of wind turbines	Number of battery storage	Capacity of converter (kW)	NPC (Rand)	LCOE (R/kWh)	Operating Cost (R/year)
Result 1: Solar PV	24 438 750	0	3	4 200 000	R567B	R0.883	R10.5B
Result 2: Solar PV and Wind turbine	24 181 500	68	3	4 200 000	R571B	R0.889	R10.8B
Result: Wind turbine	0	14 662	3	4 600 000	R2 051B	R3.19	R70.7B

5.7.3. Environmental

The environmental results indicate the emissions from the modeled system. These include the emissions of gases and particles such as carbon dioxide, carbon monoxide, unburned hydrocarbons, particulate matter, sulphur dioxide and nitrogen oxides per annum. Since the system consists of 100% renewable energy resources, the emissions from each gas and particulate was 0 kg/year.

Quantity	Value	Units
Carbon Dioxide	0	kg/yr
Carbon Monoxide	0	kg/yr
Unburned Hydrocarbons	0	kg/yr
Particulate Matter	0	kg/yr
Sulfur Dioxide	0	kg/yr
Nitrogen Oxides	0	kg/yr

Figure 5.7.1.1: Indication of the emissions output from the HRES

5.7.4. Technical

The technical results presented by the HOMER software are based on the electrical capabilities of the HRES system. The electrical capabilities of the HRES are presented below.

5.7.4.1. First optimizer result

In the solar PV system from the optimizer result, the electricity production from the LONGi Solar LR6-72P solar panel was 100%, contributing to a generation capacity of 41,526,537,861 kWh/year. The solar PV panels was able to generate 24438750kW. The size of the converter was 4220000kW and a string of three pumped hydro storage systems was required for storage.

This provided an autonomy of 72 hours. The AC primary load was 36,041,996,704 kWh/year with an excess generation capacity of 3,671,540,337kWh/year. However, the unmet electric load and the capacity shortage of the system was determined to be 14,163,296 kWh/year and 20,684,196kWh/year. Figure 5.7.2.1.1 details the results obtained from the HOMER Pro simulation and the monthly electric production.


Cost Summary | Cash Flow | Compare Economics | Electrical | Renewable Penetration | Pumped Hydro Storage Copy | LONGi Solar LR6-72PH

Production	kWh/yr	%
LONGi Solar LR6-72PH	41,526,537,861	100
Total	41,526,537,861	100

Consumption	kWh/yr	%
AC Primary Load	36,041,996,704	100
DC Primary Load	0	0
Deferrable Load	0	0
Total	36,041,996,704	100

Quantity	kWh/yr	%
Excess Electricity	3,671,540,337	8.84
Unmet Electric Load	14,163,296	0.0393
Capacity Shortage	20,684,196	0.0574

Quantity	Value	Units
Renewable Fraction	100	%
Max. Renew. Penetration	516	%

Figure 5.7.2.1.1: The electrical results obtained from HOMER Pro for the first system of the optimizer process

5.7.4.2. Second optimizer result

In the second optimizer result, the electricity production from the LONGi Solar LR6-72P solar panel was 98.2%, contributing to 41,089,416,410kWh/year. The solar PV panels was able to generate a total of 24181500kW. A total of 68 7500kW wind turbines was required. The converter size was selected to be 4220000kW and three strings of the pumped hydro storage system was required. The Enercon E-126 produced 1.81% of the total production, contributing to 758,802,873kWh/year. This contributes to a total generation capacity of 41,848,219,283kWh/year. The AC primary load was 36,056,160,000kWh/year with an excess generation capacity of 4,010,861,565kWh/year. The unmet electric load and the capacity shortage of the system wasdetermined to be 0 kWh/year and 100,456kWh/year. Figure 5.7.2.2.1 details the results obtained from the HOMER Pro simulation and the monthly electric production.

Figure 5.7.2.2.1: The electrical results obtained from HOMER Pro for the second system of the optimizer process

5.7.4.3. Third optimizer result

In the third optimizer result, the electricity production from the Enercon E-126 produced 100% of the total production, contributing to 163,611,290,053kWh/year. The third optimizer system consisted of 14662 wind turbines, a 4600000kW converter and three strings of pumped hydro storage.

The AC primary load was 36,036,127,143kWh/year with an excess generation capacity of 126,551,643,577kWh/year. The unmet electric load and the capacity shortage of the system was determined to be 20,032,857kWh/year and 35,661,481kWh/year. Figure 5.7.2.3.1 details the results obtained from the HOMER Pro simulation and the monthly electric production.

Production	kWh/yr	%
Enercon E-126 [7.5MW]	163,611,290,053	100
Total	163,611,290,053	100

Consumption	kWh/yr	%
AC Primary Load	36,036,127,143	100
DC Primary Load	0	0
Deferrable Load	0	0
Total	36,036,127,143	100

Quantity	kWh/yr	%
Excess Electricity	126,551,643,577	77.3
Unmet Electric Load	20,032,857	0.0556
Capacity Shortage	35,661,481	0.0989

Quantity	Value	Units
Renewable Fraction	100	%
Max. Renew. Penetration	2,700	%

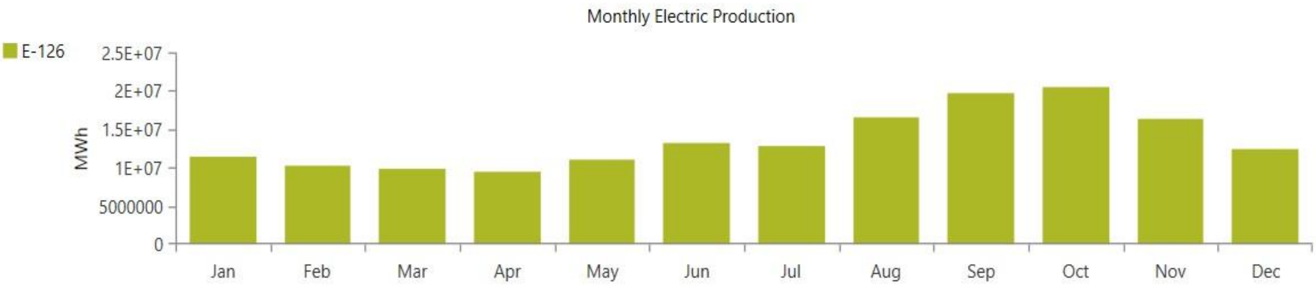

Figure 5.7.2.3.1: The electrical results obtained from HOMER Pro for the third system of the optimizer process

5.7.5. Economic

The economic results obtained consist of the levelized cost of electricity and the net present cost. This will determine the economic feasibility of each HRES.

5.7.5.1. **First optimizer result**

The NPC for the first optimizer system was estimated to be R567 000 000 000. The LCOE was determined to be R0.883 per kWh.

5.7.5.2. Second optimizer result

The NPC for the second optimizer system was estimated to be R571 000 000 000. The LCOE was R0.889 per kWh.

5.7.5.3. Third optimizer result

The NPC for the third optimizer system was estimated to be R2 051 000 000 000. The LCOE was R3.19 per kWh.

CHAPTER SIX: CONCLUSION AND RECOMMENDATIONS

6.1. Introduction

This chapter provides an analysis of the results. The HRES suited to meet the objectives of the research project is decided in this chapter. Recommendations for future research were highlighted.

6.2. Conclusion

This HRES that was designed, modeled and simulated in this research was to achieve the following objectives:

- Reduce the amount of harmful gases emitted by the Kendal power station
- Provide a cost-effective and reliable electricity supply to replace the baseload capacity of the Kendal power station.

The Homer Pro system offered three suitable HRES. A system that consisted of solar renewable resources, a system that consisted of solar and wind resources and a system that consisted of wind resources only. The most economical system according to the HOMER Pro software was the HRES which consisted of solar resources only. This is because solar PV panels are inexpensive to procure and maintain compared to wind resources. There was a substantial amount of excess electricity generated, however, this excess was insufficient to meet the load demand of the system leading to a capacity shortage and unmet electrical load. The second most inexpensive system selected by the HOMER Pro software was the system with a combination of solar and wind resources. The difference between the LCOE between the first and second systems was R0.005 which is negligible. The second system has a zero unmet electric load which means the HRES can fully meet the load demand. The third system, which is the most expensive system, requires a larger converter and multiple expensive wind turbines. The system is also not able to fully meet the load demand.

The system chosen as the most optimal system for this research project should be able to meet the objectives of this research, hence, the second optimizer system was selected as the best system for this research project. The LCOE was R0.889 and there was zero unmet electrical load. This proves that the system is cost-effective and reliable.

6.3. Recommendations

The recommendations for future research on this subject are as follows:

- Address the excess electricity generated. Instead of the excess electricity being curtailed, methods can be considered to feed the excess electricity generated back into the HOMER optimizer systems to reduce the unmet electric load and capacity shortage.
- The effect this change will have on the design of the HRES can be further assessed.
- The control strategy for the optimal operation of the system can be considered for future research.

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