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**TITLE: HYBRID ENERGY STORAGE SYSTEM FOR LARGE-
SCALE RENEWABLE ENERGY PENETRATION**

Student Name: SYLVIA MAKUPE

Registration Number: 221000417

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Supervisor's Name: DR. PETER MOSES MUSAU

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Declaration


I, SYLVIA MAKUPE, Student Number 221000417 declare that this project report is my original work, and has not been presented for a degree at the University of Rwanda or any other university. All sources of materials used in the work have been fully cited and acknowledged in the correct academic format.

Signature: 

Date...14/11/2023

This Thesis Report has been submitted for examination with the approval of the university advisor.

Approved by the Supervisor: Dr. Peter Moses Musau

Signatur: 

Date:29-Jan-2024

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List of abbreviations

PV	Photovoltaic
REI	Renewable Energy Integration
SNG	Synthetic Natural Gas
P2G	Power to Gas
HOMER	Hybrid Optimization of Multiple Energy Resources
CO ₂	Carbon Dioxide
AEL	Alkaline Electrolyzers
PEME	Proton Exchange Membrane Electrolyzer
SOEC	Solid Oxide Electrolyzers
MATLAB	Matrix Laboratory
HESS	Hybrid Energy Storage System
DC	Direct Current
COE	Cost of Energy
NPV	Net Present Value
SM500	A generic PV with 500RX produced by Solar Max Company

ABSTRACT

Integration of renewable energy on a large scale into the grid poses a huge problem for the stability of the grid due to the variations that arise with most renewable energy resources like solar and wind. Sustainable energy storage systems must be put in place to boost the penetration of renewable energy sources in the grid. These energy storages help in achieving power quality, help in load following and leveling and managing energy seasonal shifting among other functions. This work designed and simulated long-duration power-to-gas systems of hydrogen and methane energy storages coupled to a solar system to analyze the technical, economic performance and environmental emissions of the systems. 3 energy storage systems have been designed, one with hydrogen only, one with synthetic natural gas and one with a combination of hydrogen and synthetic natural gas. The weather conditions of the Salima district in Malawi have been used in the designing of the systems. HOMERPRO software has been used as a design and simulation tool, to provide an optimized system of the designed systems. Having a hybrid system of SNG and hydrogen can help achieve a higher percentage of renewable penetration into the grid because the storage systems can complement the PV when the PV is not able to produce electricity. This system can also help in the reduction of emissions like carbon dioxides and sulfur oxides and a reduction in the cost of energy and the net present cost.

Keywords: *Hydrogen, Synthetic Natural Gas (SNG), Hybrid System, Power-to-Gas, HOMERPRO, Photovoltaic, Electrolyzer*

CHAPTER ONE

1. Introduction

1.1. Background

Renewable Energy Integration (REI) is the process of Incorporating renewable energy resources like solar, wind, geothermal and among others into the existing electric grid[1]. This process plays a valuable part in achieving a more sustainable and environmentally safe energy system. Achieving REI is associated with a lot of challenges because renewable energy resources like solar and wind come with a lot of intermittenencies and there is a lot of variations in the power produced [2].

To avoid the challenges associated with REI, Energy storage systems need to be implemented because renewable energy power is also mostly available when the demand is low and sometimes unavailable when there is a need for power from the demand side[3]. These storage systems can store energy when large PV and wind turbine farms produce excess energy due to low demand and use the stored energy when renewable energy sources cannot provide enough energy to power the needed load. The energy systems should be able to supply energy for a long period whether in weeks or months to cover areas that have seasonal winds and also seasonal periods of sunshine in the case of wind turbines and photovoltaic systems respectively.

Different types of storage are currently being implemented to cover the variability and uncertainty problems that arise with renewable energy systems[4]. Energy storage systems like batteries especially Lithium-ion batteries, pumped hydro, flywheels and Power-to-Gas among others are some of the storage systems that are currently employed in the various renewable systems to store energy.

In this research, Power-to-Gas energy storage consisting of Hydrogen and Synthetic Natural gas (SNG) storage systems have been explored to find which storage system is better for large-scale renewable penetration of a solar system.

1.2. Problem Statement

Penetration of renewable energy on a large scale into the grid poses a huge problem for the stability of the grid due to the variations that arise with solar and wind energy generating systems. This project designed and evaluated Hydrogen and SNG's energy storage systems as better storage options in a large-scale renewable penetration. Hydrogen and SNG allow for large RE penetration because these energy storage systems can discharge for days to months hence, they are good for seasonal shifting[1].

1.3.Objectives

1.3.1. Main Objective

The primary goal of the project was to design and simulate a hybrid energy storage system of SNG and hydrogen with large-scale

1.3.2. Specific Objectives

To achieve the main objective, the specific objectives below were addressed

- i). Comparative assessment of the storage of hydrogen and synthetic natural gas in terms of the amount of energy that can be stored in each system.
- ii). Designing a hybrid system of SNG and hydrogen to improve performance.
- iii). Simulating and analyzing the energy storage designs using Homer Pro based on technical performances, and environmental effects.
- iv). Determining the optimal combination between the two storage systems.

1.4.Research Questions

- i). Is a hybrid system of Hydrogen and SNG able to improve the performance and storage of Solar in large renewable penetration?
- ii). Which storage systems give optimal technical, economic and environmental parameters for the same energy out?
- iii). Which energy storage system can be recommended for a large solar penetration?

1.5. Justification

A lot of Studies have been done on the use of hydrogen as long-duration energy storage as compared to the use of synthetic natural gases, let alone on analyzing the two systems together to find which one is better in terms of design and even in performance when achieving that energy storage type. This study provided knowledge on designing hydrogen and SNG storage systems for large-scale renewable penetration.

1.6.Scope

The research analyzed the performances of the hydrogen and synthetic natural gas energy storage systems to evaluate which storage between the two systems is better for large-scale renewable solar energy. The simulation was done for a case study of the Salima District in Malawi.

1.7. Report Organization

This Thesis report contains 5 main chapters. Chapter 1 introduces the topic and provides a background of the work, the main objective and the specific objectives of the system. Research questions and scope are all highlighted in this chapter. Chapter 2 provides a background of storage systems and the process of power to gas systems. Similar works and literature are provided in this chapter. This chapter also contains the problem formulation of the research. Chapter 3, the methodology provides an outline of the methods used in this research. Some methods used by other researchers have been provided in this Chapter. Chapter 4 contains the simulation results, the results analysis, as well as the validation of the results. Chapter 5 contains the research recommendations, contributions and conclusion.

CHAPTER TWO

2. Literature Review

2.1. Introduction

This chapter provides a background of power-to-gas systems; various processes involved in power-to-gas systems. A summary of the previous works done concerning the area of research, methodology, and literature, and how those works are applied in this work have also been presented. This section also explains the gaps between those researches and problems formulation of the research at hand and the chapter's conclusion

2.2. Need for Storage in Renewable Energy Integration

Energy storage is crucial in establishing a reliable and consistent supply of power in both grid-connected and off-grid energy systems. In the next 20-30 years, sustainable energy systems will solely depend on renewable energy resources and less on traditional energy resources[5]. The biggest challenge for most renewable energy resources, particularly sun and wind, is that they occur occasionally making them unreliable for consistent electricity delivery hence there is a need to establish a reliable energy storage system. Energy storage offers the following advantages[1]:

- Energy transfer; Energy storage systems can store energy in times of excess supply and provide this energy when the supply is low hence being used to compensate for energy during peak times.
- Help in energy curtailment: An increase in renewable energy systems which are distributed throughout the levels of the grid can cause the transmission lines to be transporting more energy than their capacity, especially during low demand. This can cause strain on the grid. This can be avoided by storing some energy which can be fed back into the grid at times of high demand.
- The storage system can help in load following and leveling. In this application, the storage helps in the timely following of the demand and this can help in reducing the uncertainty of the renewable energy output during times it is needed the most.

- Seasonal shifting; energy storage can store energy from renewable resources for weeks or even months and this can help in ensuring a steady energy supply in times when the resources are not available.
- Energy storage can offer power qualities and stability roles by providing reactive power into the grid which can help in mitigating voltage spikes and harmonics

2.3. Storage Systems in Large Scale Integration

Renewable energy systems (RES) are currently being adopted at an increasing rate because they are more environmentally friendly and can be renewed easily as compared to conventional energy sources. Energy storage is vital in establishing a stable renewable system because most RES are variable and not always present when the demands are needed[2]. In large renewable energy penetration to the grid, storage systems ensure that the issues of power quality and reliability are minimized and ensure that there is energy management[6].

Storage systems are categorized based on the technology, storage/ discharge duration, and working factors. Based on technology, there are electrical energy storages like capacitors, super-capacitors, double layered capacitors among others. Mechanical energy storages like pumped hydro and compressed air energy storages. Electrochemical energy storages include batteries, flow batteries, hydrogen and SNG[7]

Based on the discharge duration, there are four categories of classifying energy storage systems; very short discharge storage like capacitors and flywheels whose discharge time ranges from seconds to less than 5 minutes, short discharge storage like Lithium Ion batteries whose discharge range is from minutes to hours(5-10 hours), medium discharge storage which their discharge range is hours to a few days and examples are pumped-hydro and Compressed air storage. Lastly, we have long discharge storage which ranges from days to evening months and examples include hydrogen storage and SNG or ammonia storage[4]

2.4. Power To Gas Systems

2.4.1. Overview

Power to gas mostly written as P2G is a concept of producing gas mainly hydrogen from excess electricity through the process of electrolysis. This Hydrogen gas can be used as a final energy

vector or it can be used to produce methane, a Synthetic Natural Gas (SGN). Hydrogen can be produced from various renewable energy configurations as illustrated by[8]. The main aim of P2G is to store energy for the long term and also provide grid flexibility in terms of large-scale renewable penetration[9]. Hydrogen and SNG can be produced renewably using excess or over-generated energy from renewable forms like wind and PV systems to power the electrolysis process[10],[11]. This is a process of splitting water into hydrogen and oxygen by the use of electricity. Hydrogen may be utilized as energy in combined-cycle gas turbines or fuel cells[12]When hydrogen gas is not used directly to provide energy, it is combined with CO₂ in a methanation process to form Methane: a synthetic natural gas[13]. Electrolysis and methanation have round-trip storage and regeneration efficiencies of around 34–44% for hydrogen and 30–38% for methane, making them relatively expensive processes to operate in an intermittent mode[13]. Renewable energy curtailment is projected to increase in the future because of the increase in renewable systems as the grid cannot accommodate the extra electricity produced by these sources hence this energy can be used in the processes of power to gas. Subsystems like electrolyzers, methanation units, carbon dioxide and gas storage are very important in a P2G.

2.4.2. Electrolyzers

An electrolyzer is a component used in the process of splitting water to create hydrogen. At the moment, there are three different types of electrolyzers: solid oxide electrolysis cells, proton exchange membrane electrolyzers, and alkaline electrolyzers [14].

Alkaline electrolyzers employ potassium or sodium hydroxide solutions as their electrolyte. This electrolyzer design is at an advanced stage and is widely used. The advantages of this type of electrolyzer are that it is cheaper than the other types of electrolyzers and takes little time to start after a shutdown. However, this electrolyzer is highly corrosive and has a low current density[14]

Proton Exchange Membrane electrolyzers use a solid polymer membrane as an electrolyte. PEM electrolyzers are better in terms of fast cold start capabilities, more flexibility and better performance when coupled with dynamic and intermittent systems. The disadvantages of this electrolyzer are that it is more expensive than AEL and has a limited life span[14]

Solid oxide electrolyzers (SOEC) are a relatively new developed type of electrolyzer. It is operated at a higher temperature than the other electrolyzers and this results in it having a higher efficiency. Apart from having a higher efficiency than the other electrolyzers, SOEC can also be integrated easily for waste heat. The drawbacks of using this electrolyzer are that it is very expensive than the other AEL and PEME and it has limited long-term stability[14]

The electrical energy produced by the electrolyzer

The electrical energy produced by the electrolyzer depends on the higher heating value of hydrogen, the density of hydrogen, and the efficiency of the electrolyzer[12]. The electrolyzer energy is given by

$$E_{el} = \frac{\tau_{HHV}}{\rho_{H_2}\eta_{el}} \quad (2.1)$$

Where, E_{el} is the electrical energy consumed by the electrolyzer, τ_{HHV} is the higher heating value of hydrogen, ρ_{H_2} is the density of hydrogen, η_{el} is the efficiency of the electrolyzer

2.4.3. Methanation System

A methanation reactor can be used to create synthetic natural gas. The electrolyzers' hydrogen is supplied into the methanation process, which uses it to create methane gas by reacting with carbon dioxide. The formation of methane from hydrogen and carbon dioxide is called the Sabatier Reaction[13]. Some of the types of methanation reactors used are Biological and Thermochemical reactors. Examples of thermochemical reactors are; fluidized bed reactors, fixed bed reactors, structured reactors, and three-phase reactors [11]. Good temperature control in the methanation process has to be employed since methanation is a very exothermic reaction and this affects the catalysts used in the process [11].

2.4.4. Carbon Dioxide source

The carbon dioxide used in the Sabatier process comes from different sources. The source of CO₂ currently being adopted is Carbon Sequestration. Carbon dioxide can also be taken from biomass processes and also can be captured from the atmosphere[13].

2.4.5. Gas storage

Storage of the gas is necessary for the P2G system because the gas produced can not always be used after it has been made. SNG storage facilities are highly developed and easy to implement as compared with Hydrogen facilities since this area is relatively new. Gas can be stored in compressed gas tanks or cylinders. Hydrogen storage is more expensive to implement because of how light the gas is and special storage systems like underground storage in salt caverns are currently being employed [11].

Compressing Hydrogen for Storage

Hydrogen gas has a very small specific density hence in order to store and utilize the gas, very high compression is required to increase its volumetric energy density[15]. Energy from solar PV can be used for this process.

The energy needed to compress the hydrogen adiabatically is given by[15]:

$$E_{comp} = 0.09653P_0V_o \left\{ \left(\frac{P_1}{P_0} \right)^{0.29078} - 1 \right\} \quad (2.2)$$

Where, P_0 and P_1 are the initial and final pressures respectively. V_o is the initial specific volume of hydrogen

2.4.6. Fuel Cell

To produce electricity from hydrogen, fuel cells are required. Using fuel cells, hydrogen may be converted back into energy. Hydrogen and oxygen react in the cell to create electricity, with water as a byproduct. The electrical energy produced by the cell is given by[15];

The electrical energy from a fuel cell is given by:

$$E_{FC} = \frac{\eta_{FC}FC_{H_2}\tau_{HHV}}{\rho_{H_2}} \quad (2.3)$$

Where, η_{FC} is the efficiency of the fuel cell, FC_{H_2} is the hydrogen consumed in the fuel cell, τ_{HHV} is the higher heating value of the hydrogen, ρ_{H_2} is the density of hydrogen

2.4.7. Combined Cycle Gas Turbine

Methane gas is usually burned in gas turbines to produce electricity. The facility is coupled with equipment like combustion chambers, and generators to produce electricity. The efficiency is given by

$$\text{Efficiency} = \frac{\text{heat input out}}{\text{heat input in}} \quad (2.4)$$

The gross heat rate which is used for power generation is given by:

$$\text{Gross heat rate} = \frac{\text{heat input to the plant}}{\text{power generation}} \quad (2.5)$$

$$\frac{\text{Fuel consumed} \times \text{Gross calorific value of fuel}}{\text{Power generation}} \quad (2.6)$$

2.5. Comparison of Hydrogen and Synthetic Methane

Table 2.1 summarizes the advantages and disadvantages of Hydrogen fuel and synthetic methane

Table 2.1: Comparison of Hydrogen and SNG

Fuel	Advantages	Disadvantages
Hydrogen	<ul style="list-style-type: none"> • Higher overall efficiency than methane • Cheaper than methane since it requires the fewer units • More stable than Methane • High energy density per specific weight than other fuels 	<ul style="list-style-type: none"> • very costly in terms of storage facilities • Difficult to integrate into the existing gas grids and storage
Synthetic Methane	<ul style="list-style-type: none"> • Easy incorporation into the existing gas pipeline • Storage is cheaper than hydrogen 	<ul style="list-style-type: none"> • Low conversion efficiency as compared to the production of hydrogen alone since

	<ul style="list-style-type: none"> • Can act as carbon neutrality if the carbon for the methanation is taken from a carbon-emitting processes 	<ul style="list-style-type: none"> • Costly than hydrogen due to additional methanation and other units
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2.6. Similar Work

Storage systems play a major role in achieving 100% renewable penetration since the flexibility and issues of uncertainties are addressed by energy storage systems. Work done by **Bruno Cárdenas**[4] examines how to integrate various energy storage technologies to reduce the total cost of electricity (TCoE) on a system that is entirely made up of renewable energy sources. Short, medium, and long-duration energy stores include hydrogen, compressed air energy storage (CAES), and lithium-ion batteries. In his work, Hydrogen was categorized as long-duration storage with discharging time greater than 200 hours.[4]

Other works focus on Hybrid Energy Storage Systems (HESS) to deal with the impacts that renewable energy penetration has on the grid, rotational inertial being one of them[16]. In their work combining LI-ion and ultracapacitors as energy storage can help achieve a high penetration of renewables to the grid. The work of [17] illustrates various HESS strategies, their applications, and how those HESS can be controlled.

The use of PtG as an energy storage technology to boost the penetration of renewables into the grid has been stressed in the most recent studies that have been undertaken. **W. L. Becker** [10] undertook research on assessing the efficacy of a sustainable pathway to SNG by combining recovered CO₂ from non-renewable resources with renewable hydrogen produced from electrolysis. Their work involved doing a detailed techno-economics analysis of the SNG production process and how hydrogen feedstock cost affects the cost of SNG production. In this work, the authors stated that hydrogen can be used as an energy vector without using it for SNG production. However, because hydrogen comes with infrastructure challenges, low volumetric energy density, inefficiencies, and storage costs, SNG is preferred.

According to **Paulo Marocco et al** research, energy storage device adoption is essential to decrease reliance on fossil fuels[18]. To promote RES penetration and prevent a significant increase in energy costs, hydrogen storage technology in particular is essential in off-grid locations[18]. Their research used the -constraint approach along with the Particle Swarm

Optimization (PSO) algorithm to simultaneously address the Levelized cost of energy (LCOE) and CO₂ emissions. Synthetic natural gas was not mentioned in this paper.

Bei Li produced work similar to the one in [18]. In their research, they coupled Dematel-TOPSIS and model predictive control to examine the best ways to operate various hybrid storage systems that integrated both hydrogen and battery storage[2] This report also emphasized that one option for handling the unpredictability associated with renewable energy is a system that combines batteries and hydrogen storage. The analysis excluded synthetic natural gas and instead focused primarily on hydrogen and battery storage.

Elisa Ghirardi's [19] analysis of the least expensive generating technologies, solar panels and wind turbines; examined four scenarios of renewables adoption (40%, 60%, 80%, and 100%). The authors examined the interaction between two storage technologies—Lithium-ion batteries and hydrogen power—to maintain the stability of the power system and addressed the numerical Trnsys-based modeling for a smart grid. Due to its ability for seasonal storage without the limitations of the battery's self-discharge, their findings showed the hydrogen storage system's contribution to getting a higher renewable share[19]

A sizing method for HESS-equipped large-scale centralized PV power stations was demonstrated in a study titled by **Chao Ma** [20]The power capacity was determined by using a statistical method that took into account the effects of various weather conditions and by calculating the optimal energy capacity by using a mathematical model. The findings indicated that the pre-storage technique can further raise the target output satisfaction rate by 8.28% while the optimal capacity configuration can greatly increase the stability of PV output.

Dominguez-Gonzalez, G et al in their study titled Integration of H₂ and SNG with Legacy Power Generation Facilities [12] examined the financial and economic viability of including a hybridized P2G producing and storage system with a legacy combined cycle gas turbine (CCGT). According to the authors' findings, SNG may function as an energy vector for big capacity and is both technically and financially feasible. According to their research, merging infrastructures for methane and hydrogen using power-to-gas conversion technologies can provide future energy systems the flexibility they require. In order to advance P2H and Power to SNG to Power, which their work did not address research addressing technical limits of the usage of hydrogen and hydrogen/syngas mixes should be done.

Meng Qi [21] introduced the concept of combining Power-to-Methane and Liquid CO₂ energy storage to produce both methane and electricity and support in power shaving of the grid. Using a wind and solar renewable mix hybrid, the authors designed, optimized and evaluated the techno-economic performance of power-to-methane and liquid CO₂ energy storage.

2.7. Summary of Previous Research Works and their Gaps

In recent studies, most researchers focused on the economic analysis of hydrogen or SNG storage for large-scale renewables. The work of [12] emphasized on transportation of storage on the already-made distribution lines of natural gas but with little modification as a way of reducing the cost of storage and transportation. Other researchers like [19], [21] and [2] mainly focused on various storage systems which can be hybridized with Hydrogen to form a hybrid storage renewables penetration to enhance the stability of the grid. Studies like [4] focused on finding the optimum storage mix to provide capacity at a low cost. Most of the researchers have not studied the behaviors of hydrogen or synthetic natural gases together or each separately when connected to the grid in terms of flexibility with the grid, and how a fuel cell or SNG plant to the plants. As much as Hydrogen and SNG are long-range energy storage, most studies have been based on Hydrogen other than Synthetic Natural gas.

Table 2.2. summarizes the various types of research done by others.

Table 2.2: Summary of Similar Works

Reference	Problem addressed	Method Used	Storage system adopted	Gaps
[2]	Solving multiple hybrid storage operation problems	Two-layer allocating-and-dispatching algorithm	Hydrogen and Battery systems	<ul style="list-style-type: none"> • Lack of Accurate Measurement of temperatures. • Need to consider other hybrid storage
[4]	Integrating storage system to reduce total cost	Iterative algorithm	CAES, Hydrogen and Li-on	<ul style="list-style-type: none"> • Need to explore other combinations

[10]	PtG storage to boost renewable energy penetration	Techno analysis of power to a gas system	SNG	<ul style="list-style-type: none"> Lacks a combination of SNG and H2 both as storage
[12]	Combining PtG facilities to an existing Combined Cycle Gas turbine	Financial and economic assessment	SNG	<ul style="list-style-type: none"> Needs for an analysis of a PtG facility only
[16]	deal with the impacts that renewable energy penetration has on the grid	A Hybrid Storage System	Li-on Batteries and Ultracapacitors	<ul style="list-style-type: none"> Need for a longer duration storage system
[18]	Promote RES penetration and prevent a significant increase in energy costs	Addressing LCOE and CO2 emissions using Particle Swarm Optimization Algorithm	Hydrogen	<ul style="list-style-type: none"> Assessing other storage methods
[19]	Analyzing different scenarios of renewable penetration levels in the grid	Numerical Trnsys-based modeling of the smart grid	Hydrogen and Li-on	<ul style="list-style-type: none"> No overall behavior of the system.
[21]	Designing and analyzing the techno-performance of Power to methane		Methane	<ul style="list-style-type: none"> Explore other storage

To address the technical constraints of hydrogen and synthetic large-scale renewable penetration of a Solar PV system, this research discussed in full the technicalities that arise while dealing with these two energy systems. Having hybrid energy storage of Hydrogen and SNG can help in minimizing huge cost that arises due to the storage of hydrogen which requires a big investment because of the conditions in which hydrogen can be stably stored. Excess hydrogen will be used to form SNG which can be stored cheaply as compared to hydrogen and also improve system efficiency of the storage system because converting hydrogen entirely to SNG reduced the efficiency than using hydrogen directly for electricity generation.

2.8.Problem Formulation

In this study, the hydrogen system was composed of a fuel cell, a Proton Exchange Membrane Electrolyzer (PEM) and hydrogen storage. PV Power was used in the electrolyzer to break water into H₂ and O₂ and the H₂ will be stored in the storage unit, a Polymer Electrolyte Membrane fuel cell (PEMFC) uses the hydrogen to produce electricity and heat [2] in seasons when the PV energy is low

The Synthetic Natural gas system was composed of a PEM electrolyzer, SNG production reactor or methanation, Carbon capture and Utilization Unit to capture carbon from the atmosphere to be used in the methanation process, and a Combined Cycle Gas Turbine to produce electricity.[2], [12]

2.8.1. Main Objective

The objective was to maximize the stability of the grid through the use of these 2 storage systems. The two renewable energy systems should be able to supply 300GW of power in the grid in case the solar energy system is not capable of producing this amount. Parameters used the are energy density of the two storage systems, how flexible are the two systems in supplying electricity to the grid, and environmental issues associated with each system.

The objective function is to maximize the power produced from the fuel cell and CCGT plant to maximize the grid stability

$$\text{Max } A(Fc, CCGT) = F_c \times N_{Fc} + CCGT \times N_{CCGP} \quad (2.7)$$

where A = total power produced from the fuel cells and SNG CCGT, F_c =capacity of one fuel cell (PEMFC), N_{Fc} = number of the fuel cells required, $CCGT$ = The capacity of one combined cycle gas turbine, N_{CCGT} =number of CCGT.

Production of hydrogen used in fuel cells will depend on the amount of sunlight available, and the efficiency of the electrolyzer. The demand for energy for the electrolyzer from the PV is given by

$$E_{pv} = \frac{E_{el}}{\eta} \quad (2.8)$$

Where, E_{el} is the energy demanded by the electrolyzer, η is the efficiency.

2.8.2. Equality Constraints

The hydrogen used in fuel cells and in the methanation process depends on the amount of hydrogen produced by the electrolyzer. Hydrogen produced from the electrolyzer, expressed as weight per hour

$$W_{H2} = \frac{P_{elz}}{E_{elz}} \quad (2.9)$$

Where, P_{elz} is the electrolyzer electric power consumption (kW), E_{elz} is the electric energy consumed by the electrolyzer in kWh/kg

To store the hydrogen, the hydrogen needs to be compressed with energy from renewable resources, the energy to compress the hydrogen for storage is given by

$$E_{comp} = 0.09653P_oV_o \left\{ \left(\frac{P_1}{P_o} \right)^{0.29078} - 1 \right\} \quad (2.10)$$

Where, P_o and P_1 are the initial and final pressures respectively, V_o is the initial specific volume of hydrogen.

The power produced by the fuel cell is given as

$$P_{FC} = \frac{dE_{FC}}{dt} \quad (2.11)$$

Where P_{FC} is the power produced from a fuel cell, dE_{FC} is the change in electrical energy from the fuel cell, dt is the change in time

2.8.3. Inequality Constraints

For the methanation to be achieved. The following inequality constraints should be met,

$$T_{Lt} \leq T_{mr} \leq T_{ht} \quad (2.12)$$

Where T_{mr} is the methanation reactor operating temperature, T_{Lt} is the low operating temperature of the methanation reactor, T_{ht} is the higher operating temperature of the methanation reactor

To increase the efficiency of the methanation tank, the hydrogen coming from the electrolyzer should meet some specifications in terms of moisture, hydrogen concentration, and contaminations.

$$H_{el} > (x_1, x_2, x_3) \quad (2.13)$$

Where, H_{el} is the hydrogen from the electrolyzer, x_1, x_2, x_3 represent standard moisture, concentration, and contaminants respectively of the hydrogen to ensure maximum methanation reactor efficiency.

2.9. Chapter Conclusion

The chapter presented various works done by other researchers related to hydrogen and Synthetic natural gas as long-duration storage systems. From the research, different authors either focused on hydrogen or SNG alone. Most studies were also focused on the techno-economic analysis of incorporating these systems and did not address the technical details of each system to analyze how each system can behave when connected to the grid. The problem formulation in this work is to maximize the power output from these storage systems so as to increase flexibility as well as stability of the grid since the penetration from renewable resources is on a large scale.

CHAPTER THREE

3. Methodology

3.1. Introduction

This chapter gives details of the methodology used to solve the problem in this thesis. Different methods done by other researchers are also presented in this section to see how different or similar the methods presented in this thesis are to those other methods. This chapter also presents the model used in this work and gives a detailed outline of the simulation tool used. A mapping method for the problem and a conceptual framework of the problem is also presented in this chapter.

3.2. Previous Methods

Different methods have been used to analyze different storage systems especially those related to hydrogen and synthetic natural gas storage systems.

Bei Li et al [2] examined the best way to operate a number of hybrid storage systems. Hydrogen and battery storage were both combined into hybrid storage. First, a two-dimensional model of a fuel cell, an electrolyzer, and a battery was created and the effects of temperature were taken into account. Second, a two-layer operating strategy structure with a power allocation layer and a dispatching layer was suggested. In the allocation layer, three algorithms fuzzy logic, TOPSIS and Dematel-TOPSIS—were contrasted, whereas the MPC strategy was chosen for the dispatching layer [2]

To construct and simulate a system of reactors for the conversion of hydrogen and carbon dioxide to SNG, thermodynamic and kinetic issues of the methanation reaction were investigated in a study done by **William L. Becker et al** [10] Due to the large concentration of carbon oxides and hydrogen, the authors developed a distinctive “bulk” methanation procedure. The thermodynamic and kinetic characteristics of the methanation process were taken into consideration while designing a system of multi-staged reactors for the conversion of hydrogen and carbon dioxide to SNG [10]

The Work of **H. Ishaq and I Dincer** [8] investigated three renewable energy-based configurations for hydrogen production. Solar photovoltaic energy, geothermal energy production and biomass gasification are the renewable energy sources taken into account in

this study. This study offered a brand-new method for producing hydrogen from biomass using multistage water gas shift reactors. Aspen Plus was used to model the biomass gasification-based hydrogen production system while EES software was used to assess the solar PV and geothermal energy-based hydrogen production systems.

In Elisa Ghirardi et al [19]work, Numerical Transient System Simulation Program (TRNSYS)-based modeling of the smart grid was the methodology employed. The model enabled the annual (and transient) operation to be predicted in a variety of environmental situations. Performance of each component at each time step, energy balances and overall LCOE were the main factors assessed. With a temporal resolution of 1/8 h, simulation is carried out all year long to ensure high accuracy. The model uses an experimental meteorological dataset that takes seasonality and resource statistical variability into account to ensure accurate forecasting for a variety of scenarios.

Meng Qi et al [21] designed, optimized and comprehensively evaluated the techno-economic performance of the Power to Methane -Liquid CO₂ Energy Storage process using a renewable power mix of solar and wind. The authors formulated a model to understand the impacts of storage sizing and power allocation on the process performance. The authors were able to establish a cost-optimal design using Artificial Neural Network-based surrogate Optimization.

F. Cebulla [22] used the Linear Cost Minimization Optimization REMix to the efficiency of the electrolyze to determine the capacity, expansion and dispatch of all electricity generation as well as storage technologies in a system with more than 80% being energy sources from renewable systems.

In a work done by **Kristóf Kummer[23]**, the authors introduced a novel function showing properties similar to lifetime and efficiency. It showed that despite Power-to-Methane technology's lower energy recovery efficiency than certain other approaches because of its low self-discharge and small standby losses, it may be a good and affordable alternative for seasonal and multi-seasonal energy storage.

In the work by **B. Karacavus [24]** , a system that creates hydrogen and stores it in a compressed storage tank was designed and optimized using the Transient System Simulation Program (TRNSYS) and Generic Optimization Program (GenOpt) Packages.[24]

A summary of some of the various processes used in Power-to-Gas systems by other researchers is given in Table 3.1.

Table 3.1: Summary of Previous Methods

Reference	Method used	Strength	Weakness
[2]	Fuzzy logic, TOPSIS, and Dematel-TOPSIS— and Model Predictive Control approach	Two methods able to deal with a complex optimization problem	Needs accurate data to give accurate results
[8]	Aspen Plus	Provides an energy and exergy analysis	Only focuses on Hydrogen
[19]	Numerical Trnsys-based modeling	optimizes all design parameters and calculates each technology’s contribution.	Only focus on hydrogen
[21]	Artificial Neural Network-based surrogate Optimization	Able to determine optimal cost	Only applied in Power to methane.
[24]	Transient System Simulation Program (TRNSYS) and Generic Optimization Program (GenOpt)	Allow analysis of transient processes	Only used for hydrogen production
Proposed Method	Homer-Pro Software	Allow a combination of Hydrogen and Synthetic methane systems and provides easy and fast simulation	Since it is a hybrid system of two complex storages, a lot of parameters need to be evaluated

3.3. Method Used: Simulation using HOMER-PRO Software

Numerous techniques, some of which have been described in section 3.2, have been used to simulate and study the behavior of hybrid storage systems. So far, most simulation software

adopted is applied to a specific system section of the Power-to-Gas system and not the overall design of a hydrogen and SNG system. In this thesis, since it's a hybrid system of Hydrogen and SNG, HOMER PRO software was used to simulate and analyze the behavior of the system. Having a hybrid system of the two large storages can help in increasing flexibility as well as improving the efficiency of the system unlike adopting one system only. This helped in the easy penetration of a large renewable source, in our case PV into the grid.

HOMER-PRO simulate all the feasible configuration of the system using an original grid search algorithm and proprietary derivative-free algorithm to search for a least-cost system[25]

The HOMER-PRO algorithms can be summaries in Figure 3.1[26]

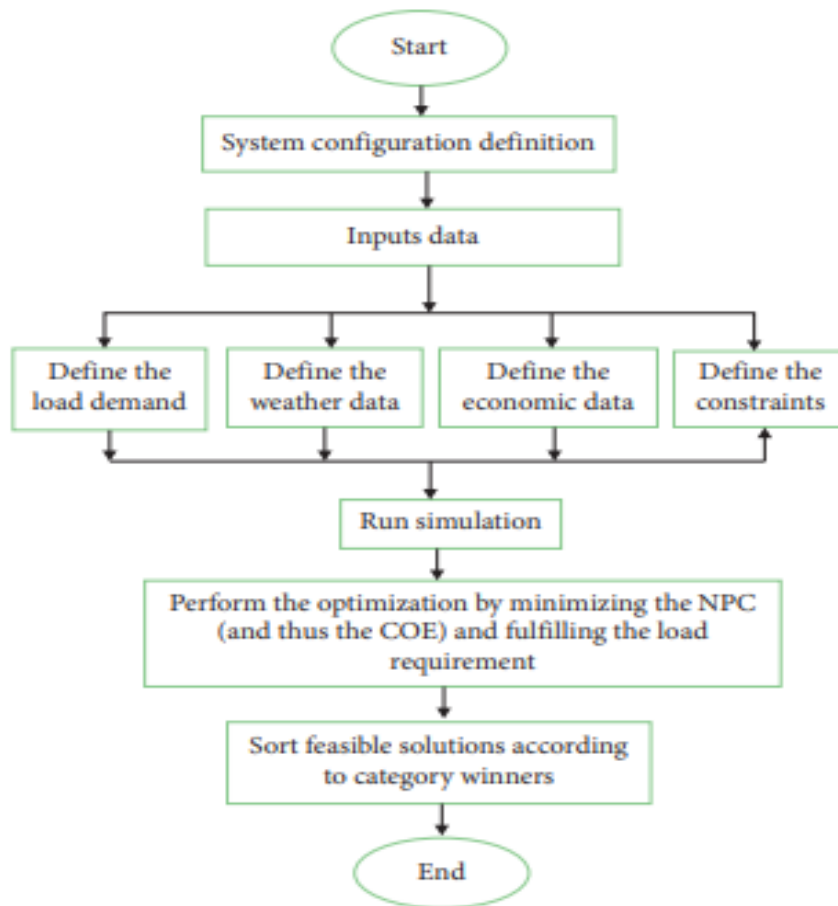


Figure 3.1: Homer Algorithm

3.4. Mapping of the Problem

The following has been done in order to implement the scope of this project

3.4.1. Site Selection

A location where the hybrid system can be implemented has been chosen. Selection of a site is important because, in the HOMER software, site data are required so as to find the weather patterns in this case insolation of the place where the project can be implemented. This provides the average insolation reaching the area of study.

The area of study in this work is the Salima district located in the central region of Malawi. It is at a distance of about 100.7km from Lilongwe district which is the capital city of Malawi. It is located along the lake shore making it one of the hottest districts in Malawi. The temperature of the district varies in the ranges of 16°C in winter to 33°C in the summer. The district is also home to a 60MW solar farm and this is the largest solar farm in Malawi.

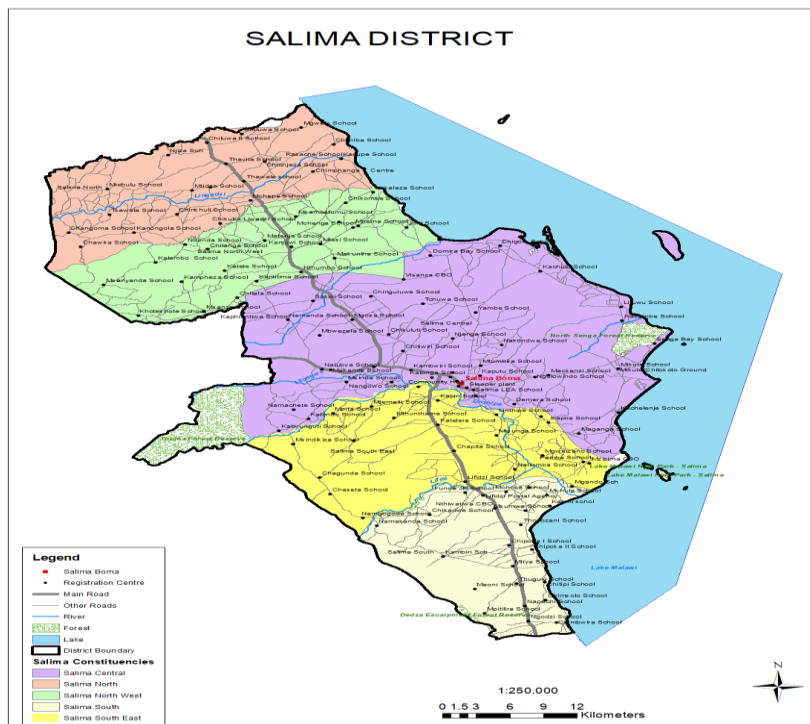


Figure 3.2: Map of Salima district (*Maps – District – Malawi Electoral Commission (mec.org.mw)*)

3.4.2. Sizing the Load and Equipment

This involves sizing the PV plant required to produce electricity to power the power-to-gas system. The process requires sizing the electrolyzer, storage, methanation, and other equipment.

Load sizing

The system has been designed to supply power to a community with 10000kWh/day of energy demand and a peak of 1460.39kW. It is assumed in this work that the electricity produced is used by households with normal loads and normal electricity uses like lighting, and powering electrical appliances like phones, TVs, radios, and cookers among others.

Sizing Systems Equipment

a) PV array

PV cell or Photovoltaic is a device that produces electricity in the form of DC current from sunlight. It is made up of semiconductor materials the common one being Silicon. This semiconductor material absorbs photons from sunlight and releases electrons. PV cell comes in 2 main categories; Monocrystalline which is made up of a single crystal structure and Polycrystalline PV cell made from multiple small crystals. PV cells are combined together to form a PV module, a combination of PV modules form a PV array and A PV array or module combines with other components like an inverter that converts DC to AC electricity and also battery storage form a PV system. In this work, a large PV array combines with Hydrogen and SNG storage to form a large PV system.

In this work, a 30000kW-capacity-Flat plate PV size has been used. It has an efficiency of 17.50%, an Operating temperature of 45°C, a derating factor of 96%, and a lifetime of 25 years, which is also the project's lifetime. \$600,000, \$30,000, and \$1000 are the capital, replacement, and maintenance costs respectively. It is abbreviated as SM500 according to the manufacturing company.

b) Electrolyzer

The process of splitting water to produce hydrogen and oxygen gas in a process called electrolysis is facilitated by using electrolyzers. In electrolyzers, there is an electrolyte that is a liquid that conducts electricity and electrodes that facilitate electrolysis reaction. The electrodes come in two forms, negatively charged electrodes called Cathodes where hydrogen is produced, and positively charged electrodes where oxygen is produced. In this work electricity from the PV array is used in the electrolyzer to split water into oxygen and hydrogen gases.

An electrolyzer with 15 years lifetime and 85% efficiency have been used in this work it has a capacity of 8000kW and its associated capital cost is \$500000, replacement cost is \$500000 and maintenance cost are \$100 because it requires minor maintenance.

c) Hydrogen Storage

Hydrogen produced by the electrolyzer needs to be stored for later use in the fuel cell or methanation process. Storage of hydrogen is very crucial because of how light and how flammable the gas is. In this work, compressed hydrogen storage has been employed. Strong storage tanks are needed when storing compressed hydrogen to withstand high pressures.

A 10000kg (10 Ton) storage tank has been used and it has a capital cost of \$50,000 and a \$100 maintenance cost per year.

d) Generator

A generator produces electricity by using different kinds of fuels ranging from liquid fuels like diesel to gas fuels like hydrogen or methane. Fuel cells are a type of generator that uses hydrogen and oxygen to produce electricity through an electrochemical reaction. The use of fuel cells is a clean way of producing electricity since the byproduct of this reaction is water.

In this work, the generator uses stored hydrogen and has a lifetime of 84000hrs. Its capital cost is \$500000 with an operation and maintenance cost of \$28.89 per operation hour. The fuel price is \$1.3 per kg. It is abbreviated as AVUS 2.5 in HOMER-Pro software.

3.4.3. Analyzing the System with Hydrogen Storage Only

This system consists of the load, the grid, the converter, the PV, the electrolyzer, the hydrogen storage tank, and the grid. The PV energy is utilized by the electrolyzer to split water and generate hydrogen gas, which is then stored in a storage tank. When there is no sunshine, this hydrogen is utilized to generate power to supplement the grid. This system was designed and simulated in HOMERPRO and its economics, emission and system performance have been analyzed.

3.4.4. Analyzing SNG System Only

This system consists of the load, the grid, the converter, the electrolyzer, PV and the generator. In this system, hydrogen produced by the electrolyzer combines with CO₂ to form Methane or SNG which is burned in the generator to produce electricity. The design and simulation of this system have been done to find the system's performance and emissions.

3.4.5. Analyzing a Hybrid System of the Two Storage Systems

This system consists of the load, the grid, the converter, the electrolyzer, PV, the hydrogen tank and the generator. In this system, some hydrogen produced by the electrolyzer is used in fuel cells to provide electricity to the grid while some hydrogen combines with CO₂ to form Methane or SNG which is burned in the generator to produce electricity. The system with all these components is designed and simulated in HOMERPRO and the behaviors of the system have been analyzed.

3.4.6. Choosing an Optimal Hybrid System

Since HOMER provides the best configuration of the system, the optimal design will be based on whether large renewable energy penetration can be achieved in the two storages implemented together.

3.5.Design validation

The designed systems have been evaluated in terms of performance of the systems; how much energy is produced from the systems and the level of renewable penetration each system has

into the grid. Economic validation has been performed in terms of Levelized Cost of Energy, Payback period and Internal Rate of Return. The emissions; carbon dioxide, carbon monoxide, Sulphur dioxides and nitrogen oxides have been evaluated from each system to determine which system has the lowest possible emission.

3.6. Coupling Mechanisms

There are 3 ways in which HESS is coupled together. Direct DC coupling is the first coupling technique. This is simpler and cost-effective it does not require a lot of components. The disadvantage of this technique is that there is little control of power flow and energy management which results in improper utilization of the storage. Using a bidirectional DC-DC converter is the second coupling mechanism used in HESS. The advantage of this mechanics is that the converter can be connected to higher energy storage hence protecting the storage from peak power and fast fluctuations of load. The challenge of this mechanism is the fluctuations of the DC bus Voltage. The third coupling mechanism is two DC/DC converters. The two DC/DC converters allow proper voltage regulation of the DC bus and this allows operation of the higher power storage system in a broader voltage band and this helps in better utilization of the storage capacity. The disadvantage of this coupling mechanism is its complexity and it is associated with higher cost than the other first two techniques[27]

3.7. Conceptual Framework

The flow of the whole work done in this research is given in Figure 3.2 below;

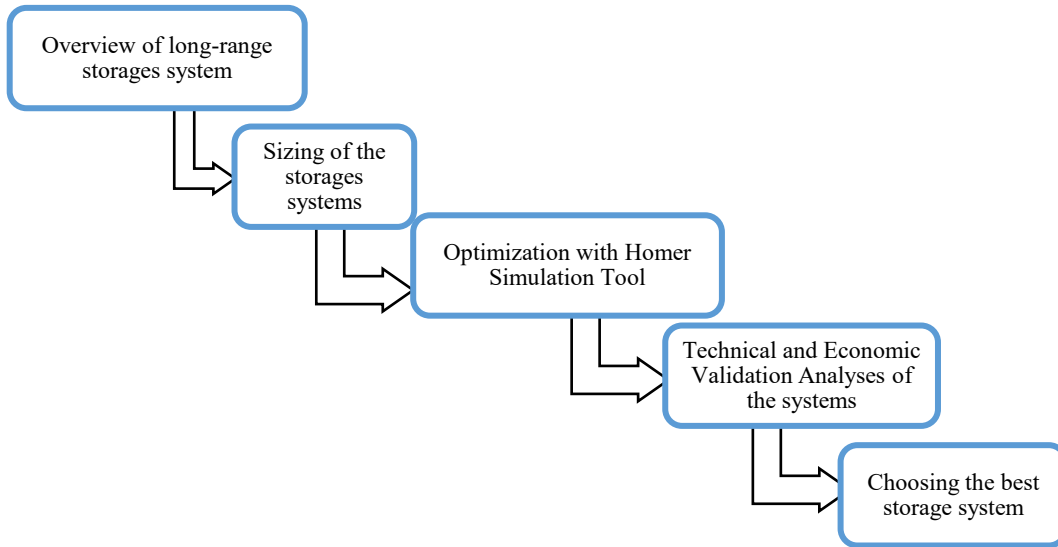


Figure 3.3: Conceptual Framework

3.8.Chapter Conclusion

This chapter provided a summary adopted by other researchers in analyzing Hydrogen or SNG systems. Most methods used were in the form of new system models as well as simulation tools like ASPEN and Homer to analyze the systems. The proposed method and the simulation tool used in this work have been explained in this section as well as the framework, mapping of the problem, and a case study to which this research can be applied.

CHAPTER FOUR

4. Results and Analysis

4.1. Chapter Introduction

This chapter provides the results and results analysis of the simulations. Modeled systems and their detailed analysis are all provided in this chapter. This chapter also contains the economic validation and environmental validation of the systems. A comparison of the results obtained in this work with other results from other researchers has been highlighted in this work as well. The last section of this chapter is a conclusion.

4.2. Modeled Systems

Figure 4. 1 shows a hydrogen system modeled in HOMER software. This system consists of the load, the grid, the converter, the PV, the electrolyzer and the hydrogen storage tank. This system all the systems are grid-connected. The PV is used to balance the system and reduce the cost of operating the grid only. The energy from the PV is used by the electrolyzer to break water to produce hydrogen gas which is stored in the storage tank. This hydrogen is used in times when there is no sunlight to produce electricity which complements the grid.

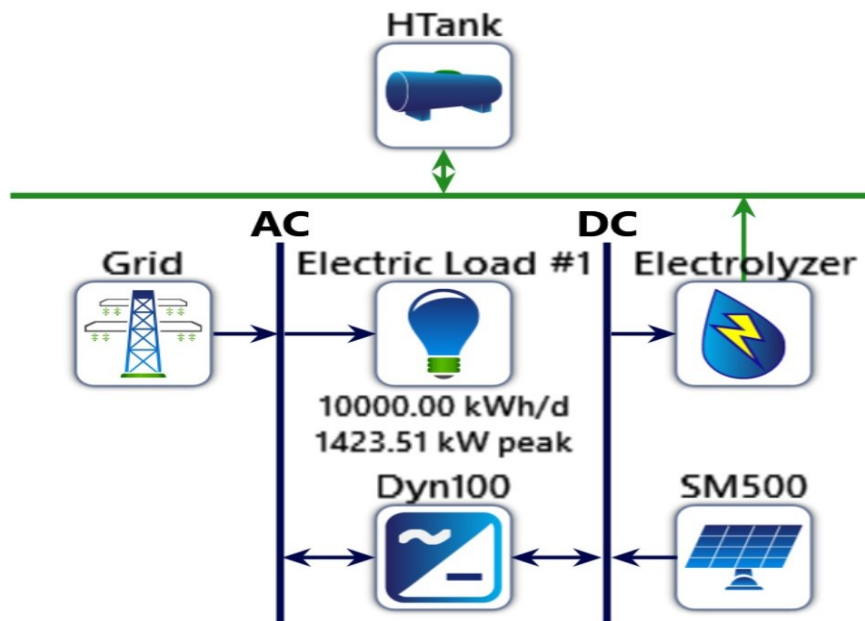


Figure 4.1: Hydrogen System

Figure 4.2 is the SNG system. This system consists of the load, the grid, the converter, the electrolyzer, PV and the generator. In this system, hydrogen produced by the electrolyzer combines with CO₂ to form Methane or SNG which is burned in the generator to produce electricity.

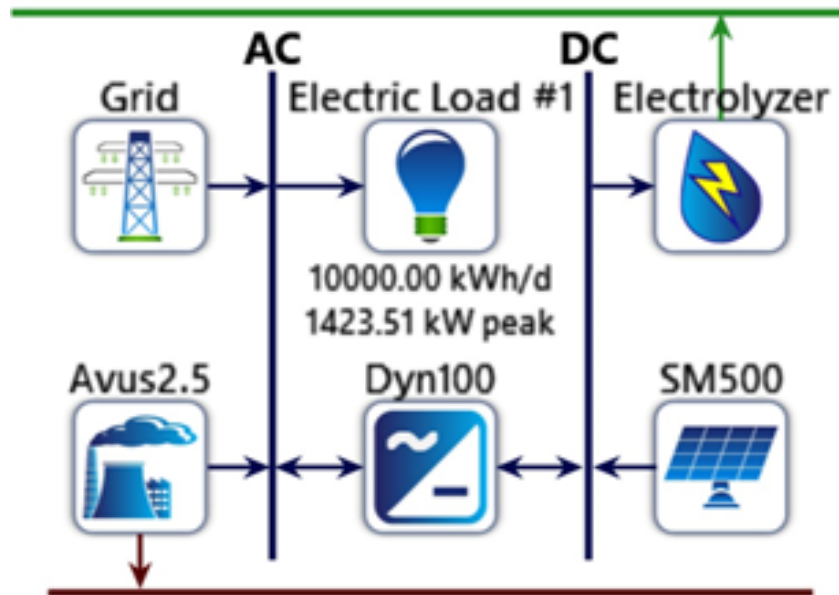


Figure 4.2: SNG System

A hybrid system combining hydrogen and SNG is shown in **Figure 4.3**. In this system, both hydrogen and SNG can be used in times when solar is not available to complement the energy from the grid. The hydrogen used comes from the electrolyzer which is powered by the energy from the PV during the afternoon.

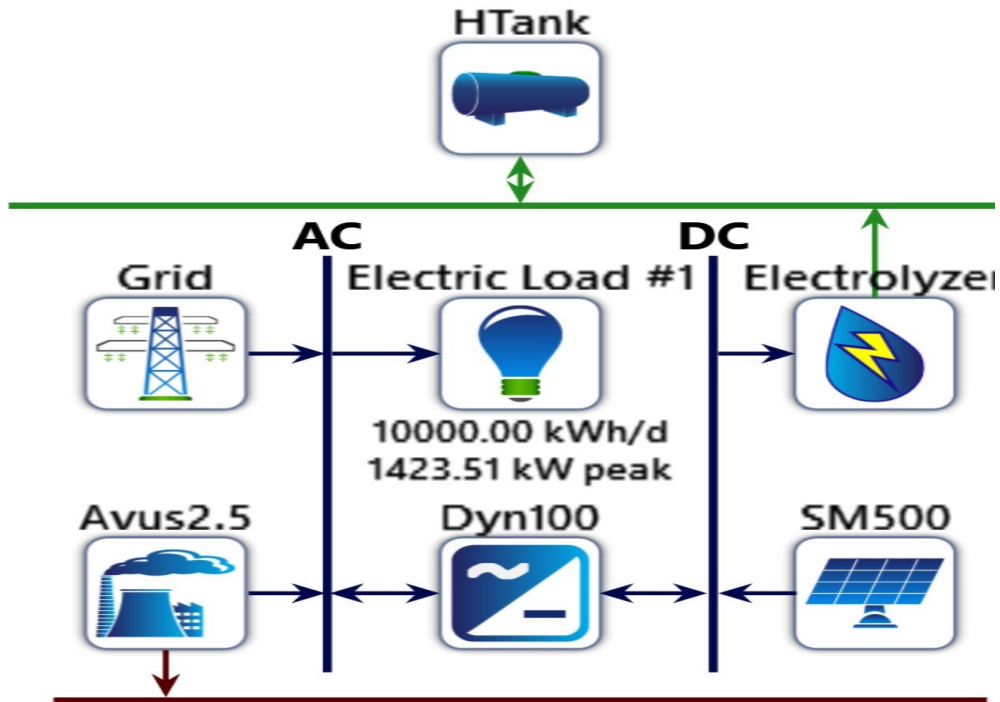


Figure 4.3: Hybrid System

The models in **Figures 4.1, 4.2 and 4.3** differs in the way energy is stored. In **Figure 4.1**, energy is stored in the form of hydrogen gas only, in **Figure 4.2** it is stored in the form of synthetic natural gas and in **Figure 4.3** energy is stored in both hydrogen and synthetic natural gas.

4.3.Case Study: Salima District in Malawi

The area of location was chosen to be Salima District (**6FC5+5FC, Salima, Malawi (13°46.8'S, 34°27.5'E)**) located in the central region of Malawi. It was chosen because of the area's climatic conditions and where Malawi's largest Solar power plant (60MW) is located.

The Global Solar Horizontal Irradiation was taken from an online source; the National Renewable Energy Laboratory Database. The average solar irradiation at the site is 5.47kW/h/m²/day and the average temperature is 23.06°C. **Figure 4.4** shows the irradiation and clearness of the area of study, and **Figure 4.5** shows the temperature of the site.



Figure 4.4: Average Monthly Solar Irradiation of the site

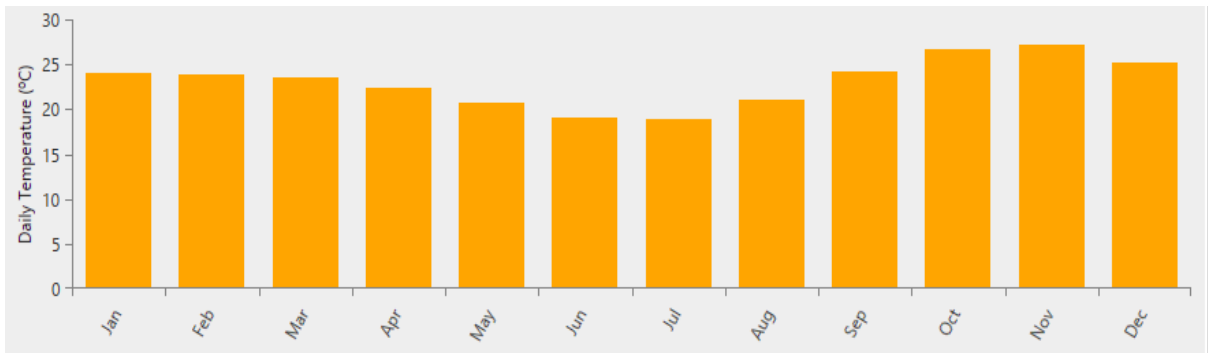


Figure 4.5: Average Monthly Temperature of the Site

The load was set at 10000kWh/day with a peak of 1423.51kW. The season load profile is presented in **Figure 4.6** with the highest load in the months of April to September as this is the winter season in the region.

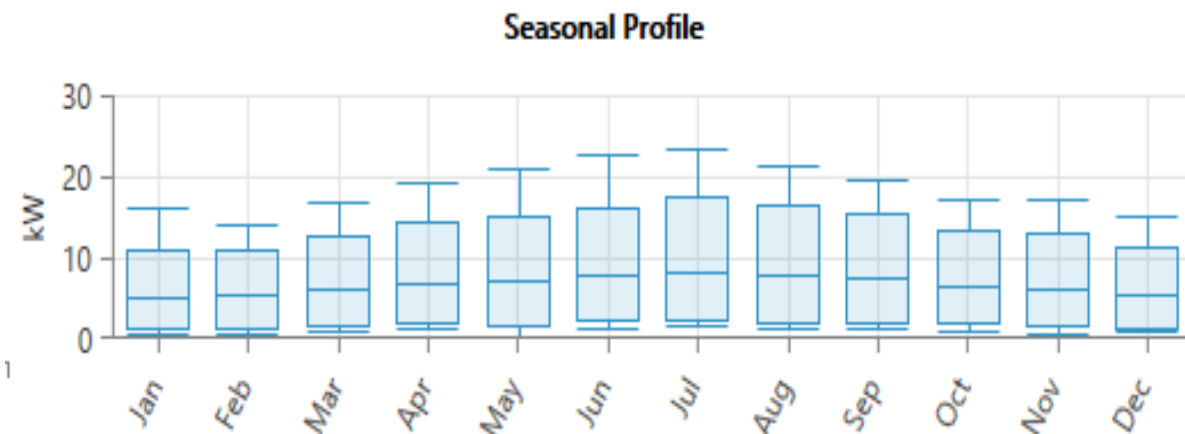


Figure 4.6: Seasonal Month Load Profile

Table 4.1. provides a summary of all the components of the hybrid system. The component's size and specifications. **Table 4.2** shows the prices of various components inputted in HOMER. The machine rating was taken considering the size of the system and the corresponding prices were also taken from the component's websites as presented in the components data sheet provided in HOMER.

Table 4.1: Summary of Components Used in the Whole System

Component	Name	Size	Unit
Generator	CCGT	2,500	kW
PV	Solar Max 500RX A with Generic PV	300,000	kW
PV dedicated converter	SM500 converter	500	kW
System converter	Dyna power SPS – 100	534	kW
Grid	Grid	999,999	kW
Electrolyzer	Generic Electrolyzer	80,000	kW
Hydrogen tank	Hydrogen Tank	10,000	kg
Dispatch strategy	HOMER Cycle Charging		

Table 4.2: Cost of Each Component Used in the System Imputed in Hybrid

Components	CAPEX (\$)	Replacement Cost (\$)	OPEX (\$)	Lifetime (Years)
Generator	500,000	775,000	11914	840000hrs
PV	600,000	0	30,000	25
PV dedicated converter	30,000	30,000	0	15
Grid	0	0	2,383,656.15	25

Electrolyzer	500,000	500,000	100	15
Hydrogen tank	50,000	0	100	25

Simulation results for the various cases are discussed in Sections 4.4 to 4.6

4.4. Hydrogen System

Figure 4.7 shows the amount of electricity produced by the hydrogen system. In this system, the PV produces 2194978kWh and from the grid is 1880319kWh. The AC load consumption in this system is 3650000kWh. **Figure 4.8** show the hydrogen produced by the Electrolyzer in a year from the hydrogen system.

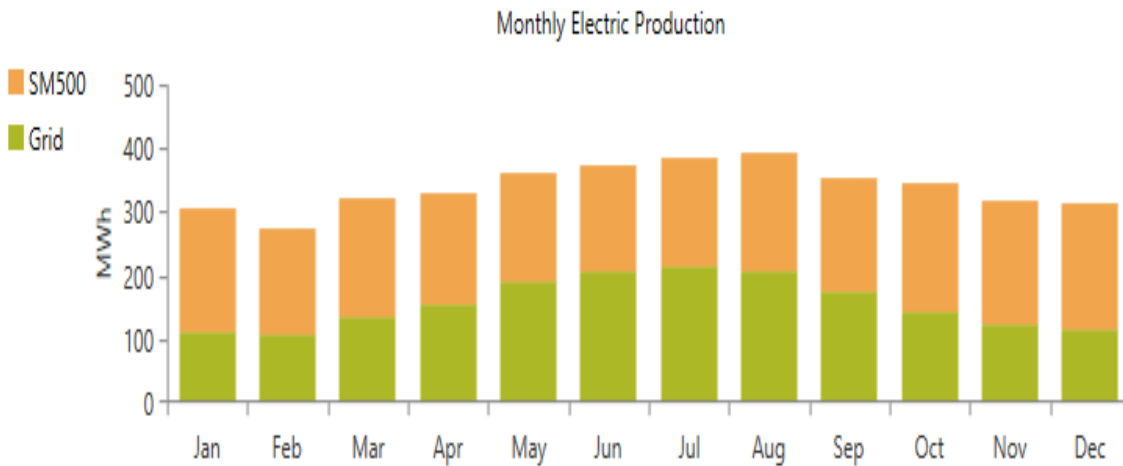


Figure 4.7: Sources Serving Load in a Hydrogen System

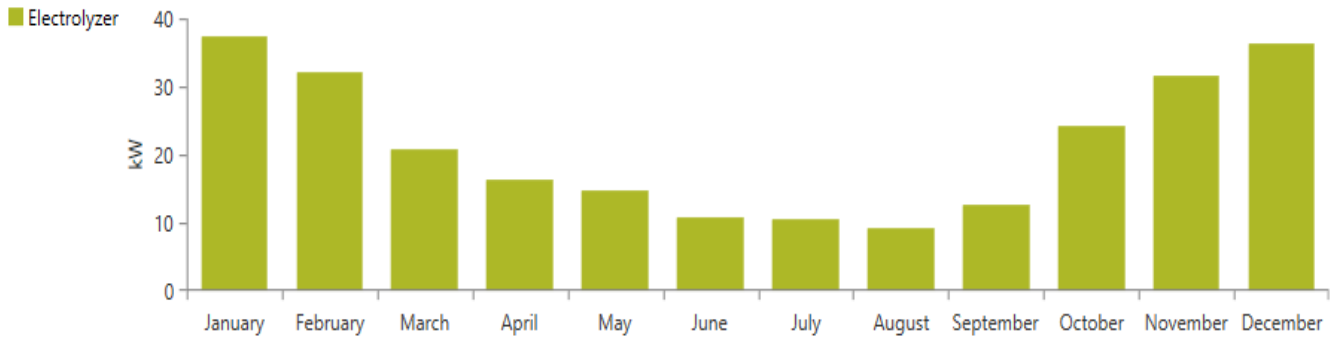


Figure 4.8: Electrolyzer Hydrogen Distribution

The Generic Electrolyzer has a rated capacity of 80,000 kW. The total annual production is 7,782 kg/yr. The electrolyzer input power is illustrated in **Figure 4.9**. From the simulation in HOMER, the mean electrolyzer input is 41.2KW, the maximum input is 433KW and the total input energy for the generic electrolyzer is 36112kWh/hr.

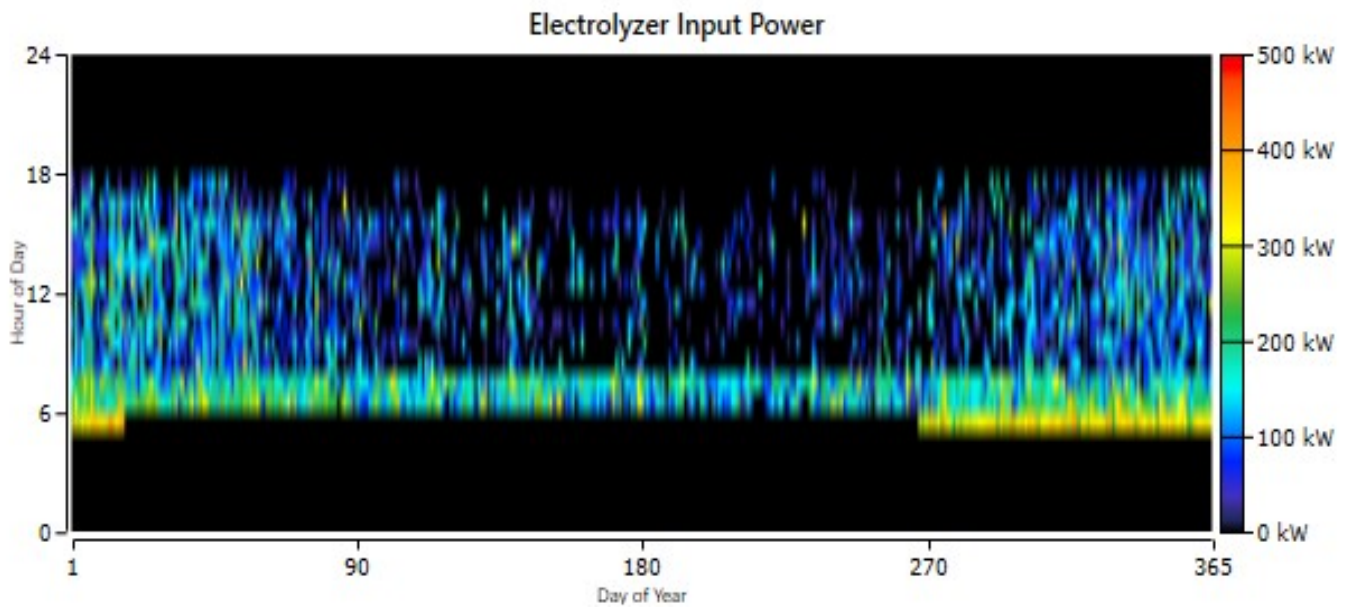


Figure 4.9. Electrolyzer Input Power

4.3.1. Comparison of the Hydrogen system with the base system

Table 4.3 gives the economic comparison of the hydrogen system with that of the base system comprising the grid only. The simple payback years of the project is 6.55 years with an internal rate of return of 13.9%.

Table 4.3: Cost Comparison of Hydrogen System and Base

Metric	Value
Present worth (\$)	\$949,294
Annual worth (\$/yr)	\$73,432
Return on investment (%)	10.1
Internal rate of return (%)	13.9
Simple payback (yr)	6.55
Discounted payback (yr)	8.51

The proposed hydrogen system has a renewable penetration of 48.5%, the NPC is \$3,769,250, a payback period of 6.55 years, an internal rate of return of 13,9% and an LCOE is \$0.07988. **Table 4.4.** highlights the emissions produced by the hydrogen system. The notable emissions from this system are CO₂ which is 1,188,362kg/year, 5152kg/year of Sulfur Dioxide, and 2520 kg/year of Nitrogen oxide.

Table 4.4: Emissions from the Hydrogen Storage

Quantity	Value	Units
Carbon Dioxide	1,188,362	kg/yr
Carbon Monoxide	0	kg/yr
Unburned Hydrocarbons	0	kg/yr
Particulate Matter	0	kg/yr
Sulfur Dioxide	5,152	kg/yr
Nitrogen Oxides	2,520	kg/yr

4.4.SNG system

Figure 4.10 shows the amount of electricity the SNG system produces. In this system, the PV produces 2194978kWh from the grid is 1880319kWh and 0 from the generator. The AC load consumption in this system is 3650000kWh. There is an unmet load of 0. The electrolyzer energy input is shown in **Figure 4.13**. Just like the hydrogen system, this electrolyzer in the SNG system has a mean electrolyzer input is 41.2KW, a maximum input is 433KW, and a total input energy for the generic electrolyzer is 36112kWh/hr.

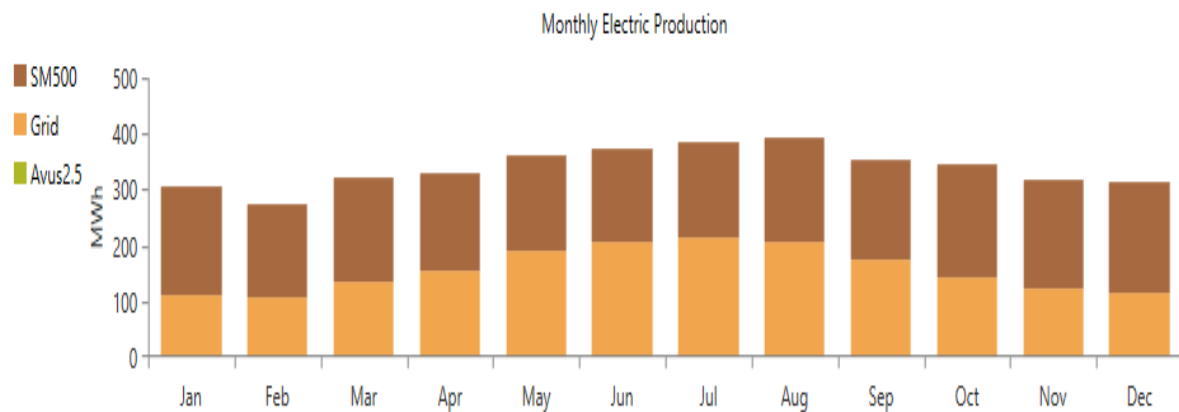


Figure 4.10: Sources Serving Load in an SNG System

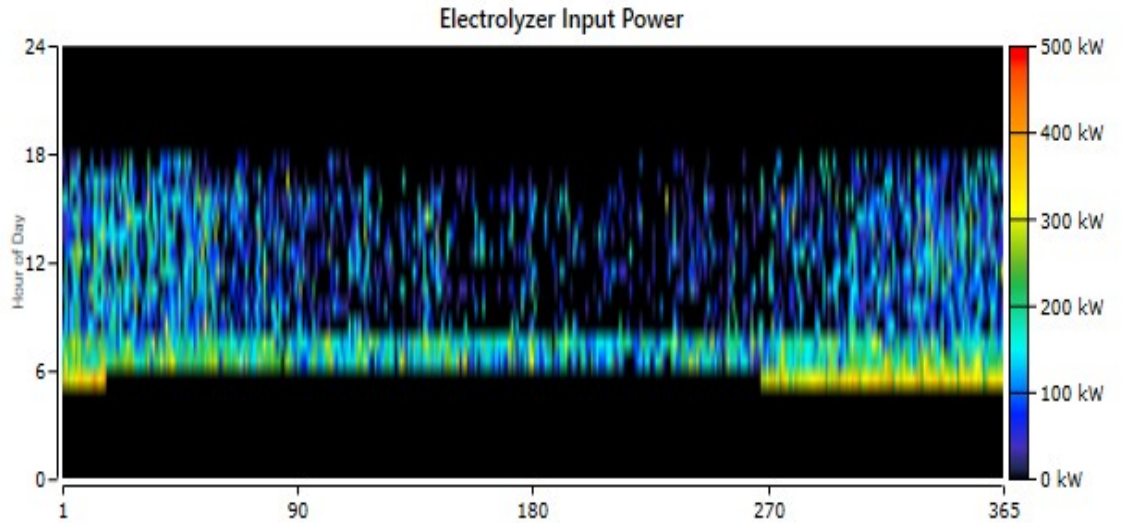


Figure 4.11: Electrolyzer Parameters

4.4.1. Comparison of the SNG system with the base system

Table 4.5. gives the economic comparison of the hydrogen system with that of the base system comprising the grid only. The simple payback years of the project is 9.1 years with a rate of return of 8.0%. The SNG system allows 48.5% renewable penetration just like the Hydrogen system but has an NPC of \$4,036,942 and LCOE is \$0.08555.

Table 4.5: Cost Comparison of the SNG System and Base

Metric	Value
Present worth (\$)	\$681,602
Annual worth (\$/yr)	\$52,725
Return on investment (%)	8.0
Internal rate of return (%)	9.7
Simple payback (yr)	9.10
Discounted payback (yr)	13.42

Emissions from the system are highlighted in Table 4.6 with the notable emissions being 1,188,362 kg/year of carbon dioxide, 5152kg/year of sulfur dioxide, and 2520kg/year of Nitrogen oxides

Table 4.6: Emissions from the SNG storage

Quantity	Value	Units
Carbon Dioxide	1,188,362	kg/yr
Carbon Monoxide	0	kg/yr
Unburned Hydrocarbons	0	kg/yr
Particulate Matter	0	kg/yr
Sulfur Dioxide	5,152	kg/yr
Nitrogen Oxides	2,520	kg/yr

4.5. Proposed Hybrid System: Having Both Hydrogen and SNG

The results of the proposed hybrid system are shown in **Figure 4.12**. From this system, the PV produces 2194978kWh of electricity, 52003kWh comes from the generator, and 1840755kWh comes from grid purchases. All this production meets the AC load consuming 3650000kWh of energy. There is 0 unmet load in this system. The hydrogen output from the electrolyzer in terms of power is given in **Figure 4.13**. The electrolyzer from this system has a mean energy input of 40.5KW with a maximum being 1048KW and 0 minimum energy input. This is illustrated in **Figure 4.14**

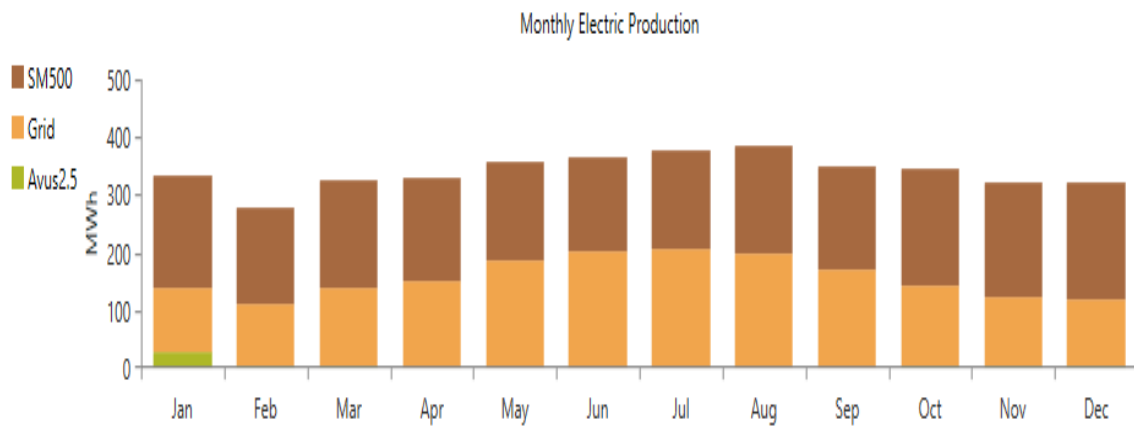


Figure 4.12: Sources Serving Load in a Hybrid System

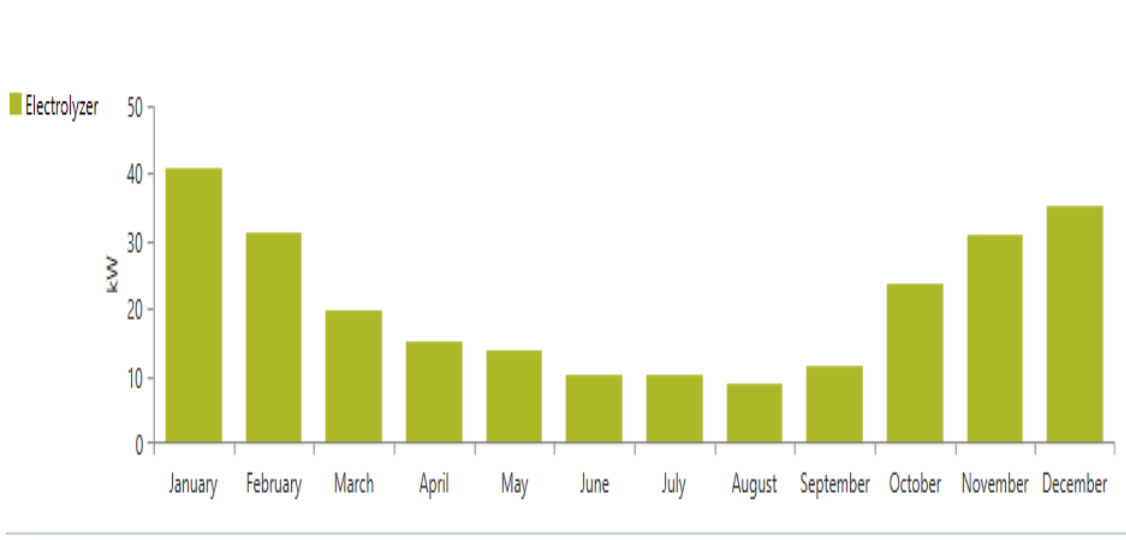


Figure 4.13. Hydrogen From Electrolyzer

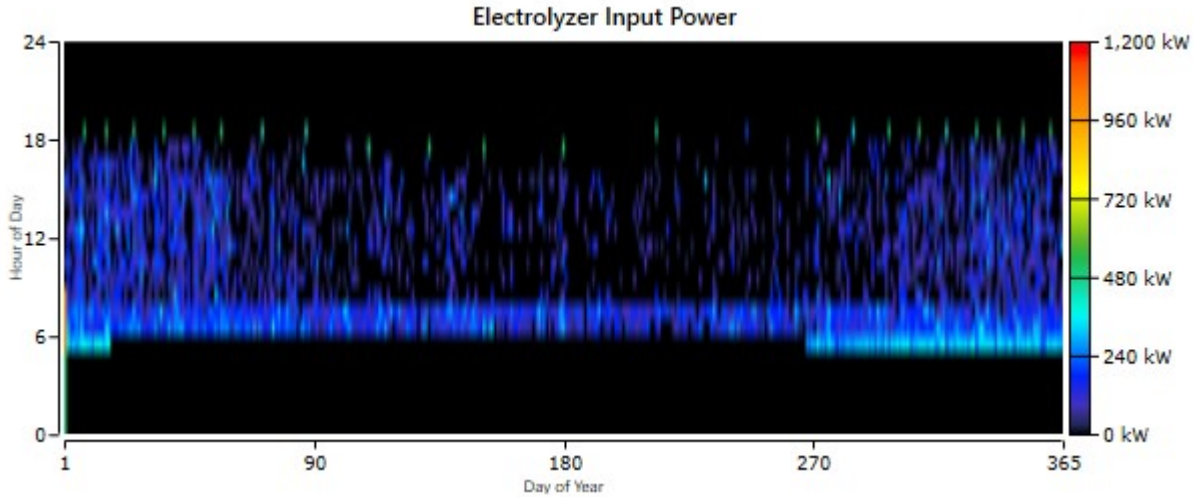


Figure 4.14: Electrolyzer Parameters of the Hybrid System

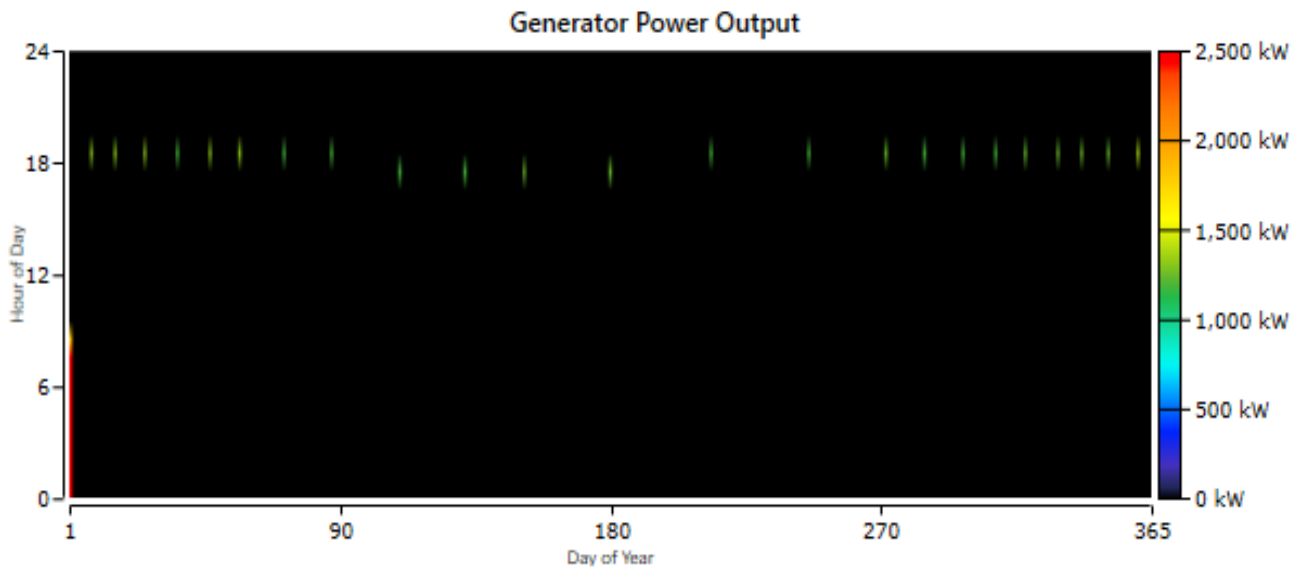


Figure 4.15: Generator Parameters

Figure 4.15 illustrates the generator power output. The generator’s electricity generation of 52003kWh/yr. The mean electrical output is 1624kW with a maximum of 2500kW and minimum electrical output of 2500kW

4.5.1. Comparison of the Hybrid system with the Base system

Table 4.7. gives the economic comparison of the hybrid system with that of the base system comprising the grid only. The simple payback years of the project is 9.26 years with a rate of

return of 7.8%. The system allows 49.2% renewable penetration, has an NPC of \$4,065,423, and a levelized cost of \$0.08569

Table 4.7: Cost Comparison of Hybrid system and Base System

Metric	Value
Present worth (\$)	\$660,872
Annual worth (\$/yr)	\$51,121
Return on investment (%)	7.8
Internal rate of return (%)	9.5
Simple payback (yr)	9.26
Discounted payback (yr)	13.77

The hybrid system comprising the hydrogen and SNG systems has emissions such as 1,165,078kg/year carbon dioxide, 4082 kg/year of carbon monoxide, 5079kg/year sulfur dioxide, and 3300kg/year of nitrogen oxides as highlighted in Table 4.8 and carbon dioxide is less than all other systems

Table 4.8: Emissions from the SNG storage

Quantity	Value	Units
Carbon Dioxide	1,165,078	kg/yr
Carbon Monoxide	4,082	kg/yr
Unburned Hydrocarbons	0	kg/yr
Particulate Matter	0	kg/yr
Sulfur Dioxide	5,079	kg/yr
Nitrogen Oxides	3,300	kg/yr

Tables 4.3, 4.4, 4.5, 4.6, 4.7, 4.8. were the results taken from simulating the designed systems in HOMER software. Homer software provides the economic comparison table results and the emissions table results of the designed systems and the base system.

From the systems designed, especially the SNG and hybrid system, AVUS 2.5 does not provide power and only provides power in January respectively because according to the simulation results, operating a combined cycle gas turbine (AVUS 2.5) results in a more costly system because of the additional methanation processes and operations to change SNG back into electricity. These processes also come with a reduced efficiency because of the methanation and combustion processes. This means the hydrogen is the one acting as storage and providing back the electricity to a great extent as compared to SNG

4.6.Results Validation

4.6.1. Economic Validation

From the modeling and simulations, 3 systems have been modeled, one with a Hydrogen system, one with a synthetic natural gas system, and one is a hybrid system with all the systems combined. All systems were modeled to serve a load of 10000kWh/day and peaks of 1423.51kW in Salima Malawi. Salima district is located in the Central region of Malawi. The area has been chosen because it has a good average temperature and experiences sunlight throughout the whole year. It is also home to an 80MW solar power plant in Malawi, the biggest of all Solar power plants.

From the results, the hydrogen system is composed of an electrolyzer, hydrogen storage, PV, converter, load, and grid and has the lowest payback period of 6.55 years and the lowest COE of \$0.07988. This is because the components used in the system are few compared to SNG and hybrid systems. This system allows 48.5% renewable penetration to the grid

The SNG systems contain all the components like the hydrogen system except the hydrogen storage tank and have an additional generator to act as a combined gas turbine to produce electricity. It has a payback period of 9.11 years and has a COE of \$0.08555 and just like the hydrogen system, allows 48.5% of renewable penetration.

The hybrid system contains all the components in the hydrogen and SNG. It has a payback period that is slightly above the SNG system at 9.26 years and its COE is \$0.08569. This system allows 49.4% of renewable energy penetration which is above the first two systems.

This renewable energy penetration is achieved mainly by the SM500 which stores its energy in form of hydrogen and SNG. Power produced by SM500 is the one used in the production of hydrogen and SNG. When there is no sunlight, the stored hydrogen and SNG is converted back to electricity and this is integrated back into the grid for continued supply of electricity. This process enhances the grid stability because storing the solar power produced by SM500 ensures there is constant supply of energy into the grid even when there is no continuous sunlight.

All these systems have been compared to a base system composed of the grid only supplying the whole load. The base system has a COE of \$0.1000 which is above all the system modeled.

Table 4.9 gives a cost comparison of the different systems designed in HOMER. All the systems are compared to the base system comprising the grid only.

Table 4.9: Economic Comparison of the systems with the base system

COST PARAMETERS	HYDROGEN SYSTEM	SNG SYSTEM	HYBRID SYSTEM	BASE SYSTEM
Net Present Cost	\$3.77M	\$4.04M	\$4.06M	\$4.72M
CAPEX	\$1.15M	\$1.60M	\$1.65M	\$0.00
OPEX	\$202,569	\$188,467	\$186,188	\$365,000
LCOE (per kWh)	\$0.0799	\$0.0856	\$0.0857	\$0.100
Renewable Solar Penetration	48.5%	48.5%	49.4%	0%

4.6.2. Technical Validation

a) Energy density

Energy density is the amount of energy released by a fuel per kg or volume of the fuel used. In the case of the system, the two fuels used, Hydrogen and SNG, hydrogen has a higher gravimetric (mass) energy density as compared to the SNG. [28] recorded that hydrogen stored in a compressed has a gravimetric density of 143MJ/kg and a volumetric density of 5.6MJ/L while natural gas has a mass density of 53.6MJ/Kg and a volumetric density of 0.0364MJ/L.

b) Storage Efficiency

Both SNG and Hydrogen storage efficiencies are generally excellent due to the negligible energy loss during storage. However, hydrogen has some losses during compression, liquefaction, and electricity conversion. SNG has a reasonably high storage efficiency since there are no substantial energy losses during storage and it is easy to store SNG at room standard conditions than hydrogen. This makes hydrogen's overall storage efficiency lower and more costly than the overall storage efficiency of the SNG. The hybrid system allows compensation of both systems in terms it reduces the storage of hydrogen which is more costly by changing some of it to SNG which can be stored more cheaply and efficiently.

c) Self-Discharging

Having a hybrid of SNG and hydrogen means that the energy can be used for seasonal energy planning. Both SNG and Hydrogen have the smallest self-discharge rate ranging from 0.003-0.3% discharge rate per day [27]

d) Charging Time

For hydrogen, the electrolyzer is the main component used in its production and can be stored in the storage tank which is used later. SNG requires the use of a methanation tank to combine CO₂ and the hydrogen produced from electrolysis to produce SNG [29]. This makes the charging time of SNG longer than the one for Hydrogen. A hybrid system is better because when no SNG is available, stored hydrogen can provide energy when SNG is unavailable. **Table 4.10** summaries the technical aspects of the hydrogen and SNG.

Table 4.10: Summary of Technical Parameters of the Hydrogen and SNG

Parameters Systems	Energy Density (Gravimetric density)	Storage Efficiency	Self-Discharging	Charging Time
Hydrogen	143MJ/kg	Lower storage Efficiency due to compression losses but more costly because of the storage facility	0.003%-0.3% per day	Lower than SNG since the production component is the electrolyzer only
SNG	53.6MJ/kg	Higher storage efficiency since it can be stored at room temperature and is cheaper than H2	0.003%-0.3% per day	Higher as compared to H2 because of the long process of producing SNG
Hybrid Systems	Has the capability of both the SNG and Hydrogen since both storages are present	Above moderate efficiency	0.003%-0.3%	Moderate Charging time

4.6.3. Environmental Validation

Table 4.11 gives a comparison of the emissions for all systems. Emissions are one of the parameters that Homer Pro uses as well to find a feasible system. The most notable emissions from all the systems are CO₂, CO, sulfur dioxide, and Nitrogen oxide

Table 4.11: Emission Comparison of the Systems

Systems	Hydrogen	SNG	Hybrid	Base System
Emissions				
Carbon Dioxide	1188362kg/yr.	1188362kg/yr.	1165078kg/yr.	2306800kg/yr.
Carbon Monoxide	0	0	4082kg/yr.	0
Sulfur Dioxide	5152 kg/yr.	5152 kg/yr.	5079kg/yr.	10001kg/yr.
Nitrogen Oxide	2520kg/yr.	2520kg/yr.	3300kg/hr.	4891kg/yr.

It can be noted that Carbon dioxide emission is the lowest in the hybrid as compared with the other systems. The hybrid system's CO₂ emission is 49.4% lower than the base system. This is indicating that a hybrid storage system has the ability to decrease the emissions of a base system that is made up of conventional sources of energy. Sulfur Dioxide and Nitrogen Oxide are also lower in the hybrid system as compared to the base. Although Nitrogen Oxide emission is slightly higher in the hybrid system than in the hydrogen and SNG systems. In the hybrid system, Carbon Monoxide is emitted due to the combustion of the SNG. This can be reduced by using this Carbon Monoxide in the methanation process, making this system have a zero-carbon footprint.

4.6.4. Comparing with other existing Systems

The results show that a hybrid system containing hydrogen and SNG can reduce the COE and the environmental emissions of an energy system that does not have these hybrid storages. In this study, a large PV power plant hybrid system has shown that it can result in a 14.3% reduction of the COE and allows a 49.4% of renewable energy penetration into the grid. A hybrid system containing hydrogen and SNG with PV has also shown that it can reduce emissions of carbon dioxide by 49.5% from 2306800kg/yr. with no hybrid system to 1165078kg/yr. with the hybrid storage system. The NPV of the hybrid system has also reduced from \$4.72 Million to \$4.06 representing a 14% decrease. A study done by [30] concurs with

these results. This study found that having a hybrid fuel cell with PV can reduce NPC and environmental emissions and allows a huge renewable penetration. In this study, the load was a laboratory with a peak load of 61kWh/d. The results from this study showed that this system can achieve a reduction of 88% in terms of cost and achieves a 96.7% renewable energy penetration. This system proved that it can reduce emissions because hydrogen fuel is cleaner than conventional fuel. Similar results were found in [31]. From this study, the results showed that incorporating hydrogen with solar systems powering a science block in India resulted in a huge renewable penetration and also reduced the emissions

Table 4.12: Summary of the Comparison of the Hybrid System with other Systems.

	Aim	Level of renewable Penetration	Cost saving	Changes in Emissions (CO₂)
[30]	Size optimization of a hybrid system of hydrogen fuel cells with PV and grid to supply the electric load of a laboratory	96.7%	88%	98.71% reduction in emissions
[31]	Designing and evaluating a stand-alone solar-hydrogen energy storage system for academic institute: A case study	358%	NA	-NA
Designed Hybrid system	Designing of a hybrid system of PV with storage for large renewable penetration	49.4%	14%	49.5% reduction

4.7.Sensitivity Analysis

The hybrid system was designed with electrolyzers having a lifetime of 15 years and an efficiency of 85%. In power-to-gas systems, the process of splitting water- electrolysis is deemed to be the most expensive sub-section of the process because of the technology behind the electrolyzers and the storing of hydrogen because of its low density. In order to reduce the

overall cost of P2G systems, more research needs to be done around the electrolysis process so as to reduce the cost associated with this process and also increase the lifetime of the electrolyzers. A sensitivity analysis was done to test how increasing the lifetime of electrolyzers can have an effect on the overall cost of the project. Table 4.12 gives the comparison of the electrolyzer having a lifetime of 10, 15, and 25 years

Table 4.13: Sensitivity Analysis of Changing the Lifetime of the Electrolyzers

COST PARAMETERS	HYBRID SYSTEM WITH ELECTROLYZER HAVING 10 YEARS LIFETIME	HYBRID SYSTEM WITH ELECTROLYZER HAVING 15 YEARS LIFETIME	HYBRID SYSTEM WITH ELECTROLYZER HAVING 25 YEARS LIFETIME
Net Present Cost	\$ 4.24M	\$4.06M	\$3.86M
CAPEX	\$ 1.65M	\$1.65M	\$1.65M
OPEX	\$ 200,651	\$186,188	\$ 171,115
LCOE (per kWh)	\$ 0.0895	\$0.0857	\$0.0815

Table 4.12 shows that increasing the lifetime of the electrolyzers can significantly reduce the cost of P2G systems. This is because, for example, if the project lifetime is 25 years as is usually the case with most Solar power projects, the electrolyzer has to be purchased 3 times when it has a 10 years lifespan, 2 times when its lifespan is 15 years, and once when its lifespan is 25 years. Increasing the lifespan of the electrolyzer by 5 years can decrease the NPV by 4-5%, OPEX can decrease by 7-8% and the LCOE decreases by 4-5% as well

4.8. Chapter Conclusion

This chapter provided the simulation results of our proposed system. It can be concluded that having storage systems in the grid can eventually reduce electricity costs and emissions. Having a hybrid system of SNG and hydrogen can help achieve a higher percentage of renewable penetration into the grid because the storage systems can complement the PV when the PV is not able to produce electricity. In this case, a 49.4% renewable penetration. Though the payback and COE are higher than having a hydrogen or SNG system only, having an increased penetration is better because the Payback and COE are different by a just slight amount and the COE is lower than the base system by 14%. Also compared with the base system, the hybrid system can result in consumers buying the electricity at a 14.3% lower cost than just having the grid without any storage.

CHAPTER FIVE

5. Conclusion and Recommendation

This chapter gives a summary of all the work done in this research project and it also provides the future works that can be done as an extension to this present research study.

5.1. Conclusion

This research aimed at designing and simulation a hybrid storage system comprising of Hydrogen Storage, and SNG storage coupled to a large solar energy resource so as to achieve a higher share of renewable being integrated into the grid. A thorough literature review has been done in order to provide a background of the research and also identify gaps in other similar research and some of the gaps have been addressed in this work. The literature review was done also to have a better understanding of the storage systems that are there and more also to understand and assess the capabilities of the storage systems adopted in this research.

The methodology section in this work focused on identifying how other researchers have been able to solve similar research and this provided a direction on the methods that have been adopted in this work. In order to achieve the aim of this work, the site was selected. This site is the area of focus that is needed when designing the models in HOMERPRO software. The site chosen is Salima District (6FC5+5FC, Salima, Malawi (13°46.8'S, 34°27.5'E) located in the central region of Malawi. The Global Solar Horizontal Irradiation was taken from an online source, the National Renewable Energy Laboratory Database. Three designs were modeled in HOMERPRO; a Hydrogen System, an SNG System, and a Hybrid System Comprising the two separate storages. These designs were designed to meet a load of 10000kW/day. Analysis of the 3 systems was done based on Economical Constraints, Environmental Constraints, and Technical Constraints. A sensitivity analysis was conducted on the electrolyzer. The lifetime of the electrolyzer was varied in a range of 10- 25 years in order to see how this can affect the overall cost of the system.

In conclusion, this study has shown that having storage systems in the grid can eventually reduce electricity costs and emissions. Having a hybrid system of SNG and hydrogen can help achieve a higher percentage of renewable penetration into the grid because the storage systems can complement the PV when the PV is not able to produce electricity. In this case a 49.4%

renewable penetration. Though the payback and COE are higher than having a hydrogen or SNG system only having an increased penetration is better because the Payback and COE are different by a just slight amount and the COE is lower than the base system by 14%. Also compared with the base system, the hybrid system can result in consumers buying the electricity at a 14.3% lower cost than just having the grid without any storage. This hybrid system can help in providing a dependable, sustainable, and flexible energy solution by integrating solar energy generation, energy storage, SNG production, and hydrogen consumption, contributing to a reduced reliance on fossil fuels and a transition to a low-carbon future. A system like this can also assist in solving the intermittent nature of solar electricity and give a

5.2. Recommendations

5.2.1. Further Work

In this work, HOMERPRO software was used as a simulation and analysis software. In the future other works can improve this research by:

- i). Modelling this system using other software like MATLAB, or PVSYST so as to analyze the systems.
- ii). Researching the Coupling techniques that can be adopted in Power-to-Gas Systems like the one adopted in this research.

5.2.2. Adoption of results

The results obtained in this thesis has shown that a Power-to-Gas energy system can significantly help in achieving a higher energy penetration and a reduction in system cost and environmental emissions. Other researchers and evening project managers can use the knowledge provided in this thesis in coming up with energy systems especially those using power-to-gas processes.

5.3. Contributions

The contribution of this work can be summarized as follows:

- i). The sizing of models' components, load and modeling and simulation of PtG systems of Hydrogen and SNG coupled to a Solar energy resource using HOMER software.
- ii). The economic, and environmental validation of hydrogen, SNG, and Hybrid systems and a comparison of these systems with the base system containing only the grid without any storage system.
- iii). The sensitivity analysis of the modeled system is based on the electrolyzer which is the most expensive component in power-to-gas systems. This was done by changing the lifetimes of the electrolyzer and observing the effects of this on the whole system.

References

- [1] Musau Peter Moses, “RENEWABLE ENERGY INTEGRATION,” Nov. 2022.
- [2] B. Li, H. Miao, and J. Li, “Multiple hydrogen-based hybrid storage systems operation for microgrids: A combined TOPSIS and model predictive control methodology,” *Appl Energy*, vol. 283, Feb. 2021, doi: 10.1016/j.apenergy.2020.116303.
- [3] E. Giglio, A. Lanzini, M. Santarelli, and P. Leone, “Synthetic natural gas via integrated high-temperature electrolysis and methanation: Part I-Energy performance,” *J Energy Storage*, vol. 1, no. 1, pp. 22–37, 2015, doi: 10.1016/j.est.2015.04.002.
- [4] B. Cárdenas, L. Swinfen-styles, J. Rouse, and S. D. Garvey, “Short-, medium-, and long-duration energy storage in a 100% renewable electricity grid: A UK case study,” *Energies (Basel)*, vol. 14, no. 24, Dec. 2021, doi: 10.3390/en14248524.
- [5] H. Ibrahim, A. Ilinca, and J. Perron, “Energy storage systems-Characteristics and comparisons,” *Renewable and Sustainable Energy Reviews*, vol. 12, no. 5. Pp. 1221–1250, Jun. 2008. Doi: 10.1016/j.rser.2007.01.023.
- [6] A. Awasthi, V. Karthikeyan, V. Das, S. Rajasekar, and A. K. Singh, “Energy storage systems in solar-wind hybrid renewable systems,” *Green Energy and Technology*, vol. 0, no. 9783319501963, pp. 189–222, 2017, doi: 10.1007/978-3-319-50197-0_7.
- [7] E. Bullich-Massagué *et al.*, “A review of energy storage technologies for large scale photovoltaic power plants,” *Appl Energy*, vol. 274, Sep. 2020, doi: 10.1016/j.apenergy.2020.115213.
- [8] H. Ishaq and I. Dincer, “Comparative assessment of renewable energy-based hydrogen production methods,” *Renewable and Sustainable Energy Reviews*, vol. 135, Jan. 2021, doi: 10.1016/j.rser.2020.110192.
- [9] C. Wulf, J. Linssen, and P. Zapp, “Power-to-gas-concepts, demonstration, and prospects,” in *Hydrogen Supply Chain: Design, Deployment and Operation*, Elsevier, 2018, pp. 309–345. Doi: 10.1016/B978-0-12-811197-0.00009-9.
- [10] W. L. Becker, M. Penev, and R. J. Braun, “Production of synthetic natural gas from carbon dioxide and renewably generated hydrogen: A techno-economic analysis of a

- power-to-gas strategy,” *Journal of Energy Resources Technology, Transactions of the ASME*, vol. 141, no. 2, Feb. 2019, doi: 10.1115/1.4041381.
- [11] S. Basu, A. John, Akshay, and A. Kumar, “Design and feasibility analysis of hydrogen-based hybrid energy system: A case study,” *Int J Hydrogen Energy*, vol. 46, no. 70, pp. 34574–34586, Oct. 2021, doi: 10.1016/J.IJHYDENE.2021.08.036.
- [12] G. Dominguez-Gonzalez, J. I. Muñoz-Hernandez, D. Bunn, and C. J. Garcia-Checa, “Integration of Hydrogen and Synthetic Natural Gas within Legacy Power Generation Facilities,” *Energies (Basel)*, vol. 15, no. 12, Jun. 2022, doi: 10.3390/en15124485.
- [13] “Mark Thurber.” [Online]. Available: <https://www.iea.org/newsroom/news/2019/february/battery-storage-is-almost-ready-to-play-the-flexibility-ga.> [Accessed: 5-March -2023]
- [14] M. Götz *et al.*, “Renewable Power-to-Gas: A technological and economic review,” *Renewable Energy*, vol. 85. Elsevier Ltd, pp. 1371–1390, Jan. 01, 2016. Doi: 10.1016/j.renene.2015.07.066.
- [15] M. El-Shimy, A. N. Afandi, and M. El-Shimy, “Overview of Power-to-Hydrogen-to-Power (P2H2P) Systems Based on Variable Renewable Sources Performance Analysis, Performance Enhancement, characteristics, optimization, and applications of variable renewable energy technologies, and sources View project Total Solar Radiation on Tilted Surface View project The 5th International Conference on Electrical, Electronics, and Information Engineering Overview of Power-to-Hydrogen-to-Power (P2H2P) systems based on variable renewable sources,” 2017. [Online]. Available: <https://www.researchgate.net/publication/319653679> [Accessed: 15-March-2023]
- [16] K. S. Efacec, W. Süßenbacher, and K. J. Sedillo, “Grid impact analysis of hybrid energy storage systems Multidisziplinäres Simulationsmodell der europäischen Elektrizitätswirtschaft View project Sustainable Consumer Engagement and Demand Response (SENDER) View project Grid impact analysis of hybrid energy storage systems.” [Online]. Available: <https://www.researchgate.net/publication/354463259> [Accessed: 25 February 2023]

- [17] M. A. Rabbani, “Smart Grids and Hybrid Energy Storage Systems: Optimization Techniques Applied in Control Strategies for Hybrid Energy Storage Systems,” in *Research Anthology on Smart Grid and Microgrid Development*, IGI Global, 2022, pp. 779–804. Doi: 10.4018/978-1-6684-3666-0.ch034.
- [18] P. Marocco, D. Ferrero, A. Lanzini, and M. Santarelli, “The role of hydrogen in the optimal design of off-grid hybrid renewable energy systems,” *J Energy Storage*, vol. 46, Feb. 2022, doi: 10.1016/j.est.2021.103893.
- [19] E. Ghirardi, G. Brumana, G. Franchini, and A. Perdichizzi, “H₂ contribution to power grid stability in high renewable penetration scenarios,” *Int J Hydrogen Energy*, vol. 48, no. 32, pp. 11956–11969, Apr. 2023, doi: 10.1016/J.IJHYDENE.2022.06.026.
- [20] C. Ma, S. Dong, J. Lian, and X. Pang, “Multi-objective sizing of hybrid energy storage system for large-scale photovoltaic power generation system,” *Sustainability (Switzerland)*, vol. 11, no. 19, Oct. 2019, doi: 10.3390/su11195441.
- [21] M. Qi *et al.*, “Flexible and efficient renewable-power-to-methane concept enabled by liquid CO₂ energy storage: Optimization with power allocation and storage sizing,” *Energy*, vol. 256, p. 124583, Oct. 2022, doi: 10.1016/J.ENERGY.2022.124583.
- [22] F. Cebulla, T. Naegler, and M. Pohl, “Electrical energy storage in highly renewable European energy systems: Capacity requirements, spatial distribution, and storage dispatch,” *J Energy Storage*, vol. 14, pp. 211–223, Dec. 2017, doi: 10.1016/j.est.2017.10.004.
- [23] K. Kummer and A. R. Imre, “Seasonal and multi-seasonal energy storage by power-to-methane technology,” *Energies (Basel)*, vol. 14, no. 11, Jun. 2021, doi: 10.3390/en14113265.
- [24] B. Karacavus and K. Aydın, “Hydrogen production and storage analysis of a system by using TRNSYS,” *Int J Hydrogen Energy*, vol. 45, no. 60, pp. 34608–34619, Dec. 2020, doi: 10.1016/j.ijhydene.2020.03.005.
- [25] https://www.homerenergy.com/pdf/HOMER2_2.8_HelpManual.pdf [Accessed:3-May-2023]

- [26] Yaouba, R. Zieba Falama, F. Ngangoum Welaji, M. Hamda Soulouknga, F. Kwefeu Mbakop, and A. Dadjé, “Optimal Decision-Making on Hybrid Off-Grid Energy Systems for Rural and Remote Areas Electrification in the Northern Cameroon,” *Journal of Electrical and Computer Engineering*, vol. 2022, 2022, doi: 10.1155/2022/5316520.
- [27] T. Bocklisch, “Hybrid energy storage approach for renewable energy applications,” *J Energy Storage*, vol. 8, pp. 311–319, Nov. 2016, doi: 10.1016/j.est.2016.01.004.
- [28] B. C. Tashie-Lewis and S. G. Nnabuife, “Hydrogen Production, Distribution, Storage and Power Conversion in a Hydrogen Economy – A Technology Review,” *Chemical Engineering Journal Advances*, vol. 8. Elsevier B.V., Nov. 15, 2021. Doi: 10.1016/j.ceja.2021.100172.
- [29] J. Lindorfer, G. Reiter, R. Tichler, and H. Steinmüller, “Hydrogen fuel, fuel cells, and methane,” in *Managing Global Warming: An Interface of Technology and Human Issues*, Elsevier, 2018, pp. 419–453. Doi: 10.1016/B978-0-12-814104-5.00014-4.
- [30] M. S. Okundamiya, “Size optimization of a hybrid photovoltaic/fuel cell grid-connected power system including hydrogen storage,” *Int J Hydrogen Energy*, vol. 46, no. 59, pp. 30539–30546, Aug. 2021, doi: 10.1016/J.IJHYDENE.2020.11.185.
- [31] A. John, S. Basu, Akshay, and A. Kumar, “Design and evaluation of stand-alone solar-hydrogen energy storage system for academic institute: A case study,” *Mater Today Proc*, vol. 47, pp. 5918–5922, Jan. 2021, doi: 10.1016/J.MATPR.2021.04.461.
- [32] [Maps – District – Malawi Electoral Commission \(mec.org.mw\)](https://mec.org.mw) [Accessed: 3 August 2023]

APPENDICES

Appendix A: HOMERPRO software interfaces showing the designed systems, economic analyses and Cost Comparisons

HOMERPRO page showing the SM500 properties

DESIGN

Add/Remove: SolarMax 500RX A with Generic PV

PV Name: SolarMax 500RX A with Ge Abbreviation: SM500

Properties

Name: **SolarMax 500RX A with Generic PV**
 Abbreviation: **SM500**
 Panel Type: **Flat plate**
 Rated Capacity (kW): **300000**
 Temperature Coefficient: **-0.4100**
 Operating Temperature (°C): **45.00**
 Efficiency (%): **17.30**
 Manufacturer: **SolarMax**
www.solarmax.com
 Notes: **This is a generic PV system with SolarMax' grid-**

Cost

Capacity (kW)	Capital (\$)	Replacement (\$)	O&M (\$/year)
300000	600,000.00	30,000.00	1,000.00

Lifetime: time (years): 25.00

Site Specific Input

Derating Factor (%): 96.00

HOMER Pro

HOMERPRO page showing the Avus2.5 properties

DESIGN

Add/Remove: CCGT

GENERATOR Name: CCGT Abbreviation: Avus2.5

Properties

Name: **CCGT**
 Capacity: **2500 kW**
 Fuel: **Stored Hydrogen**
 Fuel curve intercept: 31.2 kg /hr
 Fuel curve slope: 0.222 kg /hr/kW

Emissions

CO (g/kg fuel): 316.169828
 Unburned HC (g/kg fuel): 0
 Particulates (g/kg fuel): 0
 Fuel Sulfur to PM (%): 0
 NOx (g/kg fuel): 63.233966

Generator Cost

Initial Capital (\$): 500,000.00
 Replacement (\$): 775,000.00
 O&M (\$/op. hour): 28.800
 Fuel Price (\$/kg): 1.3

Optimization

Simulate systems with and without this generat
 Include in all systems

Electrical Bus

AC DC

Site Specific

Minimum Load Ratio (%): 50.00 CHP Heat Recovery Ratio (%): 46.70 Lifetime (Hours): 84,000.00

Minimum Runtime (Minutes): 5.00 Initial Hours 0.00

Emissions as shown in HOMERPRO

Simulation Results

System Architecture: Dynapower SPS - 100 (552 kW) Hydrogen Tank (10,000
 SolarMax 500RX A with Generic PV (300,000 kW/500 kW) Grid (999,999 kW) HOMER Cycle Charging
 CCGT (2,500 kW) Generic Electrolyzer (80,000 kW)

Total NPC:
 Levelized COE:
 Operating Cost:

Cost Summary Cash Flow Compare Economics Electrical Hydrogen Fuel Summary CCGT Renewable Penetration SolarMax 500RX A
 Dynapower SPS - 100 Generic Electrolyzer Hydrogen Tank Emissions

Quantity	Value	Units
Carbon Dioxide	1,161,745	kg/yr
Carbon Monoxide	4,040	kg/yr
Unburned Hydrocarbons	0	kg/yr
Particulate Matter	0	kg/yr
Sulfur Dioxide	5,064	kg/yr
Nitrogen Oxides	3,285	kg/yr

Cost comparison results in HOMERPRO

Simulation Results

System Architecture: Dynapower SPS - 100 (552 kW) Hydrogen Tank (10,000
 SolarMax 500RX A with Generic PV (300,000 kW/500 kW) Grid (999,999 kW) HOMER Cycle Charging
 CCGT (2,500 kW) Generic Electrolyzer (80,000 kW)

Dynapower SPS - 100 Generic Electrolyzer Hydrogen Tank Emissions
 Cost Summary Cash Flow Compare Economics Electrical Hydrogen Fuel Summary CCGT Renewable Penetration

You may choose a different base case using the Compare Economics button on the Results Summary Table.

		Architecture				
		SM500 (kW)	SM500-MPPT (kW)	Avus2.5 (kW)	Grid (kW)	Electrolyzer (kW)
Base system					999,999	
Proposed system		300,000	500	2,500	999,999	80,000

Metric	Value
Present worth (\$)	\$673,458
Annual worth (\$/yr)	\$52,095
Return on investment (%)	7.9
Internal rate of return (%)	9.5
Simple payback (yr)	9.23
Discounted payback (yr)	13.70

Appendix B: Conference Paper Abstract (IEEE PAC 2023)

Penetration of renewable energy on a large scale into the grid poses a huge problem for the stability of the grid due to the variations that arise with most renewable energy resources like solar and wind energy generating systems. This work designs and simulates long-duration power-to-gas systems of hydrogen and SNG energy storages which are coupled to a solar system that can achieve a higher penetration into the grid. A hybrid system of SNG and hydrogen has been designed in HOMERPRO software and this has been evaluated against a system that has hydrogen only, SNG only, and that which has no storage systems. The results show that having a hybrid storage of Hydrogen and SNG with Solar can result in 49.4% renewable energy penetration, a 49.5% decrease in CO₂ emissions, and a 14.3% reduction in the Cost of Energy (COE).

Appendix C: Results of Changing the Load Size of the Modelled Hybrid System

Summary of System Performance of the Solar System under Different Loads

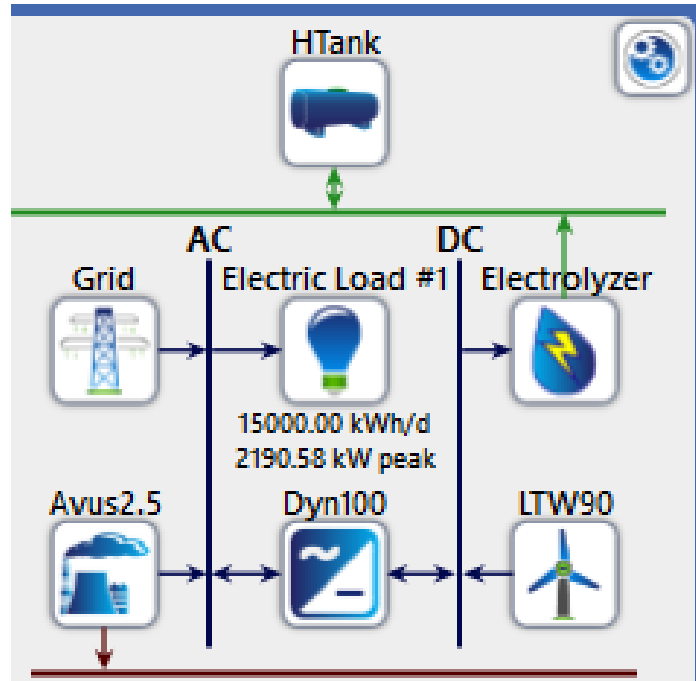
Parameters	5000kWh Per day	10000kWh Per day	15000kWh Per day	20000kWh Per day
NPC	\$2.68Million	\$4.05Million	\$6.10Million	\$8.39Million
COE	\$0.110	\$0.0853	\$0.0860	\$0.0887
Operating Cost	\$79,573	\$185,228	\$344,250	\$531,034
Initial Capital	\$1.65Million	\$1.65Million	\$1.65Million	\$1.65Million
Present Worth	\$-319,872	\$675,458	\$976,968	\$1,050,669
Payback	21.4 years	9.23years	8.16years	7.94years
Renewable Penetration Level	57.8%	49.5%	37.5%	28.7%
Internal Rate of Return	3.2%	9.5%	11.1%	11.5%

Emissions from the solar system under Different Loads

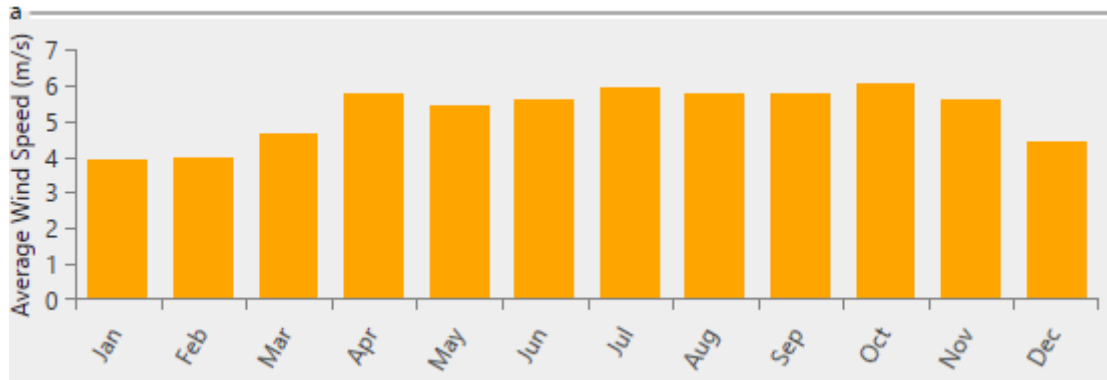
Parameters	5000kWh Per day	10000kWh Per day	15000kWh Per day	20000kWh Per day
Carbon Dioxide	487,692kg/yr.	1,161,745kg/yr.	2,172,323kg/yr.	3,290,218kg/yr.
Carbon Monoxide	9696kg/yr.	4040kg/yr.	2216kg/yr.	1828kg/yr.
Sulfur Dioxide	2180kg/yr.	5,064kg/yr.	9433kg/yr.	14,227kg/yr.
Nitrogen Oxides	3005kg/yr.	3,285kg/yr.	5056kg/yr.	7348kg/yr.

Appendix D: Results of a Similar Hybrid Model but with Wind Resources.

Hybrid System with Wind Resource.



Monthly Wind Speed of Salima



A summary of system performances at different loads in wind system

Parameters	5000kWh per day	10000kWh Per day	15000kWh Per day	20000kWh per day
NPC	\$3.53 Million	\$5.07Million	\$6.78Million	\$8.69Million
COE	\$0.0530	\$0.0669	\$0.0767	\$0.0825
Operating Cost	-\$40,645	\$78,741	\$211,216	\$359,177
Initial Capital	\$4.05Million	\$4.05Million	\$4.05Million	\$4.05Million
Present Worth	\$-1,166,322	\$-350,563	\$295,947	\$742,359
Payback	17.88 years	12.75 years	11.02 years	10.07 years
Renewable Penetration Level	93.6%	83.5%	72.6%	62%
Internal Rate of Return	2.8%	5.0%	6.6%	7.7%

Emissions from a Hybrid System with Wind Renewable Resource.

Parameters	5000kWh per day	10000kWh Per day	15000kWh Per day	20000kWh per day
Carbon Dioxide	201,627kg/yr.	608,072kg/yr.	1,179,211kg/yr.	1,955,056kg/yr.
Carbon Monoxide	3225kg/yr.	2,639kg/yr.	2150kg/yr.	1466kg/yr.
Sulfur Dioxide	896kg/yr.	2654kg/yr.	5127kg/yr.	8486kg/yr.
Nitrogen Oxides	1083kg/yr.	1826kg/yr.	2937kg/yr.	4443kg/yr.

Appendix E: Turnitin Report

makeupe

ORIGINALITY REPORT

10%

SIMILARITY INDEX

5%

INTERNET SOURCES

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STUDENT PAPERS

PRIMARY SOURCES

1	www.researchgate.net Internet Source	3%
2	Elisa Ghirardi, Giovanni Brumana, Giuseppe Franchini, Antonio Perdichizzi. "H2 contribution to power grid stability in high renewable penetration scenarios", International Journal of Hydrogen Energy, 2022 Publication	1%
3	Bei Li, Hongzhi Miao, Jiangchen Li. "Multiple hydrogen-based hybrid storage systems operation for microgrids: A combined TOPSIS and model predictive control methodology", Applied Energy, 2020 Publication	1%
4	Meng Qi, Jaewon Lee, Seokyoung Hong, Jeongdong Kim, Yi Liu, Jinwoo Park, Il Moon. "Flexible and efficient renewable-power-to-methane concept enabled by liquid CO2 energy storage: Optimization with power allocation and storage sizing", Energy, 2022 Publication	1%

5	R. Chedid, F. B. Chaaban, R. Shihab. "A Simplified Electric Circuit Model for the Analysis of Hybrid Wind-Fuel Cell Systems", 2007 IEEE Power Engineering Society General Meeting, 2007 Publication	<1 %
6	William Becker, Michael Penev, Robert J. Braun. "Production of Synthetic Natural Gas from Carbon Dioxide and Renewably Generated Hydrogen: A Techno-Economic Analysis of a Power-to-Gas Strategy", Journal of Energy Resources Technology, 2018 Publication	<1 %
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Appendix F: Comments from Examiners and how They have Been Addressed

Comments	How it has been addressed	Page Number
The candidate had reported components prices in the Table 4.2 ,however she didn't show the internet sources from where the reported prices are found, therefore she shall provide this information.	An explanation about the source of the table 4.2 has been provided	39, Appendix A: p56
The values of table 4.3 must have a source(reference) ,otherwise the candidate shall explain how those values have been determined.	An explanation about the source of the table 4.3 has been provided	39, Appendix A: p56
From Fig. 3.3, the economical analysis is the main target before selecting storage. So, I think it should be reflected in the thesis title.	As much as the economic analysis is the main target, but other factors like environmental emissions and system performance were also considered that why the title remains a general title	40-43
In Fig. 4.7, and 4.12, the abbreviations SM500 and AVUS 2.5, are not explained. From those figures also, you are recommended to explain why the AVUS 2.5 provides power only in January?? Overall, provide a short discussion for each of these graphs referring to: why and when SM500 and AVUS 2.5 provide power to the grid	An explanation has been provided on the abbreviations of SM500 and AVUS2.5 and why the power is produced in January only	22, 23, 40 Appendix A: 55
From Fig. 4. 10, the AVUS2.5 doesn't provide power. Why? You are recommended to explain.	An explanation has been provided	40
Another comment is that, no analysis carried out about the degree of penetration of the renewable energy considered. Referring to comment 2, please you can explain referring to: at which extends of penetration the storage will start providing the power?	An explanation about the degree of penetration has been provided.	41
Clarify on the measure of Grid Stability being maximized	A clarification about the grid stability has been provided.	41

Student Bio



Sylvia Lucy Makupe is currently a renewable energy engineering master's student at the African center of Excellence in Energy for Sustainable Development at the University of Rwanda. Before her masters' studies she was an academic tutor at Malawi University of Science and Technology (MUST) for a period of 8 months. Sylvia holds a second upper class bachelor's degree (Hons) in Chemical Engineering obtain in 2019 at MUST. Her research interest includes energy storage, renewable energy transition and adaptation, renewable energy integration and energy and the environment. Her contacts are silimakupe@gmail.com or smakupe@must.ac.mw for emails and +265996637701 cellphone number.