



UNIVERSITY of
RWANDA

COLLEGE OF SCIENCE AND TECHNOLOGY



AFRICAN CENTER OF
EXCELLENCE ENERGY FOR
SUSTAINABLE DEVELOPMENT

TITLE: INTEGRATION OF GREEN HYDROGEN INTO RWANDA ENERGY MARKET: CASE
OF MAYANGE VILLAGE.

Thesis Number:

ACEESD/PSE/25/... Student

Names: DUSHIMIMANA Gilbert

Registration Number: 12114101

A dissertation submitted to the African Centre of Excellence in Energy for Sustainable
Development(ACE-ESD)

College of Science and

TechnologyUniversity of

Rwanda

In partial fulfilment of the requirement for the degree of MASTER OF SCIENCE IN
RENEWABLEENERGY

Supervisor's names: Dr. UFITEYEZU Emmanuel

Co-supervisor: Ass.Professor. BIKORIMANA JMV

Kigali, March 2025

DECLARATION

Declare that the dissertation entitled “INTEGRATION OF GREEN HYDROGEN INTO RWANDA ENERGY MARKET: CASE OF MAYANGE VILLAGE” is original work and has never been submitted to any University or other institution of higher learning. It is my own research whereby other sources of materials were cited and referenced in accordance with academic rules and ethics.

Names: DUSHIMIMANA Gilbert

Signature:

This master’s thesis has been submitted for examination with my approval as dissertation advisor. Names: Dr. UFITEYEZU Emmanuel

Signature:

Date of submission:

ABSTRACT

The main goal of this research was to investigate potential of green hydrogen generation and integration into Rwanda energy market in Bugesera district Mayange/ village. The aim is to minimize grid dependency and promote the consumption of locally generated and stored energy from renewable energy. The optimum size of hybrid power system to supply load demand of Mayange village that counts high potential in solar energy was established by adopting energy balance method of HOMER (Hybrid Optimization of Multiple Energy Resources). A detailed hourly simulation analysis was conducted to determine the optimal size, cost, and performance of a hybrid energy system, utilizing two years of monthly averaged solar radiation collected for Mayange village (Latitude: 2°13.4'S, Longitude: 30°4.8'E). The findings indicated that a hybrid system consisting of a 21kW photovoltaic array, a 4-kW fuel cell system, a 12-kW power inverter, and a 4 kW electrolyzer with a 3 kg hydrogen storage tank. Importantly, this system delivers significant economic benefits, achieving over 84% energy cost savings, a return on investment of 53.6%, and a net present worth of \$12,546, recoverable in under two years. Additionally, it reduces reliance on grid power, mitigates transmission and distribution losses, enhances energy security, and cuts greenhouse gas emissions from conventional sources, offering a financially viable and environmentally sustainable solution for Rwanda's energy challenges.

Keys: Green hydrogen production, Renewable energy harvesting, Fuel cell, Photovoltaic, Electrolyzer, Hydrogen storage.

ACKNOWLEDGEMENT.

Primarily, thanks to the Almighty God for his mercy, grace, and goodness to me during this work and the whole of my life. Many, thanks to my direct supervisor Dr UFITEYEZU Emmanuel and Co-supervisor Ass. Prof BIKORIMANA JMV for their professional supervision, guidance, inspiration, and advice during this work. Would like to take this opportunity to thank my beloved wife INGABIRE Faustine, my beloved daughter ABE Benie Abigael, my beloved mother, my sister, and brothers who have always been giving me their unconditional care and support through their incomparable love. Would also like to give my thanks to all Lecturers and staff of African Centre of Excellence in Energy for Sustainable Development (ACE-ESD).

Finally, thanks to my colleagues and friends for their friendship and support during my studies and the fulfilment of this work.

DEDICATION

To my beloved wife

To my beloved daughter

To my beloved mother,

To my supervisor,

To my sister and brothers,

To my colleagues and all my friends.

TABLE OF CONTENTS

DECLARATION	i
ABSTRACT.....	ii
ACKNOLODGEEMENT.	iii
DEDICATION	iv
CHAPTER 1. INTRODUCTION	1
1.1. Background	1
1.2. Problem statement.	2
1.3. Objectives.....	2
1.3.1. Major objective.....	2
1.3.2. Specific objectives	2
1.4. Scope of the study.	2
1.5. Expected outcomes and significance of the study.....	2
1.5.1. Expected outcomes of the study.	2
1.5.2. Significance of the study	3
CHAPTER 2. THEORECTICAL BACKGROUND AND LITTERATURE REVIEW...4	
2.0. Introduction	4
2.1. Energy.	4
2.1.1. Sustainable energy development.	4
2.1.2. Energy demand	5
2.1.3. Demand Forecast ER	5
2.1.4. Different sources of energy currently used in Rwanda.	6
2.2. Obstacles Rwanda face in attaining energy security.	7
2.2.1. Deforestation.....	7
2.2.2. Price volatility of fossil fuel.	8
2.3. Hydrogen.....	8
2.4. Green hydrogen (GH).....	10

2.4.1. Worldwide operational, under construction and proposed GH project.	11
2.5. Renewable energy sources (RES) potential in the Bugesera district.	12
2.5.1. Potential of Solar Energy in Bugesera district.....	12
2.5.2 Water availability in Bugera district.....	13
2.6 Water as primary source of hydrogen.	14
2.6.1 Seawater electrolysis and energy requirements.....	15
2.7 Evolution of renewable energy exploitation.	15
2.7.1 Solar energy storage in hydrogen gas.....	16
2.8 GH production technologies.....	17
2.8.1 Electrolysis	17
2.9 Energy storage.....	19
2.9.1 Energy storage methods.....	19
2.9.2 Comparison of hydrogen storage system and other energy storage	19
2.10 Economic consideration	20
2.11 Benefits of GH in the energy sector.	21
2.11.1 Transportation.....	21
2.11.2. Power Generation	21
2.12. Integration marketing challenges of GH and ways of implantation.....	22
2.12.1. Marketing challenges.....	22
2.12.2. Implementation strategies.....	22
2.13. Impact on the environment.....	23
2.13.1. Reduction of Emissions.....	23
2.13.2. Promotion of Sustainability.....	23
2.14. Summary of literature review.....	23
CHAPTER 3. METHODOLOGY	24
3.1. Introduction.	24
3.2. Research design.....	24

3.3 Case study area.....	26
3.4 Data collection methods and their instruments.	26
3.5 Analysis of research methodology.	27
3.5.1 Selection of the site.....	27
3.5.2 Selection of the type of electrolyzer and Fuel cell	28
CHAPTER4. GH GENERATION SYSTEM MODELING AND SIZING.....	30
4.1 Introduction.	30
4.2 Parameter to consider when modeling Grid connected PVEFC system.	30
4.3 System modeling and sizing.....	31
4.3.1 Important climate data.	31
4.3.2 Load assessment	33
4.3.3 Load factor calculation	36
4.3.4 Photovoltaic power generation and load balance.	37
4.3.5 Fuel cell modeling and sizing.....	37
4.3.6 Electrolyzer modeling and sizing	38
4.3.7 Hydrogen storage sizing.	40
4.3.8 Photovoltaic system modeling and sizing.....	40
4.4 Cost estimation of integrated solar PV- electrolyzer – fuel cell and grid.	43
CHAPTER 5. SIMULATION RESULTS AND DISCUSSION.....	44
5.1 Introduction.	44
5.2 Simulating HOMER Pro software.....	44
5.2.1 System simulation choices.....	44
5.3 Simulation of the design.....	48
5.4 Load input	48
5.5 System component inputs to simulating tool.	49
5.6.1 Optimization results.....	53
5.6.2 System overall cost.	53

5.6.3 Rates of system self-consumption and self-satisfaction.	55
5.6.4 Electrical data.	56
5.6.5. Grid net contribution.....	57
5.6.6 GH production rate.	58
5.6.7 Fuel cell operating values.	59
5.6.8 Greenhouses gases emissions rate.	60
CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS.	61
6.1 Conclusion.....	61
6.2 Recommendations.	62

LIST OF FIGURES

Figure 2.1: Trends of system peak demand (MW) from Q1 2023 to Q1 2024[9].	5
Figure 2.2: Forecasted total demand and peak demand [10].	6
Figure 2.3: Energy mix in Rwanda up to 2024.	7
Figure 2.4: Current energy sources [14].	7
Figure 2.5: Deforestation rates up to 2023[16].	8
Figure 2.6: Chemical energy state.	9
Figure 2.7: Major hydrogen production methods and applications [20].	11
Figure 2.8: World GH producers [28].	12
Figure 2. 9: Bugesera PV suitability map, 2018[30].	13
Figure 2. 10: Monthly average daily global solar irradiance in Rwanda [31].	13
Figure 2. 11: Hydrographical map of Bugesera region [62].	14
Figure 2. 12: Energy requirement for hydrogen production and water purification [30].	15
Figure 2. 13: Evolution of installed capacity from renewable energy technology [33].	16
Figure 2. 14: Hydrogen production cycle and storage system [36].	17
Figure 2. 15: Electrolysis diagram [42].	18
Figure 2. 16: Generations of water electrolysis development [20].	18
Figure 2. 17: Classification of energy storage technologies [45].	19
Figure 2. 18: Fuel cell basic [50].	21
Figure 2. 19 : Hydrogen consumption and efficiency of fuel cell [51].	22
Figure 3. 1: Steps for research methodology.	25
Figure 3. 2 :Mayange geographical map [59].	26
Figure 4. 1 : Block diagram of integrated PV-ELEC-FC and Grid system with hydrogen.	30
Figure 4. 2 : Monthly average GHI and clearness.	32
Figure 4. 3: Mayange monthly average temperature (2023-2024)	33
Figure 4. 4 : Energy consumption month.	35
Figure 4. 5: Mayange hourly load demand.	36
Figure 4. 6: Mayange energy consumption profile.	36
Figure 5. 1: System algorithm.	47
Figure 5. 2: Hydrogen generation system integrated into a photovoltaic system.	48
Figure 5. 3: Load profile inputs window in HOMER.	49
Figure 5. 4: Solar PV panel input window in HOMER.	50
Figure 5. 5: Electrolyzer inputs window in HOMER.	51
Figure 5. 6: Fuel cell input window in HOMER.	51

Figure 5. 7: Hydrogen tank input.....	52
Figure 5. 8: Grid input	52
Figure 5. 9: GH generation system cash flow in bar chart.....	55
Figure 5. 10: Self-consumption and self-sufficient.....	56
Figure 5. 11: Electrical parameters.	56
Figure 5. 12: Grid dependency rate.....	57
Figure 5. 13: Monthly energy net purchase.	58
Figure 5. 14: Hydrogen production rate.....	59
Figure 5. 15: Simulation results of electrolyzer operation.....	59
Figure 5. 16: Simulation results of Fuel cell operation.....	60
Figure 5. 17: Simulation results of emissions.....	60

LIST OF TABLES

Table 2.1:Hydrogen heating value and its comparative fuel [17].	9
Table 2.2:General technical specifications of energy storage techniques [50],[51],[52].	20
Table 3.1: Summary of key criteria for selecting a suitable site for GH production.	28
Table 3.2: Summary of the most common configurations of solar powered ELC [63].	28
Table 4.1:Climate season of Bugesera district.	31
Table 4.2: Monthly Average solar radiation data for Mayange village from meteo Rwanda.	31
Table 4.3:Mayange monthly average temperature.	32
Table 4.4: Sample connected loads in Mayange sector.	33
Table 4.5:Average hourly base load demand in kWh of a day in January/2025.	34
Table 4.6: Mayange monthly electricity consumption for domestic users.	35
Table 4.7: Cost estimation of integrated solar PV-ELEC– FC- and Grid[48][49][50].	43
Table 5.1: Optimum size of proposed hybrid system.	53
Table 5.2:Cost summary of grid connected PV/FC hydrogen production power system.	54
Table 5.3: Economic comparison.	54

LIST OF ABBREVIATION

AC: Alternating Current

CESS: Chemical Energy Storage System

COE: Cost Of Energy

DC: Direct Current

ECESS: Electrochemical Energy Storage System

EESS: Electrical Energy Storage System.

ESS: Energy Storage System

EV: Electric Vehicle

FC: Fuel Cell

FES: Flywheel Energy Storage

GH: Green Hydrogen

GHI: Global Horizontal Irradiance

HOMER: Hybrid Optimization Multiple Energy Resources

kW: Kilo Watt

kWh: Kilowatt Hour

NPC: Net Present Cost

PEM: Proton Exchange Membrane

PV: Photo Voltaic

PVGIS: Photovoltaic Geographical Information System

RES: Renewable Energy Source

RE: Renewable energy.

RET: Renewable Energy Technology

SC: Super Capacitor

USD: United State Dollar

LCOE: Levelized Cost of Energy

LHV: Lower Heat Value

CHAPTER 1. INTRODUCTION

1.1. Background

Rwanda, like many developing nations, is grappling with the dual challenge of meeting increasing energy demands and reducing its carbon footprint. The country's energy landscape is characterized by a heavy reliance on biomass (wood and charcoal) and imported fossil fuels, both of which pose significant environmental and economic challenges. Biomass use leads to deforestation and indoor air pollution, while dependence on fossil fuels makes the country vulnerable to global oil price fluctuations and supply disruptions. Although Rwanda has made significant strides in expanding its hydropower capacity, this source of energy is subject to seasonal variations and the impacts of climate change, leading to periodic inconsistencies in energy supply[1]. Consequently, there is an urgent need for a sustainable, dependable, and locally producible energy source that can help Rwanda achieve energy security and environmental sustainability. GH, produced through the electrolysis of water using renewable energy sources such as solar and wind, emerges as a promising solution to these challenges. However, the integration of GH into Rwanda's existing energy market necessitates an in-depth examination of various technical, economic, and infrastructural factors[2].

The rationale for investigating the integration of GH into Rwanda's energy market is grounded in several key considerations. First, Rwanda has set ambitious targets for reducing greenhouse gas emissions and transitioning towards a green economy as part of its Vision 2050 development plan. Integrating GH aligns with these national goals by providing a clean, renewable energy source that can help mitigate the environmental impacts associated with fossil fuels. Furthermore, GH offers the potential to enhance Rwanda's energy independence by reducing reliance on imported fuels and leveraging local renewable resources. Rwanda is endowed with abundant solar and hydropower potential but due to climate change hydropower may fail to meet expected production, which can be harnessed to produce GH sustainably[3]. This not only contributes to energy security but also positions Rwanda as a leader in renewable energy innovation within the African continent. Additionally, the development of a GH industry can stimulate economic growth by creating new job opportunities, fostering technological advancements, and attracting foreign investments. By exploring the feasibility, benefits, and challenges of GH integration, this research aims to provide a comprehensive framework that can guide policymakers, investors, and other stakeholders in making informed decisions[4].

1.2. Problem statement.

Rwanda faces challenges in achieving energy security and environmental sustainability due to issues like deforestation from biomass use and fluctuations in fossil fuel prices. The country relies heavily on hydropower, which is subject to seasonal variations and climate change impacts, leading to inconsistent energy supply. The integration of GH into Rwanda's energy market could provide a sustainable, dependable, and locally producible energy source to address these challenges. GH, produced using renewable sources like solar and wind, emerges as a promising solution to mitigate environmental impacts and reduce dependence on imported fuels.

1.3. Objectives

1.3.1. Major objective

The aim was the minimization of grid dependence while promoting local renewable energy consumption. The optimization used was HOMER pro software.

1.3.2. Specific objectives

1. Assess potential production of GH in Bugesera.
2. Model and size GH generation system integrated into a PV system.
3. Optimize a GH generation system integrated into a PV system.
4. Make relevant conclusions and recommendations for practical integration of GH into Rwanda energy market.

1.4. Scope of the study.

This research focuses on examining how GH, generated from electrolysis of water under renewable energy sources like solar, might offer a sustainable, dependable, and locally producible energy source. The study encompasses modeling of the hydrogen gas production system, storage of hydrogen, and simulation of an electrolyzer, fuel cell /Photovoltaic system.

1.5. Expected outcomes and significance of the study.

1.5.1. Expected outcomes of the study.

GH integration in Rwanda energy system aligns with the country's goals of reducing emissions and transitioning to a green economy, utilizing local renewable resources like solar. GH energy policy could offer, benefits such as energy independence, maximized power generation through adopting this technology, economic growth through job creation and technological

advancements, variability of energy source and energy storage, and finally positioning Rwanda as a leader in renewable energy exploitation in Africa.

1.5.2. Significance of the study

The study's significance lies in its potential to drive positive changes in Rwanda's energy sector, promoting energy independence, environmental protection, and long-term economic growth through the adoption of GH as a key component of the country's energy market.

CHAPTER 2. THEORETICAL BACKGROUND AND LITERATURE REVIEW.

2.0. Introduction

This chapter presents theories and research done in this area and provides information about energy sources and exploitation in Rwanda. It provides also theories on GH, renewable energy sources (RES) like photovoltaic systems and electrolyzer components and the research done in this area.

2.1. Energy.

Civilization's achievements have been made possible by the expanding and more effective use of diverse energy sources to increase human potential and inventiveness. Energy is also essential for both economic expansion and ongoing human development. To eradicate poverty, enhance human wellbeing, and raise living standards, sufficient and reasonably priced energy must be made available worldwide[5]. It exists in various forms and can be transferred or converted from one form to another but cannot be created or destroyed (as per the law of conservation of energy)[6].

2.1.1. Sustainable energy development.

In its 1987 report[7], *Our Common Future*, the World Commission on Environment and Development defines sustainable development as development that “meets the needs of the present without compromising the ability of future generations to meet their own needs” (p. 8). The report further describes sustainable development “as a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development, and institutional change are all in harmony and enhance both current and future potentials to meet human needs and aspirations” (p. 46). In its broadest sense, the report notes, “the strategy for sustainable development aims to promote harmony among human beings and between humanity and nature” (p. 65). The relationship between energy production and use and sustainable development has two important features. One is the importance of adequate energy services for satisfying basic human needs, improving social welfare, and achieving economic development in short, energy as a source of prosperity. The other is that the production and use of energy should not endanger the quality of life of current and future generations and should not exceed the carrying capacity of ecosystems.

2.1.2. Energy demand

Like other essential needs, such as food and shelter, energy is a basic need of individuals throughout the world. The global increase in energy demand and environmental pollution is motivating related research and technological investments to improve energy efficiency and generation[8].

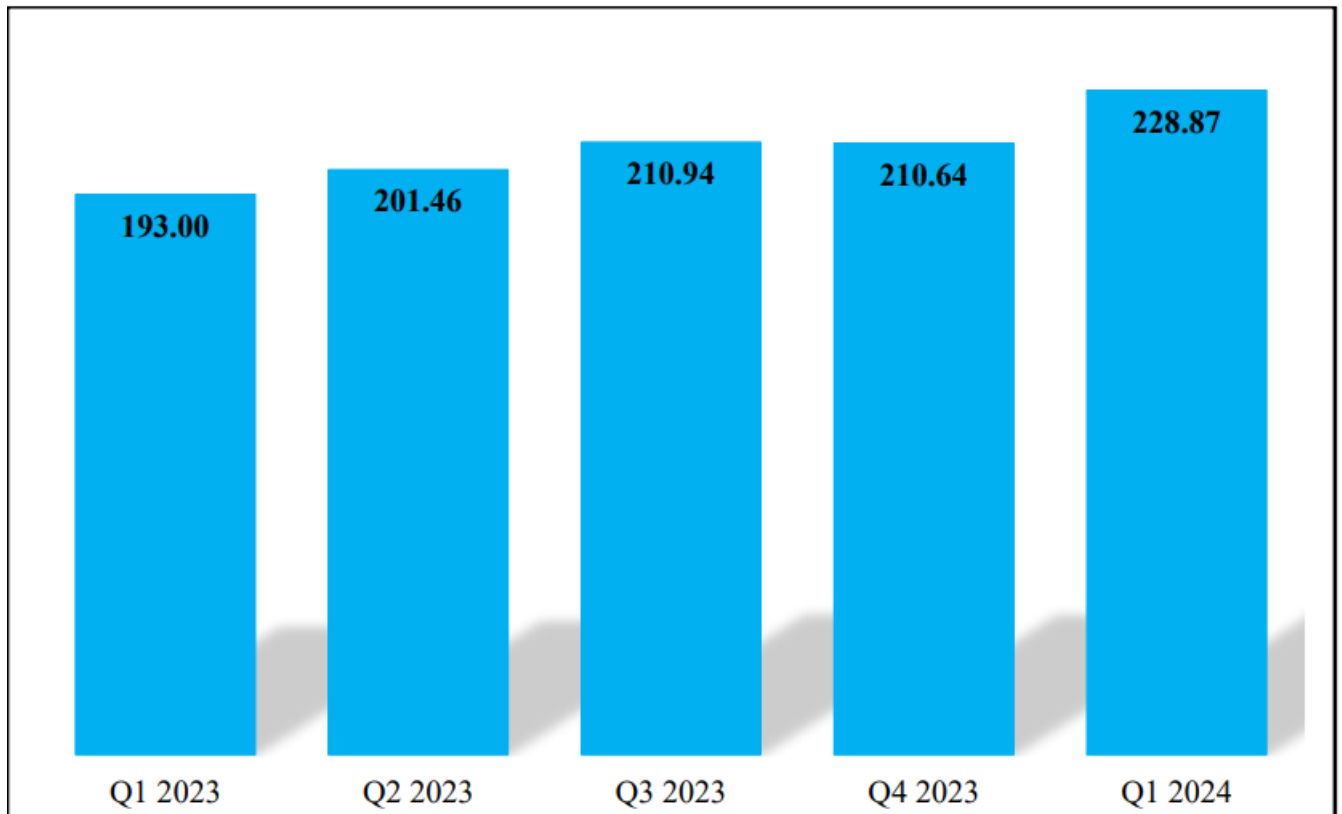


Figure 2.1: Trends of system peak demand (MW) from Q1 2023 to Q1 2024[9].

2.1.3. Demand Forecast ER

The quantity of electricity required in the nation or the region that the power system serves is estimated by demand predictions. Planning for energy generation expansion necessitates a demand projection, usually spanning five to thirty years. The best scheduling of when, how much, and what kind of generating technologies to add to an existing power system is made possible by a demand forecast. Demand estimates and analysis are also beneficial for planning the growth of transmission and distribution networks.

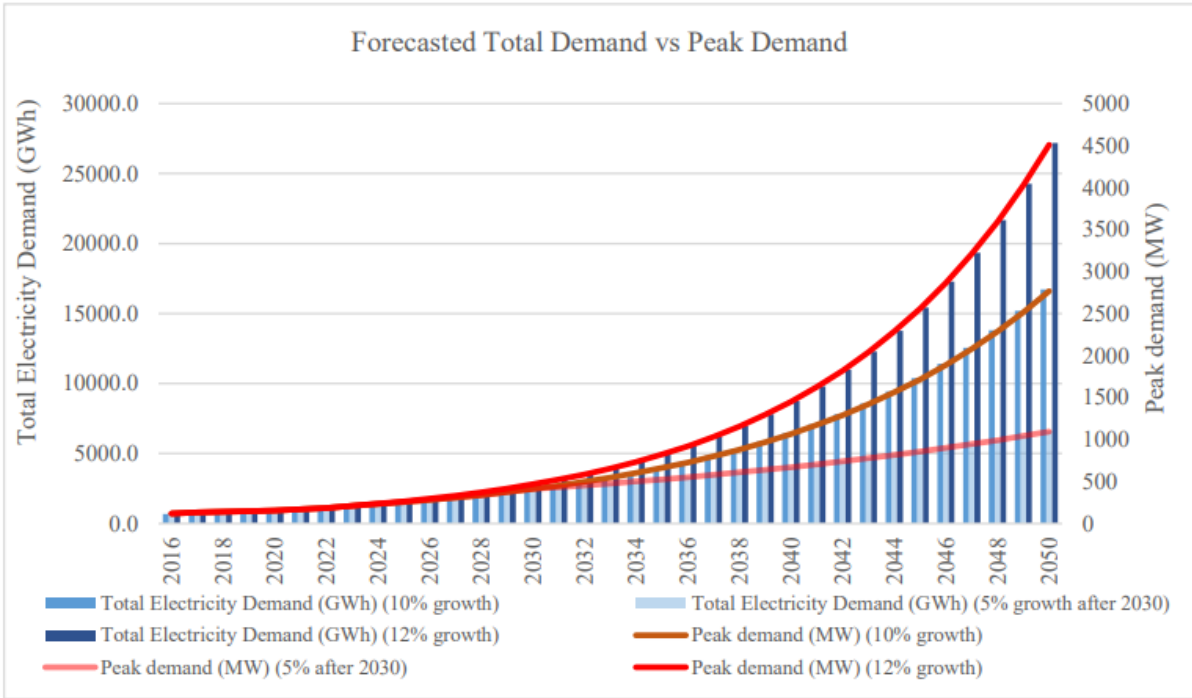


Figure 2.2: Forecasted total demand and peak demand [10].

The pressing need to address climate change, cut greenhouse gas emissions, and shift to sustainable energy sources is causing a substantial restructuring in the global energy environment. An increasing focus on renewable energy technology (RET), such as solar, wind, and hydroelectric power, is indicative of this change. GH, a sustainable energy carrier created by electrolyzing water with renewable power, is one of the emerging cornerstones of this shift. A flexible approach to de-carbonizing several industries and sectors, such as power production, transportation, and industry, is provided by GH. It can be transported and stored, making it a versatile and dependable energy source that goes well with sporadic renewable energy sources like wind and solar power[9].

2.1.4. Different sources of energy currently used in Rwanda.

The bulk of the energy used in Rwanda is derived from biomass, which is the main source of the country's low per capita energy consumption. In Rwanda, solar power, methane gas, and hydropower are the main sources of electricity, with hydropower accounting for most of the total. The energy sector faces a few obstacles despite efforts to develop the infrastructure, including high costs, poor reliability, and restricted access, especially in rural areas. In 2019, just 40% of people had access to electricity, with rural areas having access far later than urban areas[10],[11].

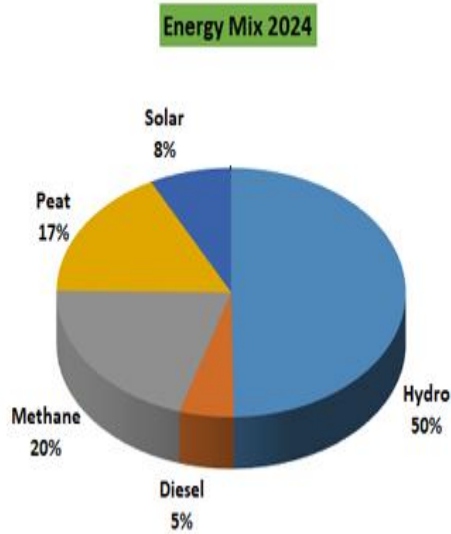


Figure 2.3: Energy mix in Rwanda up to 2024.

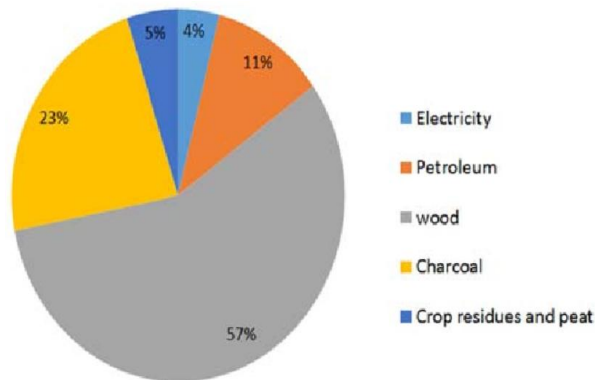


Figure 2.4: Current energy sources [14].

2.2. Obstacles Rwanda face in attaining energy security.

2.2.1. Deforestation

Deforestation in Rwanda undermines energy security by depleting biomass, the country's primary source of energy, particularly in rural areas where over 80% of the population relies on wood and charcoal for cooking. As forests are cleared, the supply of firewood diminishes, leading to scarcity and increased energy costs. This forces households to either pay more or use alternative, less sustainable energy sources. Deforestation also contributes to soil erosion and reduced water catchment, which affects hydroelectric power generation, a significant part of Rwanda's energy mix. Additionally, forest loss exacerbates climate change, further threatening renewable energy sources like hydropower. Sustainable forest management is thus crucial for maintaining energy security in the country[11][12].

From 2001 to 2023, Rwanda lost 46.2 kha of tree cover, equivalent to a 9.3% decrease in tree cover since 2000, and 32.6 Mt of CO₂ emissions[13].

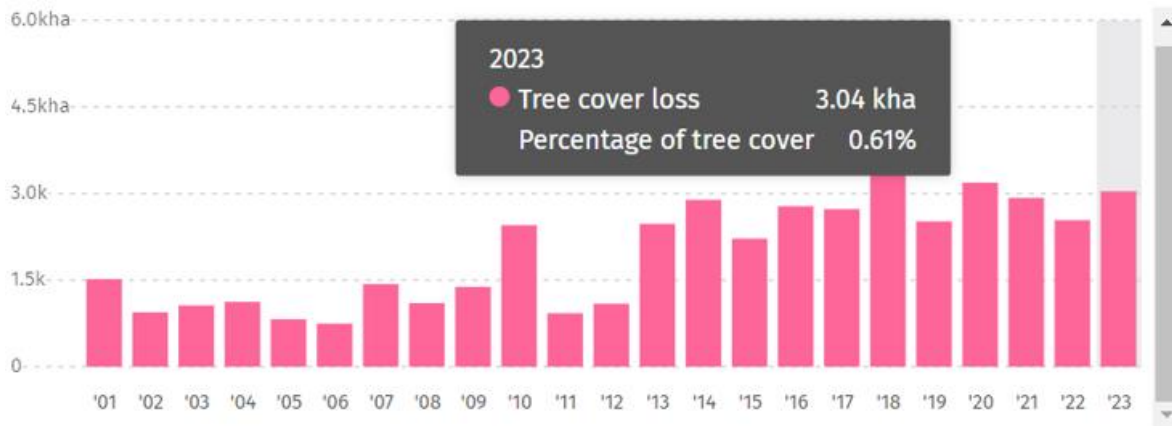


Figure 2.5: Deforestation rates up to 2023[16].

2.2.2. Price volatility of fossil fuel.

Price volatility of fossil fuels is a major obstacle to Rwanda's energy security because the country relies on imported petroleum for transport and electricity generation. Sudden increases in global oil prices lead to higher energy costs, straining the national budget and raising the cost of living. This volatility also destabilizes the economy by increasing inflation and creating uncertainty in energy planning. As fossil fuel prices fluctuate, it becomes difficult for Rwanda to maintain affordable and reliable energy access, especially for industries and transportation[14].

2.3. Hydrogen

2.3.1. Hydrogen reactivity

Chemical fuels exhibit high reactivity, as they form bonds with oxygen, resulting in lower energy states. This change in energy state is accompanied by a release of energy, which can be exploited for useful work. This process is like water flowing from a high level to a low level, where potential energy is released. This energy can be harnessed for work, such as turning a turbine. Once at a low level, the energy is spent, and it cannot perform further work. To return water to a higher level, it must either fall to a lower level or be raised through external energy sources like solar and wind energy. Alternatively, a pump can return water to a higher level, but it consumes energy[15].

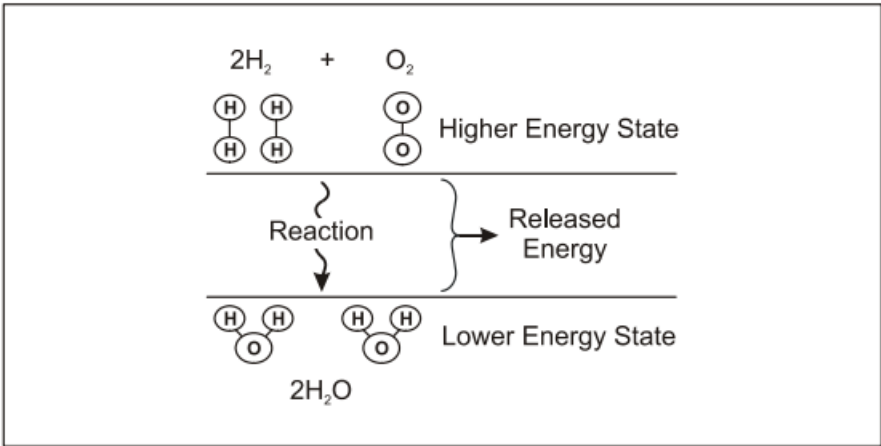


Figure 2.6: Chemical energy state.

These kinds of chemical reactions frequently require a tiny amount of activation energy to begin, but the energy generated during the reaction subsequently fuels subsequent reactions in a cascading manner. As a result, when a mixture of hydrogen and oxygen is exposed to a small amount of activated energy, such as a spark, the molecules react violently and release a significant quantity of heat, with water being the result. The water that results from this reaction vaporizes and becomes invisible to us since it is a superheated vapor, and we perceive this process as a fire or explosion. It is feasible to transform water, which is at a low energy state, to hydrogen and oxygen, which are at a higher energy state. This is the idea behind electrolysis's ability to produce hydrogen[16].

2.3.2. Energy content

Hydrogen fuel can liberate a fixed amount of energy when it reacts completely with oxygen to form water. This energy content key points & notes is measured experimentally and is quantified by a fuel’s higher heating value (HHV) and lower heating value (LHV). The difference between the HHV and the LHV is the “heat of vaporization” and represents the amount of energy required to vaporize a liquid fuel into a gaseous fuel, as well as the energy used to convert water to steam. The higher and lower heating values of comparative fuels are indicated in Table 2.1. Although the terms HHV and LHV do not apply to batteries, the energy density of a lead acid battery is approximately 46 Btu/lb (0.108 kJ/g).

Table 2.1:Hydrogen heating value and its comparative fuel [17].

Fuel/Heating values at 25°C and 1 atm	Higher Heating Value (Btu/lb)	Higher Heating Value (kJ/g)	Lower Heating Value (Btu/lb)	Lower Heating Value (kJ/g)

Hydrogen	61,000	141.86	51,500	119.93
Methane	24,000	55.53	21,500	50.02
Propane	21,650	50.36	19,600	45.6
Gasoline	20,360	47.5	19,000	44.5
Diesel	19,240	44.8	18,250	42.5
Methanol	8,580	19.96	7,760	18.05

2.4. Green hydrogen (GH)

As GH can be generated from water and RES using the electrolysis process, which emits no greenhouse gases, it is widely considered a promising fuel for future sustainable development and the transition of energy. To address climate change difficulties and achieve the global net-zero challenges, GH is being advocated more. Furthermore, during the next ten years, it is anticipated that the need for GH and its applications would rise significantly on a global scale [17].

GH is a clean fuel that, when consumed in a fuel cell, produces only water[18]. GH is a key component of the worldwide renewable energy plan because of its capacity to supply energy security and independence while integrating smoothly into the current energy infrastructure[19]. To reach their carbon neutrality targets, nations all around the world are investing in GH infrastructure and technology. GH generation is scalable and plays a crucial role in energy storage, grid balancing, and industrial process feedstock, making it an essential component of the energy mix of the future[4],[20].

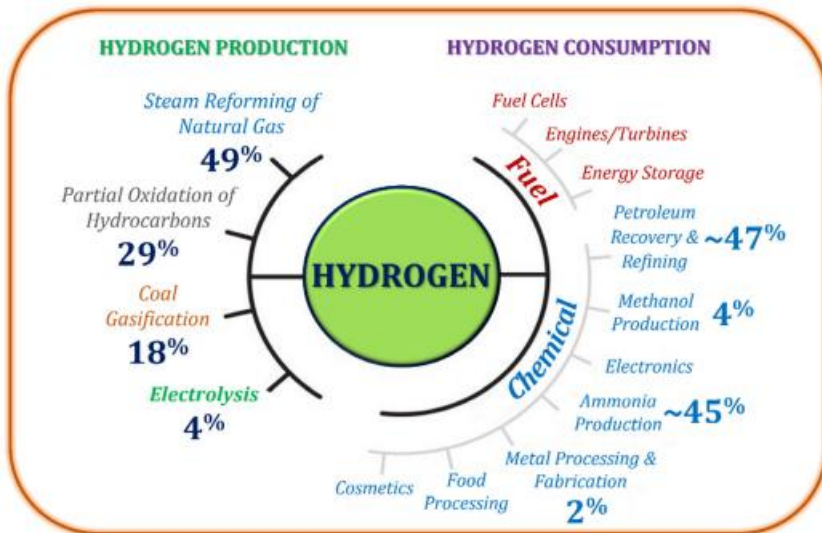


Figure 2.7: Major hydrogen production methods and applications [20].

The government of Rwanda has established aggressive goals to improve energy availability and include additional renewable energy sources. By 2024, 100% electrification is intended, with a strong emphasis on off-grid options to give rural populations access to reasonably priced and dependable electricity. Rwanda also wants to promote alternate energy sources like solar and even GH to diversify its energy mix and lessen its reliance on biomass. These initiatives are a component of a larger plan to promote economic expansion, raise living standards, and accomplish sustainable development[21],[22],[23].

2.4.1. Worldwide operational, under construction and proposed GH project.

Australia has the greatest number of GH projects among the top 20 projects in 15 countries, according to the currently available worldwide GH database. The United States, the Netherlands, Mauritania, France, and Spain are the other nations with many projects in the top 20. The largest of these projects could produce 3.6 million tons of GH annually, while the smallest could only produce 750,000 tons[24].



Figure 2.8: World GH producers [28].

2.5. Renewable energy sources (RES) potential in the Bugesera district.

2.5.1. Potential of Solar Energy in Bugesera district.

Rwanda is endowed with a solar radiation intensity of approximately 5kWh/m² /day and peak sun hours of approximately five hours per day [25]. According to Photovoltaic Geography Information System (PVGIS), the mean daily global solar irradiation on the tilted surface is 5.2 kWh/m²/day. The long-term average monthly daily global irradiation ranges from 4.8kWh/(m²day) (location Burera, month of May) to 5.8 kWh/(m²day) (location Nyanza, month of July). This indicates that there is a good potential for solar energy development in Rwanda. Overall, Rwanda has plenty of solar energy, and as shown in figure 2.8, there is plenty of sunlight every day even during rainy season. This represents good potential for solar PV development in the BUGESERA District.

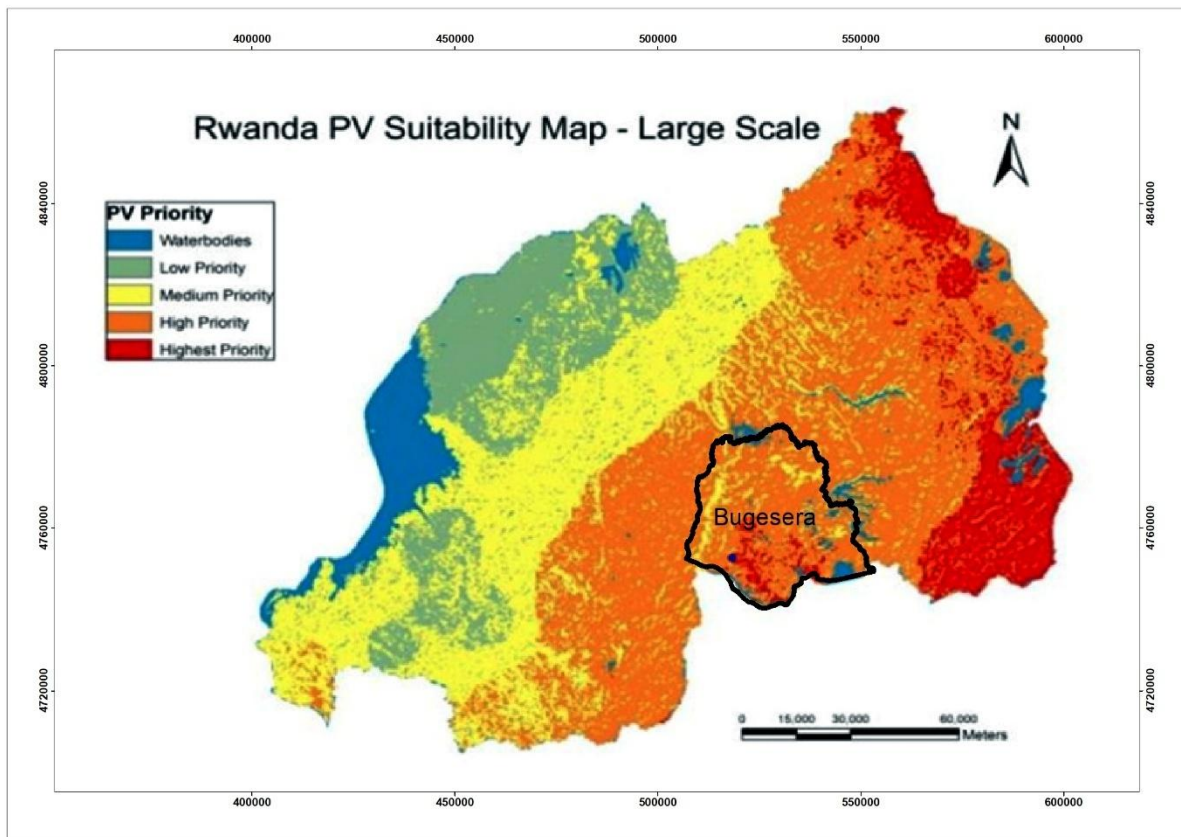


Figure 2. 9: Bugesera PV suitability map, 2018[30].



Figure 2. 10: Monthly average daily global solar irradiance in Rwanda [31].

2.5.2 Water availability in Bugera district.

Three rivers primarily define the Bugesera district's hydrographic network. Akanyaru, Nyabarongo, and Kageura are those rivers. Bugesera District has nine lakes in addition to those rivers. These lakes are Cyohoha North and South, which have a combined area of 630 hectares on the Rwandan side, Rweru, which has an area of 1857 hectares on the Rwandan side, Rumira, which has 280 hectares, Mirayi, which has 230 hectares, Kidogo, which has 220 hectares, Gashanga, which has 232 hectares, Kirimbi, which has 230 hectares, and Gaharwa, which is 230 hectares. The study was conducted in the Bugesera District's as this district has huge

2.6.1 Seawater electrolysis and energy requirements

Water electrolysis and hydrogen economies have significantly evolved over the last hundred years. Solutions to water treatment systems are not only robust and efficient but highly sophisticated. Energy consumption by the modern water electrolysis and purification system depends on feedstock water quality, permeate quality, and the technology used. The reverse osmosis plants use approximately 0.0012 kWh/l and 0.0046 kWh/l for brackish water and seawater feedstock, respectively. Permeate can be further treated in demineralized water plants using about 0.0016 kWh/l.

The energy and cost benefits linked with seawater electrolysis are almost zero. The present reverse and demineralization plants are inexpensive as the all-in cost in water desalination increases the price of hydrogen production by 0.0075 USD/kg. Energy efficiency and cost expenditure are recommended to be adopted for optimization in future electrolyzers. For instance, a mere improvement of approximately 0.2 % in the intake of energy would be deemed adequate in theory to achieve comparable results from running electrolyzers with seawater[28].

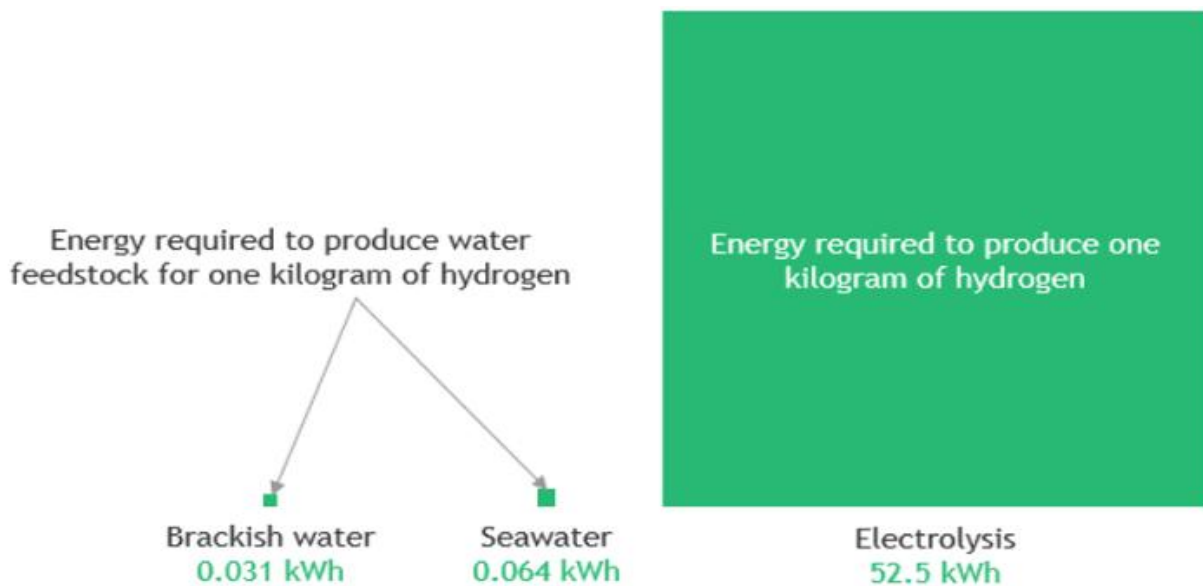


Figure 2. 12: Energy requirement for hydrogen production and water purification [30].

2.7 Evolution of renewable energy exploitation.

The use of RE contributes to global warming prevention and in fact, photovoltaic systems have been increasingly developed in recent years due to the global benefit of natural resources conservation. It is also evident that fossil fuel-based energy sources will be depleted over time since they are finite and consequently, they have been proven to contribute to global climate change[29].

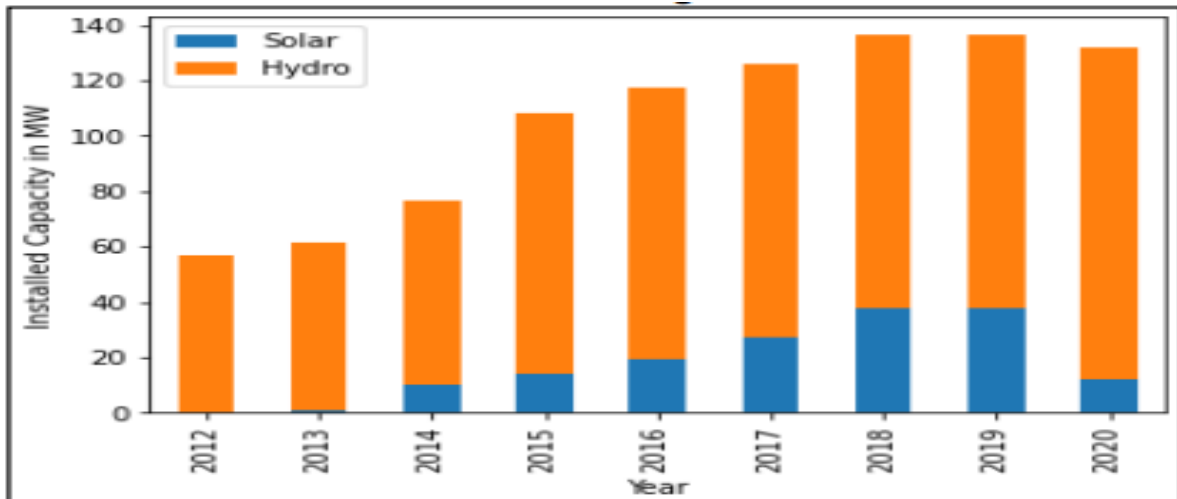


Figure 2. 13: Evolution of installed capacity from renewable energy technology [33].

2.7.1 Solar energy storage in hydrogen gas.

For ensuring total clean energy GH must be produce from renewable energy source (RES)and solar energy is the most abundant, useful, efficient, and environmentally friendly source of renewable energy[8].

It can also generate electricity on cloudy and rainy days from reflected sunlight[30]. Using photovoltaic cells to convert sunlight directly into electricity, which can then be used for electrolysis as a primary renewable energy source to produce GH.

In terms of collaboration with photovoltaic power plants, the hydrogen PEM (Proton Exchange Membrane) storage solution appears to be highly promising. Research on this technology is presently underway, along with an analysis of its real-world applications. Our lab is also involved in this study, which focuses on the advanced experimental laboratory implementation of the model hydrogen system for storing solar-generated electricity. A simplified diagram showing how PV panels store energy in hydrogen and then use that energy in fuel cells[31].

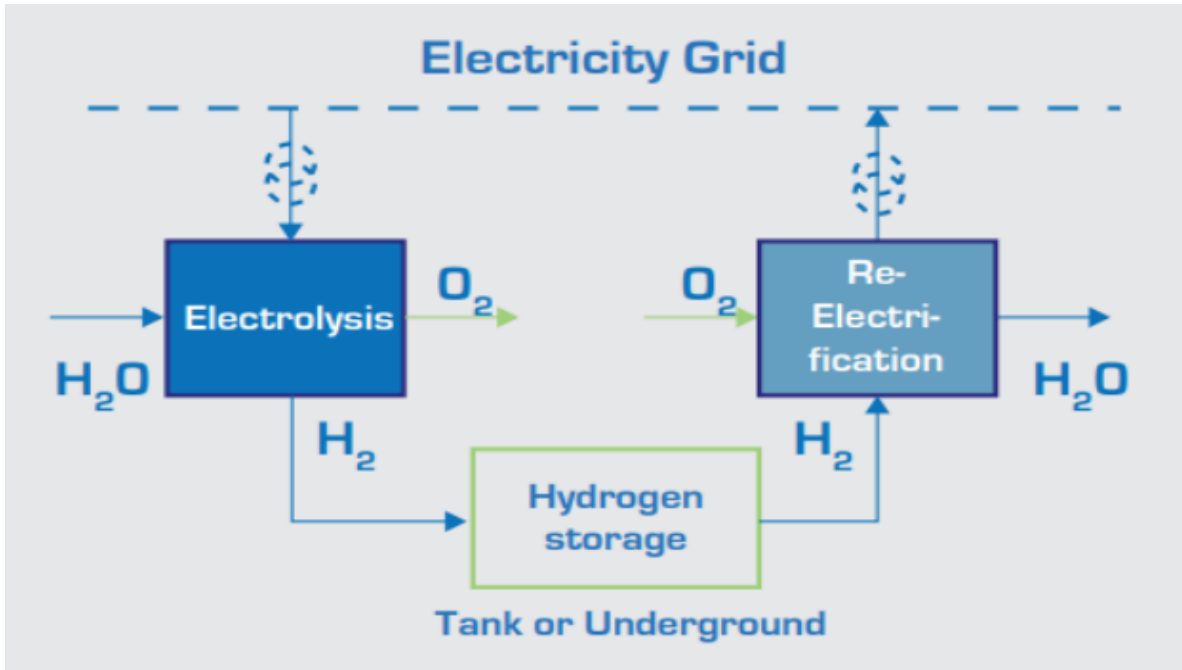


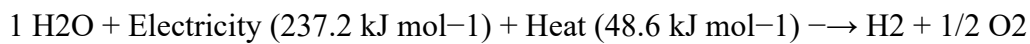
Figure 2. 14: Hydrogen production cycle and storage system [36].

2.8 GH production technologies

2.8.1 Electrolysis

Electrolysis of water is using electricity to split water into oxygen O_2 and hydrogen H_2 gas by electrolysis, which is emission-free technology. The basic approach used for producing GH is electrolysis, which involves using electricity to split water into hydrogen and oxygen[32]. The types of electrolysis technologies included among the several electrolysis technology kinds are: Alkaline, Proton Exchange Membrane, and Solid Oxide Electrolysis.

The basic reaction of water electrolysis is as follows in Equation. (2.1).



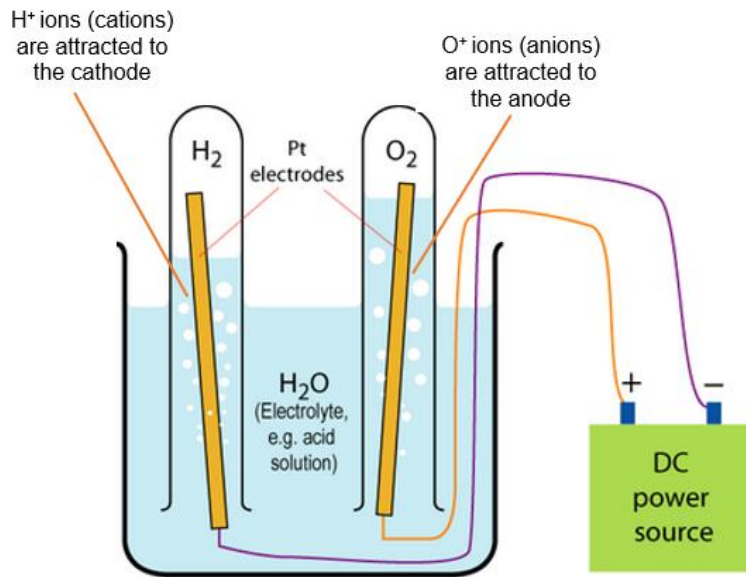


Figure 2. 15: Electrolysis diagram [42].

Water electrolysis technologies have been consistently studied and implemented in industry since the 18th century. During this period, several trends have been observed which fall into about five generations. Figure 2.15 sums up the challenges, advancements, and value of each process of water electrolysis over time.

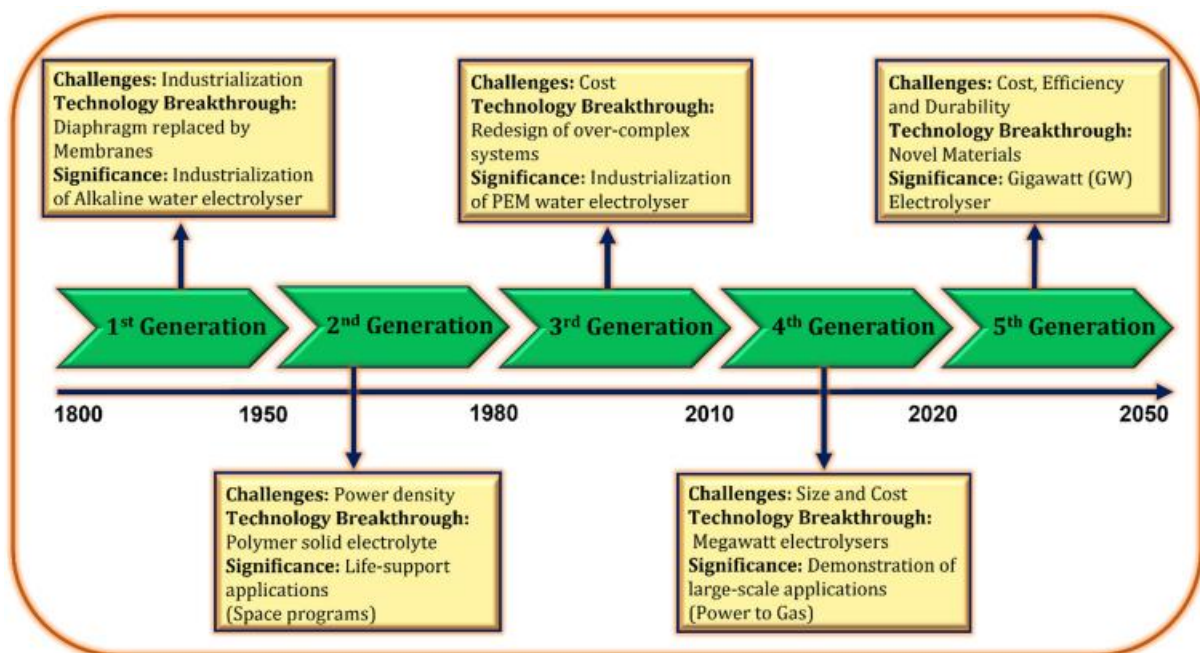


Figure 2. 16: Generations of water electrolysis development [20].

2.9 Energy storage

2.9.1 Energy storage methods

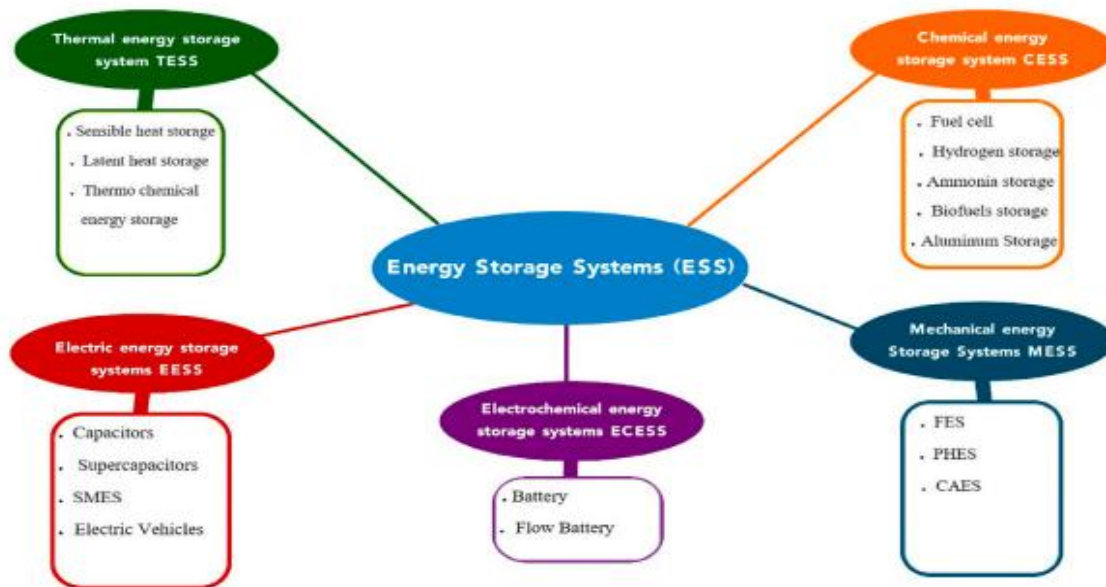


Figure 2. 17: Classification of energy storage technologies [45].

2.9.2 Comparison of hydrogen storage system and other energy storage

Battery storage systems are the salient ingredient in energy storage technologies.

The main factor responsible for the increased demand of lithium-ion battery is its high energy density, efficiency as well as excellent cycle life and its decreasing cost. The ubiquity of these batteries spans anything from large grid-connected systems right down to home installations. Additionally, to Li-ion-based batteries, other specific working battery types which have particular advantages for certain application scenario such flow and sodium ion respectively are under investigation[33]. One of the main challenge associated with batteries is degradation problem. Owing to, rising in battery temperature because of the charging and discharging cycling and aging problem that affects the battery performance over the time[34].

In large scales (tera-Joule range or more), long-term energy storage is proposed to be made possible using hydrogen as a medium for storing. Hydrogen is a storage medium that can be manufactured via electrolysis refining from surplus electricity, and when required it could again return to being transformed into electricity by fuel cells or other techniques. Hydrogen storage is a particularly relevant technology for applications where direct electrification is not viable[33].

Table 2.2: General technical specifications of energy storage techniques [50],[51],[52].

Storage Type	Efficiency (%)	Energy Density (Wh/kg)	Response Time	Storage Duration	Lifespan (years)	Environmental Impact	Cost (\$/kWh)	Suitability
Lithium-ion Batteries	85–98	100–300	Milliseconds	Hours to days	5–10	Moderate (Mining impact, limited recyclability)	\$100–350	EVs, Grid Storage
Lead-acid Batteries	70–85	30–50	Seconds	Hours	5–10	High (Toxic lead, but highly recyclable)	\$50–200	Backup Power, Small-Scale
Pumped Hydro Storage (PHS)	70–85	~1.5	Seconds-minutes	Hours to days	50+	Low (Water use, land impact)	\$50–200	Grid Storage, Large-scale
Compressed Air (CAES)	40–70	2–6	Minutes	Hours to days	25–40	Moderate (Geological constraints)	\$50–150	Grid Storage
Flywheel Storage	85–95	5–200	Milliseconds	Seconds-minutes	20+	Low (Recyclable materials, low emissions)	\$250–1000	Short-term, High Power
GH	30–70	33,300	Minutes-hours	Weeks to months	10–30	Low (If produced from renewables)	\$150–1000	Long-term Storage, Industry, Transport
Thermal Storage	50–90	50–300 kWh/m ³	Minutes-hours	Hours to months	20–40	Very Low (Non-toxic, recyclable materials)	\$10–100	Heating, Solar Storage
Supercapacitors	90–98	1–10	Milliseconds	Seconds-minutes	10–20	Moderate (Rare materials, developing recycling)	\$300–2000	High-Power Application

2.10 Economic consideration

The cost of producing GH is impacted by the pricing of renewable electricity, the efficacy of the electrolysis procedure, and the magnitude of production. With the declining expenses of

renewable energy and advancements in electrolysis technology, it is anticipated that the competitiveness of GH costs will increase [35].

2.11 Benefits of GH in the energy sector.

2.11.1 Transportation

The utilization of GH as a fuel for fuel cell electric vehicles (FCEVs), encompassing cars, buses, and trucks, presents an environmentally friendly option to traditional fossil fuels[36]. This alternative offers zero emissions, along with the potential for rapid refueling and extended driving ranges.

2.11.2. Power Generation

GH holds promise for power generation, whether through combustion in hydrogen turbines or utilization in fuel cells for electricity production[37]. Moreover, it can function as a storage medium for surplus renewable energy, aiding grid stabilization and ensuring reliable energy provision. During periods of heavy demand or when PV power generation is insufficient, the fuel cells use the stored hydrogen gas as fuel to generate electricity, which powers the load. Usually, Fuel Cells (FCs) reverse the electrolysis process, combining hydrogen and oxygen to generate electricity while releasing heat and water as waste[38][39].

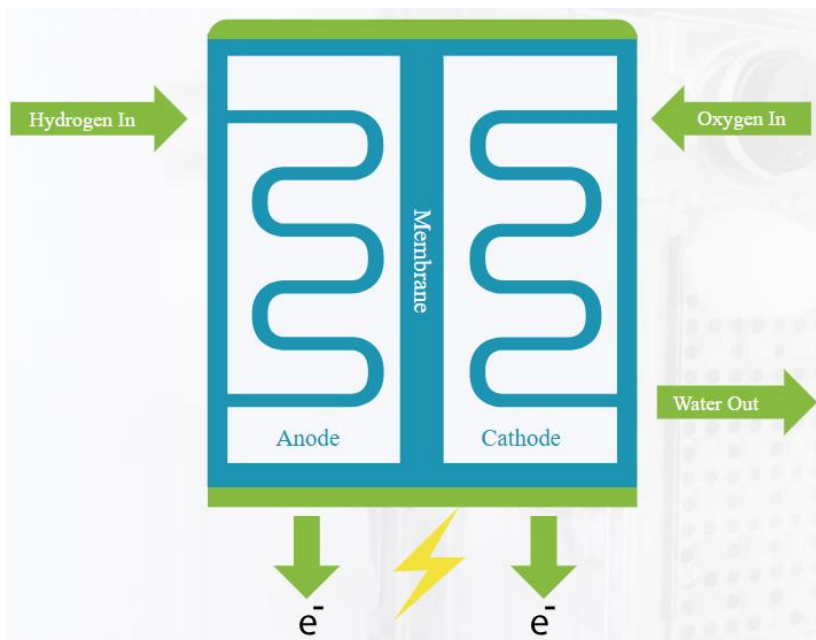


Figure 2. 18: Fuel cell basic [50].



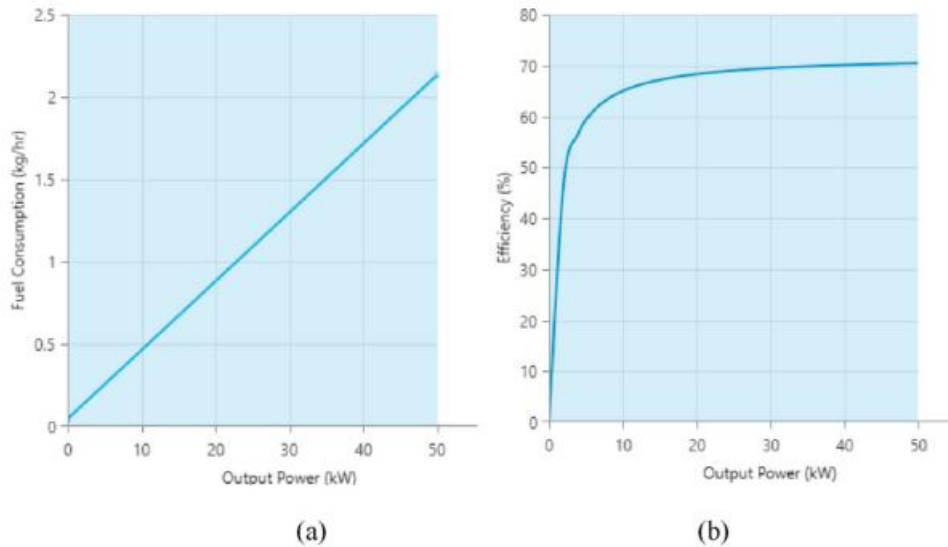


Figure 2. 19 : Hydrogen consumption and efficiency of fuel cell [51].

2.12. Integration marketing challenges of GH and ways of implantation.

2.12.1. Marketing challenges.

The integration of GH into Rwanda’s energy market faces key marketing challenges such as low public awareness, high initial costs, limited infrastructure, and unclear policies. These factors slow adoption and discourage investment. To address them, Rwanda should promote awareness through education and pilot projects, offer fiscal incentives to attract investors, develop public–private partnerships for infrastructure and research, and establish clear regulatory frameworks and safety standards. Implementing these measures will build market confidence and enable gradual, sustainable integration of GH into the national energy system.

2.12.2. Implementation strategies.

2.12.2.1. Awareness and Capacity Building

Promote education, training, and pilot projects to improve public understanding and technical skills.

2.12.2.2. Policy and Regulatory Framework

Develop clear national policies, safety standards, and incentives to guide hydrogen production, storage, and use.

2.12.2.3. Financial and Market Incentives

Introduce subsidies, tax exemptions, and investment support to reduce entry costs and attract private investors.

2.12.2.4. Infrastructure Development

Establish hydrogen production, storage, and distribution systems in partnership with public and private sectors.

2.12.2.5. Research, Innovation, and Partnerships

Encourage collaboration among universities, industries, and international organizations to support technology transfer and local innovation.

2.13. Impact on the environment.

2.13.1. Reduction of Emissions.

A key advantage of GH lies in its capacity to significantly diminish greenhouse gas emissions in diverse industries[40]. The substitution of fossil fuels with GH has the potential to markedly decrease emissions from transportation, industrial activities, and electricity generation.

2.13.2. Promotion of Sustainability.

The utilization of GH contributes to sustainability by facilitating the extensive integration of renewable energy sources, decreasing reliance on non-renewable resources, and advancing a circular economy[4]. The production and utilization of GH necessitate meticulous management to mitigate any adverse environmental consequences, such as water consumption and land utilization for renewable energy infrastructure.

2.14. Summary of literature review.

Previous studies have predominantly concentrated on the incorporation of GH into the energy sector, with a focus on technological advancements, economic viability, and policy structures. Research has highlighted the potential of GH as a clean energy carrier, especially in the decarbonization of challenging sectors like heavy industry and long-distance transportation. There has been notable headway in enhancing the effectiveness of electrolysis technologies and cutting down production expenses by leveraging economies of scale and advancements in RES. Nevertheless, numerous studies have pinpointed significant hurdles concerning storage, conveyance, and distribution infrastructure essential for the widespread acceptance of GH. Despite these achievements, there are still knowledge gaps regarding the complete environmental impacts throughout the lifecycle of GH production and utilization, encompassing water usage and land utilization consequences. Furthermore, a more thorough examination of market dynamics is necessary, including the amalgamation of GH into existing energy frameworks and its competitiveness vis-vis other sustainable energy solutions.

CHAPTER 3. METHODOLOGY

3.1. Introduction.

The methodology used to conduct this research is presented in this section of the thesis. This chapter explains in details various methods, techniques and procedures that have been used to examine GH's potential as a major contributor to the decarbonization of Rwanda energy systems are described in this chapter. Through literature review information on designs of different solar powered electrolyzer was collected and fully analyzed. The methodology of The research includes site surveys and data collection from the field of design. This section describes the methodology that followed to achieve objectives of this research. It is also discussing tools and software that have been used to simulate solar powered electrolysis system.

3.2. Research design.

The research explores the technical, economic, environmental, and policy implications of integrating GH into Rwanda's energy market using a mixed-methods design. It uses a quantitative approach, utilizing energy models, cost studies, and market trends, and a qualitative approach, engaging in stakeholder consultative processes and expert interviews. Comparative analysis of successful green hydrogen installations informs Rwanda's strategy. A case study method assesses local potential and readiness for green hydrogen uptake.

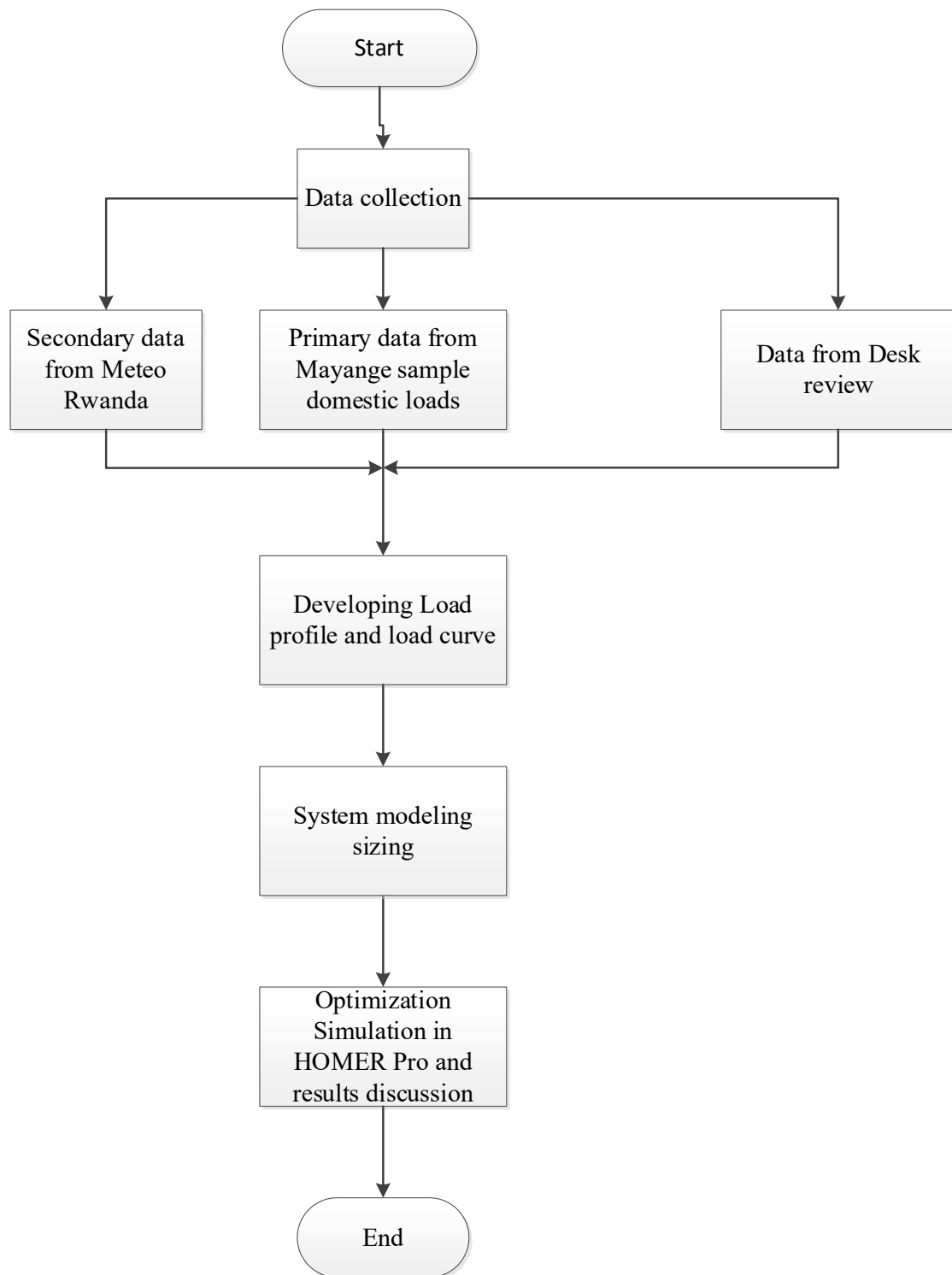


Figure 3. 1: Steps for research methodology.

3.3 Case study area.

Mayange sector is among fifteen sectors of Bugesera district in eastern province, Rwanda. The area is prone to droughts as it has a higher average daytime temperature than the Rwandan average, and lower precipitation[41].

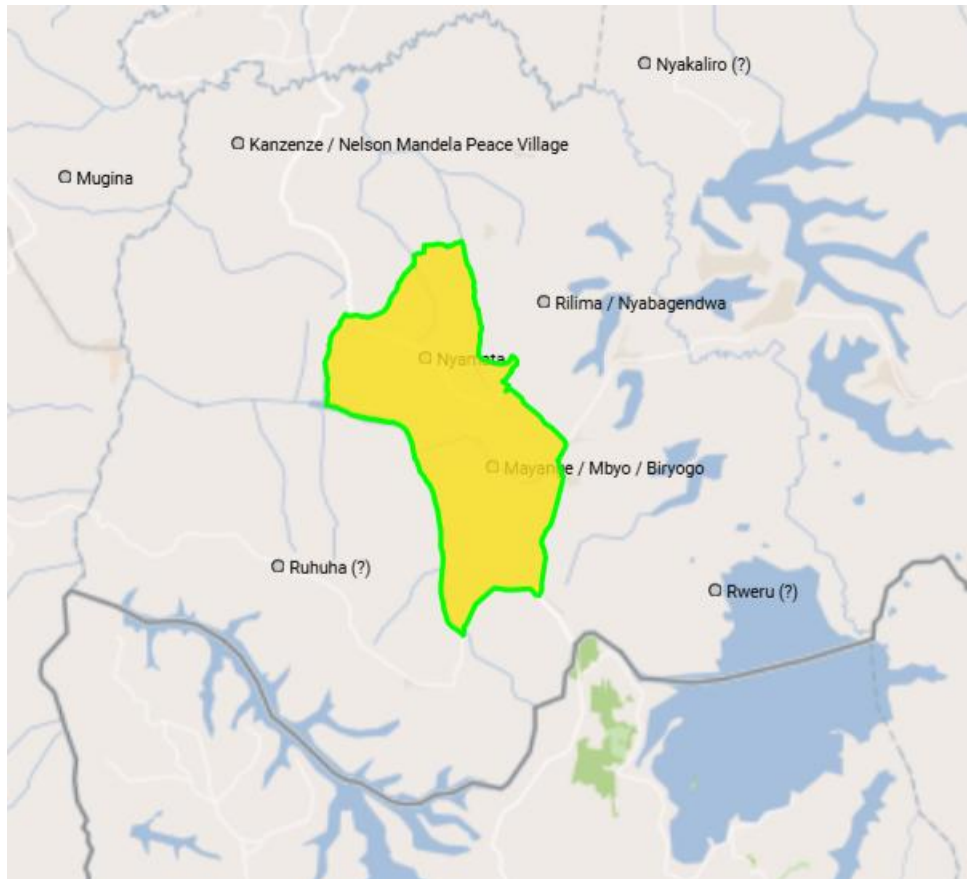


Figure 3. 2 :Mayange geographical map [59].

During the whole season, Bugesera District typically receives a lot of sunlight. The average solar radiation in this district is 5.6 kWh/m²[42]. According to the literature review Figure 2.9, the long-term monthly average daily global radiation ranges from 4.8 kWh/m²/day (location Burera, month of May) to 5.8 kWh/m²/day (location Nyanza, month of July), making this solar radiation one of the highest levels in Rwanda. Bugesera has a drier climate than other parts of the nation, with temperatures ranging from 20 to 300 degrees Celsius. Hunger emigration was caused by drought in this district in the past. However, the district has been reforested, and its natural resources have been safeguarded thanks to the increased government effort.

3.4 Data collection methods and their instruments.

The data collection techniques used in this study were survey, documentation on the design of solar-powered electrolyzer, and observation. Primary data obtained from questionnaires (see

the questionnaire in the appendix) during survey to obtain insight on types of loads frequently used by the local population, and observations provide overview on environment , while secondary data retrieved from Meteo Rwanda and literature reviews of books, journals, articles, and websites. From the literature review, based on the information deduced, the type of solar-powered electrolyzer to be implemented for the selected area was deduced. The monthly irradiance data was collected from meteo Rwanda see appendix and analyzed by HOMER software, and a PV system suitable for electrolyzer was designed. This information was needed for a feasible design of a solar-powered electrolyzer.

3.5 Analysis of research methodology.

3.5.1 Selection of the site

This is the first step a researcher takes to determine the current situation at the location of his research study before implementing the project. An electrolyzer solar PV and fuel cell system's overall performance, efficiency, and long-term viability are all influenced by the site's strategic decision. A carefully considered site can minimize environmental effects, save operating costs, and maximize electricity generation (solar PV output). The main elements considered when choosing the best location for the GH generation system are Solar radiation and water availability as discussed in chapter two.

The amount of solar radiation that the location receives is one of the main factors that produces enough energy. Areas that receive enough sunlight guarantee that the solar panels generate the most power possible, increasing the electrolyzer's output. For this purpose, regions with high levels of yearly sun radiation are very beneficial. To determine a potential site's compatibility, historical sun irradiance data of site have been examined.

Enough land must be available for the installation of the electrolyzer unit, solar panels, and any further equipment that may be needed. There should be enough room on the site to accommodate any future system expansions or changes.

Environmental issues should address conflicts or adverse effects thoughtfully. This should be done taking into consideration water supplies, preserved areas and wildlife habitats as well as the zoning laws. This is a delicate operation, and it needs to be chosen locations where environmental disruption is minimized or that comply with the local laws of environment security.

Table 3.1: Summary of key criteria for selecting a suitable site for GH production.

Site selection criteria	Description
Solar Radiation	High solar irradiance is essential for maximizing PV output and hydrogen production. Areas with ample sunlight are preferred. Historical irradiance data are evaluated for suitability.
Land Availability	Sufficient land is needed for electrolyzer units, solar panels, and additional equipment, with space for future expansion.
Environmental Considerations	Minimizing environmental impact by addressing local water resources, protected areas, and wildlife habitats, and adhering to zoning and environmental regulations.

3.5.2 Selection of the type of electrolyzer and Fuel cell

The tool used for this method was literature reviews on the common types of solar powered electrolyzer in use for GH production. The researcher gathered information of these types of solar powered electrolyzer in terms of construction cost, time responses, efficiency and solar PV power adaptability operation and maintenance costs and found that the most compatible electrolyzer is PEM. For solar-powered hydrogen production, PEM electrolyzer are often preferred due load following capability i.e PEM electrolyzer are better suited for load-following applications, adapting their production rates to match variable solar output[43].

Table 3.2: Summary of the most common configurations of solar powered ELC [63].

Criteria	Alkaline Electrolyzer	PEM (Proton Exchange Membrane)	Solid Oxide Electrolyzer (SOEC)
Cost	Lower initial cost	Higher initial cost	High cost, especially for high-temperature materials
Efficiency	60-70%	70-80%	Up to 90% (at high temperatures)
Response to Variable Load	Moderate; less suitable for	Excellent; Handles fluctuate	Limited; Operates best with stable input.

	intermittent inputs.	well.	
Operating Temperature	60-80°C	50-80°C	600-800°C
Durability	Long lifespan, robust	High, but membrane replacement may be needed.	Long lifespan but requires stable high-temperature conditions.
Electrolyte	Potassium hydroxide solution.	Solid polymer membrane.	Ceramic oxide (solid electrolyte).
Start-Up Time	Moderate (minutes)	Fast (seconds)	Slow (hours)
Scalability	Well-suited for large-scale systems.	Suited for small to medium scales but scalable.	Primarily industrial-scale applications
Maintenance	Low to moderate; relatively low maintenance needs.	Moderate; regular maintenance of membranes	High; requires high-temperature components to be maintained
Suitability for Solar PV	Moderate; not ideal for fluctuating power.	Excellent; well-matched to variable solar output	Limited; requires steady power source
Applications	Large-scale, industrial	Flexible; small to large applications	Industrial, high-efficiency integrated systems
Advantages	Low cost, reliable for continuous operation.	High efficiency, adaptable to solar variability.	High efficiency in integrated, high-temperature systems.

CHAPTER 4. GH GENERATION SYSTEM MODELING AND SIZING.

4.1 Introduction.

This chapter explores the system components, operational principles, and modeling of a PV-electrolyzer setup to optimize hydrogen production. A mathematical model is developed to analyze system performance under varying solar conditions.

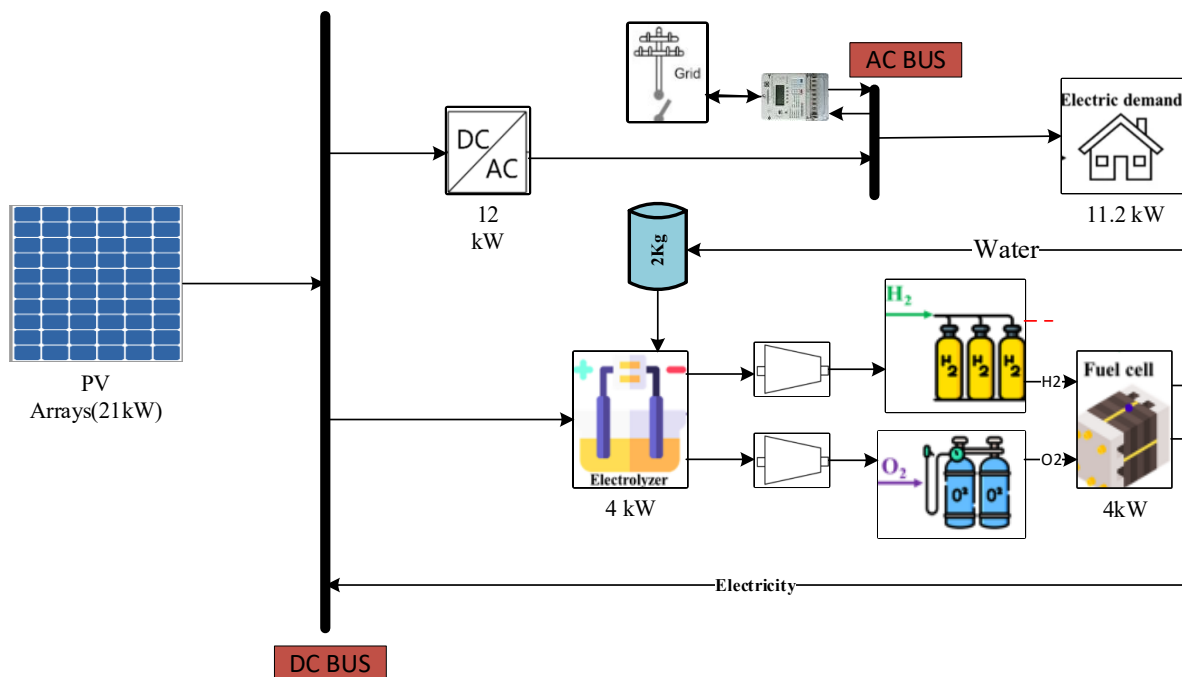


Figure 4. 1 : Block diagram of integrated PV-ELEC-FC and Grid system with hydrogen.

4.2 Parameter to consider when modeling Grid connected PVEFC system.

Designing a grid-connected PV-electrolyzer-fuel cell system requires careful consideration of various parameters to ensure optimal performance, efficiency, and economic viability.

(1) Climate data quantity of available solar irradiance. (2) Load demand profile: Helps balance energy supply, electrolyzer operation, and grid interaction. (3) PV system model: Optimized for maximum energy generation. (4) Electrolyzer model: Matches surplus PV power to optimize hydrogen production. (5) Grid availability: Influences cost-effectiveness, energy export policies, and net metering benefits. (6) Hydrogen storage capacity: Determines backup energy supply for nighttime or low solar periods. Fuel cell model: Ensures adequate power supply when solar generation is low.

4.3 System modeling and sizing.

4.3.1 Important climate data.

The Bugesera District receives a big amount of sunlight during the wall period of year as it is clearly visible from Figure 2.8 and Figure 2.9 display potential in solar energy. This District has an average solar radiation of 5.6kWh/m². This solar radiation is among the highest radiation levels in Rwanda as we have seen in a literature review.

Table 4.1:Climate season of Bugesera district.

Climate season	Duration
A short dry season	January to mid-March
Long rainy season	Mid-March to June
Long dry season	Mid-June to September
A short rainy season	Mid-October to December

Mayange climatic data were collected from Mateo, Rwanda. The location was selected because it presents a favorable climate for solar energy potential, a key parameter to consider during the design of a PV system as the primary source of energy to the load. This region has an average Solar Global Horizontal Irradiance (GHI) of 5,04 kWh/m², as shown in Table 4.2.

Table 4.2: Monthly Average solar radiation data for Mayange village from meteo Rwanda.

Month	Clearness index	Daily radiation (kWh/m ² /day)
January	0.484	4.98
February	0.505	5.32
March	0.484	5.09
April	0.484	4.88
May	0.495	4.67
June	0.554	5.01
July	0.592	5.44
August	0.562	5.49
September	0.521	5.37
October	0.469	4.91
November	0.449	4.63
December	0.466	4.74
Average		5.04

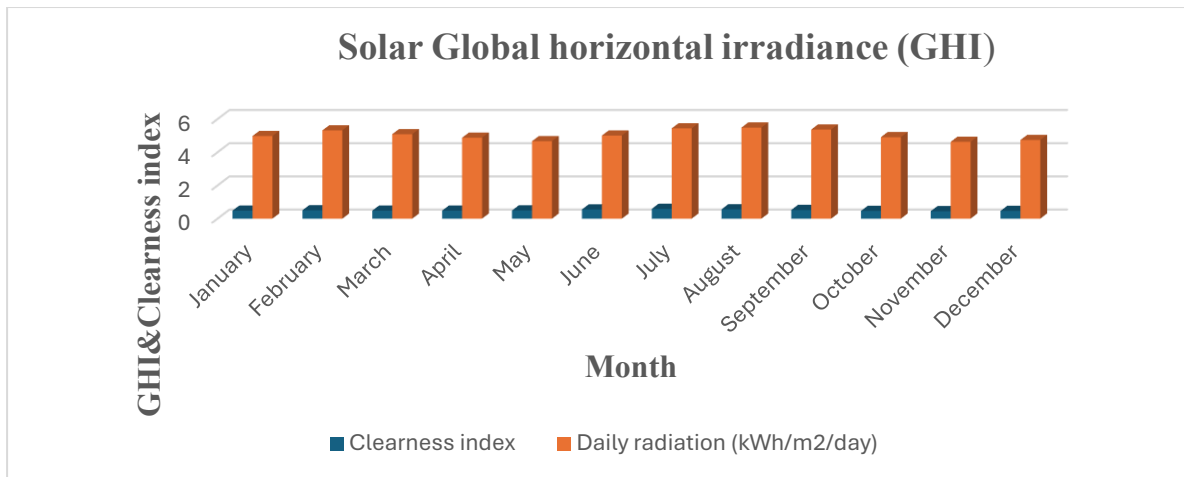


Figure 4. 2 : Monthly average GHI and clearness.

Table 4.3:Mayange monthly average temperature.

Month	Minimum	Max	Average
January	15	28	21
February	15	27	21
March	15	26	20
April	15	23	19
May	14	23	18
June	14	25	19
July	15	27	20
August	16	27	21
September	17	27	22
October	22	27	24
November	20	26	23
December	20	27	23
Annual average			20.9≈ 21

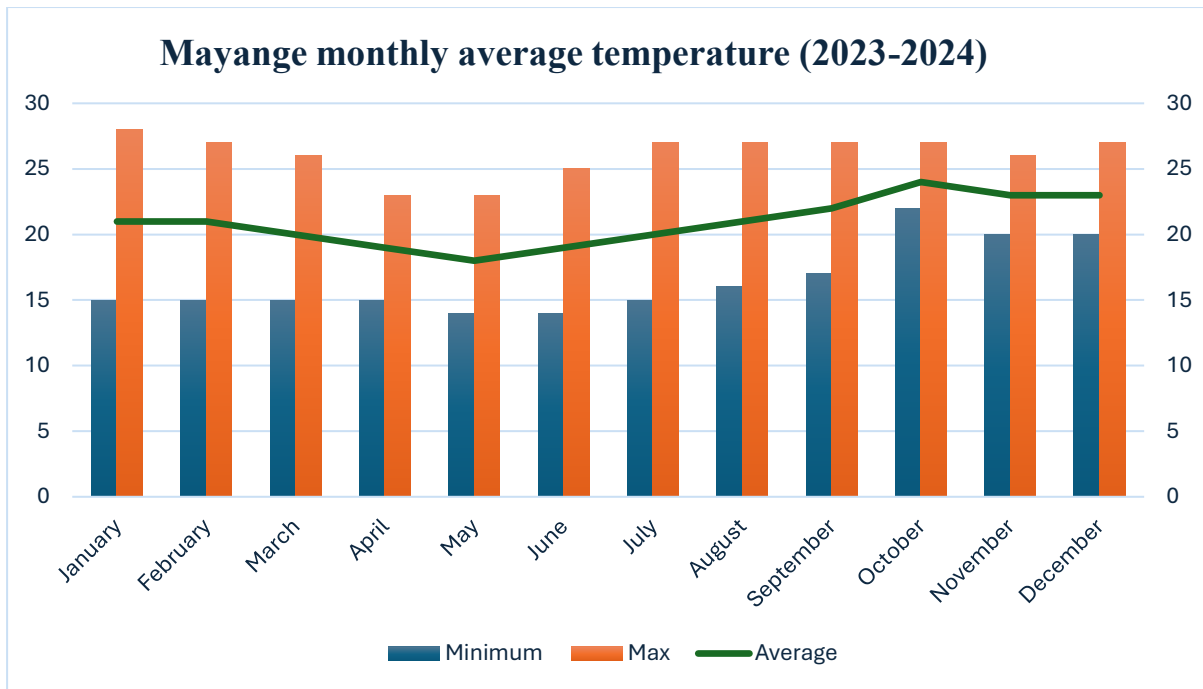


Figure 4. 3: Mayange monthly average temperature (2023-2024)

4.3.2 Load assessment

Load assessment is a major step in creating the electrical sources and figuring out the ideal system part sizes. Bugesera rural residents, particularly those in Mayange village , require electricity for a few essential sample household loads including fans, lighting, TVs, radios, refrigerators, ironing, blenders, and water heaters, and some educational uses like computers as it is found in table 4.1, but apart from these loads categories and their power ratings , an electrolyzer is an additional load that is supplied by energy surplus from PV system.

Table 4.4: Sample connected loads in Mayange sector.

No	Load name	Quantity	Power rating (kW)	Total power (Kw)	Cos ø	Total power (KVA)	Operating time (Hrs)	Daily energy(kWh)
1	Fun	3	0.8	2.4	0.9	2.67	5.5	13.2
2	Light bulbs	103	0.01	1.03	1	1.03	12	12.36
3	Television	9	0.06	0.54	1	0.54	5	2.7
4	Radios	30	0.04	1.2	1	1.20	6	7.2
5	Refrigerator	2	0.07	0.14	0.85	0.16	24.5	3.43
6	Ironing	4	1.2	4.8	1	4.80	2	9.6
7	Blender machine	2	0.24	0.48	1	0.48	3	1.44
8	Computers PC	9	0.065	0.585	1	0.59	8	4.68
	TOT (kW, kVA, kWh)			11.175		11.47		54.61

Table 4.5: Average hourly base load demand in kWh of a day in January/2025.

Hour	Fans	Lighting	TVs	Radios	Refrigerators	Ironing	Blender	Computers	Total Load (kW)/h	Total per period	Period
0	0	1.7	0	0	0.2	0	0	0	1.9	11.48	NAGHT TIME
1	0	1.7	0	0	0.2	0	0	0	1.9		
2	0	1.7	0	0	0.2	0	0	0	1.9		
3	0	1.7	0	0	0.2	0	0	0	1.9		
4	0	1.71	0	0.03	0.2	0	0	0	1.94		
5	0	1.69	0	0.05	0.2	0	0	0	1.94		
6	0	0	0.3	0.08	0.2	0.6	0	0.32	1.5	21.45	DAY TIME
7	0	0	0.3	0.1	0.2	0.7	0.3	0.44	2.04		
8	0	0	0.3	0.07	0.4	0.7	0.3	0.56	2.33		
9	0	0	0.45	0.08	0.2	0	0	0.56	1.29		
10	0.07	0	0.45	0.6	0.2	0	0	0.64	1.96		
11	0.07	0	0.3	0.05	0.2	0	0.4	0.78	1.8		
12	0.15	0	0.3	0.05	0.3	0	1.2	0.72	2.72		
13	0.08	0	0.15	0.05	0.4	0	0.2	0.72	1.6		
14	0.15	0	0	0.025	0.2	0	0.6	0.5	1.475		
15	0.2	0	0	0.025	0.2	0	0	1.1	1.525		
16	0.17	0	0.15	0.05	0.3	0	0.3	0.6	1.57		
17	0.15	0	0.3	0.05	0.2	0	0.7	0.24	1.64		
18	0.12	0.7	0.35	0.1	0.2	0.9	0.1	0.26	2.73	21.07	NAGHT TIME
19	0.1	1.3	0.45	0.1	0.2	1.14	1.7	0	4.99		
20	0.12	2.4	0.46	0.1	0.2	1.23	0	0	4.51		
21	0.07	2.8	0.45	0.05	0.2	0	0	0	3.57		
22	0.07	2.9	0.15	0.05	0.2	0	0	0	3.37		
23	0	1.7	0	0	0.2	0	0	0	1.9		
									54		

Table 4.6: Mayange monthly electricity consumption for domestic users.

Month	Days in Month	Daily Energy (kWh) (Varies by Season)	Monthly Energy (kWh)	Total kWh consumption/year
January	31	54	1674	19043.58
February	28	53.1	1486.8	
March	31	52	1612	
April	30	48.3	1449	
May	31	51	1581	
June	30	52.6	1578	
July	31	54	1674	
August	31	54.98	1704.38	
September	30	52	1560	
October	31	48.9	1515.9	
November	30	52.7	1581	
December	31	52.5	1627.5	
Average		52.17	1586.965	

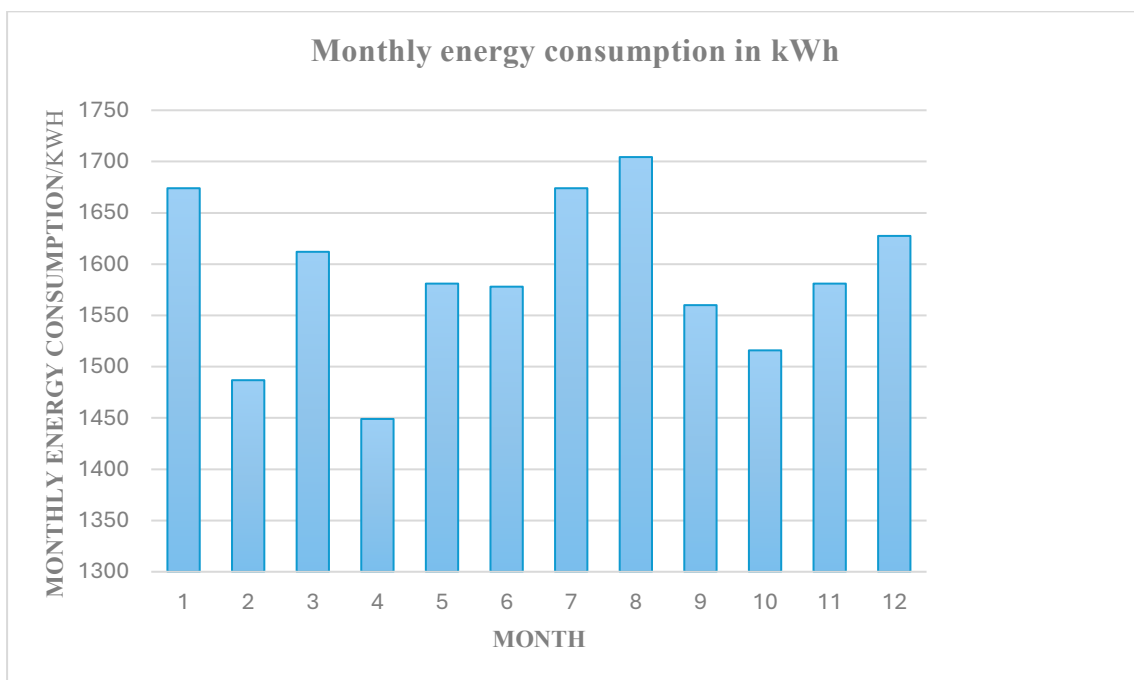


Figure 4. 4 : Energy consumption month.

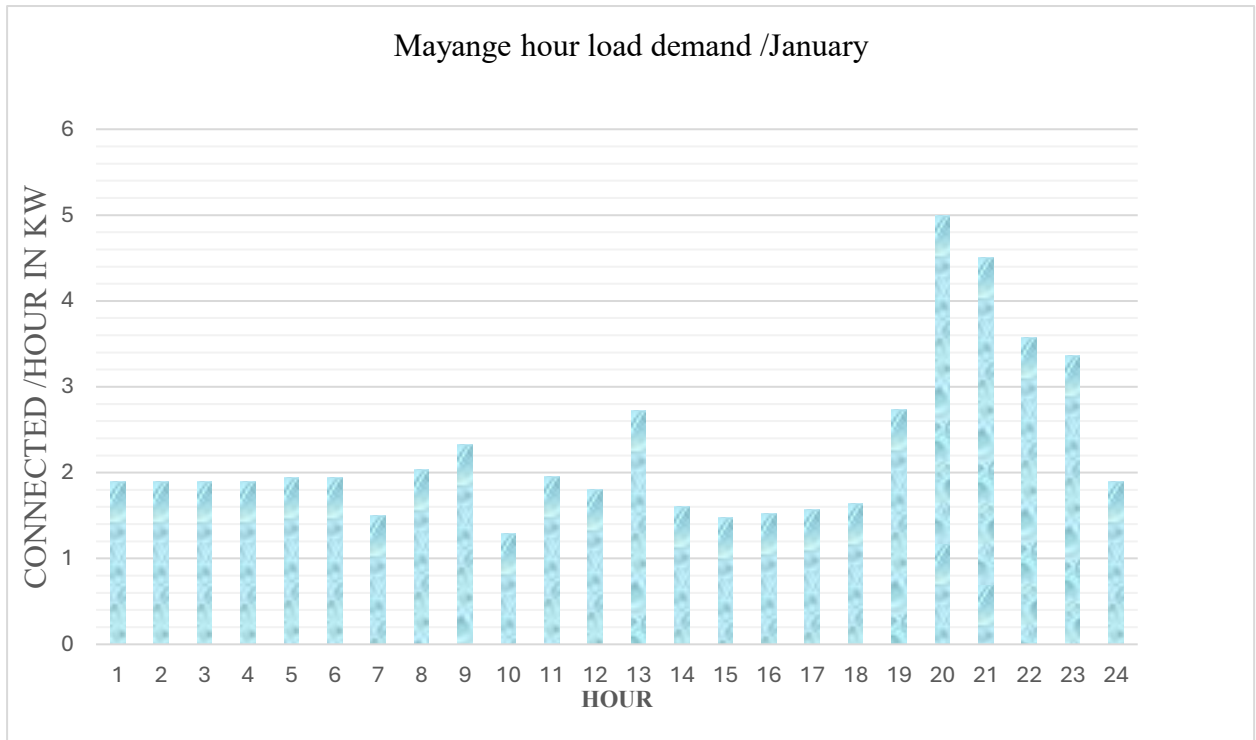


Figure 4. 5: Mayange hourly load demand.

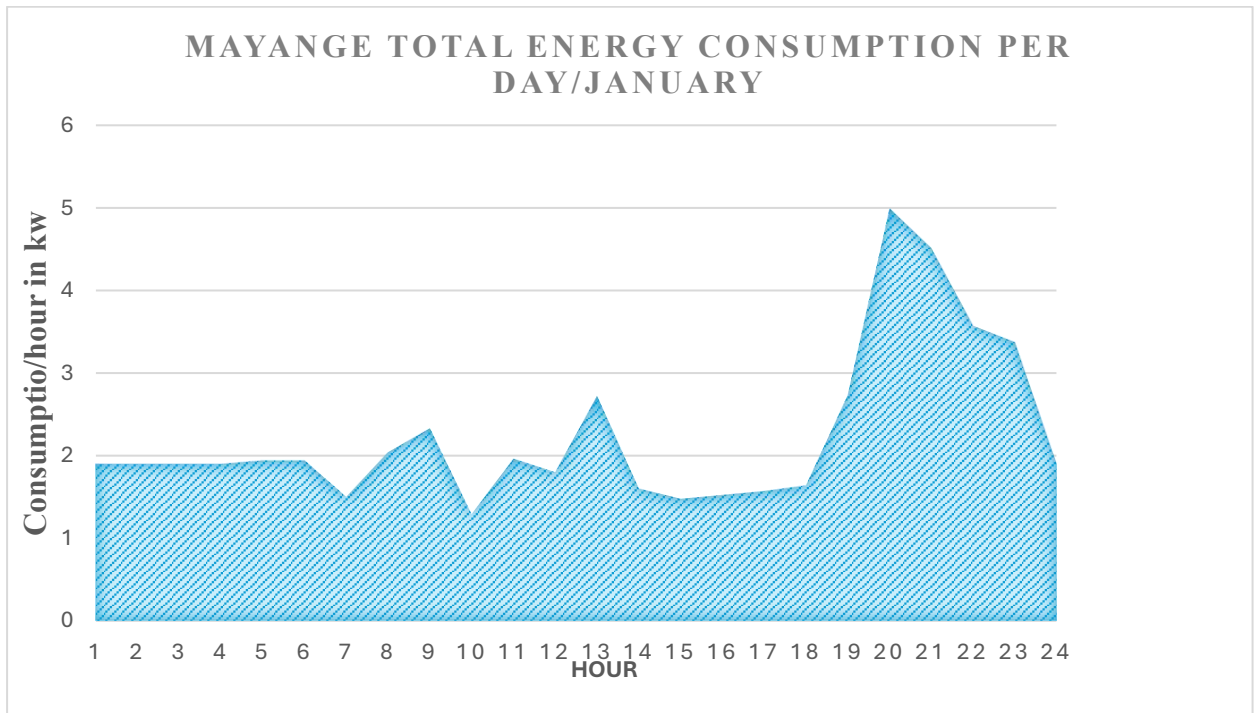


Figure 4. 6: Mayange energy consumption profile.

4.3.3 Load factor calculation

$$\text{Annual Load Factor (LF)} = \frac{kWh}{kW \times \text{Days} \times 24} \tag{4.1}$$

Where kWh and kW are total energy consumed per year and total demand, respectively.

4.3.4 Photovoltaic power generation and load balance.

The total photovoltaic (PV) energy generated must cover the domestic load (El), hydrogen production (via the electrolyzer) Eel, and any surplus energy injected into the grid Egrid:

$$\sum_t Ppv(t) = El(t) + Eel(t) + Egrid(t) \quad (4.2)$$

Energy injected and drawing from the grid is calculated by equation 4.3.

$$Egrid(t) = 3V(t)I(t)\text{Cos}\theta(t) \times t \quad (4.3)$$

where $E_{grid}(t)$, $V(t)$, $I(t)$ and $\text{Cos}\theta(t)$ represents energy injected into the grid, voltage, current, power factor and time respectively.

4.3.5 Fuel cell modeling and sizing

4.3.5.1 Energy input to fuel cell calculation

Fuel cells generate electricity by oxidizing a reducing fuel at one electrode and reducing an oxidant at another. Due to their minimum operating temperature (<100°C) quick start-up time, remarkable efficiency, and long lifetime, PEMFCs are one of the most widely used fuel cell technologies[44].

Hydrogen energy required to supply the fuel cell based on nighttime energy demand (From load profile in table 4.4: total energy demand during nighttime is 32.55 kWh , and fuel-cell efficiency of 60% [45].

$$P_{fc}(t) = \eta_{FC} \times PH_2(t) \quad (4.4)$$

The instantaneous energy input to the fuel cell must be:

$$0 < E_{fc}(t) \leq E_{fc}^{max} \quad (4.5)$$

Where $E_{fc}(t)$, E_{fc}^{max} , η_{FC} , $PH_2(t)$, $P_{fc}(t)$ is energy input to fuel cell, fuel cell maximum energy, fuel cell efficiency, hydrogen quantity, fuel cell output power at time step.

Therefore, the energy required input is calculated as follows:

$$\text{H2 energy required} = \frac{\text{Nighttime avg consumption}}{\text{Fuel cell efficiency}} = \frac{32.55}{0.6} = 54.25 \text{ kWh}$$

From this hydrogen energy that needs to be converted into electricity by fuel cells, we may calculate its corresponding quantity in kg as follows as Table 2.2 depict energy per kg in KJ/g.

119.93KJ → 1g of hydrogen

1000 g (or 1kg) of hydrogen → 119930 KJ

3600 KJ → 1 kWh

$$119930\text{KJ} \rightarrow \frac{119930\text{KJ}}{3600\text{KJ}} \text{kWh} = 33.3\text{kWh}$$

Therefore, the lower heating value (LHV) of hydrogen, is 33.33 kWh/kg.

$$\text{Mass of Hydrogen} = \frac{\text{Hydrogen Energy Required}}{\text{LHV of hydrogen}} \quad (4.6)$$

$$\text{Mass of Hydrogen(kg)} = \frac{54.25\text{kWh}}{33.33\text{kWh}} \times \text{kg} = 1.63\text{kg}$$

Since hydrogen storage will also function as a backup for times when PV generation is enough, we need an increased storage to ensure system reliability during autonomy days, and grid maintenance. A reasonable assumption is to store at least 2 days' worth of hydrogen, which means:

$$1.63\text{ kg} \times 2 = 3.26\text{ Kg of H}_2$$

3.26 kg hydrogen tank size ensures sufficiency backup energy for nighttime use, plus some buffer for cloudy periods.

4.3.5.2 Fuel cell power rating

The fuel cell rating is based on the nighttime load demand profile.

Total nighttime energy demand: 32.55 kWh.

Operating hours: Typically, 12–15 hours (overnight period plus possible back up hours in daytime)

$$\text{Fuel cell nominal power} = \frac{E_t}{t} = \frac{54.25\text{ kWh}}{15} = 3.6\text{ kW} \quad (4.7)$$

Where E_t and t are energy input at time t and time, respectively.

To manage night peak demand and fluctuations (i.e., night peak load demand 4.9 kW), a 4-5 kW PEM fuel cell is chosen for low operating temperature(50-100°C), higher operating efficiency comparable to other fuel cells, fast start up time, see technical specifications in appendix B-Table1.

4.3.6 Electrolyzer modeling and sizing

Electrolyzer sizing is crucial for efficiently converting surplus renewable energy into hydrogen for energy storage. It involves determining the required power capacity based on hydrogen quantity (*see total required quantity of hydrogen as stored energy*), operational constraints, and system efficiencies. Proper sizing ensures optimal utilization of excess power while maintaining system stability. The energy input to electrolyzer will always be in range of its maximum and minimum power.

$$P_{el}^{min} \leq P_{el}(t) \leq P_{el}^{max} \quad (4.8)$$

where P_{el}^{min} , P_{el}^{max} , $E_{el}(t)$ are, minimum power to electrolyzer, maximum power to electrolyzer and energy at time t. And energy is calculated as follows:

4.3.4.1 Energy input to electrolyzer to produce hydrogen.

The energy input is needed for the electrolyzer by dividing the hydrogen energy requirement by the electrolyzer efficiency. From[44], the amount of photovoltaic energy available at the input of electrolyzer $E_{el}(t)$ is determined by the amount of excess photovoltaic energy, amount of energy used to supply the load E_l and grid injection. See equation 4.8.

$$E_{el}(t) = E_{pv}(t) - E_{grid}(t) - E_l(t) \quad (4.9)$$

And generated hydrogen energy is:

$$EH_2(t) = E_{el}(t) \times \eta_{el} \quad (4.10)$$

Where η_{el} , $E_{el}(t)$ electrolyzer efficiency, energy input to electrolyzer at unit time step. electrolyzer input power.

3.26 kgs of hydrogen gas (H_2) $\rightarrow 54.25 \text{ kWh} \times 2 = 108.5 \text{ kWh}$ as total energy held by hydrogen at the output of electrolyzer. Therefore, total energy input is required to the electrolyzer total E_{el} is:

$$\sum_{t=1}^N E_{el}(t) \quad (4.11)$$

Where, N, t, $E_{el}(t)$ are total time, time step and energy at time step.

$$Tot. \text{ energy input} = \frac{\text{total hydrogen energy required}}{\text{electrolyzer efficiency}} \quad (4.12)$$

$$Total \text{ energy input} = \frac{108.5 \text{ kWh}}{0.7} = 155 \text{ kWh}$$

4.3.4.2 Electrolyzer power rating.

From the figure 4.5 during the day peak demand, energy demand is 2.72 kWh. Means that from the total power that remains must lie between electrolyzer rating limits.

The electrolyzer operating hours are assumed to be 12 hours, therefore:

$$Electrolyzer \text{ power rating} = \frac{\text{total energy input required}}{\text{operating hours}} \quad (4.13)$$

$$Electrolyzer \text{ power rating(nominal)} = \frac{155 \text{ kWh}}{12} = 12.9 \text{ kW} \approx 13 \text{ kW}$$

Where 155 kWh is total energy input to electrolyzer per day and twelve operating hours.

PEM can go as low as 5% of nominal capacity. On the other extreme, PEM, can operate beyond the nominal capacity, which is not possible for alkaline electrolyzer[46].

$$Min \text{ operating power for PEM electrolyzer is} = \frac{13 \text{ kW} \times 5}{100} = \text{kW} = 0.65 \text{ kW}$$

This PEM electrolyzer is better than any electrolyzer type due to its adaptation capability on a fluctuating power, better to consider slightly oversized electrolyzer to accommodate variable energy input, electrolyzer operating over more hours per day is practical. See PEM Electrolyzer technical specifications in appendix B-Table2.

4.3.7 Hydrogen storage sizing.

Hydrogen is typically stored in compressed form, at pressures ranging from 200 bar to 700 bar. As the pressure increases, the hydrogen quantity per unit increases. The density of hydrogen at 350 bars (common in stationary storage) is 23.1 g/L (0.0231 kg/L).

$$\text{Tank volume} = \frac{\text{Mass of hydrogen}(m)}{\text{Density at stored pressure}(\rho)} \quad (4.14)$$

$$\text{Tank volume} = \frac{3.26 \text{ kg}}{0.0231 \text{ kg}} \times l = 141 \text{ l} = 0.141 \text{ m}^3$$

The hydrogen storage tank will be updated with respect to the following model counting initial volume and additional quantity:

$$H_2v(t + 1) = Hv(t) + EH_2(t) - \text{Hydrogen used}(t) - \text{Losses}(t) \quad (4.15)$$

Account for storage losses.

Hydrogen storage losses depend on system design, but common losses are 1–3% per day due to leakage and boil-off. Assuming 2% daily loss, we need to store slightly more hydrogen:

$$\begin{aligned} \text{Total hydrogen required} &= \frac{\text{Mass of hydrogen}(m)}{(1-0.02)} \quad (4.16) \\ &= \frac{3.26 \text{ kg}}{(1-0.02)} = 3.32 \text{ kg} \end{aligned}$$

Thus, the final hydrogen storage capacity should accommodate at least 4 kg of hydrogen to ensure enough supply after losses. The quantity of hydrogen stored in the tank is subject to the following constraints[44]:

$$E_{\text{tank}}^{\min} \leq E_{\text{tank}}^t \leq E_{\text{tank}}^{\text{tank}} \quad (4.17a)$$

Grid injection when storage is full, see equation 4.17b.

$$\begin{aligned} H_2V(t) = H_2\text{storage} \rightarrow E_{el} &= 0 && \text{i.e surplus is injected into the grid,} \\ E_{\text{grid}}(t) &\geq 0 \quad (4.17b) \end{aligned}$$

4.3.8 Photovoltaic system modeling and sizing

Design and calculation of photovoltaic systems need to calculate the total energy needed by the system. This is done by calculating the energy needed by total loads connected to the photovoltaic system i.e. residential load and electrolyzer. The photovoltaic system consists of

numbers of PV modules which are sized based on the total amount of energy needed. The sizing of PV arrays varies according to location, solar radiation, and temperature[30].

4.3.8.1 Photovoltaic system modeling.

The power output of the solar photovoltaic field is determined by the number of solar panels (N_{PV}), the nominal power of each solar panel under standard test conditions (P_{STC}), solar radiation ($G(t)$), cell temperature ($TC(t)$), and the various losses (system losses) caused by the efficiency of the converters, cables, and so on (F_{losses}). Equation 9 gives the expression for calculating the power generated by the PV field over time[44].

$$P_{PV}(t) = N_{PV} \times P_{STC} \times \frac{G(t)}{G_{ref}} \times [1 + \alpha_p \times (TC(t) - 25)] \times F_{losses} \quad (4.18)$$

In this equation (4.11), α_p is the temperature coefficient and G_{ref} is the irradiance corresponding to standard measurement conditions (STC), which has a value of 1000 W/m². Equation 4.12 is used to calculate the temperature TC of the cells.

$$TC(t) = T_a(t) + \left(\frac{NOCT - 20}{800} \right) \times G(t) \quad (4.19)$$

Solar PV system consists of many numbers of PV modules which are sized based on the amount of energy needed. The sizing of PV arrays varies according to location, solar radiation, and temperature. Using solar irradiance of 5.04 kWh/m²/day see table 4.3: in Bugesera/Mayange village:

PV system efficient = 18.02%

System losses (losses from wiring, inverter, dust, shading, temperature effects) = 20%

Net system efficiency = PVη × (1 – System losses)

$$\text{Net system efficient} = 18\% \times (1 - (0.6 \times 0.7)) = 14.4\%$$

4.3.8.2 Photovoltaic system sizing.

Energy supplying domestic loads during daytime (12 hours) → 21.45 kWh/day and the peak load demand in the daytime is 2.72 kWh. Supply electrolyzer to produce hydrogen for nighttime storage and back cloudy day → 155 kWh/day to generate 3.26 kg of H₂.

Thus, the total required energy generation of PV array per day is:

$E_t = 21.45 + 155 = 176.45$ kWh/day. Average energy produced by a module per day i.e. during sun peak hour (SPH), at operating temperature of 21°C takes 5 hours peak sun hours of Mayange village[47] with derating factor (DF) of 88%.

$$E_{av}(pv) = SPH \times P_{pv} \times DF \quad (4.20)$$

And is calculated: $E_{av}(pv) = 5h \times 0.295 \times 0.88 = 1.29$ kWh

$$N \text{ modules required to meet total energy } (E_t): N = \frac{E_t}{E_{av}(pv)} = \frac{176.45 \text{ kWh}}{1.29 \text{ kWh}} = 136.78 \approx 137$$

$$\text{Net efficient of the system} = 18\% \times (1 - (0.6 \times 0.7)) = 14.4\%$$

The usable PV energy output per kW installed: $G(\text{kWh}) \times \eta_{\text{Syst}} = 5.04 \text{ kWh} \times 0.144 = 0.726$ kWh per kw installed. Where solar irradiance(G)= 5.04 kWh and system efficiency (η_{Syst}) = 0.144

$$E_{av}(h) = \frac{E_t}{12} = \frac{176.45}{12} 14.7, \text{ where } E_{av}(h) \text{ energy needed per hour in daytime.}$$

$$\text{The required PV power capacity: } = \frac{E_{avg}}{0.726 \text{ kWh}} \quad (4.21)$$

$$= \frac{14.7}{0.726} = 20.25 \approx 21 \text{ kw}$$

From the above calculations, to ensure hourly distribution is covered and electrolyzer is supplied for hydrogen production for storage, daily peak load, a PV system of at least 15-21 KW will allow flexibility in power distribution between direct consumption, hydrogen production, and grid export, PV panel used is CS6K-295MS due to its derating factor, high efficiency, higher operating temperature. See CS6K-295 technical specifications in the appendix B-table 4.

4.3.8.3 Inverter modeling and sizing.

The inverters must be able to convert the DC power produced by the photovoltaic array and fuel cells into AC power that can be fed the load or injected into the grid with grid parameter fulfillment. For grid connection, the inverter must have the word “utility interactive” printed directly from the label[30], and as the system will not have battery voltage range will be 235-600 V[30]. Grid-connected systems are designed based on the power generation capacity of the

photovoltaic system array, not the building's energy demands. This is because any additional power needed beyond what the PV system produces is seamlessly supplied by the grid[30].

$$\begin{cases} P_{invn} \geq PPV(t) + PFC(t) \\ P_{invn} = k \times \max(PPV(t) + PFC(t)) \end{cases} \quad (4.22)$$

where k represents inverter sizing safety factor and is equal to 0.87.

The inverter total AC output power is $11.175 \text{ kW} \approx 12 \text{ kW}$ see total (kW) in table 4.5. See technical specifications of inverter in the appendix B-Table 3. This inverter is selected due to its time step of 60 minutes.

4.4 Cost estimation of integrated solar PV- electrolyzer – fuel cell and grid.

The cost of different components used in the system varies depending on the manufacturer and the selling company. From different online selling companies like Alibaba and articles.

Table 4.7: Cost estimation of integrated solar PV-ELEC– FC- and Grid[48][49][50].

Types	Quantity	Cost \$/kW	O&M Cost \$/kW	Lifespan/year	Total cost/\$
PV Panels	137	21×330	137×1	25	7067
Electrolyzer	1	4×100	8	15	548
Fuel cell	1	4×400	0.1\$/hr	15,000 h	2076
Hydrogen Storage tank	1	0.5 /Kg	0.05/kg	25	2.75 \$
Converter (DC/AC)	1	12×40	10×12	15	600
					9412

CHAPTER 5. SIMULATION RESULTS AND DISCUSSION.

5.1 Introduction.

This chapter presents simulation results of the system composed of photovoltaic, residential load, electrolyzer, fuel cell and grid. After system optimization by HOMER simulator, it's a results discussion.

5.2 Simulating HOMER Pro software.

HOMER is a term that stands for Hybrid Optimization of Multiple Energy Resources. It can be used to manage a variety of technologies, including photovoltaic, boiler, wind, hydro, fuel cells, and loads that can be AC or DC, thermal and hydrogen[51]. HOMER is a powerful modelling tool that may be used to facilitate the development, analysis and evaluation of both grid and off-grid connected hybrid power system for distribution generation, standalone and remote applications. Simulation, optimization, and sensitivity analysis are three core features of the HOMER program. In this research, HOMER Pro software was used to analyze the optimal design for solar powered domestic load and electrolyzer as GH producing equipment for the purpose of energy storage at Mayange village, Bugesera district. This software estimated the technical feasibility of the proposed system and ranks those systems in terms of Net Present Cost (NPC), Levelized Cost of Energy (Levelized COE) and Operating Cost. This analysis was done to minimize grid dependency through storing day time surplus energy into hydrogen as backup. All simulations and optimization analyses were performed on a personal computer equipped with Local disc of 952 GB, Processor 12th Gen Intel(R) Core (TM) i7-1255U 1.70 GHz, Installed RAM: 8.00 GB (7.71 GB usable), running Windows 11, While computational speed may vary with hardware, the results presented are reproducible and independent of the specific computer used.

5.2.1 System simulation choices

HOMER software, utilized for modeling various hybrid energy systems, conducts simulations based on the configuration of selected components to evaluate system performance and determine the optimal size. The best-performing system is identified through optimization and sensitivity analysis. The objective functions of the system are as follows:

a) Optimizer minimizes grid dependency.

This objective minimizes the total energy imported from the grid over the 24-hour period, ensuring that domestic loads are met by PV generation and stored hydrogen whenever possible

$$\text{Min } \sum_{t=1}^{24} E_{grid}^+(t) \quad (5.1)$$

b) Optimizer maximizes renewable energy self-consumption.

$E_{PV, load}(t)$ is the PV energy directly used for domestic loads and $E_{el}(t)$ is the energy directed to the electrolyzer (when surplus is available). This objective encourages using as much on-site renewable energy as possible rather than wasting surplus or importing from the grid.

$$\text{Max}(\sum_{t=1}^{24} [E_{pv, load}(t) + E_{el}(t)]) \quad (5.2)$$

c) Optimizers minimize unutilized surplus when storage is full.

If hydrogen storage reaches its maximum capacity (full $H_{storage}$ tank), any extra surplus PV energy is injected to the grid. To encourage optimal use of surplus energy.

$$\text{Min } \sum_{t=1}^{24} (Excess E_{PV}(t) \cdot 1_{\{H_v(t)=H_{storage}\}}) \quad (5.3)$$

where $1_{\{H_v(t)=H_{storage}\}}$ is an indicator that is 1 when storage is full. This term discourages wasting valuable PV energy when hydrogen storage cannot accept more energy.

5.2.1.1 Search space

The optimal variables are selected in HOMER and entered in the search space worksheets. The optimization process involves adjusting the capacity and quantity of various system components. Consequently, HOMER Pro's input search space for each component is defined to facilitate the optimization process.

5.2.1.2 Sensitivity variables.

Sensitivity variables refer to factors that can be adjusted within a defined time step to evaluate their effect on system performance and optimization. Multiple optimization scenarios are conducted by applying different input. Sensitivity analysis helps determine how variables input parameters, such as component efficiency and load fluctuations, influence the optimal system configuration.

- 1) PV system capacity (P_{pv} , in kW): Determines the total daily energy generated by the PV array.
- 2) Electrolyzer rated power (P_{elc} , in kW): Specifies the maximum (and possibly minimum) power at which the electrolyzer can operate.

- 3) Fuel cell rated power (P_{fc} , in kW): Specifies the maximum power output available when converting stored hydrogen back to electricity.
- 4) Hydrogen storage capacity ($H_{storage}$, in kg or equivalent energy, e.g., kWh): The maximum amount of hydrogen that can be stored, accounting for production, storage losses, and conversion needs.
- 5) Time-dependent operating variables.

$E_{el}(t)$: Energy input to the electrolyzer at time step t (kWh).

$E_{fc}(t)$: Energy output from the fuel cell at time step t (kWh).

$H_2V(t)$: Hydrogen storage level at time step t (kg or kWh equivalent).

5.2.1.3 Dispatch strategy.

To dispatch a system including hydrogen storage, fuel cell, solar PV, grid and electrolyzer require a dispatch strategy, which means the set of regulations governing how hydrogen will be produced and stored by the system. Fuel cells and grid will switch depending on PV conditions. Under cycle-charging strategy, the solar PV operates at maximum capacity, supplying electrolyzer to generate hydrogen for energy storage, then supplying the load.

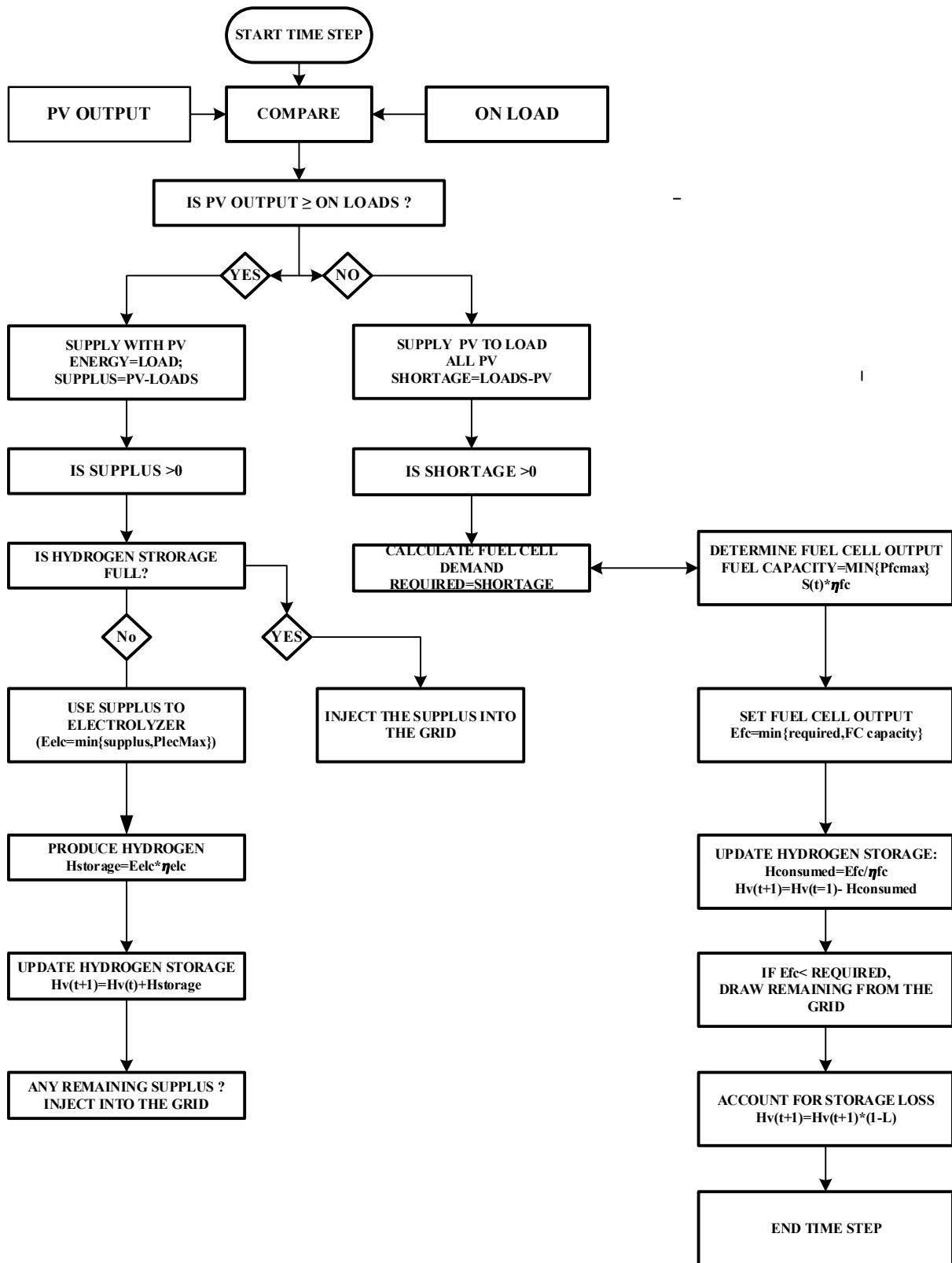


Figure 5. 1: System algorithm

5.3 Simulation of the design.

Inputs data that used for simulating a solar powered residential load with electrolyzer to generate GH as energy storage.

- (i) The total demand see table 4.5 is 11.175 kW (total connected domestic loads) and the maximum power rating of electrolyzer is 4 kW which can decrease down to 5% of nominal power.
- (ii) PV panel specifications.
- (iii) Fuel cell specifications!
- (iv) Hydrogen storage capacity.
- (v) Electrolyzer specifications
- (vi) Inverter specifications

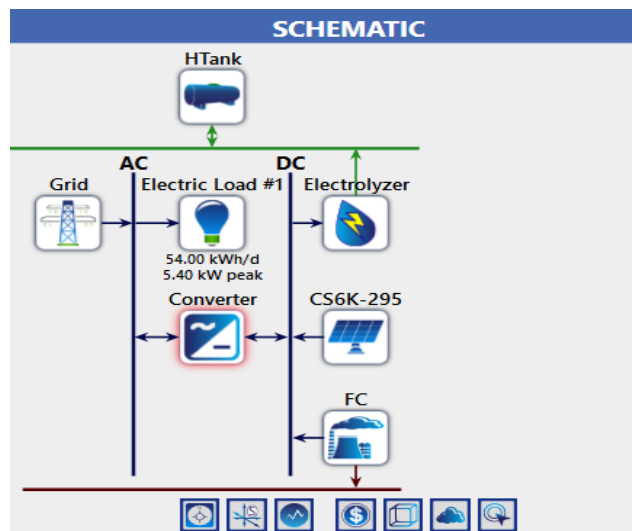


Figure 5. 2: Hydrogen generation system integrated into a photovoltaic system.

5.4 Load input

Domestic load input of 16.95 KW and electrolyzer of 5 KW. This load is hourly varying, domestic load are mostly lighting and other home appliances like fan, refrigeration, iron, TV, radio, kettle

etc.... operate 24 hours of the day, and electrolyzer of maximum operate when there is any surplus after satisfying real time load during day.

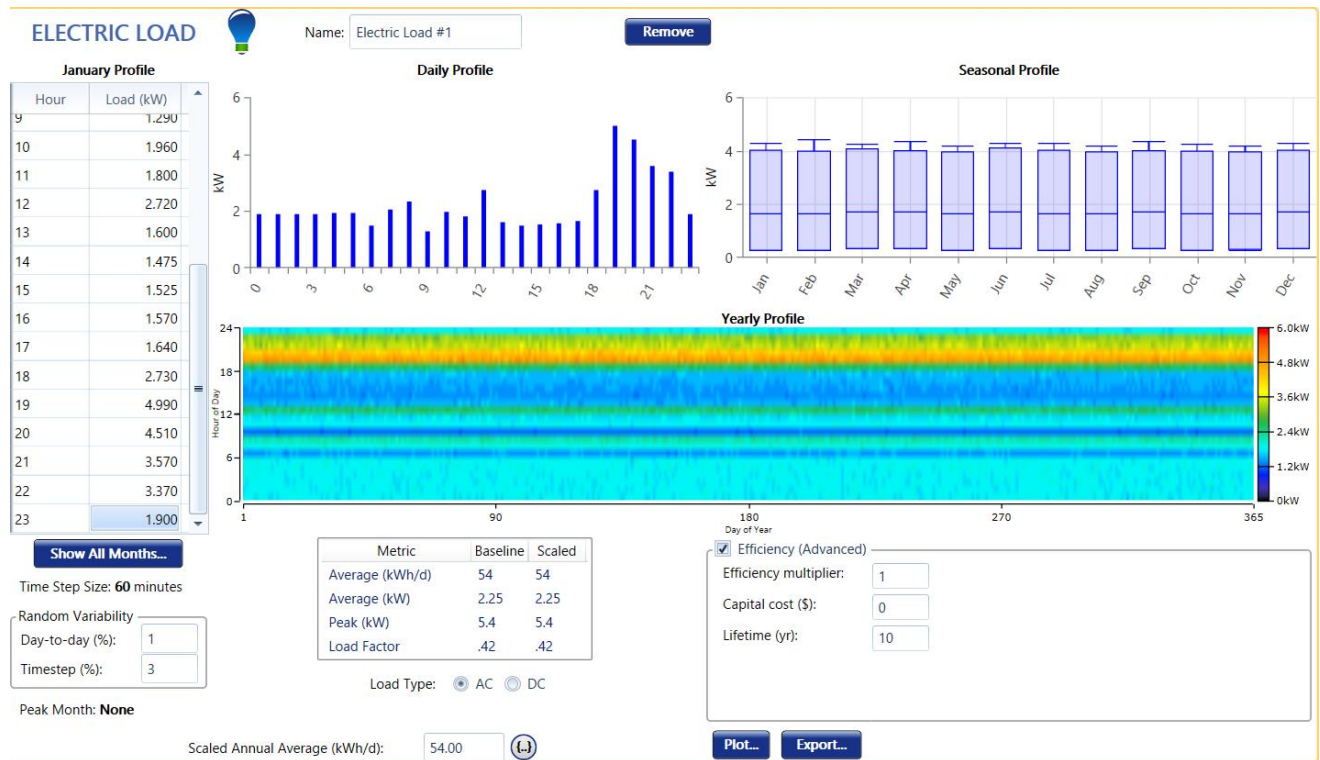



Figure 5. 3: Load profile inputs window in HOMER.

From the figure 5.3 average energy demand per day is 54.0 kWh, with an average load of 2.25 kW with a load factor of 0.42, this indicates that the system operates at 42% of its peak capacity. efficiently a system is operating.

5.5 System component inputs to simulating tool.

5.5.1 Solar PV Panel inputs.

The solar PV capacity (kW) is set according to the designed size. In search space a range of PV was provided to select the optimal PV size, derating factors, efficiency and operating temperature are predefined parameters depending on the manufacture, capital, replacement, Operation and Maintenances (O&M) cost have been inputted in HOMER Pro.

PV 

Name: Abbreviation:

Properties

Name: **CanadianSolar SuperPower CS6K-295M**

Abbreviation: **CS6K-295**

Panel Type: **Flat plate**

Rated Capacity (kW): **21**

Temperature Coefficient: **-0.390**

Operating Temperature (°C): **45.00**

Efficiency (%): **18.02**


Manufacturer: **Canadian Solar**

[Data Sheet for CS6K-295MS](#)

Notes:
The Mono-crystalline PERC cells in the SuperPower module offer superior low irradiance performance in the morning, evening and on cloudy days.
This component models CanadianSolar's

PV

Capacity (kW)	Capital (\$)	Replacement (\$)	O&M (\$/year)
<input type="text" value="1"/>	<input type="text" value="330.00"/>	<input type="text" value="330.00"/>	<input type="text" value="1.00"/>

Lifetime time (years): 

Capacity Optimization


HOMER Optimizer™

Search Space

kW

- 18
- 19
- 20
- 21

Site Specific Input

Derating Factor (%): 


Electrical Bus

AC DC

Figure 5. 4: Solar PV panel input window in HOMER.

5.5.2 Electrolyzer and fuel cell component input.

Electrical is supplied by surplus from PV array after meeting hourly load demand. The parameters like efficiency, cost per size, O&M cost life span are essential.

ELECTROLYZER 

Name: Abbreviation:

Generic Electrolyzer ▾

Properties

Name: **Generic Electrolyzer**

Abbreviation: **Electrolyzer**

Manufacturer: **Generic**

www.homerenergy.com

Notes:
This is a generic electrolyzer.

Costs

Capacity (kW)	Capital (\$)	Replacement (\$)	O&M (\$/year)
1	\$100.00	\$100.00	\$8.00

Click here to add new item

Multiplier:

Capacity Optimization

Size (kW)
4
5
6

Lifetime (years):

Efficiency (%):

Minimum load ratio (%):

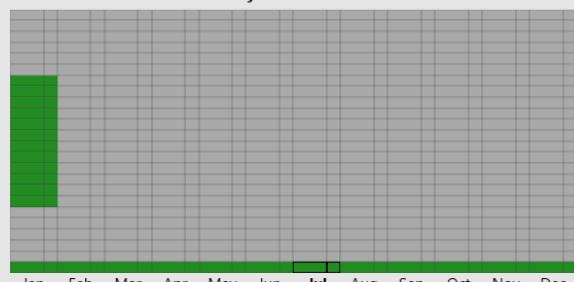
Electrical Bus: AC DC

Electrolyzer Schedule

Step 1: Select a mode: Forced On Optimizer

Step 2: Select a time period: All Week Weekdays Weekends


Step 3: Click on the chart to when the selected operating applies.



00:00
23:00

Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

Figure 5. 5: Electrolyzer inputs window in HOMER.

GENERATOR 

Name: Abbreviation:

Generic Fuel Cell (size-your-own) ▾

Properties

Name: **Generic Fuel Cell (size-your-own)**

Abbreviation: **FC**

Manufacturer: **Generic**

www.homerenergy.com

Notes:
Generic Fuel Cell, powered by Natural Gas

Costs

Capacity (kW)	Capital (\$)	Replacement (\$)	O&M (\$/op. hr)
1	\$400.00	\$400.00	\$0.010

Click here to add new item

Multiplier:

Capacity Optimization

Size (kW)
4
5

Site Specific Input

Minimum Load Ratio (%):

Heat Recovery Ratio (%):

Lifetime (Hours):

Minimum Runtime (Minutes):

Electrical Bus: AC DC

Fuel Resource: **PROPERTIES**

Lower Heating Value (MJ/kg): 120

Density (kg/m3): 0.090


Carbon Content (%): 0

Sulfur Content (%): 0

Stored Hydrogen Fuel Price (\$/kg):

Limit Consumption (kg):

Figure 5. 6: Fuel cell input window in HOMER.

HYDROGEN TANK 

Name: Abbreviation:

Properties

Name: **Hydrogen Tank**

Abbreviation: **HTank**

Manufacturer: **Generic**

www.homerenergy.com

Notes:
This is a generic hydrogen tank.

Costs

Size (kg)	Capital (\$)	Replacement (\$)	O&M (\$/year)
1	\$0.50	\$0.50	\$10.00
Click here to add new item			

Multiplier:

Capacity Optimization

Size (kg)
3
4
5

Lifetime (years):


Initial Tank Level

Relative to tank size (%):

Absolute amount (kg):

Require year-end tank level to equal or exceed initial tank level.

Figure 5. 7: Hydrogen tank input.

ADVANCED GRID 

Name: Abbreviation:

Simple Rates Real Time Rates Scheduled Rates Grid Extension

Parameters | **Emissions**

Simple Rates

Grid Power Price (\$/kWh):

Grid Net Excess Price (\$/kWh):

Net Metering

Net purchases calculated monthly.

Net purchases calculated annually.

Figure 5. 8: Grid input

5.6 Results and discussions.

The results are classified into three categories:

1. Optimization results
2. System overall cost
3. System self-consumption and satisfaction ratio.
4. Greenhouse gases emissions rates
5. Grid net contributions
6. GH production.

NB: System is grid connected photovoltaic/fuel cell hybrid power system for a residential village.

5.6.1 Optimization results.

HOMER Pro Simulator provides the lowest cost system (i.e table 5.2) that can deliver total energy demand at low cost among different possible combinations. See optimum system in table 5.1.

Table 5.1: Optimum size of proposed hybrid system.

Sensitivity		Architecture										Cost				Ren I (%)
CS6K-295 time (years)	CS6K-295 Derating (%)	CS6K-295 (kW)	FC (kW)	Grid (kW)	Electrolyzer (kW)	HTank (kg)	Converter (kW)	Efficiency1	Dispatch	COE (\$)	NPC (\$)	Operating cost (\$/yr)	Initial capital (\$)	Ren I (%)		
25.0	88.0	21.0	4.00	999,999	4.00	3.00	12.0	0	CC	\$0.0285	\$12,546	\$242.48	\$9,412	62.0		
30.0	88.0	21.0	4.00	999,999	4.00	3.00	12.0	0	CC	\$0.0279	\$12,269	\$221.07	\$9,412	62.0		
25.0	90.0	21.0	4.00	999,999	4.00	3.00	12.0	0	CC	\$0.0266	\$11,871	\$190.28	\$9,412	62.6		
30.0	90.0	21.0	4.00	999,999	4.00	3.00	12.0	0	CC	\$0.0260	\$11,595	\$168.87	\$9,412	62.6		

Architecture										Cost				System	
CS6K-295 (kW)	FC (kW)	Grid (kW)	Electrolyzer (kW)	HTank (kg)	Converter (kW)	Efficiency1	Dispatch	COE (\$)	NPC (\$)	Operating cost (\$/yr)	Initial capital (\$)	Ren Frac (%)	Total Fuel (kWh)	Hc	
21.0	4.00	999,999	4.00	3.00	12.0	0	CC	\$0.0285	\$12,546	\$242.48	\$9,412	62.0	279	2.8	

5.6.2 System overall cost.

After simulation of designed schematic architecture, with all load inputs, components capital cost, replacement cost and operation and maintenance cost, component lifetime, operating power range, return on investments, and simple payback.

Table 5.2: Cost summary of grid connected PV/FC hydrogen production power system.

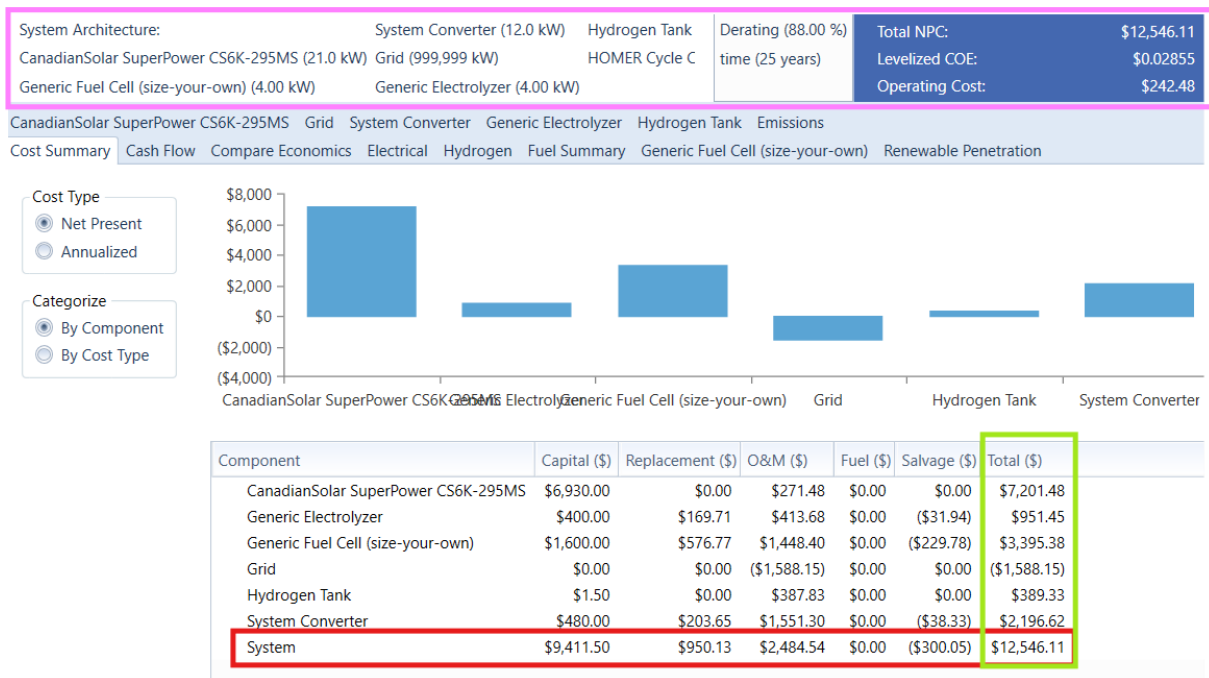
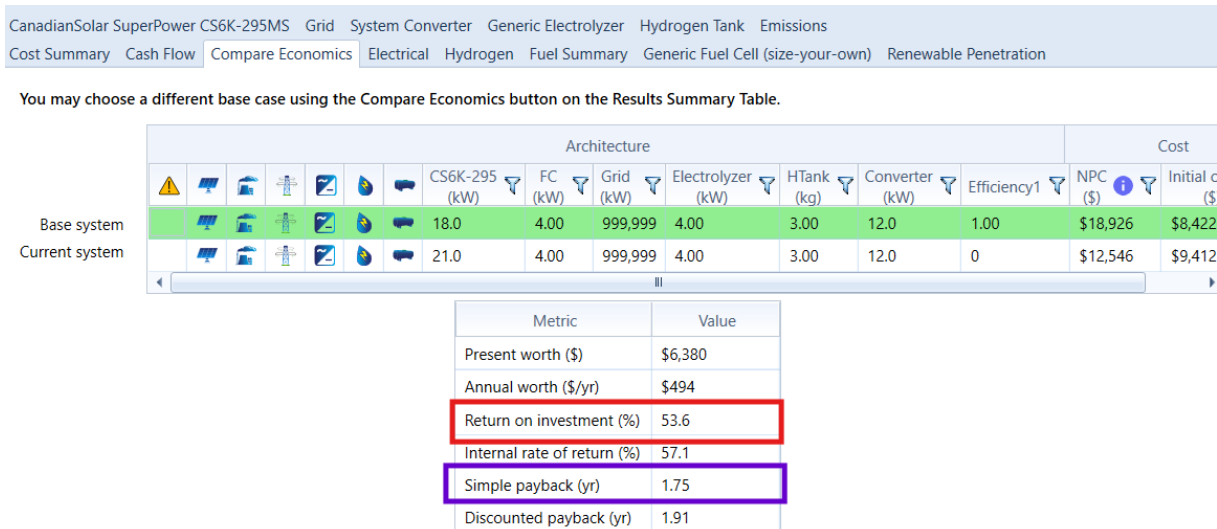


Table 5.3: Economic comparison.



From table 5.2, the cost of solar PV system is higher comparable to other system components, which is 6930 \$, cost of fuel cell is 1600\$ and cost of inverter is 480\$. The overall system initial cost is 9441\$, after considering system replacement cost, operation & maintenance cost, salvage cost total net present cost (NPC) after 25 years lifetime of the system is 12546.11 \$. Levelized cost of energy (LCOE) and operation cost (OC) were found to be 0.02855 \$ and 242.48 \$ respectively. From this levelized cost of 1kWh (0.02855) energy, locally generated electricity

is cheaper than electricity from the grid which is 0.18 \$ per kWh. Table 5.3 shows the return on investments is 53.6% and the simple payback period is 1.75 whereas the discounted payback period is 1.91.

Cost comparison

	GRID		GH-PV SYSTEM	
	Purchase price	Net excess price	Purchase price	Net sold price
Quantity in kWh	0.18\$		0.02855\$	
Tot cost				

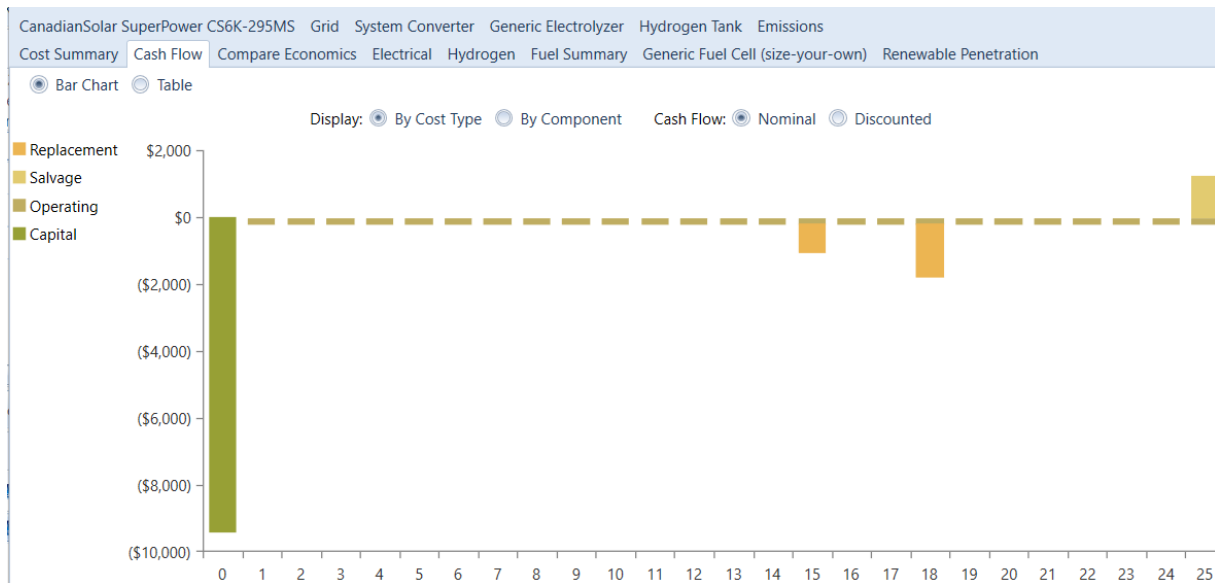


Figure 5. 9: GH generation system cash flow in bar chart.

From the figure 5.9 cash flow diagram by cost type and system nominal value, the system will take high initial capital comparable to the operating and maintenance cost. Inverter and electrolyzer will be replaced after fifteen years and fuel cells after 18 years. The value of the system after its lifetime is 1252.53 \$.

5.6.3 Rates of system self-consumption and self-satisfaction.

The self-consumption $SC(t)$, this metric defines the amounts of electricity locally generated and consumed with respect to total local generation (E_{lg}). Whereas self- sufficient $SS(t)$ measures the consumption amount supplied by local generation with respect to the total consumption(E_l)[52].

$$SC(t) = \frac{E_{lgc}(t)}{E_{lg}(t)}, \quad SS(t) = \frac{E_{lgc}(t)}{E_l(t)} \quad (5.4)$$

From the figure 5.10, SC(t) and SS(t), self-consumption and self-sufficient are 70.6% and 72.2% respectively. As a conclusion, system is slightly dependent on the grid, and this will minimize transmission and distribution power losses as more energy is being consumed near by the generation site.

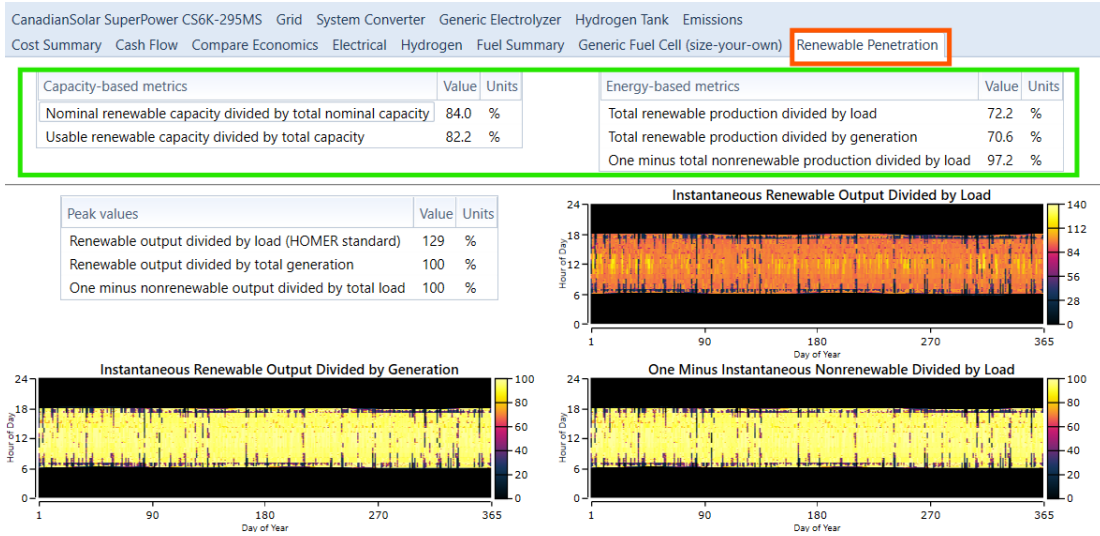


Figure 5. 10: Self-consumption and self-sufficient.

5.6.4 Electrical data.

Figure 5.11 displays annual production status, consumption status and quantity in kWh.

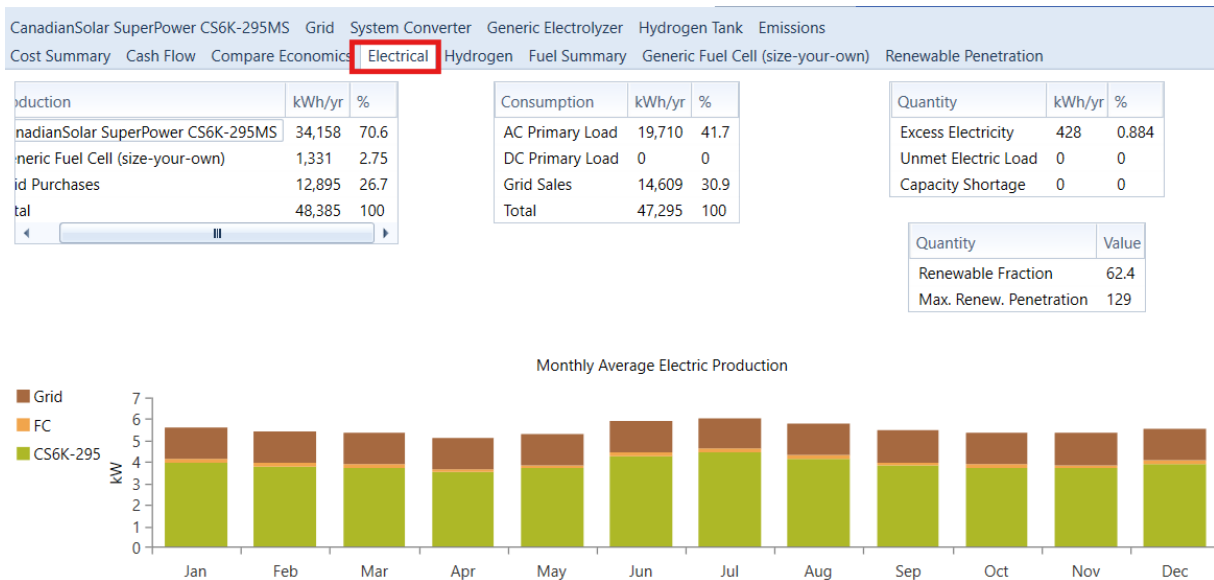


Figure 5. 11: Electrical parameters.

5.6.5. Grid net contribution.

The simulation results reveal that, grid is slightly dependent, and more energy injected into the grid than energy purchased from the grid see figure 5.10. Total annual energy purchased from the grid is 12,895 kWh and energy sold is 14,609 kWh. Net energy purchased from the grid in kWh is -1,714 kWh. In the month of April, more energy is purchased from the grid due to climate conditions generation from PV system, up to the net purchase of 80 kWh, whereas also more energy sold to the grid in July with a net of -436 kWh due climate conditions. As a conclusion, grid connection is essential to minimize system losses when their low demand and boost system reliability during maintenance. Economically, there is a profit as the purchase rate is lower than the sold rate.

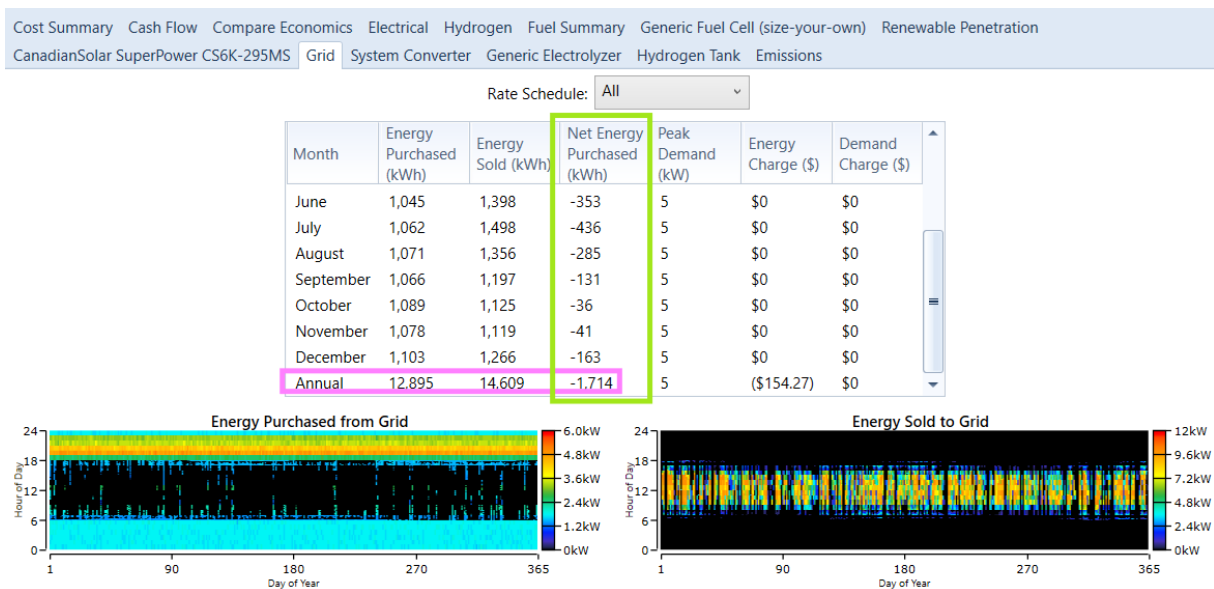


Figure 5. 12: Grid dependency rate.

Rate Schedule: All

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge (\$)	Demand Charge (\$)
January	1,115	1,305	-191	5	\$0	\$0
February	992	1,054	-62	5	\$0	\$0
March	1,114	1,184	-70	5	\$0	\$0
April	1,064	984	80	5	\$0	\$0
May	1,098	1,123	-25	5	\$0	\$0
June	1,045	1,398	-353	5	\$0	\$0
July	1,062	1,498	-436	5	\$0	\$0
August	1,071	1,356	-285	5	\$0	\$0

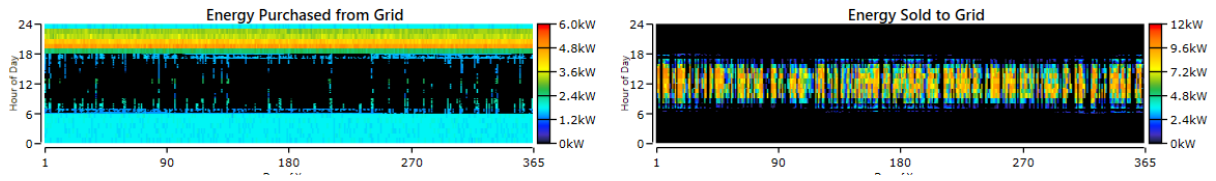


Figure 5. 13: Monthly energy net purchase.

5.6.6 GH production rate.

From Figure 5.14. Enormous quantity of hydrogen generated in the summer as bar chart rise more comparable with other season and total kilograms of hydrogen produced per year are 280 which corresponds to 100% hydrogen tank. From figure 5.15, minimum power input to the electrolyzer at less frequently with 1.48 kW, whereas the maximum input power of 4 Kw dominates the graph with red color dominance.

CanadianSolar SuperPower CS6K-295MS			Grid	System Converter	Generic Electrolyzer	Hydrogen Tank	Emissions
Cost Summary	Cash Flow	Compare Economics	Electrical	Hydrogen	Fuel Summary	Generic Fuel Cell (size-your-own)	Renewable Penetration

Production	kg/yr	%
Electrolyzer	280	100
Reformer	0	0
Total	280	100

Consumption	kg/yr	%
Generic Fuel Cell (size-your-own)	280	100
Hydrogen load	0	0
Total	280	100

Quantity	kg/yr	%
Excess hydrogen	0	0

Quantity	Value
Levelized COH	3.35

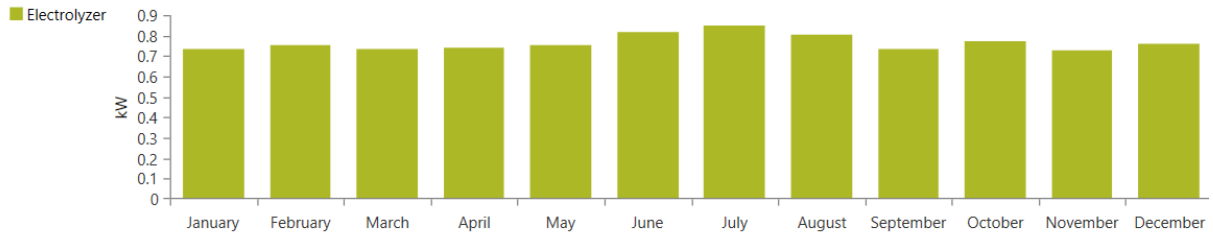


Figure 5. 14: Hydrogen production rate.

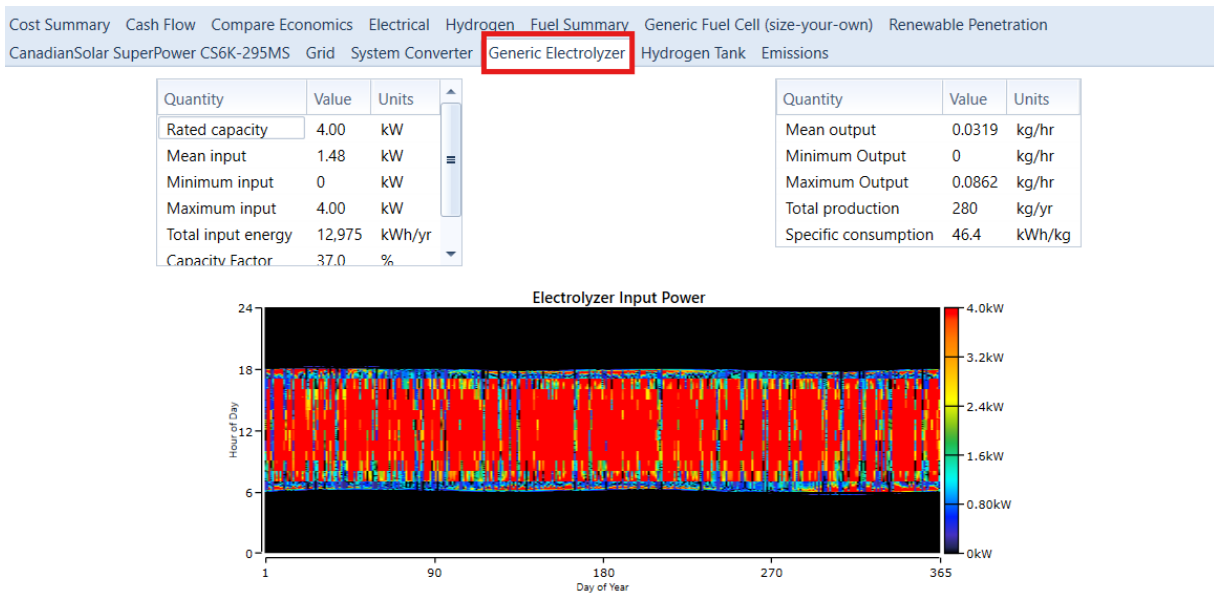


Figure 5. 15: Simulation results of electrolyzer operation.

5.6.7 Fuel cell operating values.

From Figure 5.16 Fuel cell capacity factor is 3.8 %, this means that the fuel cell is not optimally used as the dominant from the graph is blue which indicates low output power with minimum value of 0.2 Kw and maximum power 4Kw (see red color from the graph). Thermal energy produced per year is 4793 kWh.

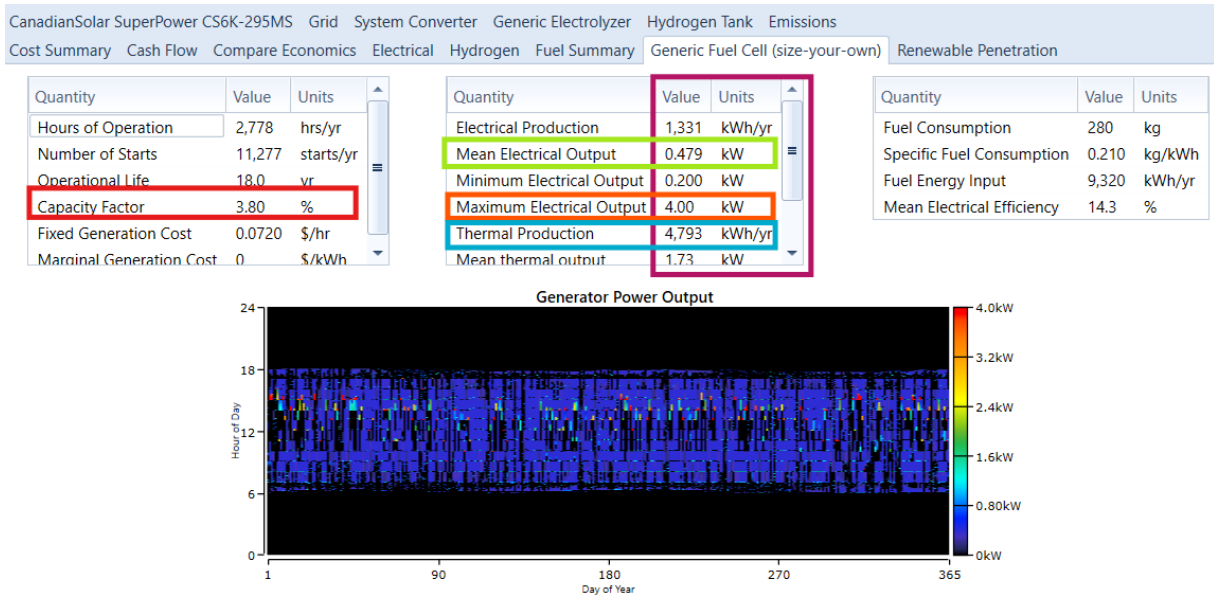


Figure 5. 16: Simulation results of Fuel cell operation.

5.6.8 Greenhouses gases emissions rate.

From results visualized in Figure 5.17, the configuration emissions are minimum, and these emissions (CO₂, CO, SO₂ and NO₂) are resulting from the grid due to the existence of different power plants including thermal power plants. As conclusion adopting many distributed generations will promote a significant reduction of these emissions when reliance on fossil fuel-based power plants is zero percent.

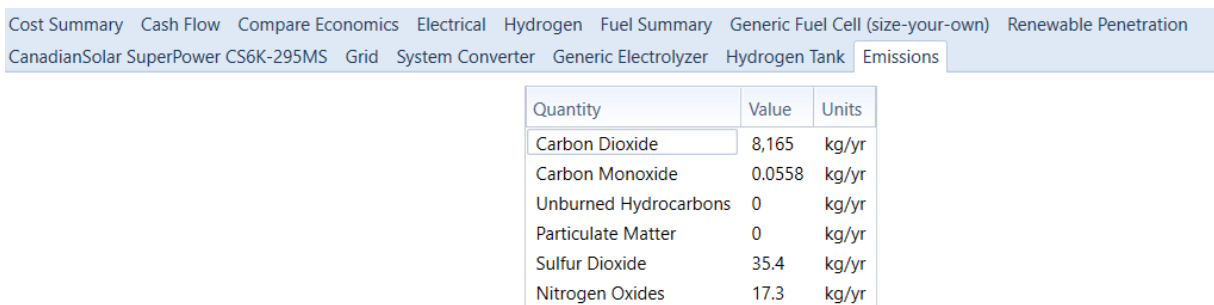


Figure 5. 17: Simulation results of emissions.

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS.

6.1 Conclusion

The research assesses the potential of renewable energy resources, focusing on photovoltaic energy and GH, to ensure a sustainable and uninterrupted power supply in the Mayange sector, Bugesera district. The assessment involved analyzing solar energy availability, estimating electricity demand, and exploring innovative energy storage solutions to reduce reliance on conventional battery storage and fossil fuels-based power plants.

To determine solar energy potential, data on the region's two-year monthly average solar radiation and clearness index was obtained from Meteo-Rwanda, corresponding to a latitude of 2.05° and a longitude of 30.5° . The average daily solar radiation ranged from 4.67 kW/m^2 in May to 5.59 kW/m^2 in August, with an overall average of 5.02 kW/m^2 per day. A detailed load analysis was conducted to ensure energy demand could be met sustainably, accounting for seasonal and daily variations. The study projected future energy needs over a five-year period, with current daily consumption estimated at 54 kWh , a peak power demand of 5.4 kW , and a load factor of 0.42 .

To promote energy storage and grid stability, the study explored the feasibility of integrating GH into the local energy system. A hybrid energy model was developed and simulated, combining a photovoltaic (PV) system, grid connection, electrolyzer, hydrogen storage tank, fuel cell, and residential load. The results demonstrated that surplus solar energy could be efficiently converted into hydrogen gas through electrolysis and stored for later use, reducing dependency on lithium-ion batteries. Instead of conventional storage solutions, excess daytime solar energy was stored as hydrogen 279 kg/yr and later converted back into electricity via a fuel cell.

Bugesera's abundant solar energy and water resources make it an ideal location for GH production, presenting a viable solution for enhancing energy security, reducing carbon emissions, and supporting Rwanda's transition to a low-carbon economy. However, large-scale implementation requires addressing key challenges, including improving the efficiency of electrolyzer and fuel cells, developing safe hydrogen storage infrastructure, ensuring economic viability, and establishing supportive government policies.

Integrating solar energy with GH storage offers a promising pathway for sustainable energy development in Rwanda. By leveraging its solar potential and adopting hydrogen-based solutions, the country can improve grid stability, minimize environmental impact, and foster economic growth in the renewable energy sector.

6.2 Recommendations.

Integration of GH into Rwanda's energy market need a comprehensive approach that addresses technical, economic, and policy-related challenges. The system's large-scale implementation will depend on well-structured infrastructure, supportive government policies, financial investment, capacity building, and market testing. Infrastructure development and system optimization are critical aspects of implementing a hydrogen-based energy system. High efficiency electrolyzer, durable storage tanks, and fuel cells are essential components for a reliable system. Establishing hydrogen refueling stations for transportation and industrial processes will enhance the usability of hydrogen as a clean energy source. Policy and regulatory support are crucial for fostering the adoption of GH. The government should establish clear policies and legal frameworks that support the production, storage, and distribution of hydrogen. Economic viability and investment strategies are also essential for the financial sustainability of GH technology. Public-private partnerships, specialized training programs, and public awareness campaigns can drive innovation and cost reductions. Pilot projects and market testing will demonstrate the practicality and reliability of hydrogen-based energy systems.

REFERENCES

- [1] B. Safari, "A review of energy in Rwanda," *Renew. Sustain. Energy Rev.*, vol. 14, no. 1, pp. 524–529, 2010, doi: 10.1016/j.rser.2009.07.009.
- [2] I. Chakraborty, A. K. Bohre, P. Kumar, and R. A. D. O.-10. 1155/2024/825862. E. R. -, "No Title."
- [3] P. M. Falcone, M. Hiete, and A. Sapio, "Hydrogen economy and sustainable development goals: Review and policy insights," *Curr. Opin. Green Sustain. Chem.*, vol. 31, p. 100506, 2021, doi: 10.1016/j.cogsc.2021.100506.
- [4] I. Marouani *et al.*, "Integration of Renewable-Energy-Based Green Hydrogen into the Energy Future," *Processes*, vol. 11, no. 9, 2023, doi: 10.3390/pr11092685.
- [5] C. Steiker and J. Steiker, "Part I," *Comp. Cap. Punishm.*, pp. 1–1, 2019, doi: 10.4337/9781786433251.00007.
- [6] A. C. Melissinos, F. Lobkowitz, R. Lindsay, B. Gregory, and H. N. Hanson, *Physics for Scientists and Engineers , Vol . I*, vol. 44, no. 9. 1976. doi: 10.1119/1.10359.
- [7] B. R. Keeble, "The Brundtland Report: 'Our Common Future,'" *Med. War*, vol. 4, no. 1, pp. 17–25, 1988, doi: 10.1080/07488008808408783.
- [8] M. S. Cengiz and M. S. Mamiş, "Price-efficiency relationship for photovoltaic systems on a global basis," *Int. J. Photoenergy*, vol. 2015, 2015, doi: 10.1155/2015/256101.
- [9] A. I. Atteya, D. Ali, M. Hossain, and N. Sellami, "A Comprehensive Review on The Potential of Green Hydrogen in Empowering the Low-Carbon Economy: Development Status, Ongoing Trends and Key Challenges," *Green Energy Environ. Technol.*, vol. 2, no. May, pp. 1–53, 2023, doi: 10.5772/geet.23.
- [10] T. Vision, "Chapter 8 : Energy Resources," vol. 2020, no. Ror, pp. 1–17, 2007.
- [11] AfDB, "Rwanda Energy Sector Review and Action Plan," *African Dev. Bank Gr.*, pp. 1–108, 2013, [Online]. Available: https://www.afdb.org/fileadmin/uploads/afdb/Documents/Project-and-Operations/Rwanda_-_Energy_Sector_Review_and_Action_Plan.pdf
- [12] E. U. E. I. EUEI, "Biomass Energy Strategy (BEST)," *Biomass Energy Strateg.*

- Rwanda-Volume 2backgr. Anal.*, vol. 2, no. June, pp. 1–114, 2009, [Online]. Available: [https://www.undp.org/content/dam/uganda/docs/UNDPUG2014 - Biomass BEST Strategy\(compressed\).pdf](https://www.undp.org/content/dam/uganda/docs/UNDPUG2014 - Biomass BEST Strategy(compressed).pdf)
- [13] “dcc3511065daaf85e1cc4ecf335f3f4838eee6b6 @ www.globalforestwatch.org.” Accessed: Oct. 07, 2024. [Online]. Available: <https://www.globalforestwatch.org/dashboards/country/RWA/?category=forest-change>
- [14] M. Van der Hoeven, “Energy price volatility in fossil fuel markets,” *G20 Leader’s Summit*, no. june, pp. 122–125, 2012, [Online]. Available: http://www.iisd.org/gsi/sites/default/files/g20lib_gsi_2012_addressingbarriers.pdf
- [15] Hydrogen Fuel Cell Engines and Related Technologies, “Module 1: Hydrogen Properties,” *Hydrog. Fuel Cell Engines*, p. 41, 2001, [Online]. Available: http://www1.eere.energy.gov/hydrogenandfuelcells/tech_validation/pdfs/fcm01r0.pdf
- [16] NCERT, “Unit 9: HYDROGEN,” pp. 276–290.
- [17] S. Shiva Kumar and H. Lim, “An overview of water electrolysis technologies for green hydrogen production,” Elsevier Ltd, 2022. doi: 10.1016/j.egy.2022.10.127.
- [18] “No Title.” Accessed: Oct. 07, 2024. [Online]. Available: <https://www.energy.gov/eere/fuelcells/hydrogen-fuel-basics>
- [19] United Nations Industrial Development Organization, International Renewable Energy Agency, and German Institute of Development and Sustainability, “Green Hydrogen For Industrial Development: A Policy Toolkit For Developing Countries,” 2023.
- [20] A. Islam *et al.*, “Accelerating the green hydrogen revolution: A comprehensive analysis of technological advancements and policy interventions,” *Int. J. Hydrogen Energy*, vol. 67, pp. 458–486, May 2024, doi: 10.1016/J.IJHYDENE.2024.04.142.
- [21] “959db50a8839991bc2c9fe6596af8d7ed74662ed @ www.reg.rw.” Accessed: Oct. 10, 2024. [Online]. Available: <https://www.reg.rw/what-we-do/access/offgrid>
- [22] “rwanda-targets-more-than-300mw-of-energy-by-2024-minister-gatete @ www.mininfra.gov.rw.” Accessed: Oct. 12, 2024. [Online]. Available: <https://www.mininfra.gov.rw/updates/news-details/rwanda-targets-more-than-300mw-of-energy-by-2024-minister-gatete>

- [23] “ingredients-for-accelerating-universal-electricity-access-lessons-from-afe-rwanda-inspirational-approach @ www.worldbank.org.” Accessed: Oct. 04, 2024. [Online]. Available: <https://www.worldbank.org/en/news/feature/2024/04/10/ingredients-for-accelerating-universal-electricity-access-lessons-from-afe-rwanda-inspirational-approach>
- [24] P. O. By, “the World ’ S 20 Largest Green”.
- [25] “Country Guide :,” no. June, 2020.
- [26] “a539d4447c310264e6bc02ec825eadff10635686 @ rmi.org.” Accessed: Oct. 15, 2024. [Online]. Available: [https://rmi.org/hydrogen-reality-check-distilling-green-hydrogens-water-consumption/#:~:text=All methods of producing hydrogen,\(kg\) of hydrogen via electrolysis.](https://rmi.org/hydrogen-reality-check-distilling-green-hydrogens-water-consumption/#:~:text=All methods of producing hydrogen,(kg) of hydrogen via electrolysis.)
- [27] Hydrogen Europe, “Hydrogen Production & Water Comsumption,” no. December, pp. 3–5, 2020, [Online]. Available: https://www.researchgate.net/publication/283014981_Development_of_a_Life_Cycle_Inventory_of_Water_Consumption_Associated_with_t
- [28] “No Title.” Accessed: Oct. 16, 2024. [Online]. Available: <https://www.weforum.org/agenda/2023/09/seawater-electrolysis-a-hydrogen-revolution-or-technological-dead-end-here-are-the-numbers/>
- [29] H. Gloria, H. Olivier, and I. M. Angella, “Contribution of Solar Energy for Sustainable Urban Development in Rwanda,” no. June, 2023, doi: 10.13189/cea.2019.070601.
- [30] A. Bhatia, “Design and Sizing of Solar Photovoltaic Systems Credit,” *CEDengineering*, no. 877, pp. 37–42, 2022.
- [31] P. Moldrik and Z. Hradilek, “Hydrogen production for solar energy storage,” *Renew. Energy Power Qual. J.*, vol. 1, no. 9, pp. 518–523, 2011, doi: 10.24084/repqj09.379.
- [32] S. Shiva Kumar and H. Lim, “An overview of water electrolysis technologies for green hydrogen production,” *Energy Reports*, vol. 8, pp. 13793–13813, 2022, doi: 10.1016/j.egy.2022.10.127.
- [33] Onyinyechukwu Chidolue, Bright Ngozichukwu, Kenneth Ifeanyi Ibekwe, Adetomilola Victoria Fafure, Cosmas Dominic Daudu, and Valentine Ikenna Illojiana,

- “Advancements in energy storage technologies: A review across Canada, USA, and Africa,” *Glob. J. Eng. Technol. Adv.*, vol. 18, no. 1, pp. 001–008, 2024, doi: 10.30574/gjeta.2024.18.1.0011.
- [34] D. A. Elalfy, E. Gouda, M. Fawzi, V. Bure, and B. E. Sedhom, “Comprehensive review of energy storage systems technologies , objectives , challenges , and future trends,” vol. 54, no. July, 2024, doi: 10.1016/j.esr.2024.101482.
- [35] D. K. Madheswaran, A. Jayakumar, R. Velu, R. Raj, and E. G. Varuvel, *Polymer based flow field plates for polymer electrolyte membrane fuel cell and the scope of additive manufacturing: A techno-economic review*, vol. 46, no. 14. 2022. doi: 10.1002/er.8645.
- [36] E. Parks and B. P. Series, “Applications of Green Hydrogen in,” 2023.
- [37] CIF, “Potential Role of Green Hydrogen,” no. September, 2022.
- [38] A. L. Bukar and C. W. Tan, “A review on stand-alone photovoltaic-wind energy system with fuel cell: System optimization and energy management strategy,” *J. Clean. Prod.*, vol. 221, pp. 73–88, 2019, doi: 10.1016/j.jclepro.2019.02.228.
- [39] 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, 2021, doi: 10.1016/j.ijhydene.2020.11.185.
- [40] K. V. Allamraju, *Green Hydrogels*. 2021. doi: 10.1007/978-981-15-9643-8_8.
- [41] “No Title.” Accessed: Oct. 17, 2024. [Online]. Available: [https://en.wikipedia.org/wiki/Bugesera_District#:~:text=Bugesera is a district \(akarere,the old Kingdom of Bugesera.&text=The district is the location,genocide at Ntarama and Nyamata.](https://en.wikipedia.org/wiki/Bugesera_District#:~:text=Bugesera%20is%20a%20district%20(akarere,the%20old%20Kingdom%20of%20Bugesera.&text=The%20district%20is%20the%20location,genocide%20at%20Ntarama%20and%20Nyamata.)
- [42] N. Hagumimana *et al.*, “Concentrated Solar Power and Photovoltaic Systems: A New Approach to Boost Sustainable Energy for All (Se4all) in Rwanda,” *Int. J. Photoenergy*, vol. 2021, 2021, doi: 10.1155/2021/5515513.
- [43] U.S. Department of Energy’s - DOE, “Hydrogen Shot,” *Hydrog. fuel cell Technol. Off.*, 2022, [Online]. Available: <https://www.energy.gov/eere/fuelcells/hydrogen-shot>
- [44] I. Amoussou *et al.*, “The Optimal Design of a Hybrid Solar

- PV/Wind/Hydrogen/Lithium Battery for the Replacement of a Heavy Fuel Oil Thermal Power Plant,” *Sustain.*, vol. 15, no. 15, 2023, doi: 10.3390/su151511510.
- [45] “China-60kw-Hydrogen-Fuel-Cell-System-Pem-Fuel-Cell-for-Vehicles @ hfsinopower.en.made-in-china.com.” [Online]. Available: <https://hfsinopower.en.made-in-china.com/product/imWUcqjbhQpX/China-60kw-Hydrogen-Fuel-Cell-System-Pem-Fuel-Cell-for-Vehicles.html>
- [46] V. A. Martinez Lopez, H. Ziar, J. W. Haverkort, M. Zeman, and O. Isabella, “Dynamic operation of water electrolyzers: A review for applications in photovoltaic systems integration,” *Renew. Sustain. Energy Rev.*, vol. 182, no. May, p. 113407, 2023, doi: 10.1016/j.rser.2023.113407.
- [47] Y. . Salifu, “Environmental and social audit of Kpone Landfill,” 2019. [Online]. Available: <https://www.mwh.gov.gh/wp-content/uploads/2019/02/0Final-Report-Kpone-EnvSoc-Audit-Feb232019.pdf>
- [48] C. Ghenai and M. Bettayeb, “Grid-Tied Solar PV/Fuel Cell Hybrid Power System for University Building,” *Energy Procedia*, vol. 159, pp. 96–103, 2019, doi: <https://doi.org/10.1016/j.egypro.2018.12.025>.
- [49] “best-price-power-210w-solar-panel @ www.alibaba.com.” Accessed: Feb. 25, 2025. [Online]. Available: <https://www.alibaba.com/showroom/best-price-power-210w-solar-panel.html>
- [50] S. Kharel and B. Shabani, “Hydrogen as a long-term large-scale energy storage solution to support renewables,” *Energies*, vol. 11, no. 10, 2018, doi: 10.3390/en11102825.
- [51] I. Renewable and E. Agency, “ELECTRICITY STORAGE AND RENEWABLES : COSTS AND MARKETS TO 2030,” no. October, 2017.
- [52] A. Ciocia *et al.*, “Systems : Effect of Grid Limitation and Storage Installation,” 2021.

APPENDICES

APPENDIX A: Survey questionnaire: identification of household loads and usage time

Survey questionnaire: identification of household loads and usage time.

Survey title: Household Load Assessment in Mayange Sector, Bugesera District

Survey purpose: This survey aims to collect data on the types of electrical appliances used by households and their daily operational time to support energy system planning.

Target respondents: Household representatives

Survey duration: Approximately 10–15 minutes

Section 1: General Information.

1. Household ID (For Surveyor Use Only):
2. Name of Respondent:
3. Household Size (Number of People Living in the House):
4. Main Source of Electricity:

- a) National Grid:
- b) Solar Home System:
- c) Generator:
- d) Other (Specify:

Section 2: Household appliances and usage

Instructions: For each appliance listed, please indicate whether you own it and estimate the number of hours it is used per day.

Appliance	Do you have this appliance? (Yes/No)	Quantity and (Wattage)	Estimated Daily Usage (Hours)
Lighting (Bulbs)			
Fans			
Television			

Radio			
Refrigerator			
Iron			
Blender			
Computers/Laptops			
Electric Cooker			
Water Heater			
Phone Charger			
Other (Specify)			

Section 3: Electricity consumption and usage patterns

1. What time of day do you use most of your electrical appliances? (Tick all that apply)

Morning: 6:00 AM - 12:00 PM (Noon):

Afternoon: 12:00 PM (Noon) - 6:00 PM:

Evening: 6:00 PM - 10:00 PM:

Night: 10:00 PM - 6:00 AM:

2. Do you experience power shortages or blackouts?

Yes

No

3. If YES, what alternative source of power do you use during blackouts?

.....

.....

.....

Section 4: Additional Comments

1. What challenges do you face regarding electricity supply in your household?

.....
.....
.....
.....
.....

2. What improvements would you suggest for better access to electricity in your area?

.....
.....
.....
.....
.....

Thank you for your time and cooperation!

Surveyor Name: _____

Date of Survey: _____

APPENDIX B: Technical specifications of the system.

Table 1.

Fuel cell		
Specification	Value	Unit
Fuel Type	Hydrogen (H ₂ , 99.99% purity)	-
Rated Power Output	4-5	kW
Voltage Output	48	V DC
Current Output	40–100	A
Efficiency (Electrical)	60%	%
Hydrogen Consumption	~0.42	Nm ³ /kWh
Operating Temperature	60–80	°C
Start-up Time	<1	minute
Stack Lifetime	50,000	hours
Cooling Method	Air or Liquid	-
Noise Level	<55	dB
Weight	50–100	kg
Dimensions (L×W×H)	600 × 400 × 500	mm
Emissions	Zero (Only Water Vapor)	-

Table B2.

Electrolyzer		
Product Name		
Efficiency	≥70%	%
Rated Voltage	≤48	V
Operating Current	~14 A – 271	A
Operating Temperature	40 – 100	°C
Operating Pressure	Up to 30	Barr
Hydrogen Purity	≥99.	%

Table B3.

Inverter		
Model	IP-400-3P	-
DC Input Voltage Range	235-600	V
AC Output Voltage	400	VL-L
Rated Power	12 kW	KW
AC Frequency	50/60 Hz (Selectable)	Hz
Efficiency	≥ 97%	%
Communication Interfaces	RS485, Ethernet, Modbus	-
Certifications	IEC 62109	-
Operating Temperature Range	-20 to +60	°C

Table B4.

PV Panel		
Model	CS6K-295MS	
Panel type	Flat plate	
Power	0.295	W
Temperature coefficient	-0.39	°C
Operating temperature	45	°C
Efficiency	18.02	%
Derating factor	88	%