Addis Ababa University

College of Technology and Built Environment

School of Mechanical & Industrial Engineering

System Modeling and Investigation of Rural Electrification Using Solar Power and Hydrogen Fuel Cell Technology: A Case Study for Ayaber Kewet Woreda

A Thesis Submitted to the School of Graduate Studies of College of Technology and Built Environment, Addis Ababa University in partial fulfillment for the Degree of Master of Science in Mechanical Engineering (Thermal Stream)

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By

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Declaration

I hereby declare that the work which is being presented in this thesis entitled “System Modeling and Investigation of Rural Electrification Using Solar Power and Fuel Cell Technology: A Case Study for Ayaber Kewet Woreda” is original work of my own, has not been presented for a degree of any other university and all the resource of materials used for this thesis have been duly acknowledged.

Shalom Abebaw Bekele

Date

This is to certify that the above declaration made by the candidate is correct to the best of my Knowledge.

Tilahun Nigussie (PhD) (Advisor)

Date

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Abstract

Renewable energy has become a critical component in supporting global development and industrialization. Among the various renewable options, solar energy stands out due to its widespread availability and environmentally friendly nature. Ethiopia is rich in natural resources, yet many of its rural regions, such as Ayaber in the Kewet Woreda, still lack access to electricity. This lack of electrification remains a major obstacle to economic progress and local business development.

This study explores the potential of providing electricity to Ayaber using a hybrid energy system that combines solar power with hydrogen fuel cell technology. To address the limitation of solar power's intermittency—particularly its inability to generate electricity at night—the system integrates fuel cells as a backup power source to ensure reliable energy supply during non-sunny hours.

The design and optimization of the energy system were conducted using the Homer Pro Energy software, which utilized meteorological, technical, and economic data as inputs. Findings suggest that a combination of photovoltaic panels and fuel cells presents a feasible solution for rural electrification, with the potential to increase electricity access by approximately 0.1% of the population.

A sensitivity analysis was also performed to assess how system performance and cost-effectiveness might improve as equipment prices decrease. The initial model yields a cost of energy (COE) of $0.345 per kilowatt-hour, which is slightly above the current market rate in Ethiopia. However, the analysis indicates that as the costs of fuel cells and electrolyzers decline—likely through large-scale production—the COE could drop to around $0.20/kWh, improving the system's economic viability.

While the present cost is relatively high, the prospects for cost reduction through technological advancement and manufacturing scale are promising. To further support the deployment of such hybrid systems, additional studies are needed to assess the integration of fuel cells with other renewable technologies, aiming to build a more robust and sustainable energy infrastructure.

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Introduction

1.1. Chapter Summary

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1.2. Background

Energy plays a foundational role in global development and is essential to the process of industrialization. From powering machines and equipment to enabling transportation and communication, energy underpins nearly every sector of modern life. For example, the transportation industry—including cars, trucks, ships, and airplanes—relies heavily on fossil fuels. Similarly, manufacturing operations depend on a constant energy supply to maintain production. Without a reliable energy source, modern society would essentially grind to a halt [1].

Traditionally, energy has been produced through the consumption of fossil fuels such as oil, coal, and natural gas. However, this approach is increasingly unsustainable. These resources are not only finite—with current consumption patterns suggesting oil could run out in about 50 years, coal in 100 years, and natural gas in 60 years—but they are also a major contributor to climate change. The combustion of fossil fuels emits large quantities of greenhouse gases like carbon dioxide, which trap heat in the atmosphere and accelerate global warming. This environmental degradation has led to more frequent and severe natural disasters, including floods, droughts, and hurricanes.

On the other hand, renewable energy sources such as solar, wind, hydro, geothermal, and biomass offer sustainable alternatives. These sources do not emit harmful pollutants or greenhouse gases, making them environmentally friendly. Moreover, they are naturally replenished and widely available, which enhances local energy security by reducing the need for fuel imports and long-distance transmission.

Despite these benefits, the shift to a fully renewable energy-based system comes with its own set of challenges. It demands substantial investments in infrastructure, innovation, and supportive policy frameworks. Technical hurdles, such as energy storage and supply intermittency, must be addressed. In addition, ensuring equitable access to clean energy for all populations remains a significant goal. Nevertheless, the transition holds immense potential—it can combat climate change, reduce environmental pollution, create new employment opportunities, and enhance national energy independence [2].

Ethiopia is uniquely positioned in this global energy transition, boasting the capacity to generate over 60,000 megawatts of power from renewable sources like hydroelectricity, wind, solar, and geothermal energy [3]. Currently, hydropower dominates the energy sector in Ethiopia, accounting for more than 90% of the country's installed capacity. Major installations such as the Grand Ethiopian Renaissance Dam, Gilgel Gibe III, and Tekeze collectively produce over 8,620 megawatts as of September 2021 [4].

Wind energy is another significant resource, with the potential to produce more than 1,000 megawatts. The Ashegoda Wind Farm, for instance, contributes 120 megawatts to the national grid. Although Ethiopia enjoys high solar irradiance, solar energy development remains limited. However, its potential exceeds 5,000 megawatts, and recent initiatives have seen the installation of solar panels in rural areas for lighting and cooking purposes.

Geothermal energy also holds promise, with an estimated potential of over 4,000 megawatts. Sites like Aluto Langano, Tendaho, and Abaya have been identified as key geothermal zones, yet only one plant is currently operational, and the sector is still in its nascent stage [5].

Over the past decade, Ethiopia has experienced rapid economic growth, driven by expansions in agriculture, manufacturing, and services. This growth, which has averaged around 10% annually, has dramatically increased electricity demand. Yet the nation's power infrastructure has struggled to keep pace. Presently, Ethiopia has a generation capacity of about 4,500 MW, with on-grid electricity reaching 33% of the population and off-grid solutions serving another 11%. Despite these efforts, only 44% of the population has access to electricity, and rural areas remain particularly underserved [6].

Recognizing the transformative impact of electricity on poverty reduction and economic development, the Ethiopian government has launched a national electrification initiative. This program targets expanding grid coverage to 60% and includes various supportive measures: feed-in tariffs to incentivize private investment in renewables, a Rural Electrification Fund to support off-grid projects, and a regulatory framework aimed at attracting foreign capital into the energy sector. Nevertheless, significant challenges remain in achieving universal electrification, especially in remote and underserved areas.

To further these goals, Ethiopia is exploring innovative renewable energy strategies. A notable milsestone came on June 3, 2022, when Fortescue Future Industries (FFI) received a license for green hydrogen and ammonia production in the country. While hydropower serves as Ethiopia's primary electricity source, it currently utilizes only 6% of its total potential. Solar and wind energy resources remain largely untapped and present opportunities for greater integration into the national energy system [8].

One promising approach to rural electrification is the development of intelligent hybrid micro-grid systems that combine photovoltaic (PV) and micro-hydropower technologies. These systems are especially valuable in off-grid regions, where communities often rely on diesel generators or kerosene lamps for basic lighting needs. By blending solar and micro-hydro resources, it's possible to create a stable and sustainable power supply tailored to local conditions.

Researchers have modeled various hybrid configurations, accounting for environmental factors like terrain, solar radiation, and water availability. These simulations aim to identify the most efficient systems for delivering energy to rural Ethiopian villages [9]. In one case, energy usage patterns revealed that daytime electricity needs—primarily for agricultural and domestic purposes—could be met through solar power, while nighttime demands were minimal and could be supplemented by wind energy. To ensure reliability, fuel cells were proposed as backup power sources during periods of low solar and wind generation.

In addition to technical viability, these studies also evaluated economic and social considerations. Estimates included capital expenditures for equipment like PV panels, wind turbines, and fuel cells, as well as long-term operation and maintenance costs. The analysis concluded that hybrid systems offer a cost-effective and sustainable solution for improving energy access in rural areas, with the added benefit of enhancing quality of life.

These findings support broader efforts to meet the United Nations' Sustainable Development Goals by promoting investment in clean energy infrastructure. While much attention has been given to hydro and wind energy in Ethiopia, hydrogen fuel cell technology remains relatively underexplored. There is a growing need to assess the efficiency and economic feasibility of fuel cells, especially within Ethiopia's energy landscape.

Solar power, due to Ethiopia's ample sunshine, is a particularly promising renewable source. In places like the Ayaber district, integrating solar PV with hydrogen fuel cells offers a reliable off-grid electricity solution. This system stores surplus solar energy during the day for use at night, reducing reliance on fossil fuels and ensuring continuous access to clean power.

1.3. Statement of the problem

A significant portion of Ethiopia's rural population still lives without access to electricity, primarily due to inadequate power infrastructure. This lack of electrification is a major hurdle to economic progress and limits the growth of local enterprises. In the absence of reliable electricity, rural households largely depend on firewood for cooking—a practice that is not only inefficient and unreliable but also harmful to both human health and the environment [8]. Continued reliance on wood fuels contributes heavily to deforestation, soil erosion, and even desertification, all of which result in lasting ecological degradation [11].

Moreover, using wood or charcoal for daily cooking exposes households—especially women—to toxic smoke. Women, who often bear the brunt of cooking duties and spend more time indoors, face a higher risk of respiratory illnesses. The World Health Organization reports that over four million premature deaths each year are linked to indoor air pollution from traditional cooking, with women and children being the most vulnerable.

The situation underscores the urgent need for a sustainable, affordable, and climate-resilient energy alternative. Renewable energy technologies like solar and wind offer viable solutions. These clean energy sources are becoming more cost-effective and accessible, making them practical options for bringing electricity to remote communities. Their adoption could significantly reduce greenhouse gas emissions and support Ethiopia in reaching its environmental and climate targets.

Despite Ethiopia's vast renewable energy potential—estimated at around 30,000 megawatts—only a small fraction, about 8.82%, has been harnessed to date [4], [12]. This highlights a widespread underutilization of the country's resources. Solar energy, in particular, offers immense opportunity, with average solar irradiance ranging between 4.5 and 7.5 $kWh/m^2/day$ [13]. Yet, despite this potential, the country continues to lean heavily on outdated and unsustainable energy sources. Even agricultural residues, which represent about 34% of the country's exploitable energy, fall short in addressing rural energy needs [5].

Addressing this energy shortfall—especially in rural areas—requires serious commitment from the government, private sector, and academic institutions. This study contributes to that effort by proposing a system model that explores the feasibility of powering rural communities with solar energy supplemented by hydrogen fuel cells. This hybrid approach is seen as a promising and forward-thinking solution capable of delivering consistent, clean energy to off-grid areas.

Solar power, harnessed through photovoltaic systems, provides a dependable energy source during the day. Hydrogen fuel cells, meanwhile, serve as efficient and adaptable storage devices, converting hydrogen and oxygen into electricity, heat, and water. When sunlight is unavailable—especially at night—the stored energy in hydrogen fuel cells can meet local electricity demand. Compared to batteries, fuel cells offer notable advantages: hydrogen has a higher energy density, fuel cells perform better in cold conditions, and they refuel much faster than battery systems [15].

Implementing this solar-hydrogen system in Ethiopia's rural areas could profoundly improve living conditions by delivering reliable energy, reducing reliance on biomass, and fostering socioeconomic development. It represents a transformative opportunity to bridge the energy access gap in a sustainable and scalable way.

1.4. Objectives

This study intends to model the system and investigate the rural electrification of Ayaber district using solar powered hydrogen fuel cell technology.

1.4.1. Specific Objectives

- Determine the various social units in the target community including population.
- Determine or estimate the average electric needs of the target village.
- Obtain the solar irradiance data for the target location
- Model the system and carry out optimization based on net present cost under normal inflation condition
- Carry out sensitivity analysis to see how cost reduction in some products affect the overall

1.5. Significance of the research

This study focuses on assessing the practicality of implementing a solar-powered hydrogen fuel cell system in a rural Ethiopian village. By examining the electricity consumption patterns of households, community centers, and small enterprises, the research aims to offer a clear understanding of the local energy demands. Hydrogen fuel cell technology stands out as a viable solution for off-grid areas, as it can generate electricity independently of a central power grid. Deploying this technology could empower the community to achieve energy self-sufficiency—a major leap forward in its developmental trajectory.

In addition to providing reliable power, hydrogen fuel cells offer several environmental and health-related benefits. In many rural regions, wood remains the primary source of energy for cooking and lighting. This reliance on biomass has been linked to respiratory illnesses due to the inhalation of harmful smoke, especially among women and children. Replacing firewood with a cleaner energy solution like hydrogen can significantly reduce indoor air pollution and its associated health risks. It also helps curb deforestation by decreasing the community's dependence on wood as an energy source, thereby supporting local ecological preservation.

The transition to hydrogen fuel technology would also have positive social effects. In many rural households, the responsibility of collecting firewood falls on women and children, consuming hours of their day. With a more accessible and efficient energy supply, this time could be redirected toward education, economic activities, or other forms of personal development. The hydrogen system could power essential needs such as cooking, lighting, and small appliances, improving daily life and fostering long-term sustainability.

Introducing hydrogen fuel cell (HFC) technology in Ethiopia could mark a transformative moment for the nation's energy landscape. Globally, HFC systems are being adopted as clean alternatives to fossil fuels due to their high efficiency and environmentally friendly output—water vapor being the only emission [16]. As this technology enters the Ethiopian market, it is likely to spark interest from private investors eager to explore its commercial potential. The government can capitalize on this momentum by encouraging private sector participation in research, development, and deployment of HFC solutions.

Such a move would also open new research avenues and stimulate technological innovation. As academic and technical institutions engage with HFC technology, they could drive the development of new renewable energy solutions tailored to Ethiopia's unique context. Importantly, hydrogen fuel cells could serve as a cornerstone in Ethiopia's strategy to meet its ambitious renewable energy goal—producing 100% of its electricity from renewable sources by 2030 [17]. By offering a dependable, sustainable energy option, hydrogen technology could play a vital role in turning this national vision into a reality.

1.6. Limitations

This research will center on the modeling and simulation of a photovoltaic (PV) hydrogen fuel cell system to evaluate its potential efficiency and operational performance. To achieve this, **Homer Pro Energy software** will be employed to simulate system behavior under a range of environmental and usage conditions. The primary goal is to identify an optimized system configuration capable of meeting the community's energy demand at the lowest **Net Present Cost (NPC)**.

The simulation will utilize demographic and energy consumption data sourced from **WorldData.com**. While this data may not precisely reflect the specific conditions of the selected rural village, it provides a reasonable approximation for estimating average household energy demand. This enables the modeling of system performance in scenarios representative of rural Ethiopian communities.

The simulation makes several foundational assumptions to streamline analysis. For instance, it assumes that the **hydrogen storage tank is fully charged (100%) at the beginning of the simulation year**. Additionally, factors such as the **availability, consumption, and cost of water**, which are essential for hydrogen production via electrolysis, are not included in the Homer Pro simulation parameters. These simplifications highlight areas for future research, where more detailed modeling could assess how such variables influence system feasibility, efficiency, and economic viability.

Researchers are encouraged to investigate these assumptions further in subsequent studies to gain deeper insights into the long-term performance and cost-effectiveness of PV-hydrogen systems in similar contexts.

1.7. Organization of the research

The research is structured into six chapters, each with a specific focus and purpose. The first chapter serves as an introduction to the study and provides a background on the topic, including any relevant historical or contextual information. The problem statement is also presented in this chapter, outlining the main objective of the research. Lastly, the research objective is clearly defined to provide a clear direction for the study.

The second chapter is dedicated to reviews of various studies in the field, providing a comprehensive understanding of the topic and highlighting gaps in the existing literature. This chapter is essential in establishing the significance of the research and identifying areas for further investigation.

The third chapter of the research focuses on explaining the research methodologies used in the study. This section includes an overview of the research design, data collection methods, and data analysis techniques. It is important to provide a clear explanation of these methods to demonstrate that the study is reliable and valid.

The fourth chapter illustrates the research model and simulation. This section presents the conceptual framework of the study and provides a visual representation of how the research was conducted. The model and simulation are essential in understanding the study's results and conclusions.

The fifth chapter discusses data analysis with discussions. This section presents the results of the study and explains how they were analyzed. The discussions provide an interpretation of the findings and their significance for the research question. This chapter is important in demonstrating how the research objective was achieved.

The sixth and final chapter discusses the findings and recommendations for future studies. This section summarizes the main findings of the study and provides recommendations for future research. The conclusions drawn from the study are presented, and their implications are discussed. This chapter is essential in demonstrating the significance of the research and its contribution to the field.

2. Chapter Two

Literature Review

2.1. Chapter Summary

The second chapter is dedicated to reviews of various studies in the field, providing a comprehensive understanding of the topic and highlighting gaps in the existing literature. This chapter is essential in establishing the significance of the research and identifying areas for further investigation.

2.2. Pre-history of Hydrogen

The element hydrogen was officially discovered in 1766 by the British chemist and physicist Henry Cavendish, who identified it as a distinct substance that produced water when burned—a property that led to its naming as "hydro-gen," meaning "water-former." However, references to the production of this combustible gas predate Cavendish's discovery. Historical records indicate that alchemists and early chemists in the Middle Ages observed reactions between metals like iron, zinc, and tin and mineral acids such as sulfuric and hydrochloric acid, which produced flammable gases—most likely hydrogen. For example, in the 14th century, German alchemist Johann von Rupescissa described generating a "spirit" by reacting iron filings with diluted sulfuric acid. Similarly, in the 17th century, the Flemish chemist Jan Baptist van Helmont observed a gas he termed *gas sylvestre*—a precursor understanding of what we now identify as hydrogen.

Hydrogen holds a foundational place in the universe, comprising approximately 75% of its elemental mass. With an atomic structure consisting of a single proton and one electron, hydrogen is the simplest and lightest element. Despite its abundance in the cosmos, hydrogen is rarely found in its pure form on Earth, where it typically exists as part of compounds such as water (H_2O) or hydrocarbons.

To utilize hydrogen as a fuel source, it must be extracted from these compounds. One of the most common and environmentally friendly methods is electrolysis, where an electric current is passed through water to separate hydrogen and oxygen atoms. The hydrogen gas is then collected and stored for use. Other extraction methods include steam methane reforming (SMR)—which uses high-temperature steam to extract hydrogen from hydrocarbons—and biomass gasification, where organic matter like agricultural waste is heated to produce hydrogen-rich gas.

Despite its advantages, hydrogen presents storage and transportation challenges due to its low volumetric energy density. In its gaseous form, hydrogen occupies a much larger volume than conventional fuels like gasoline, making it less efficient to store and transport. To overcome this, hydrogen can be compressed to high pressures (up to 80 MPa) or converted to a liquid state by cooling it below -252.87°C, dramatically reducing its volume. In fact, liquid hydrogen occupies only 1/800th the volume of its gaseous form at room temperature and atmospheric pressure.

In summary, hydrogen offers numerous benefits as an energy source, including its abundance, high energy-to-weight ratio, and clean combustion (emitting only water vapor). However, practical implementation hinges on overcoming hurdles related to production efficiency, storage, and distribution, particularly in large-scale or remote applications [18][19].

Hydrogen exists in three phases, liquid, solid and gas. As shown below in the phase diagram in Figure 2- 1, liquid hydrogen exists only in small region between the solid line and the line from the triple point at 21.2 K and the critical point at 32K.

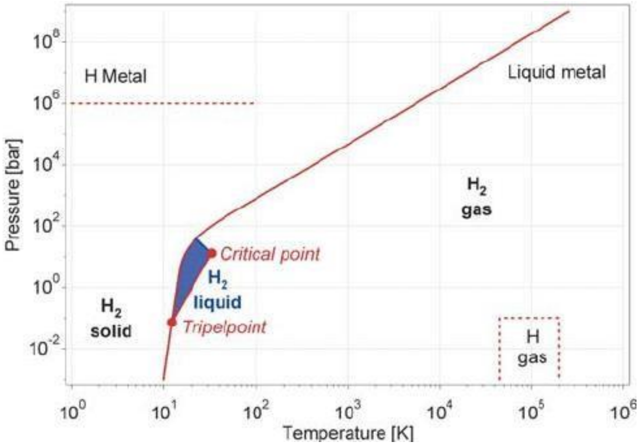


Figure 2- 1 Triple Point Phase of Hydrogen [19]

Hydrogen is an extremely flammable gas, capable of burning in air over a wide concentration range—from 4% to 77% by volume. At an optimal concentration of 29% by volume, hydrogen achieves its maximum flame temperature of approximately 2318 K, making it an ideal candidate for high-temperature applications such as fuel cells, internal combustion engines, and rocket propulsion systems.

One of the key advantages of hydrogen as a fuel is its exceptionally low ignition energy requirement. A stoichiometric mixture of hydrogen and oxygen can be ignited with as little as 0.02 millijoules (mJ) of energy—an order of magnitude lower than the 0.29 mJ needed to ignite a methane-oxygen mixture. This characteristic allows for easier ignition but also demands strict safety protocols when handling hydrogen in confined environments.

From an energy standpoint, hydrogen offers one of the highest energy yields per unit mass of any known fuel. Its lower heating value (LHV) is approximately:

- 2.4 times greater than that of methane,
- 2.8 times greater than petrol (gasoline), and
- 4 times greater than coal.

This makes hydrogen particularly attractive for energy-intensive applications, especially in contexts where weight is a critical factor, such as in aerospace and portable energy systems.

The combustion of hydrogen with oxygen is a highly exothermic reaction, with a standard enthalpy change (ΔH) of –286 kJ/mol, producing only water vapor as a byproduct:

$$\boldsymbol{(g) + O(g) \rightarrow 2H_2O(l) + 572\ kJ\quad (286\ kJ\ mol^{-1})}$$

(2.1)

This clean combustion process contributes to hydrogen’s status as an environmentally friendly and zero-emission energy carrier, particularly when the hydrogen is produced using renewable sources such as solar, wind, or hydroelectric power. The versatility and sustainability of hydrogen production pathways further enhance its potential as a cornerstone of the future clean energy economy [20].

2.3. Solar Hydrogen

Hydrogen generated through solar-driven water splitting is widely regarded as a fuel of the future [21]. This technology holds the potential to replace fossil fuels and dramatically reduce global dependence on hydrocarbons and coal, thereby mitigating CO_2 emissions—a major contributor to global warming and climate change [19].

The central objective of this study is to model a hybrid power system and assess the feasibility of electrifying Kewet Woreda using solar photovoltaic (PV) systems in conjunction with hydrogen fuel cell backup technology. This approach not only supports the region's electrification goals but also promotes long-term sustainability.

Hydrogen produced from renewable solar energy and abundant water resources offers a clean and sustainable solution to the world's growing energy demands. It is a strategic response to both environmental concerns and global energy security challenges [22].

Among various renewable energy options—such as solar thermal, geothermal, wind, and biomass—solar PV systems have seen the most substantial advancements in both technology and cost-effectiveness. These improvements have positioned solar PV as one of the most economical methods for renewable electricity generation [23]. However, the cost of hydrogen fuel cells remains relatively high compared to other renewable technologies, and continued research is required to enhance their economic viability [24].

The Earth receives an immense amount of solar energy each year—approximately 3.9×10^{24} megajoules—which is 10,000 times greater than current global energy demand. In theory, harvesting just 1% of this solar energy would be sufficient to meet humanity's total energy needs [25].

Importantly, the solar water-to-hydrogen-to-water cycle as shown in Figure 2- 2, stands as the only truly closed material cycle among all known human energy systems. Unlike other cycles—which often extract finite resources from the Earth's crust and return them to the biosphere in toxic, radioactive, or environmentally harmful forms—this hydrogen cycle is both clean and sustainable [19].

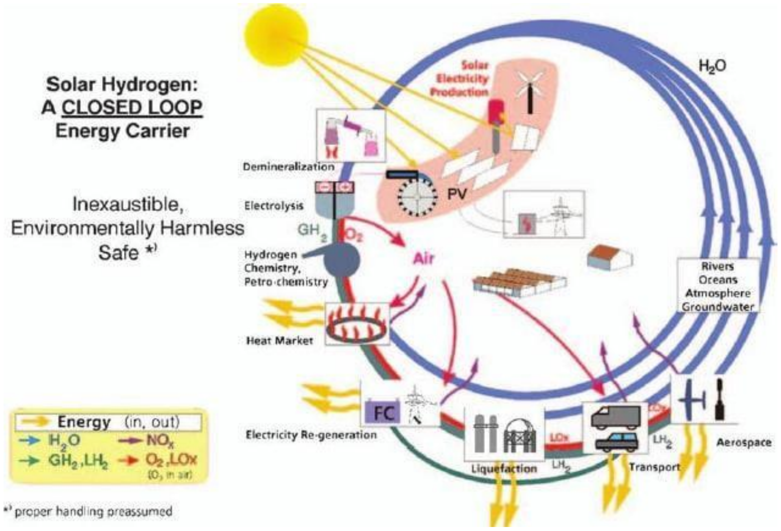


Figure 2- 2 Water-to-Hydrogen-to-water closed cycle [19]

Solar Hydrogen technology starts its operation by electrolysis process, which we will see in depth next.

2.4. Electrolysis

Water electrolysis is a process whereby electrical energy is used to split water molecules into their constituent elements—hydrogen and oxygen—within a device known as an electrolyzer. This method serves as a fundamental approach for producing clean hydrogen fuel. Once generated, hydrogen can be recombined with oxygen in a fuel cell to produce electricity, thereby converting the stored chemical energy into electrical energy for practical use [26].

The theoretical foundation of electrolysis was significantly advanced by Michael Faraday, who conducted some of the earliest systematic studies on the subject. His work led to the formulation of Faraday’s Laws of Electrolysis, which remain essential to understanding the electrochemical process:

The amount of substance produced at each electrode during electrolysis is directly proportional to the quantity of electricity (charge) passed through the electrolytic cell.

For a given amount of electricity, the mass of the substance produced is proportional to its equivalent weight.

These laws not only explain the basic principles behind hydrogen production via electrolysis but also form the basis for quantitative analysis in electrochemical systems. Their relevance continues in modern applications, including renewable hydrogen production systems that integrate solar PV and hydrogen fuel cell technologies.

2.4.1. Electrode Kinetics

The reaction kinetics at the electrodes of an electrolytic cell are significantly influenced by several design and operational factors, including the specific technology employed, the structure and geometric configuration of the cell, and the type of electrolyte utilized. These factors can introduce inefficiencies in the form of reduced conversion effectiveness. A major contributor to such inefficiencies is polarization—also referred to as over-potential or over-voltage—which arises from electromotive forces that oppose the desired electrochemical reactions during cell operation. Polarization not only reduces the cell's voltage efficiency but also increases energy consumption, thereby impacting the overall system performance [27].

2.4.2. Activation Polarization

Activation polarization, also referred to as **activation over-potential**, is a key factor contributing to the overall polarization in electrochemical systems, such as fuel cells, batteries, and electrolyzers. It originates from the intrinsic resistance to charge transfer at the electrode–electrolyte interface. This phenomenon arises due to the sluggish kinetics of electrochemical reactions, particularly at the initiation stage. As a result, an additional voltage—known as the **activation over-potential**—must be applied to overcome this barrier and enable the electrochemical reaction to proceed at a desirable rate. Activation polarization is especially pronounced at low current densities and plays a significant role in determining the efficiency and performance of electrochemical devices.

$$\eta_{act} = \frac{RT}{\alpha z F} \log \frac{i_o}{i} \tag{2.2}$$

Where:

- α is the coefficient of the *charge transfer coefficient*
- *io* is the density of the exchange current and
- *i* is the density of the current passing through the electrode surface.

This equation tells us that in any PV/FC system, a low α or low *io* increases activation polarization, meaning more energy is needed to start the reaction in the fuel cell or electrolyzer, reducing efficiency. Therefore optimizing electrode materials (e.g., using catalysts like platinum) can increase *io* and improve performance, critical for cost-effective rural electrification.

The charge transfer coefficient depends on the reaction mechanisms between the electrons and the catalysts and usually acquires a value between one and zero [28].

2.4.3. Ohmic Polarization

Ohmic losses, also known as ohmic polarization, arise from the internal resistance within electrochemical cells. These losses are primarily due to two factors: the resistance of the electrode materials to electron flow and the resistance of the electrolyte to ion flow. Among these, electrolyte resistance typically contributes the most to overall ohmic losses.

Minimizing these losses is crucial for improving cell efficiency. This can be achieved by reducing the distance between the electrodes and minimizing the thickness of the electrolyte, thereby shortening the ion transport path and decreasing resistance.

Ohmic losses can be quantified using the following equation:

$$\eta_{ohm} = IR \tag{2.3}$$

Where I is the current in the cell and R is the total resistance of the cell [29].

2.4.4. Concentration Polarization

Mass transport phenomena at the inlet and outlet of an electrochemical cell play a critical role in maintaining efficient device operation. If the flow rate of reactants and removal of products are insufficient to sustain the required current density, performance losses occur. Specifically, when the current density is high, the system may experience concentration polarization.

Concentration polarization arises due to the limited diffusion rate of reactants through the electrolyte. This limitation causes a steep concentration gradient near the electrode surface, resulting in a voltage drop compared to the ideal, polarization-free case. The inadequate supply of reactants or accumulation of products at the reaction interface significantly hinders the electrochemical reaction rate, leading to reduced cell performance.

Managing concentration polarization requires optimizing flow rates, cell geometry, and the physical properties of the electrolyte to ensure effective mass transport throughout the electrochemical system.

From *Fick's first law*5, the diffusive transport can be described as:

$$\boldsymbol{i} = \frac{\boldsymbol{nFD(C_B - C_S)}}{\boldsymbol{\delta}} \tag{2.4}$$

D is the diffusion coefficient of the reactants, CB is their concentration in the electrolyte, CS is the concentration on the electrode surface, and is the thickness of the diffusive layer. The maximum limit value of i can be calculated when CS is close to zero, and it can be reached when the concentration of the reactants at the entry point is too low [30].

2.4.5. Transfer Polarization

The voltage variation at the electrodes of an electrochemical cell is primarily influenced by the electrochemical behavior of those electrodes. One of the key factors contributing to this variation is transfer polarization, also known as charge transfer over-potential. This form of polarization represents the additional voltage required to initiate and sustain the flow of electric current between the electrodes due to kinetic limitations of the electrochemical reactions.

Transfer polarization can be quantitatively described using an empirical, nonlinear equation, typically derived from the Butler-Volmer equation. This equation accounts for the relationship between the current density and the activation energy required for the electrochemical reaction to occur. The resulting over-potential is especially significant at low and high current densities and must be considered when designing efficient fuel cells and electrolyzers.

Understanding and minimizing transfer polarization is crucial for improving the overall efficiency of hydrogen fuel cells and other electrochemical systems.

$$\boldsymbol{U = a + b \log i} \tag{2.5}$$

Where a e b are the coefficients determined by experiments [31].

2.5. Fuel Cells

A fuel cell is an electrochemical device that converts the chemical energy of a fuel—typically hydrogen—and an oxidizing agent, commonly oxygen from the air, into electricity through redox reactions. Unlike traditional batteries, which store a finite amount of chemical energy internally, fuel cells require a continuous external supply of fuel and oxygen to sustain the reaction. Consequently, as long as these inputs are available, fuel cells can generate electricity indefinitely [32].

Benefits of Fuel Cells:

Clean and Efficient: Fuel cells emit only water vapor and heat as byproducts, making them environmentally friendly.

Versatile Applications: They can simultaneously generate electricity and thermal energy (cogeneration), and are capable of powering a range of systems—from portable electronics to residential buildings and vehicles.

Scalability: Fuel cells can be designed to meet a wide range of power requirements, from small-scale portable devices to large-scale power plants.

Challenges of Fuel Cells:

High Costs: The current cost of fuel cell systems remains relatively high compared to other energy technologies.

Technological Maturity: Fuel cell technology is still developing and is not as commercially mature or widespread as solar or wind energy.

Lack of Infrastructure: There is a significant gap in the infrastructure necessary to support widespread hydrogen production, distribution, and fueling stations.

Despite these challenges, fuel cells hold substantial promise as a sustainable energy solution. With continued technological advancement and cost reductions, fuel cells are expected to become an increasingly important component of the global renewable energy landscape.

2.5.1. Types of Fuel Cells

Fuel cells are categorized based on the type of electrolyte they use and their operational characteristics. Each type has unique advantages and is suited for specific applications. The main types include:

Proton Exchange Membrane Fuel Cells (PEMFCs):

PEMFCs are the most commonly used type of fuel cell due to their low operating temperature, compact size, and quick start-up time. They are widely employed in portable electronic devices, backup power systems, and automotive applications.

Alkaline Fuel Cells (AFCs):

AFCs were among the first fuel cells developed and have been historically used in space missions, including NASA's Apollo program. They offer high efficiency and are also used in submarines and hospitals where clean and quiet energy is essential.

Molten Carbonate Fuel Cells (MCFCs):

These high-temperature fuel cells are primarily used for stationary power generation. They operate at around 650°C, allowing for high efficiency and the ability to internally reform fuels. However, they are more complex and costly than PEMFCs.

Solid Oxide Fuel Cells (SOFCs):

SOFCs are also used in stationary power generation and operate at even higher temperatures (around 800–1000°C). They are the most efficient type of fuel cell in terms of energy conversion but also the most expensive due to their material and thermal requirements.

2.6. Fuel Cell Design

A very important design consideration is the overall stack design and configuration. When considering the design of a fuel cell stack, several factors should be considered. Some of these factors may include:

a. Size,
b. weight, and volume at desired power
c. Cost
d. Operating temperature
e. Humidification and water management
f. Fuel and oxidant pressure
g. Fuel type(s) and storage

These factors then translate into design requirement, which helps one to design the entire fuel cell system.

2.6.1. Fuel Cell Design Parameters

Table 2- 1 Fuel Cell Design Parameters

Fuel Cell Design Parameters	
Requirements	1. Power Density/Voltage 2. Efficiency 3. Start-up 4. Transient Response 5. Weight Size/Shape
Operation Conditions	6. Temperature 7. Pressure 8. Humidity 9. Flow Rate
Porous Electrode Layer or Gas Distribution Layer	10. Thickness 11. Material Properties such as porosity, conductivity, temperature resistance, chemical resistance
Electrode Layer	12. Thickness/Loading 13. Material Properties such as porosity, conductivity, temperature resistance, chemical resistance
Catalyst Layer	14. Thickness/Loading 15. Composition
Fuel Cell Design	16. Bipolar Plate Material 17. Channel Design/Layout 18. Channel Size 19. Rib Size 20. End Plate Material 21. Cooling Channels 22. Cell Interconnects

Given on the above Table 2- 1, when designing a fuel cell stack, two key independent variables must be taken into account. Typically, the desired maximum power, voltage, and/or current are predefined based on the application’s requirements. It’s important to remember that power output is directly determined by the product of the stack’s voltage and current:

$$\boldsymbol{W_{FC} = v_{ST} * I} \tag{2.6}$$

To design the fuel cell stack’s power output, it’s essential to account for the maximum possible power and any voltage spikes that might occur during operation [33]. A good starting point in the design process is to examine the polarization curves of different fuel cell types. These curves as shown on Figure 2- 3 Polarization Curve of a PEM Fuel Cell [34], illustrate the relationship between the cell’s potential (voltage) and the current density, providing valuable insight into the performance characteristics of the fuel cell.

The operating point at nominal power is defined by the cell voltage and current density, which can be selected at any point along the polarization curve. This choice plays a critical role in determining both the size and efficiency of the stack. Selecting a higher cell voltage typically results in better efficiency, which depends on factors such as the materials used, the design of the flow channels, and the optimization of system parameters like temperature, heat management, humidity, pressure, and reactant flow rates. The following equation can be used to estimate the fuel cell stack’s efficiency [34]:

$$\boldsymbol{V_{cell} = (i)} \tag{2.7}$$

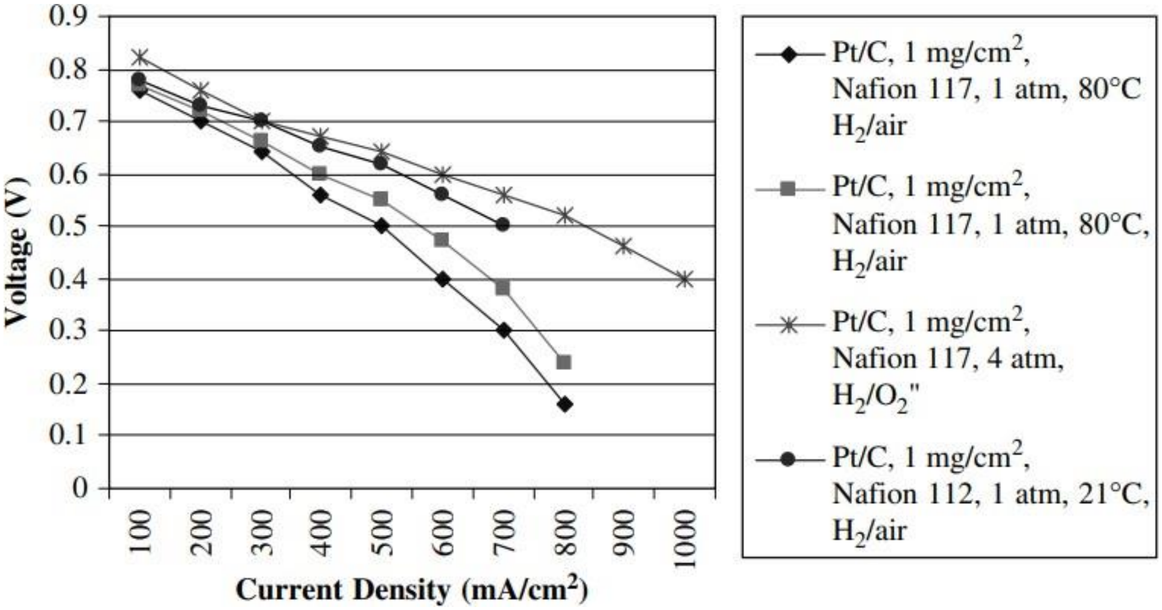


Figure 2- 3 Polarization Curve of a PEM Fuel Cell [34]

Most fuel cell developers use a nominal voltage of 0.6 to 0.7 V at nominal power [35].

The figure above represents a Linear Region of the Ohmic Polarization, the linearity is due to ohmic polarization caused by resistance and greater losses.

i. Number of Cells

The maximum voltage requirement and the desired operating voltage are frequently used to determine the number of cells in the stack. The total stack potential is the product of the average cell potential and the number of cells in the stack [36].

The number of cells can be determined as follows.

$$\boldsymbol{V_{ST} = V_{cell} * N_{cell}} \qquad (2.8)$$

The cell area must be carefully designed to deliver the required current for the fuel cell stack. To determine the stack's maximum power output, this current is multiplied by the total stack voltage. While cells in most fuel cell stacks are connected in series to increase voltage, parallel configurations can also be used to boost total output current. However, it's generally advisable to avoid using too many cells with very small or excessively large active areas, as these configurations can complicate assembly and lead to significant resistive losses:

$$\eta = \frac{\text{v cell}}{1.48} \tag{2.9}$$

Where:

- V_cell is the actual operating voltage of the fuel cell (in volts)
- η is the efficiency of the fuel
- 1.48 is the theoretical voltage of a hydrogen fuel cell (in volts)

ii. Hydrogen Requirement

Using the following equations, the amount of hydrogen required to meet the energy demand can be calculated using this efficiency [37]:

$$\boldsymbol{Hydrogen\ Requirement} = \frac{\boldsymbol{Energy\ Requirement}}{\boldsymbol{Fuel\ Cell\ Power * Hydrogen\ to\ Energy\ Ratio}} \tag{2.10}$$

2.7. Stack Configuration

A fuel cell stack consists of several essential components, including individual fuel cells, gaskets, bipolar plates with electrical connectors, and end plates. These components are typically assembled and secured using mechanical fasteners such as bolts, rods, or clamps. In some designs, the components may be integrally fused into a single monolithic structure to enhance durability and reduce assembly complexity.

When designing a fuel cell, several critical considerations should be kept in mind:

- Fuel and oxidant must be evenly distributed across the entire surface of each cell.
- Temperature should remain uniform throughout the stack.
- For polymer electrolyte fuel cells, the membrane must be carefully managed to prevent drying out or becoming flooded with excess water.

- Resistive losses should be minimized to maintain efficiency.
- Proper sealing is essential to prevent gas leakage.
- The stack must be mechanically robust and capable of withstanding the environmental conditions in which it will operate.

Figure Figure 2- 4 Fuel Cell Stack Configuration[38], illustrates the most common configuration of a fuel cell stack. In this design, a bipolar plate—featuring flow fields on both sides—is used to separate each membrane electrode assembly (MEA). This structure facilitates the efficient distribution of both fuel and oxidant to the respective electrodes. At the end plates of the stack, however, flow fields are present only on the inner-facing side, as they interface with just one MEA. This configuration is widely adopted across virtually all fuel cell types, stack sizes, and fuel sources, due to its effectiveness and scalability [38].

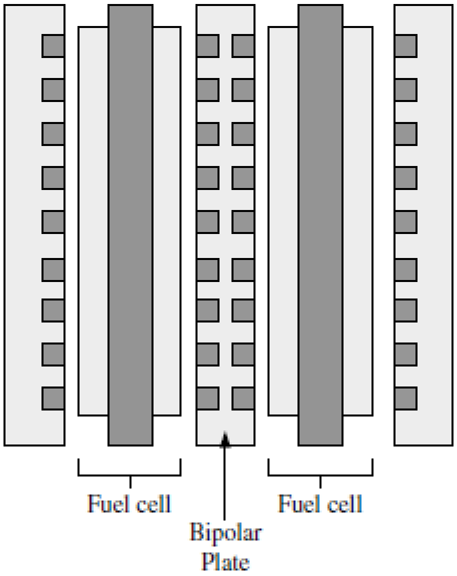


Figure 2- 4 Fuel Cell Stack Configuration[38]

2.8. Hydrogen Tanks

Hydrogen tanks play a critical role in photovoltaic (PV)-based fuel cell systems, serving as the primary storage medium for hydrogen gas, which is subsequently used to power the fuel cells. The type and design of the hydrogen storage tank are determined largely by the application context and the overall system size [39].

There are two main categories of hydrogen tanks:

- High-pressure tanks: Constructed from lightweight, high-strength materials such as carbon fiber composites or aluminum alloys, these tanks are designed to store hydrogen at pressures typically ranging from 5,000 to 10,000 psi. Their compact size and reduced weight make them ideal for mobile or portable applications, such as fuel cell vehicles. However, these advantages come at a higher manufacturing cost compared to other storage options.
- Low-pressure tanks: Typically made of steel or stainless steel, these tanks store hydrogen at much lower pressures, often around 100 psi or less. They are more cost-effective and robust, making them suitable for stationary applications, where space and weight constraints are minimal. However, their larger size and heavier construction can limit their deployment in mobile systems.

The selection of a hydrogen tank in PV-fuel cell systems is influenced by multiple factors, including cost considerations, weight and space limitations, system efficiency, and the intended use-case (e.g., residential backup power vs. mobile applications).

In conclusion, hydrogen storage is a vital component in ensuring the reliability and efficiency of solar-powered fuel cell systems. As storage technologies advance and economies of scale improve, it is expected that the cost of hydrogen tanks will decrease, thereby enhancing the accessibility and adoption of clean energy solutions across diverse applications.

2.9. Previous Study Literatures

Several recent studies have explored the techno-economic feasibility of hybrid renewable energy systems that integrate solar, wind, and fuel cell technologies for off-grid and rural electrification applications.

Mikias Hailu and Getachew Bekele [10] conducted a techno-economic feasibility study of an emission-free hybrid power system incorporating solar, wind, and fuel cells to provide sustainable electricity to *Nifasso*, a rural village in Ethiopia. Their results revealed a broad array of viable system configurations, all yielding a relatively narrow range of cost of energy (COE), thereby demonstrating the economic competitiveness of such systems.

Similarly, Abiy Mekonnen, Ravikumar Hiremath, and Derje Shiferaw [9] used MATLAB Simulink to model and simulate a hybrid system composed of photovoltaic (PV), micro-hydro, and energy storage components. Their system, developed for rural *kebele* communities, employed a fuzzy logic controller to balance resource availability with demand, thus optimizing overall energy generation and supply.

Ajay Kumar [40] studied a solar-fuel cell hybrid energy system aimed at delivering reliable and continuous electricity in India. The study highlighted the system's potential for environmental sustainability and cost-effectiveness, concluding that hybrid configurations are superior to conventional energy sources in both efficiency and long-term viability.

Fernando de Sisternes and Christopher Jackson [41] analyzed the role of green hydrogen in advancing renewable energy in developing countries. Their report reviewed ongoing pilot projects, underscoring the strategic advantages, technological risks, and implementation barriers associated with green hydrogen integration.

In a case study of Duqm, Oman, Al-Sulaimani et al. [42] assessed a solar-wind-fuel cell hybrid system using HOMER Pro software. Their evaluation confirmed both technical feasibility and economic viability, reporting a levelized cost of energy (LCOE) of \$0.436/kWh.

Njita et al. [43] explored a comprehensive hybrid system in Cameroon's Far North Region, integrating PV, battery storage, fuel cell, electrolyzer, and biogas technologies. Their findings, derived using

HOMER Pro, indicated that the system was technically robust and cost-effective, with an LCOE of \$0.323/kWh.

In a related study conducted in India, Majidi et al. [44] analyzed a PV/fuel cell/battery hybrid system for residential applications. Also employing HOMER software, they concluded that the system was technically and economically sound, yielding an LCOE of \$0.39/kWh.

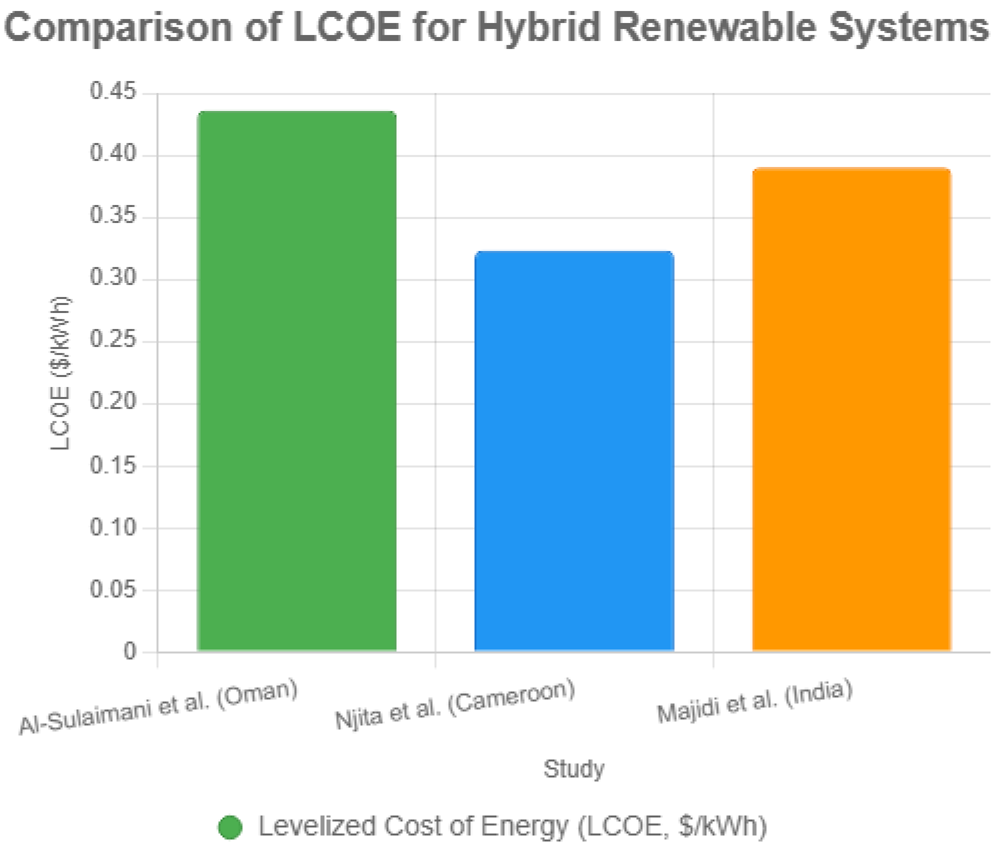


Figure 2- 5 Comparisn of LCOE for Hybrid Renwable Systems

2.10. Summary of Literature Review

This literature review has examined the application of hybrid power systems for rural electrification in developing countries, with particular emphasis on studies employing the HOMER software to evaluate both the technical and economic viability of such systems. A consistent finding across the reviewed studies is that hybrid energy systems—especially those integrating solar, wind, fuel cells, and energy storage technologies—present a viable and cost-effective alternative to traditional grid-based electricity.

Notably, the levelized cost of energy (LCOE) achieved by these systems is often comparable to or even lower than that of conventional grid-connected solutions. In addition to their cost competitiveness, hybrid power systems offer several key advantages:

- Enhanced reliability: Ability to provide uninterrupted power during grid outages or supply fluctuations.
- Reduced environmental impact: Significantly lower greenhouse gas emissions than fossil fuel-based alternatives.
- Increased resilience: Stronger performance in remote or disaster-prone areas due to decentralized architecture and multi-source redundancy.

Collectively, these benefits underscore the transformative potential of hybrid renewable systems in addressing energy access challenges across the Global South. However, their performance and economic feasibility are highly dependent on local factors such as renewable resource availability, demand profiles, infrastructure conditions, and policy frameworks.

2.11. Rationale for the Present Study

In light of these insights, the present study aims to contribute to the existing body of knowledge by specifically assessing the technical and economic feasibility of photovoltaic/fuel cell (PV/FC) hybrid systems in the Ethiopian context. Ethiopia’s diverse geography, variable resource availability, and ongoing rural electrification efforts make it a compelling case for targeted research.

The study aspires to generate practical insights that can assist researchers, energy planners, and policymakers in:

- Optimizing hybrid system configurations for rural deployment,
- Enhancing system performance through appropriate technology integration, and
- Developing scalable, context-sensitive strategies for sustainable electrification of underserved communities.

3. Chapter Three
Methodology

3.1. Chapter Summary

This chapter presents the research methodology adopted in this study. It outlines the research design, data collection methods, sampling techniques, and the procedures used for data analysis. Clearly articulating the methodology ensures transparency, enhances the reliability of the study, and allows for replicability by other researchers. Furthermore, the methodological approach has been selected to align with the objectives of the research, ensuring that the findings are both valid and relevant to the study context.

3.2. Research Approach

This study employs a quantitative research approach, emphasizing the collection and analysis of numerical data to support objective, data-driven conclusions. The core objective is to evaluate the average household energy demand of the target beneficiaries in order to design a solar-powered hydrogen fuel cell system.

Key parameters considered in this analysis include:

- Household population size
- Per capita energy consumption
- Solar Global Horizontal Irradiance (GHI)

These data inputs are critical for modeling and simulation, which are used to determine the optimal system size and capacity requirements of a solar-hydrogen hybrid energy solution. The quantitative methodology enhances the study's accuracy, replicability, and relevance by grounding the design process in empirical and measurable evidence, thereby ensuring a scientifically robust system performance evaluation.

3.3. Population and Demography

The study focuses on Ayaber Kewet Woreda, situated in the North Shewa Zone of the Amhara Region in Ethiopia. This area is predominantly rural, characterized by dispersed settlements with only a few small urban centers. According to the 2023 national census conducted by the Central Statistical Agency (CSA) of Ethiopia, the woreda has a total population of 163,122, comprising 84,068 men and 79,054 women [45].

The high population density of the region is primarily attributed to its fertile agricultural land and favorable climate, which support agriculture as the dominant economic activity. Most residential structures in the woreda are traditional, built from mud, wood, and straw, although some modern dwellings constructed with cement and bricks are found in the semi-urban areas.

Understanding this demographic and socioeconomic context is critical for accurately assessing household energy demand and for designing energy systems that are technically feasible, economically viable, and culturally appropriate for the local population.

3.4. Household Energy Demand

This study utilizes secondary energy consumption data sourced from World Data as a baseline for modeling and simulating a solar-powered hydrogen fuel cell system. To contextualize and strengthen the analysis, relevant literature on rural electrification and energy access in Ethiopia has also been reviewed, offering critical insights into the country's broader energy landscape.

Although these secondary data sources may not perfectly reflect the unique energy consumption patterns of households in Ayaber Kewet Woreda, they provide a practical and informative starting point. Due to limited availability of localized data—a situation further complicated by recent regional conflicts—such references are essential for guiding system modeling, as well as for informing future research and policy development.

According to World Data (www.worlddata.info), the average annual electricity consumption per capita in Ethiopia is approximately 79.25 kWh [46]. However, it is important to acknowledge that actual energy demand can vary significantly based on several factors, including:

- Geographic location (urban vs. rural)
- Household income levels
- Access to electrical appliances and infrastructure
- Cultural habits and lifestyle practices

For instance, urban households tend to consume more electricity due to greater access to appliances and services, whereas rural households—such as those in Ayaber Kewet Woreda—often have lower energy consumption, shaped by limited infrastructure and traditional living conditions.

Therefore, while the national average of 79.25 kWh per capita serves as a useful benchmark, it may not accurately represent the actual energy needs of the local population. This underscores the importance of localized data collection and the need to customize energy system design to meet the specific requirements of rural communities.

3.5. System Model and Simulation

This research investigates the technical and economic feasibility of implementing a solar-powered hydrogen fuel cell system through computational modeling and simulation. The study begins by collecting essential input data, including:

- Average household electricity demand
- Daily, monthly, and annual solar radiation levels

These inputs will be sourced from existing literature, the National Metrology Institute of Ethiopia, and specialized software tools such as RETScreen Expert.

Following data collection, computational modeling software will be employed to simulate the performance of the proposed solar-hydrogen hybrid system. The model will incorporate key variables such as:

- Solar Global Horizontal Irradiance (GHI)
- Capital and replacement costs
- Operation and maintenance (O&M) costs
- Net Present Cost (NPC)
- Levelized Cost of Energy (LCOE)

This simulation framework allows for a dynamic assessment of the system under a variety of scenarios, such as fluctuating solar radiation and varying energy demand. These simulations are essential to evaluate system efficiency, energy reliability, and economic viability.

To ensure the validity of the results, the model's output will be benchmarked against findings from similar studies on solar-powered hydrogen fuel cells. This comparative analysis serves to verify the accuracy of the simulation and reinforce the credibility of the methodology used.

Ultimately, the study aims to provide a comprehensive analysis of the performance, cost-effectiveness, and scalability of the solar-hydrogen system. The findings are expected to offer practical insights for researchers, policymakers, and development planners seeking to design sustainable energy solutions for rural communities in Ethiopia.

4. Chapter Four

System Modeling and Simulation

4.1. Chapter Summary

This chapter presents the research model and simulation framework developed for the study. It outlines the conceptual and analytical structure used to guide the investigation, offering both visual and descriptive representations of how the solar-powered hydrogen fuel cell system was modeled and simulated.

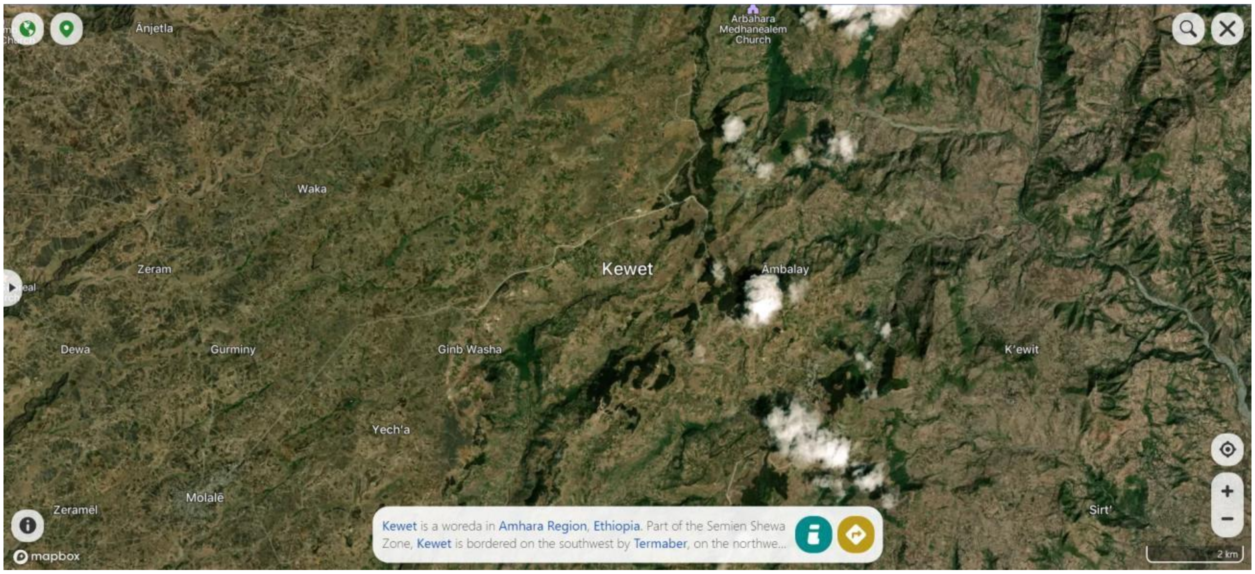
By illustrating the flow of data, the interactions among key system components, and the methodological steps followed, this chapter establishes the foundation for interpreting the results and drawing meaningful conclusions. The framework integrates technical, economic, and environmental variables to assess the system's performance under various conditions.

The model and simulation serve a central role in evaluating the technical feasibility and economic viability of implementing a solar-hydrogen hybrid energy solution for rural electrification. This structured approach ensures that the analysis is systematic, reproducible, and aligned with the study’s objectives.

4.2. Location and Resource

This study focuses on Ayaber Kewet Woreda, located in the northern part of Ethiopia, within the Amhara Region. Geographically, the woreda is situated at approximately 10.0° N latitude and 39.770° E longitude, as illustrated in Figure 4- 1 Location of Ayaber on the Map [47]. This area was strategically selected due to its predominantly rural population, agricultural livelihood, and the urgent need for sustainable and reliable energy solutions.

The selection of this location is particularly relevant given its limited access to grid electricity and its suitability for renewable energy deployment, especially solar-based systems. Understanding the geographical and climatic conditions of Ayaber Kewet is essential for accurate modeling and simulation of the solar-powered hydrogen fuel cell system. These contextual insights ensure that the proposed solution aligns with local energy demand profiles, resource availability, and infrastructure constraints.



Kewet is a woreda in Amhara Region, Ethiopia. Part of the Semien Shewa Zone, Kewet is bordered on the southwest by Termaber, on the northwe...

Figure 4- 1 Location of Ayaber on the Map [47]

4.3. Energy Consumption

Electricity consumption in rural areas of Ethiopia remains notably low compared to national and global averages. According to data from World Data [46], the average annual electricity consumption per capita in rural Ethiopia is approximately 79.25 kWh. Given the predominantly rural character of Ayaber Kewet Woreda, this figure is adopted as a baseline estimate for modeling household energy demand in the study area.

This assumption provides a practical and contextually appropriate benchmark for simulating the energy needs of the local population. While actual consumption may vary due to socioeconomic, geographic, and infrastructural factors, the selected value offers a reasonable starting point for the design and simulation of a solar-powered hydrogen fuel cell system aimed at rural electrification. For a population of 163,122[45] this is approximately 12,927,418.5 kWh of energy demand per year for Ayaber Kewet Woreda.

4.4. Solar Energy Conversion

4.4.1. Overview of Solar Energy

Solar energy, derived from the radiant light and heat emitted by the sun, represents one of the most abundant and promising sources of **renewable energy**. As a **clean, sustainable, and environmentally friendly** alternative to conventional fossil fuels, solar energy plays a pivotal role in the global transition toward low-carbon energy systems. At its core, solar energy conversion involves the **direct or indirect harnessing of sunlight** to produce electricity or thermal energy [48].

The two primary methods of harnessing solar energy are **photovoltaic (PV) systems** and **solar thermal systems**:

- **Photovoltaic (PV) Systems**:
  PV systems convert sunlight directly into electricity using solar panels composed of numerous **photovoltaic cells**, typically made from **semiconductor materials** such as silicon. When exposed to sunlight, these cells excite electrons, creating an electric current. The electricity generated can either be consumed immediately or stored in batteries for later use. PV systems are highly **versatile and scalable**, suitable for installation on rooftops, ground-mounted arrays, or integrated into building materials, making them ideal for **decentralized energy generation** [49].
- **Solar Thermal Systems**:
  In contrast, solar thermal systems convert solar radiation into **thermal energy** using specialized **solar collectors**. This heat can be utilized for a range of applications, including **domestic water heating, space heating, and industrial processes**. Common technologies include **flat-plate collectors**, **evacuated tube collectors**, and **concentrated solar power (CSP)** systems, the latter of which uses mirrors or lenses to focus sunlight onto a receiver to achieve higher temperatures [50].

This study models photovoltaic (PV) systems, which convert sunlight into electricity using silicon-based cells, as the primary energy source for the PV/FC hybrid system. PV efficiency (20.9%, Table 4-3) and solar GHI (Section 4.10.2) are key inputs for simulating energy generation in Ayaber Kewet Woreda [59].

4.4.2. Advantages of Solar Energy

Solar energy offers numerous advantages, making it one of the most promising alternatives to conventional fossil fuels:

- **Abundant and Renewable**:
  The sun delivers a vast and continuous supply of energy, rendering solar power an **inexhaustible resource** available in most regions of the world.
- **Environmentally Friendly**:
  Solar energy systems produce **no greenhouse gas emissions** during operation. By displacing fossil fuel use, they contribute significantly to **reducing carbon emissions** and **mitigating climate change**.
- **Low Maintenance and High Reliability**:
  Once installed, solar power systems typically require **minimal maintenance** and offer **long operational lifespans**, enhancing their **cost-effectiveness** and making them suitable for both residential and off-grid rural applications [51].

4.5. Challenges and Future Outlook

Despite its compelling benefits, solar energy adoption faces several notable challenges:

- **Intermittency**:
  Solar power generation is inherently **weather- and daylight-dependent**, leading to fluctuations in energy output. This intermittency necessitates the integration of **reliable energy storage systems** to ensure a continuous energy supply during cloudy days or nighttime.
- **Storage Requirements**:
  Efficient and affordable **energy storage technologies**, particularly advanced batteries and hydrogen storage solutions, are crucial for enhancing the stability and reliability of solar-powered systems.

4.6. Future Outlook

Despite these challenges, solar energy continues to demonstrate **immense potential** in shaping a **sustainable and resilient energy future**. Its integration spans diverse applications—from rural electrification and urban energy systems to industrial operations and utility-scale power generation. Increasing investment by **governments, private sectors, and development agencies** underscores a global recognition of solar power’s vital role in advancing **energy security**, **economic development**, and the **transition to a low-carbon economy**.

4.7. Fuel cell and their functions

Fuel cells are devices that generate electricity through a chemical reaction, rather than combustion. They do this by converting the chemical energy in fuels directly into electrical energy, which makes them highly efficient and low in emissions. This makes them a promising, clean alternative to traditional power generation methods.

Each fuel cell has three main parts: an electrolyte, an anode, and a cathode. The electrolyte allows ions to move through it, while the anode and cathode are where the key reactions happen. There are several types of fuel cells, including Proton Exchange Membrane (PEM) fuel cells, Solid Oxide Fuel Cells (SOFC), and Direct Methanol Fuel Cells (DMFC). Each one works a bit differently.

In a PEM fuel cell, hydrogen gas is fed into the anode. There, it’s split into protons and electrons. The protons pass through a special membrane to reach the cathode, while the electrons travel through an external circuit—producing electricity. At the cathode, oxygen from the air combines with the protons and electrons, creating water as a byproduct.

SOFCs, on the other hand, run at high temperatures and can use different types of fuel like hydrogen or natural gas. The fuel is supplied to the anode, where it's broken down, releasing hydrogen ions and electrons. The ions pass through a solid ceramic electrolyte to the cathode, while the electrons travel through a circuit to generate power. At the cathode, the ions and electrons meet oxygen and produce water.

DMFCs work a bit differently by using methanol directly as fuel, so there's no need for an external converter. Methanol is sent to the anode, where it's oxidized to produce carbon dioxide, protons, and electrons. The protons go through a polymer membrane, and the electrons power a circuit. At the cathode, oxygen joins with the protons and electrons to make water.

Fuel cells have many benefits. They're efficient because they don't burn fuel, which means fewer emissions. They also run quietly and can keep producing electricity as long as they have fuel [52]. But there are still some challenges. These include high costs, durability issues, and the need for sustainable fuel sources. Building up the infrastructure for hydrogen production and supply is also a big hurdle [53].

Still, fuel cells show a lot of potential as a clean, efficient way to generate power. With ongoing improvements and wider use, they could play a major role in reducing greenhouse gas emissions and supporting a more sustainable energy future.

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4.8. Performance of Fuel Cell

The maximum electrical work (W_{el}) obtained in a fuel cell operating at a constant temperature and pressure is given by the change in gibbs fre energy (ΔG) of the electrochemical reaction:

$$W_{el} = \Delta G$$

(4.1)

Where,

- 'n' is the number of electrons participating in the reaction
- F is the Faraday's constant and
- E is the ideal potential of the cell, also called the Nernst potential.

The Nernst equation describes how the ideal standard potential (E°) of a fuel cell changes under non-standard conditions. It shows how the actual cell potential (E) is affected by the concentrations or partial pressures of the reactants and products [54]. In simple terms, it helps predict how changes in the operating environment—like pressure or concentration—can influence the voltage output of the cell.

Generally, for an electrochemical cell:

- The cell potential goes up when the pressure of the reactants increases.
- The cell potential goes down when the pressure of the products increases.

This is especially important in hydrogen fuel cells. For example, increasing the pressure of the hydrogen and oxygen used in the fuel cell can boost the cell's voltage. Research has shown that fuel cells often perform better at higher operating pressures because of this pressure effect.

Under standard conditions (298 K), the ideal cell potential for a hydrogen fuel cell—where hydrogen and oxygen react to produce water—is:

- 1.229 volts if the water produced is in liquid form.
- 1.18 volts if the water is in the form of steam.

The difference between these two values (1.229 V − 1.18 V = 0.049 V) reflects the extra energy required to turn water into steam. That energy comes from the cell, lowering its voltage and efficiency when steam is the product.

In short, the Nernst equation helps explain how pressure changes affect fuel cell performance and connects the cell’s voltage to thermodynamic concepts like Gibbs free energy as shown in Figure 4- 2 H2/O2 Fuel Cell Ideal Potential as a Function of Temperature [54].

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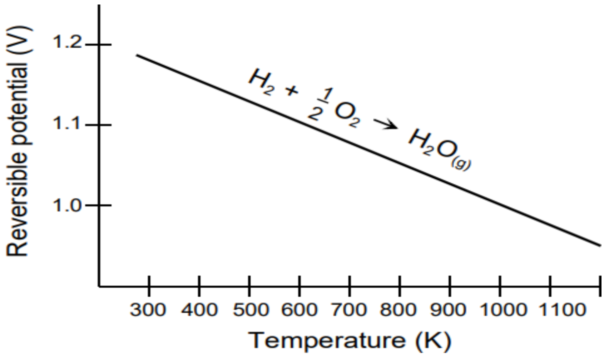

Figure 4- 2 H2/O2 Fuel Cell Ideal Potential as a Function of Temperature [54]

4.8.1. Cell Efficiency

The thermal efficiency of a fuel conversion device is defined as the amount of useful energy produced relative to the change in enthalpy, ΔH, between the product and feed streams.

$$\eta = \frac{Useful\ Energy}{\Delta H} \tag{4.2}$$

Traditionally, when we generate electricity from fuel, it goes through several steps—first, the chemical energy in the fuel is turned into heat, then that heat is used to produce mechanical energy, which is finally converted into electricity. This process usually involves a heat engine. However, as Carnot explained, the efficiency of such engines is limited by the temperatures at which they absorb and release heat.

Fuel cells work differently. Instead of going through all those steps, they convert chemical energy straight into electricity through an electrochemical reaction. In an ideal case, like in a perfectly efficient fuel cell, the amount of usable electrical energy we can get is determined by the change in what's called Gibbs free energy (ΔG) during the reaction—essentially, the energy available to do useful work at that specific temperature.

This ratio represents the maximum possible efficiency, assuming no energy losses. It highlights how fuel cells can, in theory, achieve higher efficiencies than conventional heat engines by skipping the intermediate steps and directly producing electricity from chemical energy.

$$\eta_{ideal} = \frac{\Delta G}{\Delta H} \tag{4.3}$$

The most widely used efficiency of a fuel cell is based on the change in the standard free energy for the cell reaction

$$H_2 + \frac{1}{2} O_2 \rightarrow H_2 0_{(1)} \tag{4.4}$$

Given by

$$\Delta G_0 = G_0,H_2O(l) - G_0,H_2 - \frac{1}{2} G_0,O_2 \tag{4.5}$$

Where:

- **ΔG_0**: Standard Gibbs free energy change (kJ/mol) for the fuel cell reaction.
- **$G_0,H_2O(l)$**: Standard Gibbs free energy of liquid water (kJ/mol).
- **G_0,H_2**: Standard Gibbs free energy of hydrogen gas (kJ/mol).
- **G_0,O_2**: Standard Gibbs free energy of oxygen gas (kJ/mol).

This equation calculates the standard Gibbs free energy change for the hydrogen fuel cell reaction ($H_2 + \frac{1}{2}O_2 \rightarrow H_2O(l)$), which determines the maximum electrical work available (Equation 4.1: W_el = ΔG). In the HOMER Pro simulation, ΔG_0 is used to estimate the ideal cell potential (via $\Delta G = -nFE$), guiding the modeling of the fuel cell's theoretical efficiency. This ensures the simulation accurately predicts the energy output for meeting Ayaber Kewet Woreda's electricity demand, supporting the study's objective of assessing technical feasibility.

When the water produced in the fuel cell is in liquid form, the system operates more efficiently.

However, in gas-fueled fuel cells, as fuel utilization increases, the activity—or availability—of the reactants decreases. Since the cell voltage can never exceed the lowest local potential within the cell, this drop in reactant activity imposes an additional limitation on efficiency. This relationship is illustrated in Figure 4- 3 Effect of fuel utilizaton on voltage efficiency and overall cell efficiency [54], showing how higher utilization can actually lead to lower overall cell performance.

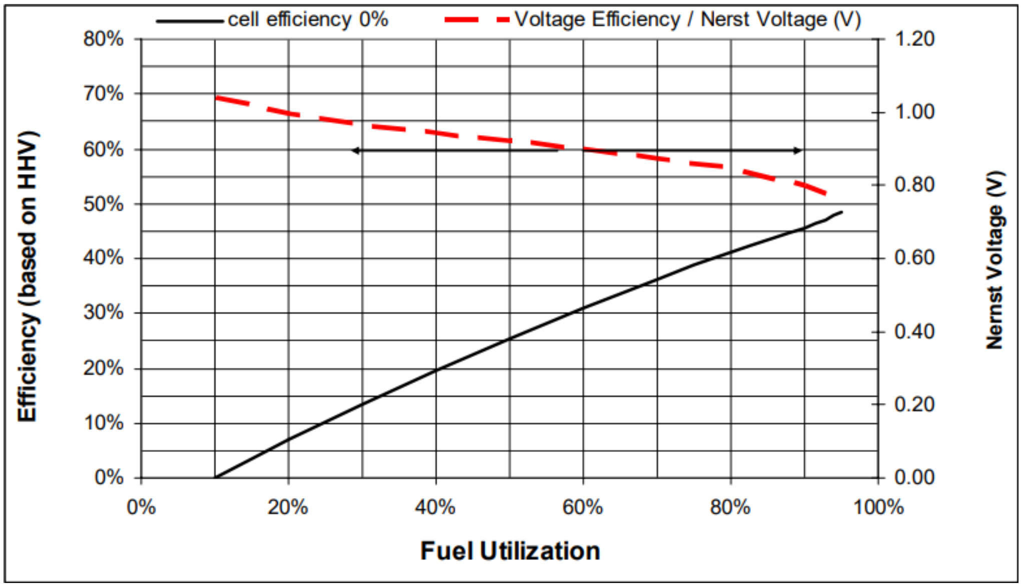

Figure 4- 3 Effect of fuel utilizaton on voltage efficiency and overall cell efficiency [54]

4.8.2. Energy and Exergy Analysis of PEMFC

In a Proton Exchange Membrane Fuel Cell (PEMFC), also known as a Polymer Electrolyte Membrane Fuel Cell, pure hydrogen is supplied to the anode side of the cell. There, it comes into contact with a thin plastic membrane coated with a platinum-based catalyst. This catalyst helps split the hydrogen molecules into protons (hydrogen ions) and electrons.

The electrons are directed through an external circuit, generating electricity, before reaching the cathode side of the fuel cell to complete the electrical loop. Meanwhile, the protons travel through the proton exchange membrane to the cathode. On the cathode side, oxygen is introduced, where it reacts with the incoming protons and electrons to form water—specifically, high-purity water (99.9%)—along with heat as a byproduct.

4.8.3. Electro-Chemical analysis of PEMFC

The electro-chemical reactions inside the PEMFC can be expressed as follows:

$$A(A): H_2 \rightarrow 2H^{+} + 2e^{-}9 \tag{4.6}$$

$$Cath(C): 2H^{+} + 2e^{-} + -O_2\tfrac{1}{2}\rightarrow H_2O + Heat \tag{4.7}$$

Where:

- **H^+**: Protons (hydrogen ions) from the anode reaction.
- **e^-**: Electrons traveling through the external circuit.
- **O_2**: Oxygen gas supplied to the cathode.
- **H_2O**: Liquid water produced as a byproduct.
- **Heat**: Thermal energy released during the reaction.

This equation (4.7) describes the electrochemical reaction at the cathode of a Proton Exchange Membrane Fuel Cell (PEMFC), where protons, electrons, and oxygen combine to produce water and heat. In the HOMER Pro simulation, this reaction is critical for modeling the fuel cell's electricity generation process, as it determines the power output (Equation 4.14: P = V * I) when solar PV input is unavailable (e.g., at night). This supports the study's goal of designing a reliable energy system for rural electrification in Ayaber Kewet Woreda.

$$Overall: H_2 + \frac{1}{2} O_2 \rightarrow 2H_{2O} \tag{4.8}$$

To calculate the molar fractions of hydrogen and oxygen at anode and cathode respectively:

$$X_{H_2} = (\frac{1}{1+X_4*(1+\xi_A)*(\frac{2}{\xi_{A-1})}} \tag{4.9}$$

And

$$X_{O_2} = \frac{1-X_{H_2O,C}}{1+\left(\frac{X_C}{2}\right)*\xi_C} \tag{4.10}$$

Water molar fractions at anode and cathode can be calculated using saturations pressure P_{sat} As follows:

$$X_{H_2O,} = \frac{P_{sat}}{P_A} \tag{4.11}$$

And

$$X_{H_2}o,c = \frac{P_{sat}}{P_C} \tag{4.12}$$

Further, P_{sat} of fuel cell based of hydrogen temperature can be obtained as:

$$P_{sat} = 10^{(-2.179+0.02953*T-9.1837*10^{-5}*T^2+1.4454*10^{-7}*T3)} \tag{4.13}$$

The electrical power is known as follows:

$$P = V * I \tag{4.14}$$

$$P_{PEMFC} = V_{PEMFC} * j \tag{4.15}$$

Here, V_{PEMFC} is the input voltage and j is the current density. To avoid the effect of area, j is represented as follows:

$$j = \frac{I}{A} \tag{4.16}$$

The overall PEMFC voltage can be expresses as difference of reversible and irreversible cell voltage.

$$V_{PEMFC} = V_{rev} - V_{irrev} \tag{4.17}$$

4.8.4. PEMFC thermal modeling

The total energy in PEMFC can be calculated as following:

$$\Delta H = \Delta G + T\Delta S \tag{4.18}$$

Here, ΔG and $T\Delta S$ are the electric energy (change of Gibb's free energy) and thermal energy demand, respectively. The values of G, H and S of corresponding H_2, O_2, and H_2O can be taken from JANAF thermochemical tables[55].

The energy efficiency of PEMFC system can be formulated using the following relations[56].

$$\eta_{en}, PEMFC = \frac{HHV_{H_2} * n_{H_2}}{Q_{elec} + Q_{heat'} + Q_{heat.H2O}} \tag{4.19}$$

Where, HHV_{H2} and n_{H2} high heating value and molar flow rate of H_2, respectively. The Q_{elec} and $Q_{heat,PEM}$ are the rate of input of electric and thermal energy, respectively. The Qheat, H2O is the rate of input thermal energy for heating the water. The Q_{elec}, $Q_{heat,PEM}$ and $Q_{heat,H2O}$ can be obtained as follows:

$$Q_{elec} = P_{pemfc} = V_{pemfc,}stack * j \tag{4.20}$$

$$Q_{heat,H_2o} = (\frac{j}{(2F)(H_{H_2O,T} - H_{H_2O,T0})} \tag{4.21}$$

Here, H^T $and\ H^{T_o}$ are the enthalpies of water at temperature T and T_o, respectively:

$$Q_{heat,PEM} = (\frac{j}{(2*F)} * (T \triangle S - S_g) \tag{4.22}$$

Here, S_g is the entropy generation due to irreversibility or over potentials. It can be formulated as [57]:

$$S_g = n_eF(V_{irrev}) = n_eF(\eta_{act} + \eta_{ohm} + \eta_{conc}) \tag{4.23}$$

The total exergy of PEMFC can be calculated by the following exergy balance[56]:

$$Ex_{in} = Ex_{out} + Ex_{loss} \tag{4.24}$$

$$Ex_{loss} = Ex_{dis} + Ex_{des} \tag{4.25}$$

Here, Ex_{in} and Ex_{out} are representing the exergy rate of in and out, respectively. While Ex_{dis} and Ex_{des} are the exergy dissipation (exergy of stream transfer towards the environment) and exergy destruction (due to irreversibility's), respectively. The exergy efficiency PEMFC can be represented by given relation:

$$\eta_{ex,PEMFC} = \frac{Ex_{out}}{Ex_{in}} \tag{4.26}$$

Here,

$$\frac{Ex_{out}}{Ex_{in}} = \frac{Ex_{H_2} * n_{H_2}}{(Ex_{elec} + Ex_{heat,PEM} + Ex_{heat,H_20})} \tag{4.27}$$

$$Ex_{elec} = P_{P,k} = V_{PEMFC,Stack} * j \tag{4.28}$$

Where, T_o and T_{FC} are temperature of reference environment and fuel cell, respectively:

$$Ex_{heat,H_2O} = Q_{heat,H_2O} * (1 - \frac{T_0}{T_{source}}) \quad (4.29)$$

Here, T_{source} is the temperature of the heat source.

The Ex_{H2} is exergy of the hydrogen and it can be calculated as following, neglecting the kinetic and potential exergies terms:

$$Ex_{H_2} = (Ex_{ch} + Ex_{ph})_{2} \quad (4.30)$$

The physical and chemical exergies can be formulated by[56]:

$$Ex_{ph,H_2} = c_p * T_0 * [(\frac{T_{H_2}}{T_0} - 1 - \ln\left(\frac{T_{H_2}}{T_0}\right) + \left(\frac{k-1}{k}\right) * \ln(\frac{P_{H_2}}{P_0}) \quad (4.31)$$

And

$$Ex_{ch,_2} = \Sigma x_{H_2} E_{xo,ch,H_2} + R_{H_2} T_o \Sigma x_{H_2} ln x_{H_2} \quad (4.32)$$

Where, c_p is specific heat of H_2, R_{H2} is the gas constant of H_2, T_{H2} and P_{H2} are the outlet temperature and pressure of H_2, respectively, k is adiabatic constant, and $E_{xo,ch,H2}$ is the standard chemical exergy of H_2.

4.9. Integration of Solar and Fuel Cell Technologies

By combining solar and fuel cell technologies, we can overcome the limitations of each system and create a more efficient and reliable energy solution. One common approach is to integrate photovoltaic (PV) panels with fuel cells in a hybrid system. During the day, PV panels capture solar energy and generate electricity, which can either be used immediately or stored in batteries for later. Any excess electricity can also be used to produce hydrogen through electrolysis. This hydrogen is then stored and later used by fuel cells to generate electricity when solar power is unavailable—like at night or on cloudy days.

This type of integration brings several advantages. First, it allows for better use of solar energy by storing excess power as hydrogen, helping to ensure a consistent electricity supply even when sunlight isn't available. Second, it boosts overall system efficiency by making use of the waste heat produced by fuel cells for heating purposes, such as warming spaces or water. Third, it supports decentralized power generation and reduces dependence on the grid, which is especially valuable in remote or off-grid areas.

Solar-fuel cell hybrid systems can be applied in many sectors. In homes and businesses, they provide reliable electricity, heating, and hot water, while reducing reliance on fossil fuels and cutting carbon emissions. In transportation, they allow fuel cells to power electric vehicles, extending driving range and reducing the need for frequent charging. These systems can also power unmanned aerial vehicles (UAVs), increasing flight duration and energy efficiency.

However, there are still challenges to address. The cost of PV panels, fuel cell systems, and hydrogen storage can be high, raising concerns about economic feasibility. Further technological development and standardization are also needed to ensure that the different components of these systems can work together seamlessly.

In summary, integrating solar and fuel cell technologies offers a promising path toward more sustainable energy systems. By combining solar's renewable but intermittent nature with the steady, dependable output of fuel cells, we can create cleaner, more reliable, and more efficient energy solutions for the future.

4.10. Homer Pro Simulation

4.10.1. System Requirements

The average per capita energy consumption in Ethiopia is approximately 79.25 kWh per year, which translates to about 0.2168 kWh—or 216.8 watt-hours—per day [46]. Based on the estimated population of Ayaber Kewet Woreda, which is around 163,122 people, the total daily energy consumption is estimated to be approximately 33,364.84 kWh. This figure will be used as the daily load in our simulation.

Several constraints will be applied during the simulation process:

- A constant daily power load will be used, as actual metering or billing data is not available.
- A 100% minimum renewable energy requirement will be enforced, meaning the system must rely entirely on renewable sources for energy generation.

- A maximum annual capacity shortage of 20% will be allowed, ensuring that any power shortfalls remain within this limit.

For geographical input in HOMER Pro, the location of Ayaber Kewet will be manually specified by entering the name directly into the platform as shown in Figure 4- 4 Geographic location of kewet on homer pro.

2Q3C+Q5 Mengist, Ethiopia (10°0.3'N , 39°46.2'E)

Ayaber

(UTC+03:00) Nairobi

Figure 4- 4 Geographic location of kewet on homer pro

Since we don't have actual data of hourly load profile of Ayaber Kewet region, this study will assume to take a scaled load profile of 33,364.84 kWh per day for all days, weeks, months and year for the daytime as shown in Figure 4- 5 Load Profile.

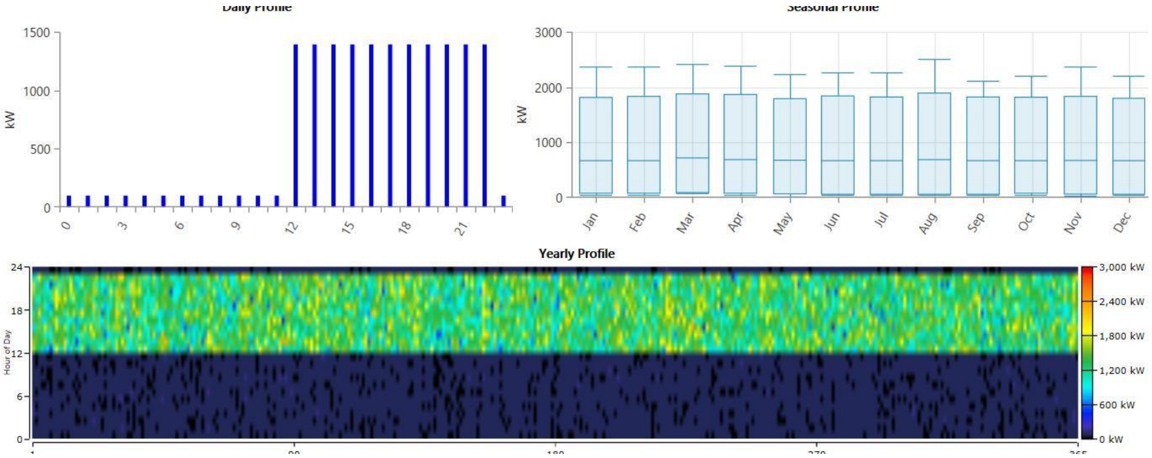

Figure 4- 5 Load Profile

4.10.2. Solar Data

The monthly average solar global horizontal irradiance (GHI) data as shown in Figure 4- 6 Solar GHI resource, can be obtained from Homer Pro by downloading the NASA prediction of Worldwide Energy Resource

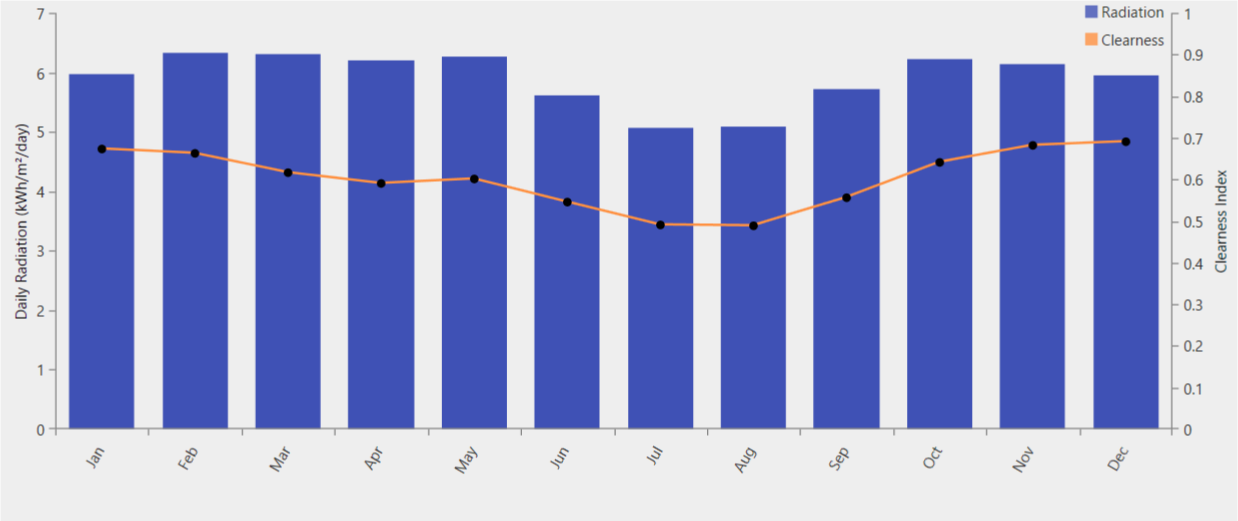

Figure 4- 6 Solar GHI resource

4.10.3. Project economics

Homer Pro requires economic parameter input that impact the net present value and levelized energy cost as shown on Table 4- 1 . These parameters are the nominal discount rate, the expected inflation rate, and the project's lifetime. These parameters are used in the formula to identify the real discount rate.

$$i = \frac{i_n - f}{1+f} \qquad (4.33)$$

Where

- i real discount rate [%]
- i_n nominal discount rate [%]
- f inflation rate [%]

Table 4- 1 Project Economics

Parameter	**Value**
Nominal discount rate (%)	3.5%
Expected inflation rate (%)	28.2%

4.10.4. Constraints

In order to assess the viability of the project it is mandatory to input constraints to get a result that efficiently resembles the desired outcome.

Table 4- 2 Constraints

Constraints	**Value**
Minimum renewable fraction	100%

The minimum renewable fraction is set to 100% as this project is aimed to electrify the rural region with a 100% renewable power source.

4.10.5. System Schematics

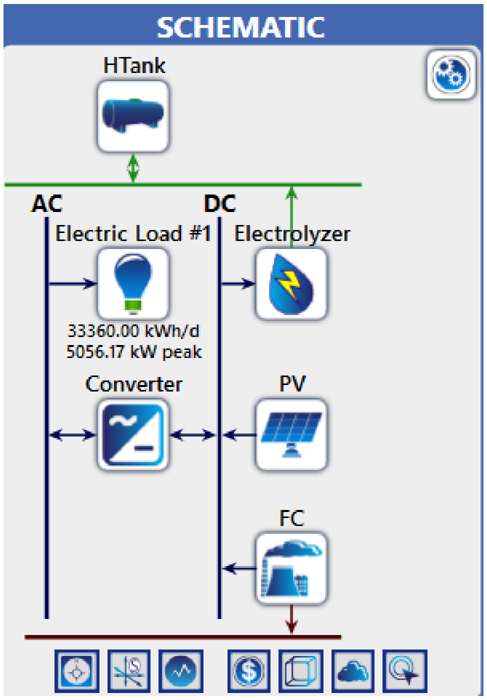

Figure 4- 7 System Schematics

As shown in Figure 4- 7 System Schematics, the electrolyzer, photovoltaic (PV) system, and fuel cell all operate on **DC (direct current)** power. However, since the electric load in this setup requires **AC (alternating current)**, a converter is necessary to bridge the two.

In this study, **AC power is preferred over DC** for long-distance transmission, and for good reason. AC systems offer several key advantages: they allow for efficient transformation of voltage levels using transformers, which helps minimize resistive losses during transmission. Voltage control is also easier with AC, enabling power to be transmitted at high voltages and then stepped down as needed for local distribution. Additionally, AC equipment—such as transformers and circuit breakers—is generally **more cost-effective**, **widely available**, and **compatible with most electrical appliances**, making it a practical choice that fits well with existing infrastructure.

4.10.6. System Input Parameters

Table 4- 3 System Input Parameters

System	Parameter	Value	Reference
PV	Capital cost ($/kW) installed	560	[58]
	O&M cost ($/kW/year)	8.405	[58]
	Replacement cost ($/kW)	560	[58]
	Lifetime (years)	25	[59]
	Efficiency (%)	20.9	[59]
	Temperature coefficient	-0.47%/^{0}C	[59]
Electrolyzer	Capital cost ($/kW) installed	1405	[60]
	O&M cost ($/kW/year)	6	[61]
	Replacement cost ($/kW)	1405	[60]
	Lifetime (years)	15	[62]
	Efficiency (%)	80	[62]
Hydrogen Storage Tank	Capital cost ($/kW) installed	502	[63]
	O&M cost ($/kW/year)	5	[63]
	Replacement cost ($/kW)	502	[63]
	Lifetime (years)	25	[63]
Fuel Cell	Capital cost ($/kW)	2938.68	[64]

	installed		
	O&M cost ($/kW/year)	43.81	[65]
	Replacement cost ($/kW)	2938.68	[64]
	Lifetime (h)	60,000	[64]
	Efficiency (%)	50	[64]

5. Chapter Five

Results and Discussion

5.1. Chapter Summary

Chapter Five focuses on **data analysis and discussion**. It presents the study’s findings and explains the methods used to analyze them. The discussion section interprets these results, highlighting their relevance to the research questions. This chapter plays a crucial role in showing how the study’s objectives were met and what the findings mean in the broader context of the research.

5.2. Research Findings

The system consists of a photovoltaic array, fuel cell, electrolyzer, hydrogen storage tank, and a converter. It is designed to meet the community’s electrical demands throughout the year. The fuel cell serves as a backup power source, supplying electricity when the photovoltaic system is not generating, such as during nighttime. The optimally sized components of the system are summarized in the table below..

Table 5- 1 System Cost and Production Output

Parameter	**Name**	**Value**	
		Output (kW)	**Total Cost**
System Components	PV	32,805	$27.1M
	Fuel cell	3,000	$9.43M
	Electrolyzer	7,000	$16.8M

	Converter		4,148	$2.04M
	Hydrogen tank		2,000	$1.4M
	System		-	$56.8M
Electrical output	Total Electricity production (kWh/year)	Fuel Cell	4,126,985	
		PV	57,718,083	
Economic parameters	Net present cost		$56.9M	
	Levelized Cost of energy		$0.345/kWh	

Figure Figure 5- 1 System Cost, illustrates the total system cost broken down by component. It highlights that the most expensive elements in the system are the Generic Flat Plate PV system, the Generic Electrolyzer, and the Generic Fuel Cell.

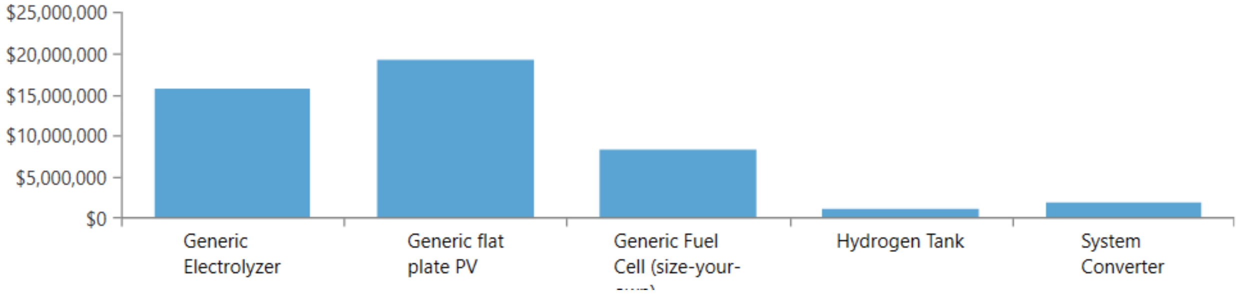

Figure 5- 1 System Cost

The overall annual electricity production of the system is shown in the figure below. The fuel cell contributed approximately 6.67% of the total electricity generated. As illustrated in Figure 5- 2 System monthly electric production, the fuel cell primarily operates during the winter months when solar radiation levels are low. In contrast, during the summer season, the photovoltaic system is generally sufficient to meet the energy demand, reducing the reliance on the fuel cell. Additionally, the fuel cell is mostly utilized during nighttime hours when solar energy is unavailable.

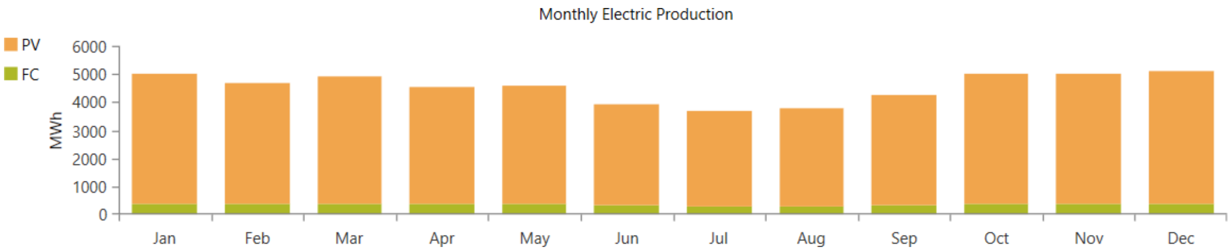

Figure 5- 2 System monthly electric production

Figures Figure 5- 3 Photovoltaic power output and Figure 5- 4 Electrolyzer power input illustrate the hourly output power of the PV module and the hourly input power of the electrolyzer over the course of the year. As shown, the photovoltaic system typically operates between 8:00 AM and 6:00 PM, which aligns with the operating hours of the electrolyzer. This correlation exists because the electrolyzer relies on electricity from the PV system to produce hydrogen, and this process occurs during the same time window. Over the span of one year, the electrolyzer consumed a total of 25,357,066 kWh of electricity to produce 547,427 kilograms of hydrogen. This results in an energy consumption rate of approximately 46.32 kWh for every kilogram of hydrogen produced.

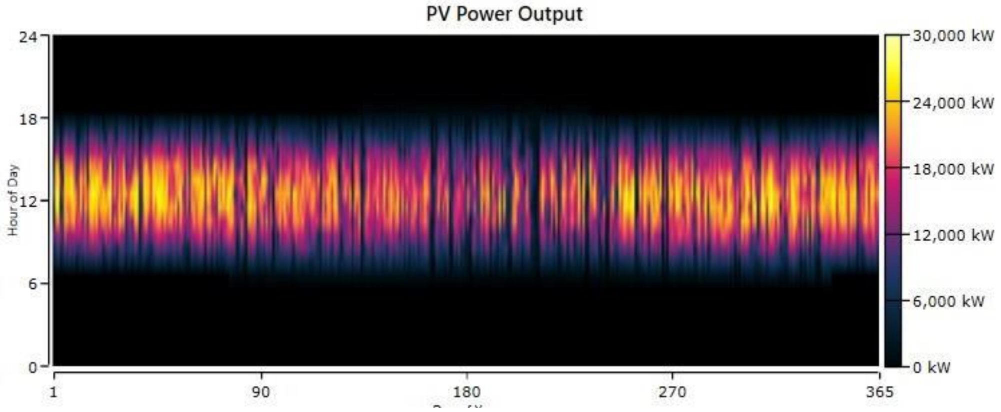

Figure 5- 3 Photovoltaic power output

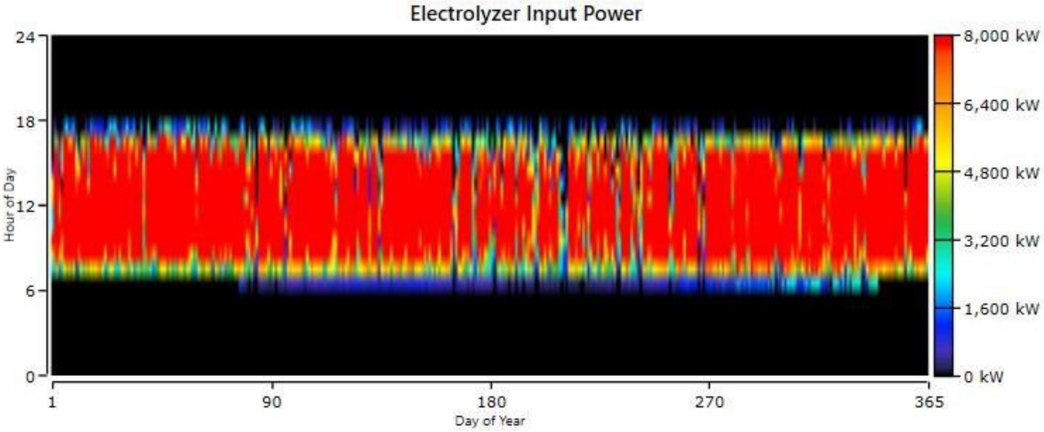

Figure 5- 4 Electrolyzer power input

Figure 5- 5 Fuel Cell generator power output shows that the fuel cell consistently operates at night, when the PV system is inactive due to the absence of sunlight. Since Ethiopia's weather conditions remain relatively stable throughout the year, there isn't a significant variation in the fuel cell's operating pattern

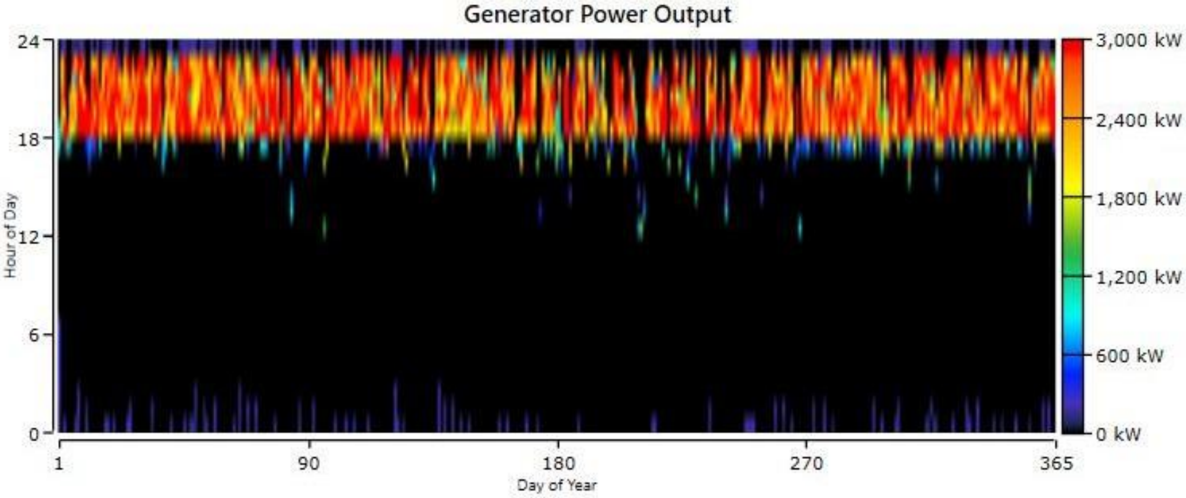

Figure 5- 5 Fuel Cell generator power output

Figure 5- 6 Hydrogen tank level for one year illustrates the hydrogen tank level throughout the year. The amount of hydrogen stored fluctuates from month to month, mainly due to changes in solar irradiance, which affect the PV system's power output and the fuel cell's hydrogen consumption.

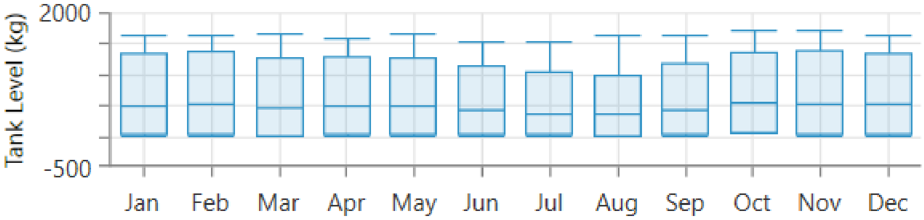

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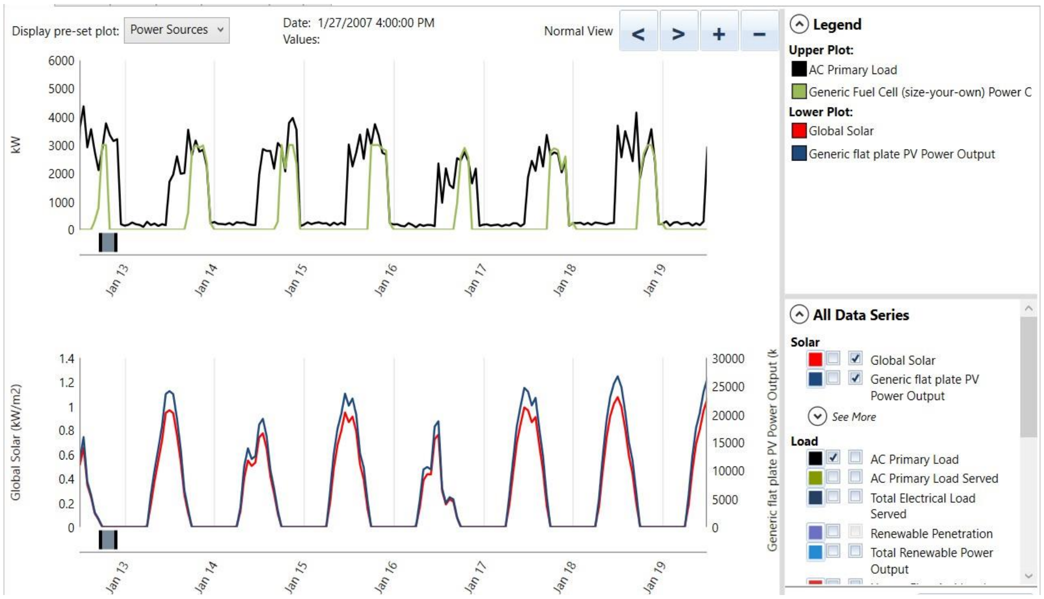
Figure 5- 6 Hydrogen tank level for one year

Figure 5- 7 AC load and system power consumption shows how the system responds to changes in global solar irradiance. The data, taken from a week in January, illustrates that the fuel cell primarily operates at night when the photovoltaic system is unable to meet the electricity demand.



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Values:

Figure 5- 7 AC load and system power consumption

According to the results, PV system has a capacity of 28,581 kW which is equal to 28.58 MW, considering the assumption that a 1kW PV system requires 6 meter square land for installation, the modeled system requires 171,486 meter squared of land. This is approximately 0.0218% of land area of kewet [66].

5.3. Results of sensitivity analysis

Fuel cell technology is still evolving, and future large-scale production is expected to reduce costs by around 50% [24], [64]. Currently, the most expensive components in the system are those involved in green hydrogen production and usage—specifically, the fuel cell and electrolyzer. To better understand how economic factors, including the cost of energy, are affected by potential cost reductions, a sensitivity analysis was conducted focusing on these two components.

The results can be seen shown below.

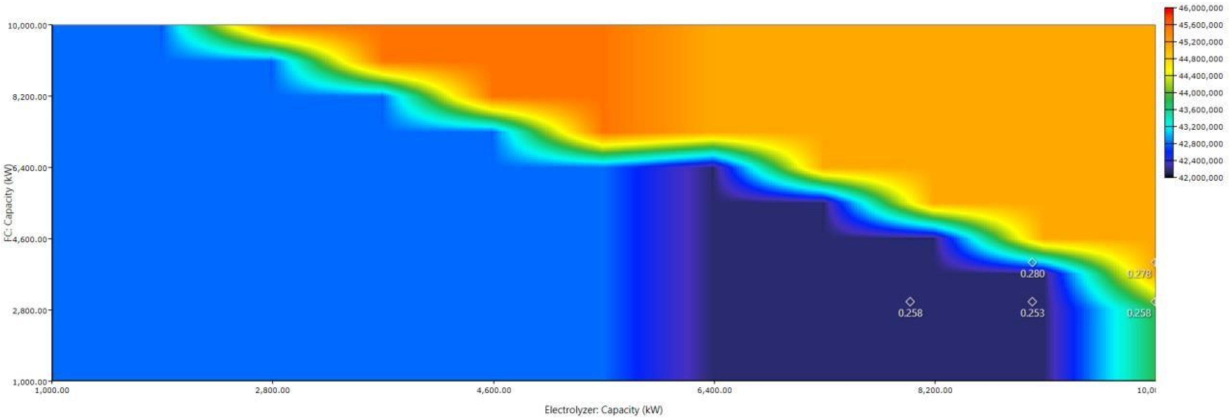

Figure 5- 8 Sensitivity analysis, fuel cell and electrolyzer

As shown on Figure 5- 8 Sensitivity analysis, fuel cell and electrolyzer, the lowest possible value for the cost of energy is 0.25 $/kWh if the capital and replacement cost of the fuel cell and electrolyzer is reduced by 50%.

6. Chapter Six

Conclusion and Recommendations

6.1. Chapter Summary

The sixth and final chapter presents the key findings of the study along with recommendations for future research. It provides a summary of the main results and highlights their relevance to the research objectives. The conclusions drawn are discussed in terms of their broader implications, offering insight into how the study contributes to the existing body of knowledge. This chapter plays a crucial role in underscoring the value of the research and suggesting directions for further investigation.

6.2. Conclusion

Based on the findings of this study, PV-fuel cell hybrid systems show strong potential as a reliable and efficient source of electricity. The system modeled in this research was able to meet the energy demand of Kewet Woreda using 100% renewable energy—without generating any carbon dioxide emissions.

The system included photovoltaic panels, a fuel cell, an electrolyzer, a hydrogen storage tank, and a converter. The primary power source is the PV system, which supplied about 93.3% of the total electricity, while the fuel cell provided the remaining 6.63%. The PV system was intentionally oversized to ensure it could meet both the immediate electricity demand and supply enough energy to the electrolyzer for hydrogen production. In a grid-connected project, this excess energy could potentially be sold to the grid for profit, although that aspect was not considered in this study. The fuel cell primarily operated at night when solar power was unavailable, helping to maintain a steady power supply.

The net present cost (NPC) of the project was estimated at $56.8 million, with a cost of energy (COE) of $0.3451 per kilowatt-hour. However, with anticipated reductions in the costs of fuel cells and electrolyzers—potentially up to 50% in the future [24], [64]—a sensitivity analysis showed that the NPC could drop to $41.6 million and the COE to $0.25 per kilowatt-hour.

Ultimately, this project demonstrates that successfully deploying such a system could improve electricity access in the area by about 0.1%.

6.3. Recommendation

There are several promising research directions that could help improve the efficiency of PV-fuel cell renewable energy systems. One key area is the integration of other renewable sources such as wind turbines, geothermal energy, or hydropower. Using these additional resources to power the electrolyzer could increase hydrogen production and enhance the overall efficiency and reliability of the system.

In this thesis, weather and solar data were obtained using the National Renewable Energy Laboratory (NREL) tool. However, future studies could benefit from comparing different weather datasets or combining multiple sources to get more accurate and comprehensive insights into system performance.

Additionally, since fuel cells generate waste heat during operation, exploring ways to capture and utilize that thermal energy—for example, for heating purposes—could further boost the system's overall efficiency. Simulating systems that incorporate multiple renewable energy sources and make use of all available energy outputs can lead to more sustainable and cost-effective solutions.

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System Simulation Report

File: New_Project_Kewet.homer

Author: Tilahun Nigussie (PhD) and Shalom Abebaw (Msc)

Location: 4XHF+Q3 Jewha, Ethiopia (10°7.8'N, 39°58.4'E)

Total Net Present Cost: $56,895,560.00

Levelized Cost of Energy ($/kWh): $0.345

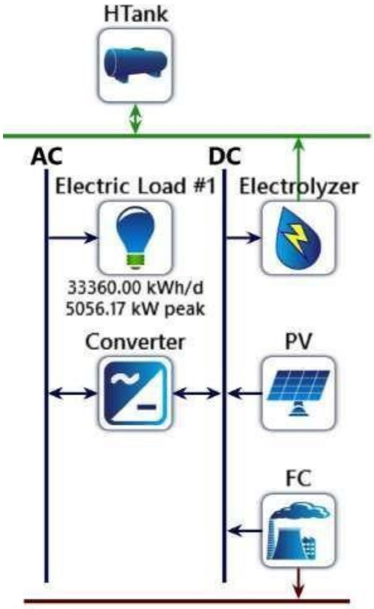
Notes: This project aims to investigate the rural electrification of Ayaber Kewet Woreda using Solar Powered Fuel Cell technology.

Table of Contents

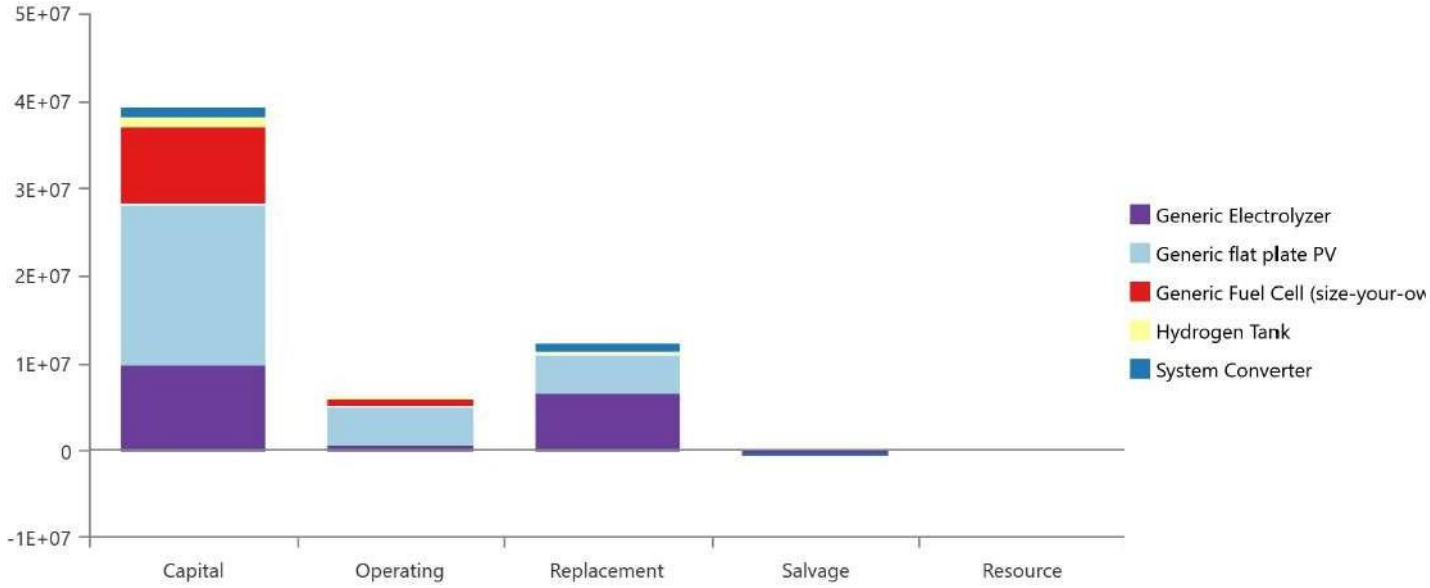
System Architecture

Component	Name	Size	Unit
Generator	Generic Fuel Cell (size-your-own)	3,000	kW
PV	Generic flat plate PV	32,805	kW
System converter	System Converter	4,148	kW
Electrolyzer	Generic Electrolyzer	7,000	kW
Hydrogen tank	Hydrogen Tank	2,000	kg
Dispatch strategy	HOMER Load Following		

Schematic



Cost Summary



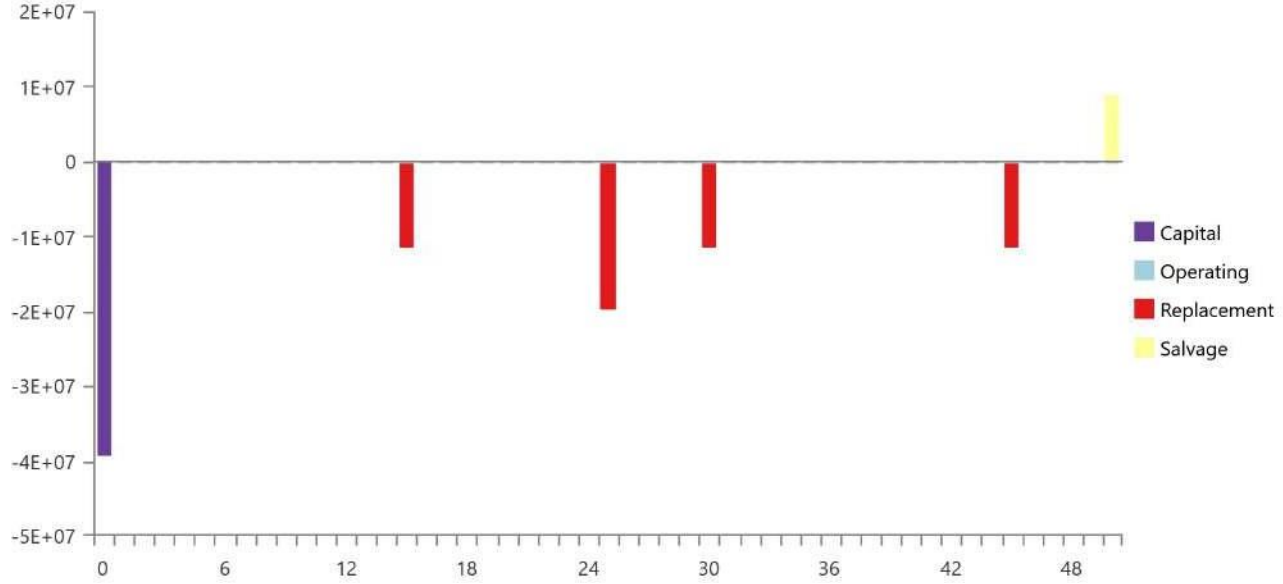
Net Present Costs

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Generic Electrolyzer	$9.84M	$673,025	$6.69M	-$376,274	$0.00	$16.8M
Generic flat plate PV	$18.4M	$4.42M	$4.40M	$0.00	$0.00	$27.2M
Generic Fuel Cell (size-your-own)	$8.82M	$700,427	$0.00	-$85,477	$0.00	$9.43M
Hydrogen Tank	$1.00M	$160,244	$240,516	$0.00	$0.00	$1.40M
System Converter	$1.24M	$0.00	$847,017	-$47,610	$0.00	$2.04M
System	$39.3M	$5.95M	$12.2M	-$509,360	$0.00	$56.9M

Annualized Costs

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Generic Electrolyzer	$613,751	$42,000	$417,753	-$23,481	$0.00	$1.05M
Generic flat plate PV	$1.15M	$275,726	$274,635	$0.00	$0.00	$1.70M
Generic Fuel Cell (size-your-own)	$550,163	$43,710	$0.00	-$5,334	$0.00	$588,539
Hydrogen Tank	$62,654	$10,000	$15,009	$0.00	$0.00	$87,664
System Converter	$77,657	$0.00	$52,858	-$2,971	$0.00	$127,544
System	$2.45M	$371,436	$760,255	-$31,787	$0.00	$3.55M

Cash Flow



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-3E+07
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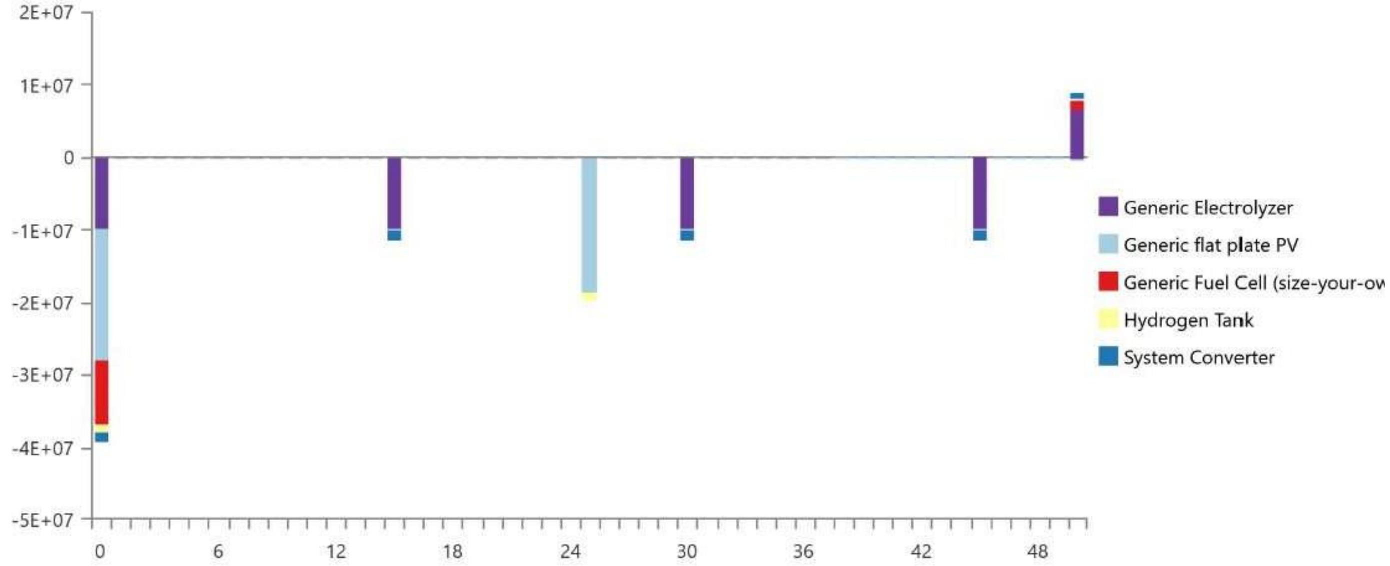
Capital
Operating
Replacement
Salvage



2E+07
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18
24
30
36
42
48
Generic Electrolyzer
Generic flat plate PV
Generic Fuel Cell (size-your-ow
Hydrogen Tank
System Converter

Electrical Summary

Excess and Unmet

Quantity	Value	Units
Excess Electricity	27,253,332	kWh/yr
Unmet Electric Load	1,871,066	kWh/yr
Capacity Shortage	2,445,159	kWh/yr

Production Summary

Component	Production (kWh/yr)	Percent
Generic flat plate PV	57,718,083	93.3
Generic Fuel Cell (size-your-own)	4,126,985	6.67
Total	61,845,068	100

Consumption Summary

Component	Consumption (kWh/yr)	Percent
AC Primary Load	10,305,334	30.3
DC Primary Load	0	0
Deferrable Load	0	0
Total	34,049,350	100

Generator: Generic Fuel Cell (size-your-own) (Stored Hydrogen)

Generic Fuel Cell (size-your-own) Electrical Summary

Quantity	Value	Units
Electrical Production	4,126,985	kWh/yr
Mean Electrical Output	1,416	kW
Minimum Electrical Output	0.979	kW
Maximum Electrical Output	3,000	kW
Thermal Production	7,777,146	kWh/yr
Mean thermal output	2,669	kW
Min. thermal output	2,180	kW
Max. thermal output	3,216	kW

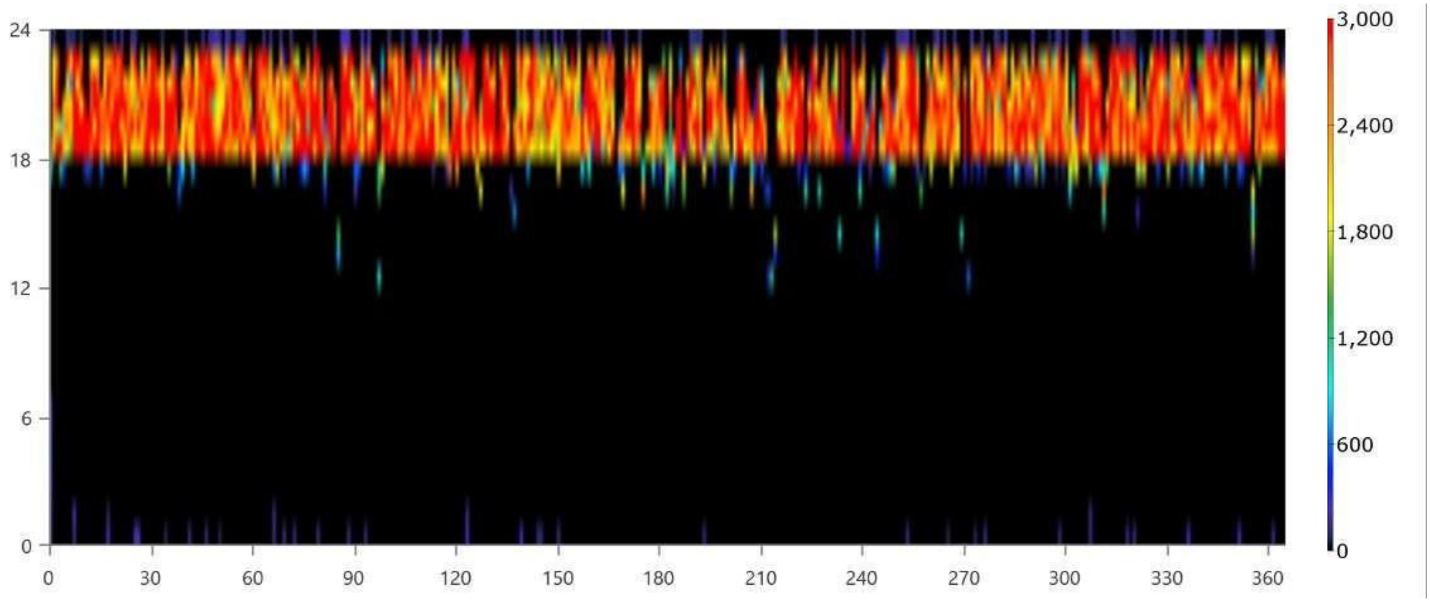
Generic Fuel Cell (size-your-own) Fuel Summary

Quantity	Value	Units
Fuel Consumption	512,667	kg
Specific Fuel Consumption	0.124	kg/kWh
Fuel Energy Input	17,088,894	kWh/yr
Mean Electrical Efficiency	24.2	%

Generic Fuel Cell (size-your-own) Statistics

Quantity	Value	Units
Hours of Operation	2,914	hrs/yr
Number of Starts	425	starts/yr
Operational Life	60.2	yr
Capacity Factor	15.7	%
Fixed Generation Cost	65.3	$/hr
Marginal Generation Cost	0	$/kWh

Generic Fuel Cell (size-your-own) Output (kW)



PV: Generic flat plate PV

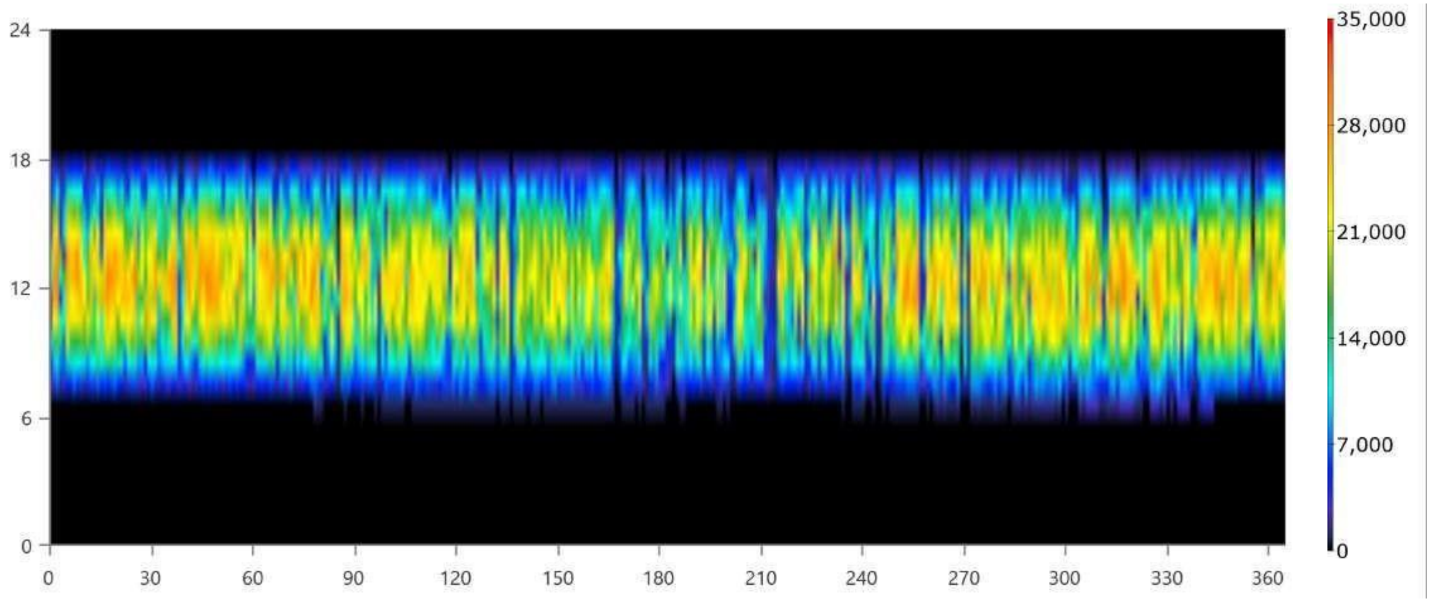
Generic flat plate PV Electrical Summary

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	31,523	kW
PV Penetration	474	%
Hours of Operation	4,384	hrs/yr
Levelized Cost	0.0294	$/kWh

Generic flat plate PV Statistics

Quantity	Value	Units
Rated Capacity	32,805	kW
Mean Output	6,589	kW
Mean Output	158,132	kWh/d
Capacity Factor	20.1	%
Total Production	57,718,083	kWh/yr

Generic flat plate PV Output (kW)



Converter: System Converter

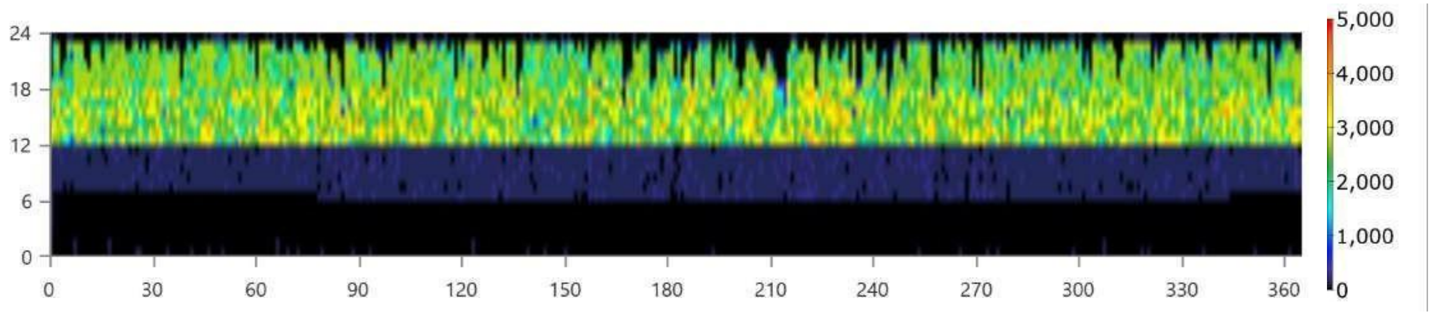
System Converter Electrical Summary

Quantity	Value	Units
Hours of Operation	5,969	hrs/yr
Energy Out	10,305,334	kWh/yr
Energy In	10,847,720	kWh/yr
Losses	542,386	kWh/yr

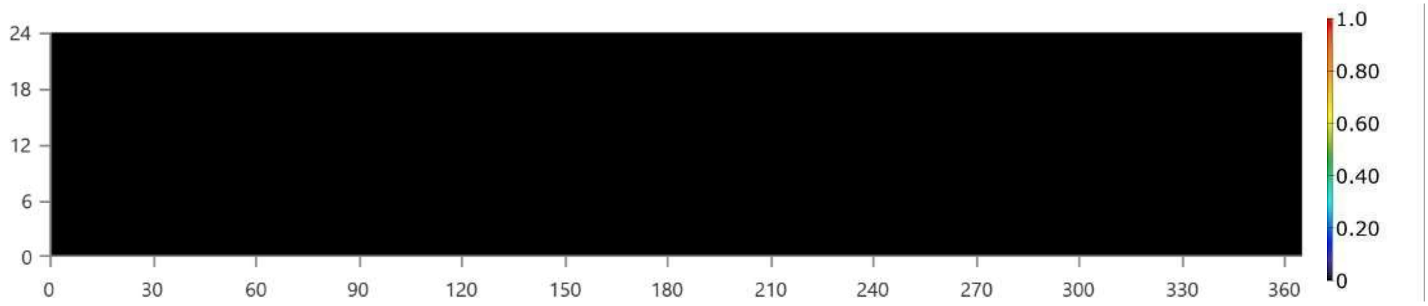
System Converter Statistics

Quantity	Value	Units
Capacity	4,148	kW
Mean Output	1,176	kW
Minimum Output	0	kW
Maximum Output	4,148	kW
Capacity Factor	28.4	%

System Converter Inverter Output (kW)



System Converter Rectifier Output (kW)



Electrolyzer: Generic Electrolyzer

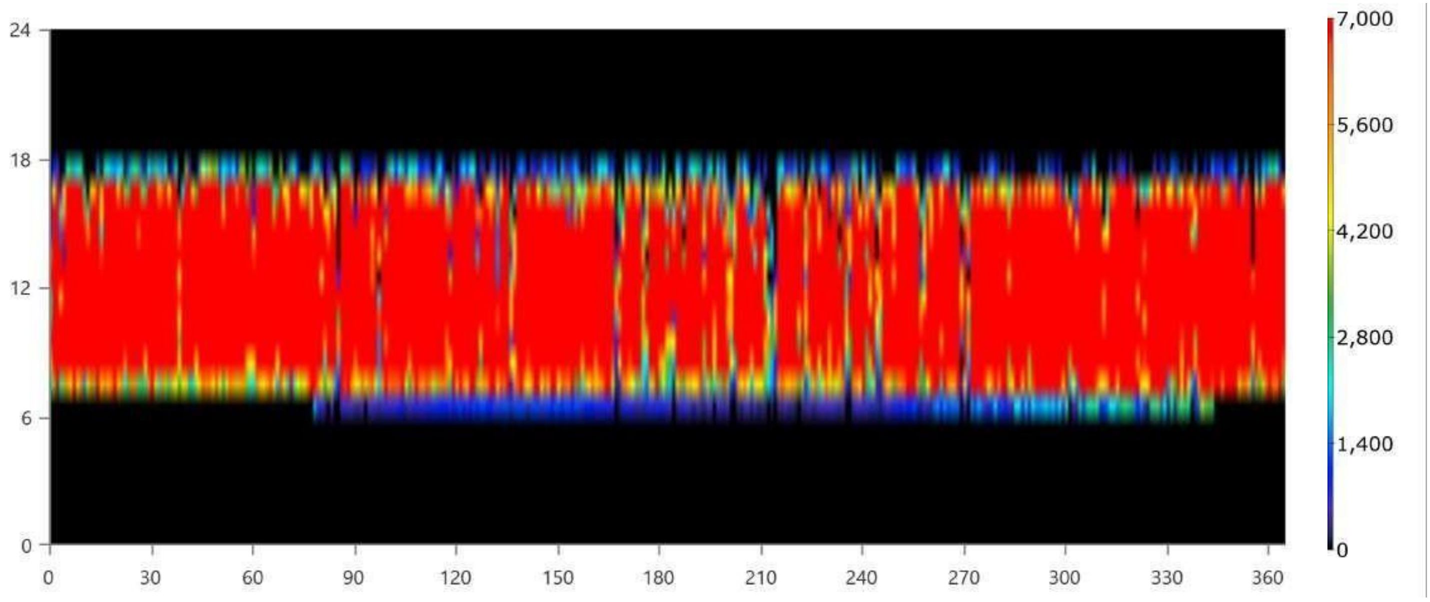
Summary

Quantity	Value	Units
Mean output	58.4	kg/hr
Minimum Output	0	kg/hr
Maximum Output	151	kg/hr
Total production	511,667	kg/yr
Specific consumption	46.4	kWh/kg

Statistics

Quantity	Value	Units
Rated capacity	7,000	kW
Mean input	2,711	kW
Minimum input	0	kW
Maximum input	7,000	kW
Total input energy	23,744,017	kWh/yr
Capacity Factor	38.7	%
Hours of operation	4,120	hr/yr

Generic Electrolyzer Input Power (kW)



Hydrogen Tank: Hydrogen Tank

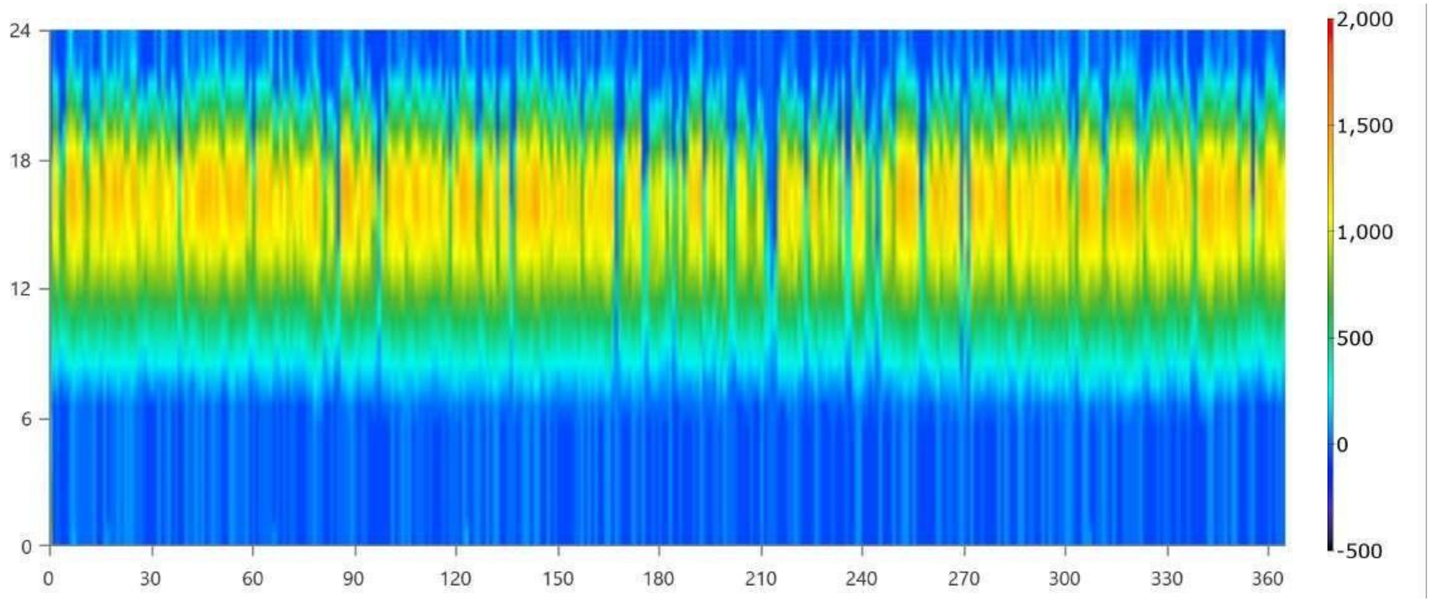
Properties

Quantity	Value	Units
Hydrogen storage capacity	2,000	kg
Energy storage capacity	66,667	kWh
Tank autonomy	48.0	hr

Statistics

Quantity	Value	Units
Content at beginning of year	1,000	kg
Content at end of year	0	kg

Hydrogen Tank Level (kg)

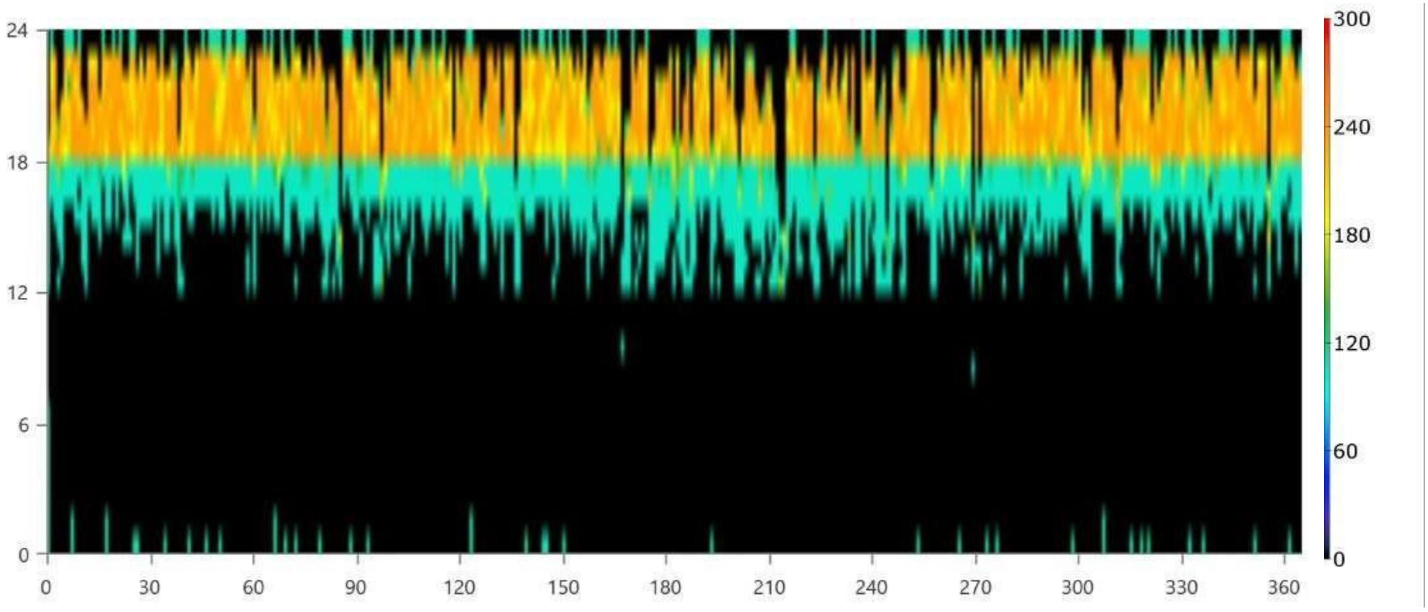


Fuel Summary

Stored Hydrogen Consumption Statistics

Quantity	Value	Units
Total fuel consumed	512,667	kg
Avg fuel per day	1,405	kg/day
Avg fuel per hour	58.5	kg/hour

Stored Hydrogen Consumption (kg/hr)



Emissions

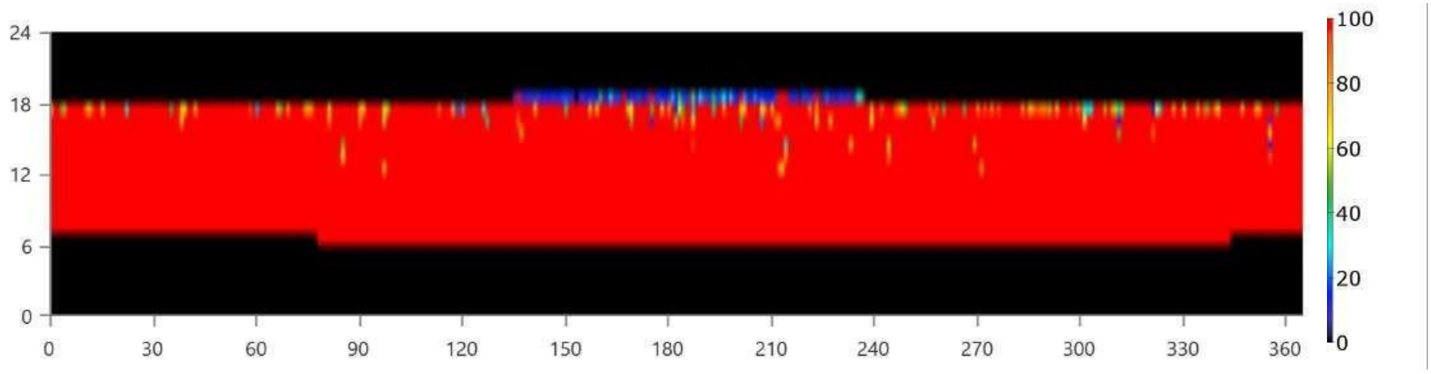
Pollutant	Quantity	Unit
Carbon Dioxide	-161	kg/yr
Carbon Monoxide	103	kg/yr
Unburned Hydrocarbons	0	kg/yr
Particulate Matter	0	kg/yr
Sulfur Dioxide	0	kg/yr
Nitrogen Oxides	10.3	kg/yr

Fuel Summary

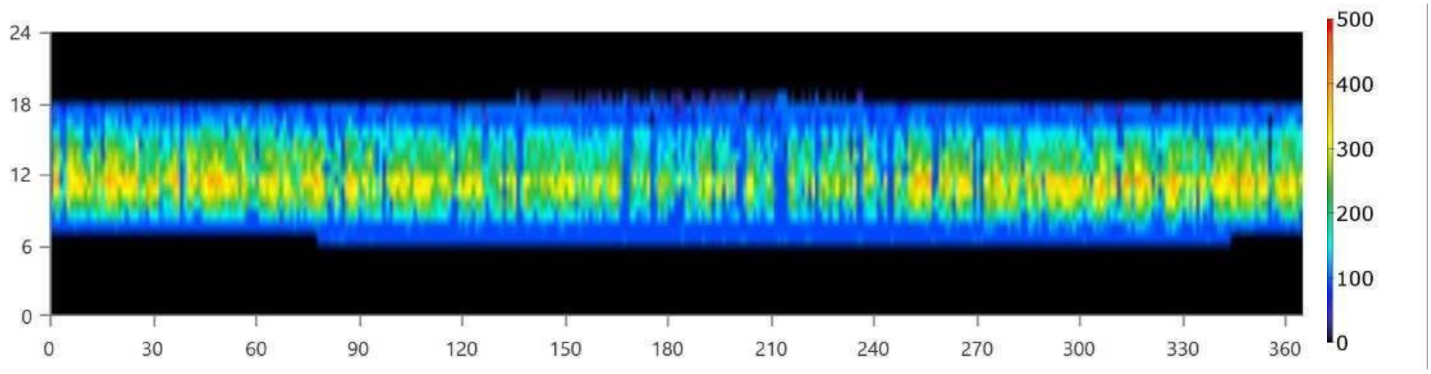
Renewable Summary

Capacity-based metrics	Value	Unit
Nominal renewable capacity divided by total nominal capacity	91.6	%
Usable renewable capacity divided by total capacity	89.7	%
Energy-based metrics	**Value**	**Unit**
Total renewable production divided by load	170	%
Total renewable production divided by generation	93.3	%
One minus total nonrenewable production divided by load	87.9	%
Peak values	**Value**	**Unit**
Renewable output divided by load (HOMER standard)	432	%
Renewable output divided by total generation	100	%
One minus nonrenewable output divided by total load	100	%

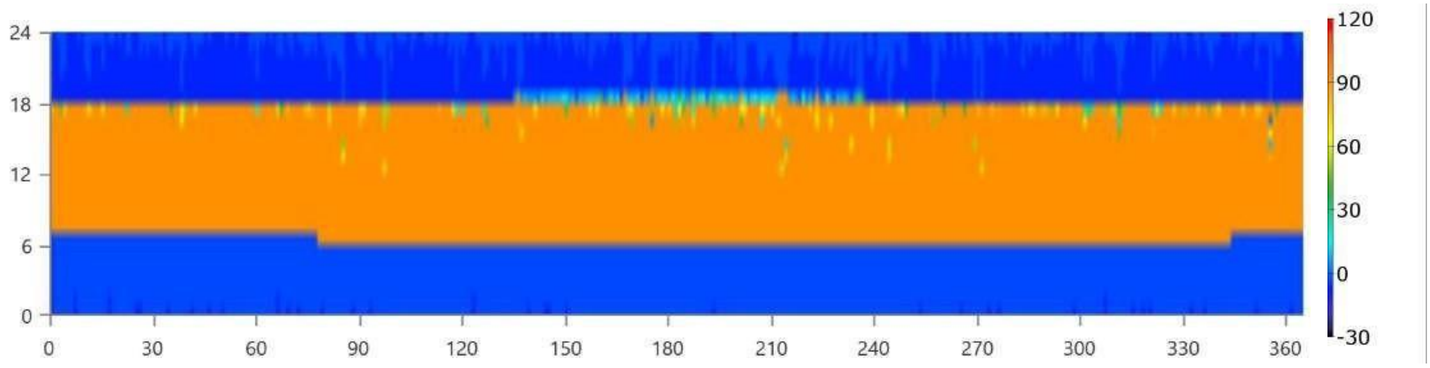
Instantaneous Renewable Output Percentage of Total Generation



Instantaneous Renewable Output Percentage of Total Load



100% Minus Instantaneous Nonrenewable Output as Percentage of Total Loa



Off-grid PV Fuel Cell Project Proposal

PREPARED FOR:
Kewet Woreda, PV Fuel Cell System to Electrify
Kewet Woreda
4XHF+Q3 Jewha, Ethiopia

PREPARED BY:
Shalom Abebaw and Tilahun Nigussie (PhD),
PhD and Graduate Student
Addis Ababa University,
shalomabebaw@gmail.com
+251930542909

This proposal was generated using HOMER Pro, a dynamic software engine that runs complex simulations of your hybrid electrical system's energy data and system components to determine the least-cost solution and most effective risk-mitigation strategies. Originally developed at the US Department of Energy's National Renewable Energy Laboratory (NREL), HOMER software set the global standard for optimizing microgrid design. More than 200,000 HOMER Pro users worldwide have produced economic feasibility studies, system design, engineering insight, and energy cost savings.

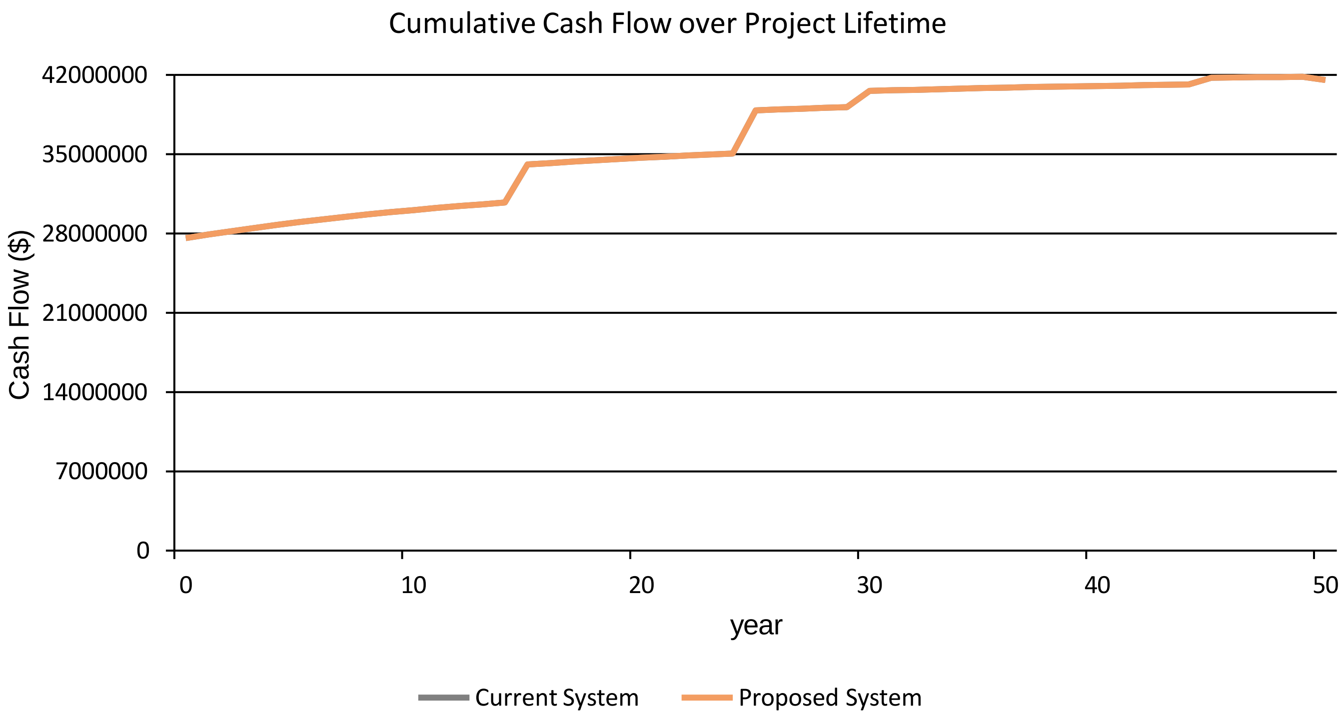
Table of Contents

Project Summary

CURRENT SYSTEM

The electric needs of 4XHF+Q3 Jewha, Ethiopia are met with 26,083 kW of PV and 3,000 kW of generator capacity. Your operating costs for energy are currently $871,652 per year.

We recommend not making alterations to the current system because it is the most economical choice.



ABOUT ADDIS ABABA UNIVERSITY

The leading research institute in Ethiopia

Customer Testimonials

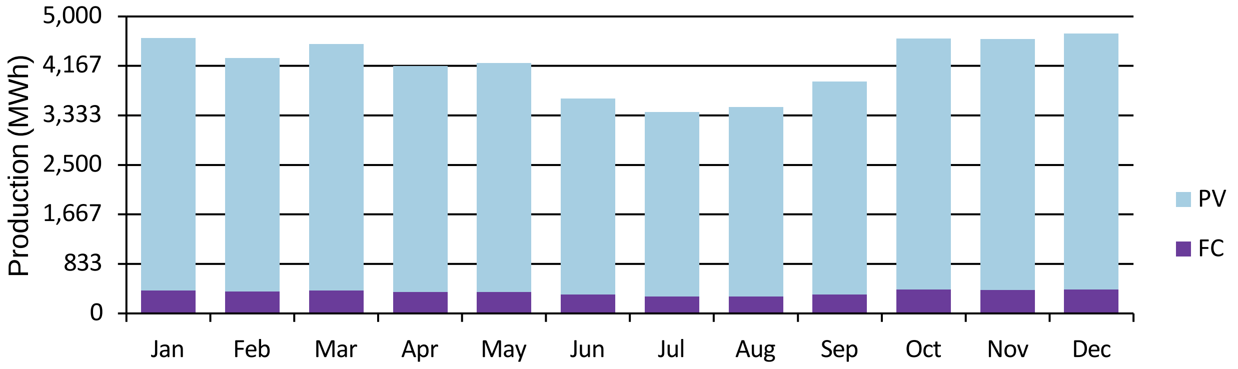
Use this space to provide statements made about your company by satisfied customers. Quotes and positive comments are valuable to prospective clients as they evaluate their options and decide whether your company's services provide the best solution to fit their needs. Testimonial statements demonstrate how others have benefited from your company's services, making them a powerful tool for establishing trust and encouraging potential clients to take action.

—John J. Client, CEO - Your Happy Client, Inc.

Consumption Summary

Electric Consumption

This microgrid requires 101849 kWh/day and has a peak of 13171 kW. In the proposed system, the following generation sources serve the electrical load.



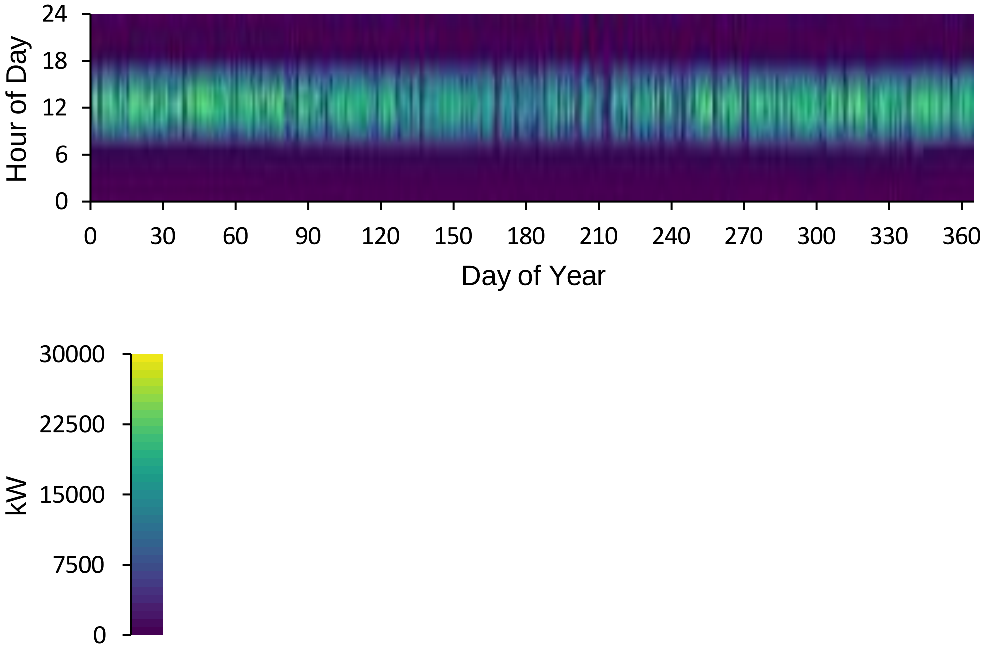
Engineering Details

PV: Generic flat plate PV

The Generic PV system has a nominal capacity of 26,083 kW. The annual production is 45,890,948 kWh/yr.

Rated Capacity	26,083 kW
Capital Cost	$14.6M
Specific Yield	1,759 kWh/kW
PV Penetration	377 %

Total Production	45,890,948 kW
Maintenance Cost	219,226 $/yr
LCOE	0.0294 $/kWh



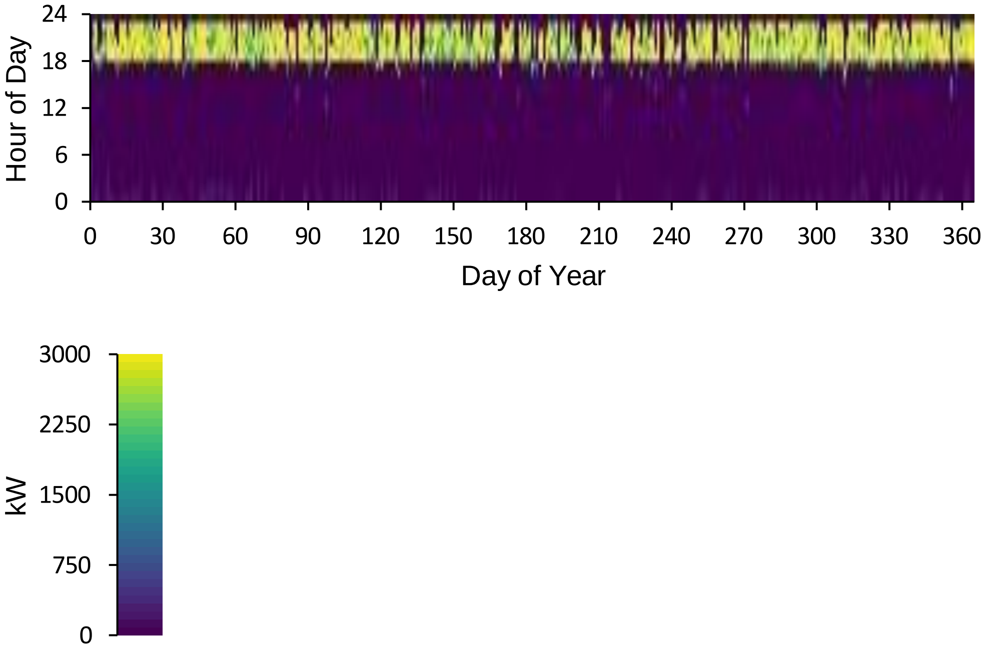
Engineering Details

Generator: Generic Fuel Cell (size-your-own) (Stored Hydrogen)

Power output from the Generic generator system, rated at 3,000 kW using Stored Hydrogen as fuel, is 4,290,667 kWh/yr.

Capacity	3,000 kW
Operational Life	50.9 yr
Capital Cost	$4.41M
Fuel Consumption	578,492 kg
Thermal Production	8,995,437 kWh/yr
Marginal Generation Cost	0 $/kWh

Generator Fuel	Stored Hydrogen
Generator Fuel Price	1.00 $/kg
Maintenance Cost	51,705 $/yr
Electrical Production	4,290,667 kWh/yr
Hours of Operation	3,447 hrs/yr
Fixed Generation Cost	40.1 $/hr

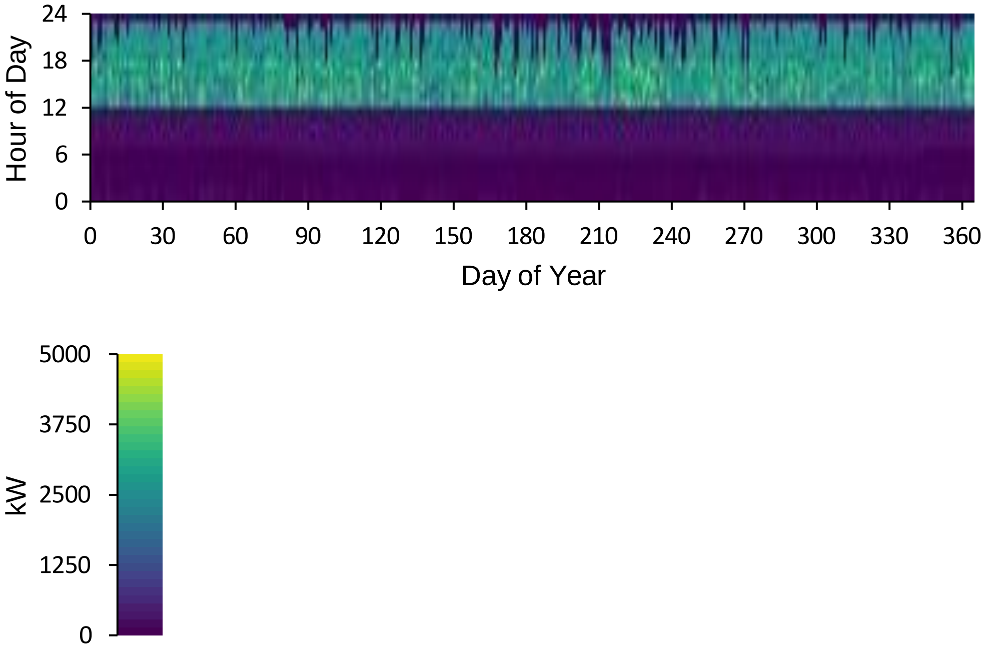


Engineering Details

Converter: System Converter

Capacity	4,171 kW
Mean Output	1,183 kW
Minimum Output	0 kW
Maximum Output	4,171 kW
Capacity Factor	28.4 %

Hours of Operation	6,225 hrs/yr
Energy Out	10,359,431 kWh/yr
Energy In	10,904,664 kWh/yr
Losses	545,233 kWh/yr

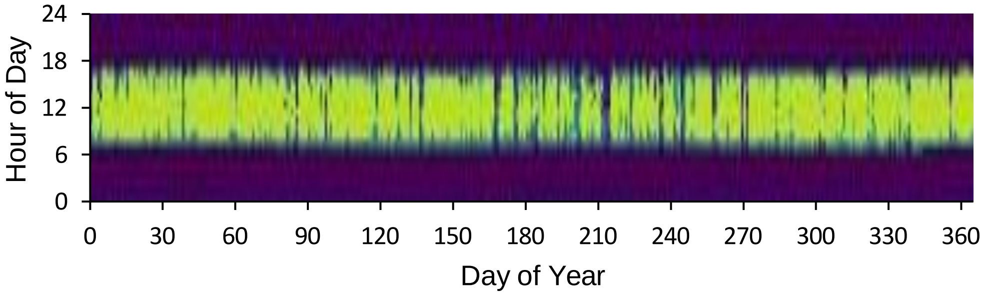


Electrolyzer

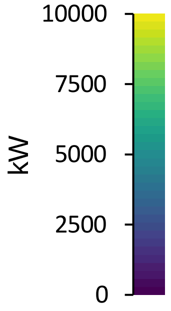
The Generic Electrolyzer has a rated capacity of 9,000 kW. The total annual production is 577,492 kg/yr.

Initial Capital	$6.32M
Rated Capacity	9,000 kW
Total Input Energy	26,798,642 kWh/yr
Hours of Operation	4,022 hr/yr
Minimum Output	0 kg/hr

Operating Expenses	54,000 $/yr
Capacity Factor	34.0 %
Total Production	577,492 kg/yr
Specific Consumption	46.4 kWh/kg
Maximum Output	194 kg/hr



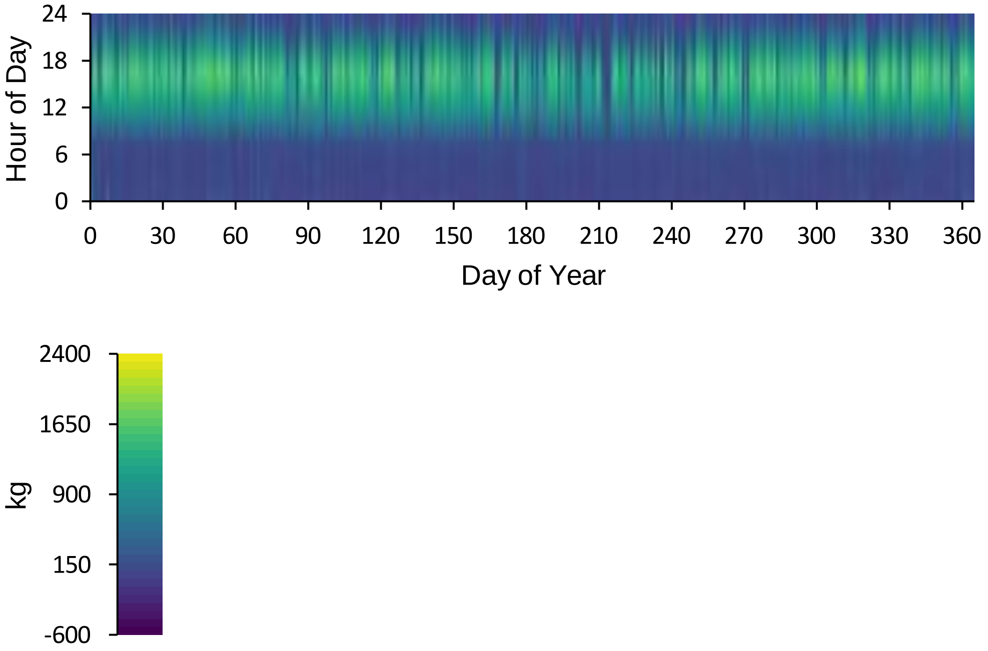
Engineering Details



Hydrogen Tank

Hydrogen Storage Capacity	2,000 kg
Content at Beginning of Year	1,000 kg
Tank Autonomy	48.0 hr

Energy Storage Capacity	66,667 kWh
Content at End of Year	0 kg



Cash Flows

Project Lifetime	50 years	Expected Inflation Rate	2.0%
Nominal Discount Rate	8.0%	Real Interest Rate	5.9%

Year	1	2	3	4	5	6	7	8	9	10
Generic Electrolyzer	($54,000)	($54,000)	($54,000)	($54,000)	($54,000)	($54,000)	($54,000)	($54,000)	($54,000)	($54,000)
Generic flat plate PV	($219,226)	($219,226)	($219,226)	($219,226)	($219,226)	($219,226)	($219,226)	($219,226)	($219,226)	($219,226)
Generic Fuel Cell (size-your-own)	($51,705)	($51,705)	($51,705)	($51,705)	($51,705)	($51,705)	($51,705)	($51,705)	($51,705)	($51,705)
Hydrogen Tank	($10,000)	($10,000)	($10,000)	($10,000)	($10,000)	($10,000)	($10,000)	($10,000)	($10,000)	($10,000)
System Converter	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00

Year	11	12	13	14	15	16	17	18	19	20
Generic Electrolyzer	($54,000)	($54,000)	($54,000)	($54,000)	($54,000)	($54,000)	($54,000)	($54,000)	($54,000)	($54,000)
Generic flat plate PV	($219,226)	($219,226)	($219,226)	($219,226)	($219,226)	($219,226)	($219,226)	($219,226)	($219,226)	($219,226)
Generic Fuel Cell (size-your-own)	($51,705)	($51,705)	($51,705)	($51,705)	($51,705)	($51,705)	($51,705)	($51,705)	($51,705)	($51,705)
Hydrogen Tank	($10,000)	($10,000)	($10,000)	($10,000)	($10,000)	($10,000)	($10,000)	($10,000)	($10,000)	($10,000)
System Converter	$0.00	$0.00	$0.00	$0.00	($1.25M)	$0.00	$0.00	$0.00	$0.00	$0.00

Year	21	22	23	24	25	26	27	28	29	30
Generic Electrolyzer	($54,000)	($54,000)	($54,000)	($54,000)	($54,000)	($54,000)	($54,000)	($54,000)	($54,000)	($54,000)
Generic flat plate PV	($219,226)	($219,226)	($219,226)	($219,226)	($219,226)	($219,226)	($219,226)	($219,226)	($219,226)	($219,226)
Generic Fuel Cell (size-your-own)	($51,705)	($51,705)	($51,705)	($51,705)	($51,705)	($51,705)	($51,705)	($51,705)	($51,705)	($51,705)
Hydrogen Tank	($10,000)	($10,000)	($10,000)	($10,000)	($10,000)	($10,000)	($10,000)	($10,000)	($10,000)	($10,000)
System Converter	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	($1.25M)

Year	31	32	33	34	35	36	37	38	39	40
Generic Electrolyzer	($54,000)	($54,000)	($54,000)	($54,000)	($54,000)	($54,000)	($54,000)	($54,000)	($54,000)	($54,000)
Generic flat plate PV	($219,226)	($219,226)	($219,226)	($219,226)	($219,226)	($219,226)	($219,226)	($219,226)	($219,226)	($219,226)
Generic Fuel Cell (size-your-own)	($51,705)	($51,705)	($51,705)	($51,705)	($51,705)	($51,705)	($51,705)	($51,705)	($51,705)	($51,705)
Hydrogen Tank	($10,000)	($10,000)	($10,000)	($10,000)	($10,000)	($10,000)	($10,000)	($10,000)	($10,000)	($10,000)
System Converter	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00

Year	41	42	43	44	45	46	47	48	49	50
Generic Electrolyzer	($54,000)	($54,000)	($54,000)	($54,000)	($54,000)	($54,000)	($54,000)	($54,000)	($54,000)	($54,000)
Generic flat plate PV	($219,226)	($219,226)	($219,226)	($219,226)	($219,226)	($219,226)	($219,226)	($219,226)	($219,226)	($219,226)
Generic Fuel Cell (size-your-own)	($51,705)	($51,705)	($51,705)	($51,705)	($51,705)	($51,705)	($51,705)	($51,705)	($51,705)	($51,705)
Hydrogen Tank	($10,000)	($10,000)	($10,000)	($10,000)	($10,000)	($10,000)	($10,000)	($10,000)	($10,000)	($10,000)
System Converter	$0.00	$0.00	$0.00	$0.00	($1.25M)	$0.00	$0.00	$0.00	$0.00	$834,142

Year
Generic Electrolyzer
Generic flat plate PV
Generic Fuel Cell (size-your-own)
Hydrogen Tank
System Converter

Glossary and Abbreviations

Net Present Value

The total net present cost (NPC) of a system is the present value of all the costs the system incurs over its lifetime, minus the present value of all the revenue it earns over its lifetime. Costs include capital costs, replacement costs, O & M costs, fuel costs, emissions penalties, and the costs of buying power from the grid. Revenues include salvage value and grid sales revenue. HOMER calculates the total NPC by summing the total discounted cash flows in each year of the project lifetime.

Total Annualized Cost

- is the annualized value of the total net present cost. The annualized cost of a component is the cost that, if it were to occur equally in every year of the project lifetime, would give the same net present cost as the actual cash flow sequence associated with that component. HOMER calculates annualized cost by first calculating the net present cost, then multiplying it by the capital recovery factor.

Simple payback

- is the number of years at which the cumulative cash flow of the difference between the current system and base case system switches from negative to positive. The payback is an indication of how long it would take to recover the difference in investment costs between the current system and the base case system.

Return on Investment (ROI)

- is the yearly cost savings relative to the initial investment. The ROI is the average yearly difference in nominal cash flows over the project lifetime, divided by the difference in capital cost.

Internal rate of return (IRR)

- is the discount rate at which the base case and current system have the same net present cost. HOMER calculates the IRR by determining the discount rate that makes the present value of the difference of the two cash flow sequences equal to zero.

Refer to HOMER Pro Online Help Manual

Abbreviations

FC	Generic Fuel Cell (size-your-own)
PV	Generic flat plate PV
Converter	System Converter
Electrolyzer	Generic Electrolyzer
HTank	Hydrogen Tank

HOMER Energy

About HOMER Pro

HOMER® Pro simulates engineering and economic feasibility of microgrid or distributed energy systems that are off-grid or tied to an unreliable grid and enables the design of least-cost electrical systems and risk-mitigation strategies. The software provides insight into cost-effectively combining conventional and renewable energy, storage, grid resources (where available), and load management.

In a single data run, HOMER Pro simulates the operation of a hybrid microgrid or distributed energy system for an entire year, evaluating and optimizing the electrical system design, load profiles, components, fuel costs, and environmental variables. The simulation produces key information on technical performance, risk-mitigation, and projected cost-savings to inform system design and optimization. Results are presented in a succinct Microgrid Proposal. For more information, visit HomerEnergy.com.

About HOMER Energy by UL

HOMER software is used by more than 200,000 users in 193 different countries.

HOMER Energy by UL is the developer and distributor of HOMER software, a global standard for energy modeling tools that analyze solar-plus-storage, microgrids, and other distributed energy projects.

HOMER software helps engineers and project developers navigate the complexities of designing cost-effective and reliable microgrids that combine traditional and renewable generation sources. The company makes two software platforms: HOMER Pro for the design of least-cost hybrid microgrid or distributed energy systems for use off-grid or when tied to an unreliable grid; and HOMER Grid, which helps design behind-the-meter solar-plus-storage systems to reduce costs and lower carbon footprints.

Since its founding in Boulder, Colorado in 2009, HOMER Energy software has proven effective for analyzing complex distributed energy systems, including grid-tied hybrid renewable microgrids and situations where the grid is insufficiently reliable, such as islands and remote communities. In 2019, HOMER Energy was acquired by UL. More than 200,000 HOMER Pro users in over 190 countries have produced economic feasibility studies, system design, engineering insight, and energy cost savings. Learn more at www.homerenergy.com.

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