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Sensitivity and performance analysis of a comprehensive PEM cell model and fuel cell based renewable autonomous RHFC system for Saint Martin Bangladesh

A thesis presented to the Department of Mechanical and Production Engineering, Islamic University of Technology in partial fulfilment of the requirement for the award of the degree of

Bachelor of science in Mechanical Engineering

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<u>CANDIDATE'S DECLARATION</u>

This is to certify that the work presented in this thesis, titled, **"Sensitivity and performance analysis of a comprehensive PEM cell model and fuel cell based renewable autonomous RHFC system for Saint Martin Bangladesh"** is the outcome of the investigation and research carried out by us under the supervision of **DR. MD. REZWANUL KARIM**, Associate Professor Department of Mechanical & Production Engineering, Islamic University of Technology.

It is also declared that neither r this thesis nor any part of it has been submitted elsewhere for the award of any degree or diploma.

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ABSTRACT

Providing uninterrupted electricity to remote regions, such as Saint-Martin Island, that have a high potential for renewable energy sources but lack a large-scale grid connection is a formidable challenge. Such decentralized electricity generation and distribution results in the Regenerative Hydrogen Fuel Cell (RHFC) system, which combines the production of hydrogen in a PEM electrolyzer, its storage in a Metal-hydride storage system, and its re-use in a PEM fuel cell to generate electricity. PEMFC having a much higher life expectancy and hydrogen storage having a greater energy storage facilitates RHFC system to eliminate the use of Battery-diesel generator in Saint Martin that has harmful environmental effects such as greenhouse emissions and (Pb) emissions. Based on the results of simulation and the real-time data for Saint Martin, Bangladesh in the years 2021-22, a comprehensive RHFC model incorporating all potential energy sources such as solar, wind, and wave energy is developed and simulations are performed. In addition, a sensitivity analysis is conducted to analyze the optimal operating conditions for the selected fuel cell. The designed 220kW RHFC system is capable of supplying more than 100 residences, at least 10 hotels or restaurants, as well as government offices, markets, and hospitals. Based on the results of simulation and the current market price of the system's components, the levelized cost of energy (LCOE) is calculated to be 10.13 cents per kilowatt-hour, making it a viable option for renewable energy generation. The designed control system in MATLAB/Simulink has the option to be integrated into an advanced autonomous technology known as IoE (Internet of Energy) to support digital infrastructure that will usher in a new revolution in the energy generation industry.

CONTENTS

LIST OF FIGURES

NOMENCLATURE

A_1	Internal water surface area of the chamber (m^2)
A_2	area of the turbine inlet (m^2)
C_p	Power coefficient
C_t	Capital Expenses (CAPEX)
E_{g_o}	Band gap energy of silicon semiconductor(eV)
E_{act}	Activation Overpotential (V)
E_{conc}	Concentration Overpotential(V)
E_o	Standard Potential of the Hydrogen-Oxygen Reaction (V)
E_{ohm}	Ohmic Overpotential (V)
E_t	Electricity generated by the system
F_{EH2}	Amount of hydrogen required(mol/s)
F_t	Fuel cost
H_{in}	Average internal wave height(m)
H_{ref}	Height at which reference speed is measured(m/s)
I_{PH}	PV photocurrent from solar (A)
I_{RS}	Reverse saturation current (A)
I_{SC}	Short circuit current of the cell (A)
I_{SH}	Shunt current (A)
I_e	Current applied to the electrolyser
I_o	Dark saturation current (A)
I_{pv}	Solar PV current transfer (A)

K_i	Short circuit current
L_{ch}	Chamber length (m)
M_t	Operation & maintenance expenses (OPEX)
N_p	Number of parallel cells
N_s	Number of cells in series
P_{H_2}	partial hydrogen pressure at the anode (atm)
P_{H_2O}	Partial pressure of water at cathode (atm)
P_{O_2}	partial oxygen pressure at the cathode (atm)
P_a	Air velocity term
P_{in}	Inlet power
P_{pt}	Air pressure term
R_{SH}	Shunt resistance (Ω)
R_i	Cell internal Resistance (Ω)
R_s	Series resistance (Ω)
T_m	Wave period (s)
T_{ref}	Reference temperature(K)
V_1	Chamber inlet velocity (m/s)
V_2	Turbine inlet velocity(m/s)
V_{FC}	Fuel Cell Voltage (V)
V_{Nernst}	Nernst Voltage (V)
V_{OC}	Open circuit voltage(V)
V_T	Thermal voltage(V)
V_{el}	Electrolyser voltage(V)
V_{ref}	Reference wind speed(m/s)

V_w	Wind velocity at hub height (m/s)
f_{fH2}	Molar flow rate (mol/s)
i_L	Limiting current density (A.cm^{-2})
i_o	Exchange current density (A.cm^{-2})
n_f	Efficiency of electrolyser
p_2	Upstream inner pressure
p_o	Exhaust pressure
η_1	Free surface elevation
η_{elec}	Electrical efficiency
η_{mech}	Mechanical efficiency
λ_0	Theoretical wave length (m)
F	Faraday constant (C/mol)
$F(V)_{weibull}$	Weibull probability function
G	Solar irradiance(W/m^2)
H	Hub height (m)
I	Operating current(A)
Q	Volume flow rate
R	Universal gas constant ($\frac{J}{K}.mol$)
S	Stochiometric Ratio
T	Operating Temperature (k)
V	Operating voltage(V)
c	Scale parameter
d	Water depth (m)
i	Operating current density (A.cm^{-2})

k	Boltzmann’s constant
k_f	Shape factor
n	Ideality factor of the diode
q	Electron charge (C)
Φ	Velocity potential
α	Charge transfer coefficient
θ	Angular chamber length(rad)
λ	Actual wave length (m)
ρ	Density of air
ω	Angular frequency

CHAPTER 1: INTRODUCTION

There are advantages and disadvantages to the fact that today's civilization is entirely dependent on fossil fuels. Fossil fuels are the primary energy source for the majority of today's infrastructure since they are widely available and straightforward to use. The drawbacks of burning fossil fuels, however, are much more serious. The most noteworthy of these detrimental greenhouse gases produced by the usage of fossil fuels is carbon dioxide. The primary cause of global warming is carbon dioxide. Because greenhouse gas emissions are bad for both people and animals, most industrialized nations are moving toward cleaner, more environmentally friendly ways to generate electricity. For instance, Hydrogen, biofuels, geothermal energy, ocean energy, solar energy, wind energy, and hydropower [1].

Moving on to alternative sources of energy, there are several options that are being explored in order to reduce our dependence on fossil fuels. One such option is solar energy, which utilizes photovoltaic (PV) cells to directly convert sunlight into electricity. These cells are commonly found in solar panels, streetlights, and water turbines [2]. In addition to solar energy, wind energy is also being heavily researched and utilized in areas with high wind velocities, such as coastal and wide-open plains regions. Another promising option is wave power technology, which converts the kinetic energy of ocean waves into electricity using oscillating water columns and absorbers. Both wind and wave energy have the potential to significantly reduce fossil fuel consumption and the associated negative impact on the environment [3].

Nowadays, hydrogen fuel cells are a very appealing alternative because of their cutting-edge technology, which produces electricity and water as the only byproducts of a chemical interaction between hydrogen and oxygen to create electrical power. As an alternative to conventional combustion engines, which emit harmful emissions like carbon dioxide and nitrogen oxides, hydrogen fuel cells are highly appealing due to this. Up to 60% of the energy in hydrogen can be converted into useful electricity by hydrogen fuel cells, which are very effective. This compares favorably to traditional combustion engines, which typically convert only 20% to 30% of the energy contained in fossil fuels into useful work [4]. One of hydrogen fuel cells' greatest benefits is their potential to drastically lessen our reliance on fossil fuels, a limited resource and a significant cause of climate change.

However, the availability of hydrogen fuel, the cost of components, and the efficiency of the cell all have a role in how widely used hydrogen fuel cells are. Understanding how these elements will affect the overall effectiveness and economics of a hydrogen fuel cell system may be done with the use of sensitivity analysis. A hydrogen fuel cell will be subjected to a sensitivity analysis in this study, which will look at how important factors including cell efficiency, hydrogen cost, and fuel use affect the system's total cost and efficiency.

So far solar PV cells are a widely used and relatively mature technology, with a declining cost of installation and maintenance. Deserts and tropical regions with abundant sunlight are suitable for solar photovoltaics. The primary issue with the PV system is that its power output is weather dependent. For example, a PV system may not produce electricity at night. Since the PV system generates power intermittently, it may not always be sufficient to meet demand. PV systems can be combined with wind, waves, fuel cells, battery banks, ultracapacitor banks, and hydrogen storage containers. Poor nations and rural areas without a reliable grid connection amplify the difficulties and potential benefits. Nearly 1.1 billion individuals lack access to electricity worldwide [5]. In developing nations, the diesel generators used to generate electricity pose health, environmental, and economic risks. Electricity boosts income for rural communities' quality of life, clean water, health care, education, and communications. To "leapfrog" to modern energy generating technologies that can aid them in resolving environmental problems, developing nations require affordable and reliable power.

To resolve this problem, an autonomous Solar PV/Wind/Regenerative Hydrogen Fuel Cell Energy Storage System was investigated, this technology presents a promising solution to the energy crisis by utilizing renewable energy sources and hydrogen fuel cells for energy storage. The integration of solar PV and wind energy sources, along with a regenerative hydrogen fuel cell system, enables a self-sustaining and eco-friendly energy generation and storage system [6]. The ultimate goal of this project is to design and analyze a self-sufficient autonomous Regenerative Hydrogen Fuel Cell (RHFC) system for use in backup renewable energy storage, with the intention of lowering initial investment costs and replacing polluting diesel generators. The suggested setup is comprised of an electrolyzer for water, which uses the surplus of electricity generated by renewable energy sources to separate water into its component parts, hydrogen and oxygen. After that, the hydrogen is placed in a sorption solid-hydrogen energy storage cell for long-term storage. This method has the advantage of storing hydrogen at low pressure and low temperature, which precludes the need for hydrogen compression [7]. Since the Solid-Hydrogen Energy Storage Cell suffers from almost no self-discharge, it is capable of storing energy for extended periods of time and, as a result, can be utilized for seasonal switching. As a result, hydrogen has a storage potential that is far larger than that of other methods. When the electricity produced by renewable sources is not enough to meet the demand, a Polymer Electrolyte Membrane Fuel Cell (PEMFC) is utilized to generate electricity from hydrogen. The only byproducts are water and heat in this process.

The integrated RHFC system is designed in this project, and its performance is simulated using MATLAB/Simulink. The analysis begins by outlining the system's primary components and examining the critical parameters for each component. These components may be modeled separately and combined using MATLAB/Simulink. After that, the optimized energy system is simulated, and the findings are utilized to compute the Levelized Cost of Electricity (LCOE). This financial criterion is critical in analyzing the cost-effectiveness of energy-generation systems. LCOE estimates, while extremely sensitive to the underlying data, provide a foundation for comparing projects and technologies. The long-term objective of this energy system is to develop a dependable, sustainable, and load-following energy storage and generating system that might increase the availability of electricity, so improving the quality of life in underdeveloped countries.

1.1: Background of the study

1.1.1: Saint Martin as location

Saint Martin's Island is located in the northeastern part of the Bay of Bengal, off the coast of Cox's Bazar, Bangladesh. It is situated approximately 9 kilometers south of the mainland. The island is positioned at a latitude of about 20.635°N and a longitude of around 92.336°E.

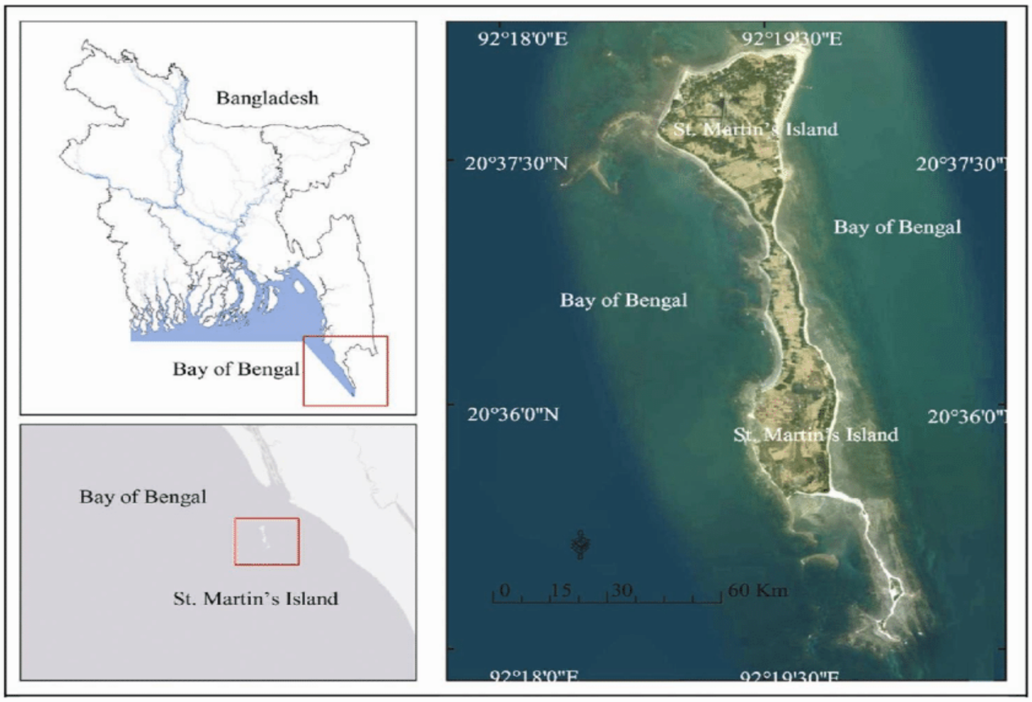


Figure 1: Geographic location of Saint Martin, Bangladesh

Geographically, Saint Martin's Island is part of the southernmost region of Bangladesh. It is situated within the Chittagong Division, specifically in the Cox's Bazar District. The island is separated from the mainland by the vast expanse of the Bay of Bengal. Covering an area of approximately 8 square kilometers, Saint Martin's Island is relatively small in size. It is characterized by its coral reef formations, sandy beaches, and diverse marine ecosystem. The island's strategic location in the Bay of Bengal makes it susceptible to influences from the monsoon climate, with distinct wet and dry seasons. Being a coastal island, Saint Martin's Island experiences a tropical climate. The temperatures remain warm throughout the year, with relatively high humidity. The island receives ample rainfall, particularly during the monsoon season, which typically occurs from June to September.

The geographic location of Saint Martin's Island contributes to its unique natural environment. Surrounded by the Bay of Bengal's waters, the island offers a rich marine ecosystem that supports vibrant coral reefs, tropical fish species, and other marine life. Its proximity to the mainland and Cox's Bazar, one of the longest natural sandy beaches in the world, makes it a popular destination for tourists seeking coastal and marine adventures.

Saint Martin is an ideal location for a regenerative hydrogen fuel cell system for several reasons:

- **Abundant Renewable Resources:** Saint Martin enjoys ample sunlight and strong winds, making it suitable for generating renewable energy. Solar and wind power can be harnessed to produce electricity for the electrolysis process required to generate hydrogen.
- **Environmental Sustainability:** A regenerative hydrogen fuel cell system produces clean energy with zero emissions, contributing to environmental sustainability. Choosing Saint Martin aligns with the island's commitment to reducing carbon emissions and promoting eco-friendly practices.
- **Energy Independence:** Saint Martin heavily relies on imported fossil fuels for its energy needs. By implementing a regenerative hydrogen fuel cell system, the island can reduce its dependence on fossil fuels and achieve greater energy independence.
- **Diverse energy application:** Hydrogen has various applications, including transportation, electricity generation, and heating. Implementing a regenerative hydrogen fuel cell system in Saint Martin opens up opportunities for utilizing hydrogen in different sectors, promoting technological innovation and diversifying the island's energy portfolio.
- **Economic Opportunities:** Developing a regenerative hydrogen fuel cell system can create new economic opportunities for Saint Martin. It can attract investments, stimulate job growth in the renewable energy sector, and potentially foster a local hydrogen economy.
- **Resilient Energy Infrastructure:** Saint Martin is susceptible to extreme weather events, such as hurricanes. A regenerative hydrogen fuel cell system can enhance the island's energy resilience by providing a decentralized and reliable energy source that can operate independently of the main power grid during emergencies.

Overall, selecting Saint Martin as a location for a RHFC system brings together the advantages of renewable energy, environmental sustainability, energy independence, diverse energy applications, economic opportunities, and resilient infrastructure.

1.1.2: Renewable sources over diesel generators

Renewable sources are preferred over diesel generators for several reasons:

- **Environmental Impact:** Renewable energy sources such as solar, wind, and hydroelectric power produce energy with minimal emissions of greenhouse gases and contaminants. In contrast, diesel generators emit harmful substances such as carbon dioxide (CO_2), nitrogen oxides (NOx), sulfur dioxide (SO_2), and particulate matter, causing air pollution and contributing to climate change. By utilizing renewable energy sources, we are able to reduce our carbon footprint and mitigate the resulting negative environmental effects.
- **Sustainability:** Renewable sources are essentially inexhaustible and abundant, unlike fossil fuels like diesel, which are finite resources that deplete over time. By harnessing renewable sources, we can ensure a long-term and sustainable energy supply, reducing our reliance on non-renewable fossil fuels.

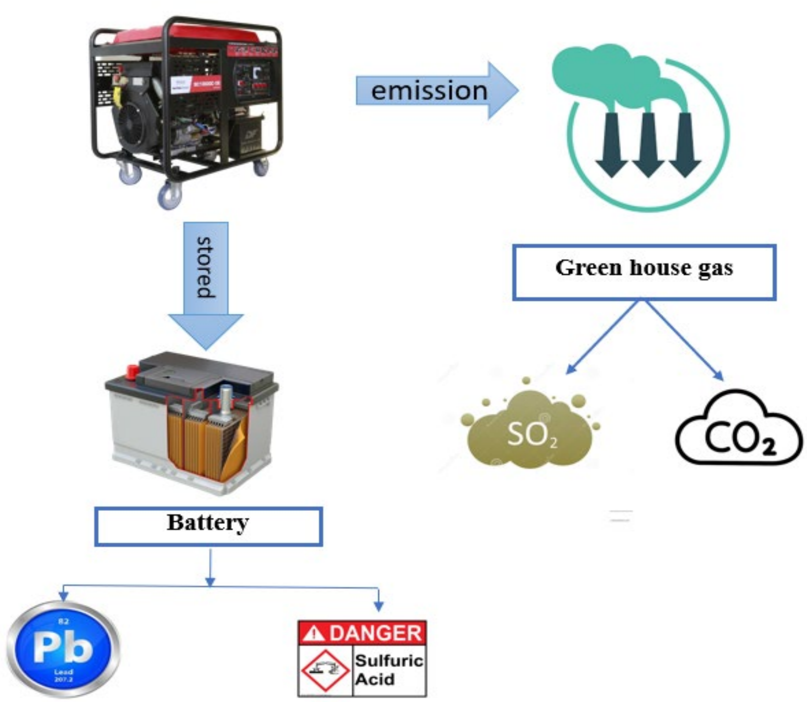


Figure 2 :Drawbacks of Diesel generator & Battery

- **Cost-effectiveness:** While the upfront costs of implementing renewable energy systems can be higher compared to diesel generators, renewable sources offer long-term cost savings. Once installed, renewable systems have lower operational and maintenance costs since their fuel sources (sunlight, wind, water) are essentially free. In contrast, diesel generators require a continuous supply of fuel, which can be expensive and subject to price volatility.
- **Energy Independence:** Diesel generators rely on a constant supply of diesel fuel, often requiring importation and transportation logistics. In contrast, renewable sources are localized and can provide energy independence. This reduces vulnerability to fuel price fluctuations and supply disruptions, enhancing energy security.
- **Noise and Vibrations:** Diesel generators are noisy and can cause vibrations, leading to potential disturbances and discomfort for nearby communities. Renewable sources, particularly solar and wind power, operate silently and have minimal effects on the surrounding environment and communities.
- **Resilience and Reliability:** Renewable energy systems, especially when combined with energy storage technologies, can provide a more resilient and reliable energy supply. They are less prone to failures caused by fuel shortages, mechanical issues, or natural disasters compared to diesel generators, ensuring a consistent power supply even during challenging circumstances.

Given these advantages, renewable sources offer a cleaner, more sustainable, cost-effective, and reliable energy solution compared to diesel generators. They align with global efforts to combat climate change, reduce pollution, and transition towards a greener and more sustainable energy future.

1.1.3: Hydrogen Hub & the future

The concept of a "Hydrogen Hub" has come to light as a promising plan for the generation, distribution, and use of hydrogen as an energy carrier. In order to encourage the widespread usage of hydrogen across many economic sectors, these hubs serve as focal locations or geographic areas. This section provides a summary of the value and potential of hydrogen hubs in accelerating the shift to a sustainable energy future.

The decarbonization of multiple sectors, such as transportation, industry, power generation, and heating, is a pressing global challenge. Hydrogen has gained considerable attention as a key enabler in this endeavor. Hydrogen Hubs hold the potential to drive the decarbonization process by providing a centralized infrastructure for the production of green hydrogen using renewable energy sources. By replacing fossil fuels with hydrogen, hydrogen hubs contribute significantly to reducing greenhouse gas emissions across various sectors.

One crucial aspect of hydrogen hubs is their ability to integrate renewable energy sources, such as solar and wind power, into the hydrogen production process. These hubs serve as a means to store excess renewable energy in the form of hydrogen, addressing the intermittency of renewable sources and ensuring a reliable and dispatchable energy supply.

Figure 3: Africa’s Global Green Hydrogen hub [8]

In addition to the technological aspects, the success of hydrogen hubs relies on cross-sectoral collaboration. These hubs bring together stakeholders from different sectors, including energy producers, equipment manufacturers, transportation companies, and policymakers. Collaboration and knowledge sharing within hydrogen hubs foster innovation, create synergies, and drive the development of new technologies and business models related to hydrogen production, storage, and utilization.

Furthermore, the development of hydrogen hubs necessitates the establishment of dedicated infrastructure, including hydrogen production facilities, pipelines, storage tanks, and refueling stations. These infrastructure developments drive economic growth, create job opportunities, and attract private sector investments.

International cooperation and collaboration are crucial elements for the advancement of hydrogen technologies and the establishment of a global hydrogen economy. Hydrogen hubs can serve as platforms for countries and regions to share expertise, research findings, and best practices. Such cooperation accelerates the deployment and harmonization of hydrogen technologies and standards worldwide.

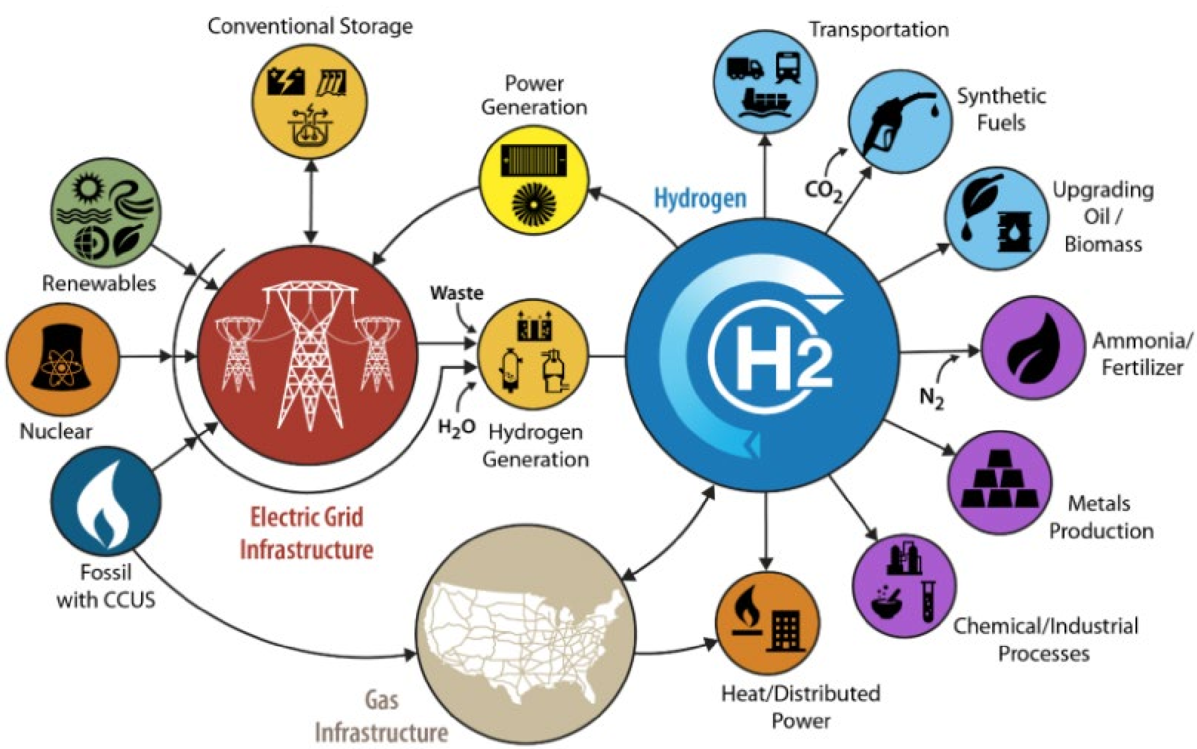


Figure 4: The Regional Clean Hydrogen Hubs Solution by U.S. Department of Energy's [9]

Hydrogen hubs also have the potential to position themselves as energy exporters. Regions with favorable renewable resources can produce green hydrogen and convert it into carriers like ammonia or transport it in liquid or compressed form to regions or countries lacking indigenous renewable energy sources. This enhances global energy trade and contributes to the development of a global hydrogen economy.

Moreover, the development of Hydrogen hubs is expected to drive technological advancements and cost reductions in hydrogen production, storage, and utilization technologies. Extensive research and development efforts will focus on improving the efficiency, durability, and affordability of hydrogen-related equipment and infrastructure.

In conclusion, the emergence of hydrogen hubs represents a significant opportunity for the transition towards a sustainable energy future. These hubs serve as catalysts for the widespread adoption of hydrogen as a clean and sustainable energy carrier. By facilitating the decarbonization of multiple sectors, integrating renewable energy sources, fostering cross-sectoral collaboration, developing infrastructure, promoting international cooperation, enabling energy exports, and driving technological advancements, hydrogen hubs play a vital role in shaping the energy landscape of the Future,

1.1.4: Benefits of an autonomous RHFC system

An autonomous Regenerative Hydrogen Fuel Cell (RHFC) system offers numerous benefits, with one of the key advantages being energy independence. By operating independently of the grid, this system reduces reliance on external energy sources and ensures a consistent power supply. Through the process of converting hydrogen into power using fuel cells, an autonomous RHFC system generates its own electricity, making it highly suitable for remote or off-grid locations where access to traditional power infrastructure may be limited or unreliable.

A hydrogen hub focuses on the overall infrastructure and ecosystem for hydrogen production, storage, distribution, and utilization, while a RHFC System specifically refers to a closed-loop energy system that combines hydrogen production through electrolysis with hydrogen utilization in fuel cells.

Additionally, the integration of renewable energy sources is facilitated by an autonomous RHFC system. It can be combined with renewable energy generation systems such as solar panels or wind turbines to produce green hydrogen, which is then utilized to generate electricity through fuel cells. This integration allows for the efficient storage and utilization of excess renewable energy, addressing the intermittent nature of renewable sources and enhancing the overall sustainability of the system.

Moreover, the autonomous nature of the RHFC system contributes to enhanced reliability and resilience. By eliminating the need for external power sources, it reduces the risk of power outages and disruptions. This is particularly valuable in critical applications where uninterrupted power supply is essential, such as in telecommunications, emergency services, or remote monitoring systems.

In summary, the benefits of an autonomous RHFC system include energy independence, renewable energy integration, enhanced reliability, environmental sustainability, and flexibility. These advantages make it a compelling choice for applications that prioritize off-grid or remote power generation, as well as those seeking clean and reliable energy solutions with minimal environmental impact.

1.1.5: Fuel cell over battery

A fuel cell system offers distinct advantages over batteries for certain applications:

- **Longer Continuous Operation**: Fuel cells can provide continuous power for extended periods, as long as fuel (hydrogen) is supplied. This makes them suitable for applications that require prolonged or uninterrupted power, such as backup power systems, remote sensing devices, and electric vehicles with extended range requirements. Batteries, on the other hand, have limited energy storage capacity and need periodic recharging.
- **Quick Refueling:** Refueling a fuel cell system with hydrogen is typically faster than recharging a battery. It takes minutes to refill a fuel cell system compared to hours required for battery recharging. This makes fuel cells more convenient for applications that demand rapid refueling, such as fleet vehicles or mobile power systems.
- **Lighter Weight:** Fuel cells are generally lighter than batteries, which is advantageous for weight-sensitive applications like aerospace, transportation, and portable devices. Fuel cells produce electricity through electrochemical reactions, while batteries rely on chemical reactions, which often involve heavier materials.
- **Higher Energy Density:** Fuel cells have higher energy density than batteries, meaning they can store and deliver more energy per unit weight or volume. This results in longer

operating times or extended range capabilities for fuel cell-powered devices or vehicles. Batteries, despite recent advancements, generally have lower energy density.

- **Scalability:** Fuel cells offer greater scalability compared to batteries. They can be easily scaled up or down depending on the power requirements of a specific application. Fuel cell systems can be designed for small-scale portable devices or large-scale stationary power generation, accommodating a wide range of power needs. Batteries, while flexible to a certain extent, may have limitations in scaling up for high-power applications.
- **Environmental Impact:** Fuel cells produce electricity through electrochemical reactions between hydrogen and oxygen, generating only water vapor and heat as byproducts. This makes them environmentally friendly with zero direct emissions. On the other hand, batteries may contain toxic chemicals or (Pb) that require proper disposal and can contribute to environmental pollution if mishandled.

It's worth noting that the choice between fuel cells and batteries depends on the specific application requirements, such as power demand, duration, weight constraints, and refueling/recharging considerations. While fuel cells offer advantages in certain scenarios, batteries excel in other applications, especially those requiring compact size, fast discharge, and easy recharging. Both technologies play significant roles in advancing clean energy solutions and will continue to evolve as complementary options in various sectors.

1.1.6: PEM over other fuel cells

Among all of the fuel cells available three most prominent categories are PEMFC, SOFC and AFC. These can be described according to their outcomes and benefits as following:

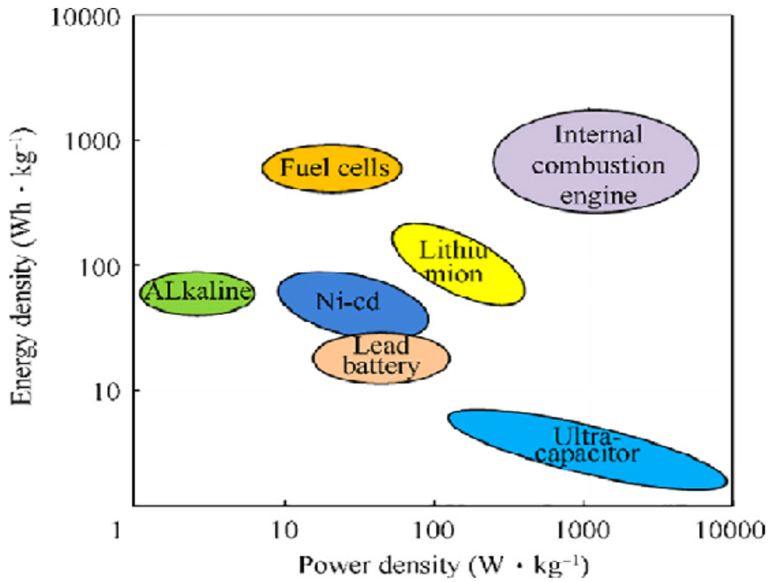


Figure 5: Power and energy density of fuel cell & batteries [10]

- **Efficiency:** The most efficient fuel cells are proton exchange membrane (PEM) fuel cells, with an efficiency of up to 60%, followed by solid oxide fuel cells (SOFCs), with an efficiency of up to 50%.
- **Power density:** SOFCs have the highest power density of all fuel cell types, making them suitable for stationary power applications like buildings.
- **Sustainability:** Solid oxide fuel cells (SOFCs) have the longest lifespan of all fuel cell varieties and can operate for up to 40,000 hours, making them suitable for long-term use
- **Cost:** Polymer electrolyte membrane (PEM) fuel cells are the most cost-effective due to their reduced material and manufacturing costs.
- **Environmental effect:** Alkaline fuel cells (AFCs) are considered the most eco-friendly because they can use non-toxic, non-combustible fuels like hydrogen and oxygen.

Besides the efficiency and costing there are other factors justifying the choice of PEMFC over others such as:

- Fast response time
- Fast start-up time
- Low operating temperature (60-100 deg Celsius)
- Lightweight and compact

Considering these aspects PEMFC is the most suitable fuel cell to proceed further research.

1.1.7: Oscillating Water column over other wave converters

There are several other technologies that can harness wave energy. Point absorbers, for example, utilize the vertical or horizontal motion of floating buoys or structures to capture wave energy. These devices often incorporate a power take-off (PTO) system that converts the motion of the buoys into electricity. Point absorbers can be deployed individually or in arrays and offer flexibility in installation and maintenance due to their relatively small size.

Attenuators, on the other hand, are long, segmented structures that float parallel to the wave direction. As waves pass through the segments, relative motion is generated between them, which is then converted into electricity. Attenuators are designed to align with the prevailing wave direction and can capture energy from multiple wave directions, making them efficient and versatile wave energy converters.

Overtopping devices are another type of technology that harnesses wave energy. These devices allow waves to flow over a ramp or structure, filling a reservoir or basin. The potential energy stored in the collected water is then used to generate electricity through turbines or hydroelectric systems. Overtopping devices are particularly suitable for areas with significant wave height and provide the advantage of energy storage in the form of potential energy, which can be utilized when needed.

Figure 6: Oscillating Water Column [11]

The Oscillating Water Column (OWC) offers several advantages over other wave energy conversion technologies, making it a preferred choice in certain scenarios. Here are some reasons why the OWC may be favored over other wave energy converters:

- **Environmental Compatibility:** The OWC has minimal impact on marine ecosystems. It operates without direct mechanical interaction with the waves, minimizing potential harm to marine life. Instead, it captures wave energy through the movement of air within the chamber, ensuring a minimal ecological footprint. This aspect makes the OWC an environmentally friendly choice for wave energy conversion.
- **Adaptability to Wave Conditions:** The OWC is well-suited for a wide range of wave conditions. It can effectively capture energy from both small and large waves due to its ability to adjust to varying wave heights. This adaptability allows the OWC to operate efficiently in different coastal areas, making it a versatile choice for wave energy conversion.
- **Robustness and Reliability:** The OWC is known for its mechanical simplicity, resulting in a robust and reliable system. With fewer moving parts compared to other technologies, the OWC has reduced chances of mechanical failure and requires less maintenance. Its design enables it to withstand harsh marine environments and extreme weather conditions, ensuring consistent and reliable power generation.

- **Scalability and Cost-effectiveness:** The OWC can be easily scaled up or down based on specific power requirements. It is suitable for small-scale applications, such as powering coastal communities, as well as larger-scale installations for utility-scale power generation. The modular nature of the OWC facilitates customization and cost-effectiveness, allowing for optimized system design and efficient use of resources.
- **Resource Availability:** Coastal regions often experience consistent and predictable wave patterns, providing a reliable and abundant source of renewable energy. The OWC can efficiently harness this wave energy resource, making it an attractive option for coastal areas seeking sustainable and continuous power generation.

While the OWC has these advantages, it is essential to consider site-specific conditions, wave characteristics, and project requirements when selecting the most suitable wave energy conversion technology. Other technologies, such as point absorbers, attenuators, and overtopping devices, may offer distinct advantages in certain situations, and the choice ultimately depends on factors such as wave conditions, site location, and project objectives.

1.2: Objective of the study

The objective of this study is to conduct a sensitivity and performance analysis of a comprehensive Proton Exchange Membrane fuel cell (PEMFC) model and a fuel cell-based renewable autonomous Renewable Hydrogen Fuel Cell (RHFC) system for Saint Martin, Bangladesh. The study aims to achieve several specific goals. Firstly, a dynamic PEMFC model will be constructed to simulate the behavior of the fuel cell under varying environmental parameters. This model will provide valuable insights into the performance of the PEMFC system. Next, a sensitivity analysis will be performed on the PEMFC model, focusing on parameters such as temperature, pressure, resistance, and voltage. This analysis will help identify the key factors that influence the performance of the fuel cell and allow for optimization of its operation.

Furthermore, a Regenerative Hydrogen Fuel Cell (RHFC) model will be developed, which will be powered by renewable energy sources. The study will include feasibility and cost analysis of the

RHFC model, evaluating its economic viability and potential for implementation.The performance variation of the RHFC system will be demonstrated for different seasons in Bangladesh, considering the unique environmental conditions of the region. This analysis will provide valuable insights into the system's adaptability and efficiency throughout the year.Moreover, real-time data for Bangladesh will be utilized to calculate the renewable energy power output throughout the year. This assessment will provide an understanding of the system's capability to harness and utilize renewable energy sources effectively.

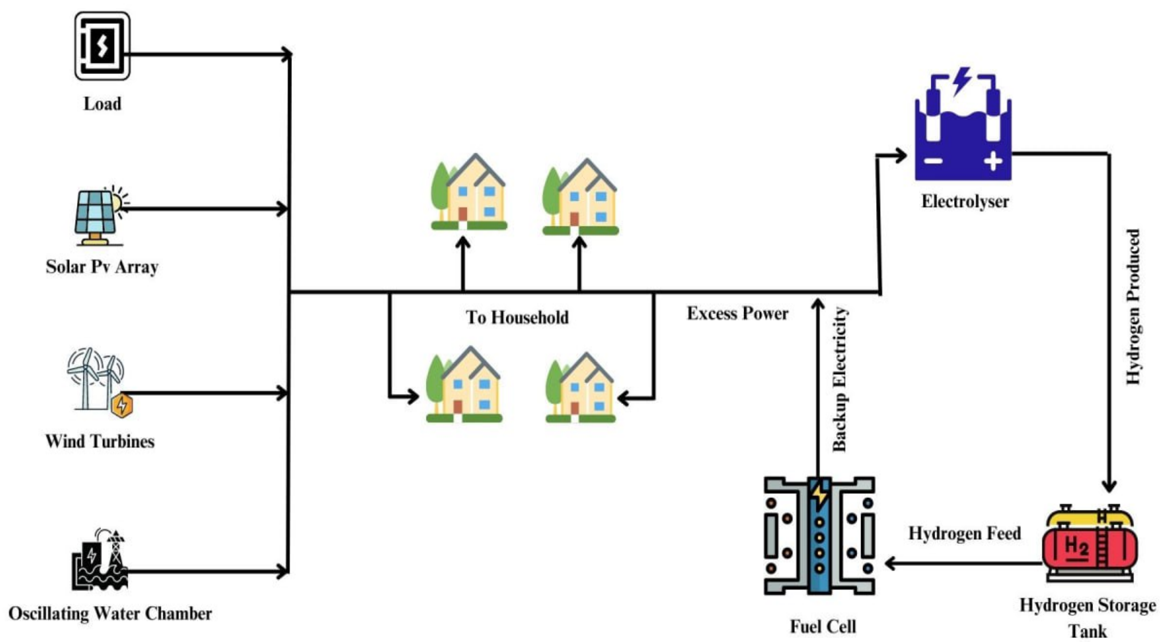


Figure 7: The Proposed RHFC system for Saint Martin

In summary, this study aims to construct dynamic PEMFC and RHFC models, perform sensitivity and performance analyses, evaluate the feasibility and cost of the RHFC system, demonstrate its performance for different seasons, and calculate the renewable energy power output. The findings from this study will contribute to the understanding and advancement of fuel cell-based renewable energy systems, particularly in the context of Saint Martin, Bangladesh.

CHAPTER 2: LITERATURE REVIEW

In this section, a detailed review of established literature has been performed about RHFC system. The first three sections are about the application of PEM fuel cell, solar, wind and OWC. The third section focuses on the sensitivity and performance analysis of PEM fuel for getting optimum ranges parameter. The final section gives a detailed overview of the RHFC model.

2.1: Review of PEM Fuel Cell

Fuel cells with proton exchange membranes (PEMs) have become a very promising technology for clean and effective energy conversion. PEMFC work at relatively low temperatures and have a solid polymer electrolyte membrane, which makes them suitable for a variety of uses including transportation, stationary power generation, and portable gadgets. This review attempts to provide a thorough overview of the current state of PEM fuel cell research and development while highlighting key innovations and discoveries.

Zhang et al. [12] presented a comprehensive review of recent advances in PEMFC, with a particular focus on materials development, operating conditions, and durability. The paper discusses various types of catalysts, electrolyte membranes, and electrode materials that have been investigated to improve cell performance and durability. It also highlights the importance of optimal operating conditions for enhancing the overall efficiency and long-term stability of PEMFC. Li et al. [13] provided a comprehensive review of recent advancements in bipolar plates for PEM fuel cells. The paper discusses various materials, manufacturing techniques, and surface modifications that have been explored to enhance the performance and sustainability of bipolar plates. It also examines the challenges associated with corrosion, gas permeation, and water management, and presents strategies to mitigate these issues. The review emphasizes the crucial role of bipolar plates in optimizing the overall performance of PEMFC. Xing et al. [14] reviewed the recent progress and future perspectives of advanced catalysts for the oxygen reduction reaction (ORR) in PEM fuel cells. The paper discusses various types of catalysts, including platinum-based and non-platinum-based catalysts, as well as their synthesis methods and electrochemical performance. It also highlights the challenges associated with catalyst degradation and presents strategies for improving the ORR kinetics and catalyst durability. The review offers valuable insights into the development of efficient and cost-effective catalysts for PEM fuel cells.

This review highlights key findings and advancements in the field of Proton Exchange Membrane (PEM) fuel cells. The reviewed papers discuss various aspects of PEMFC including materials development, operating conditions, durability, bipolar plates, water management.

2.2: Review of Solar PV Cell

Solar Photovoltaic (PV) cells are at the forefront of renewable energy technologies, providing a clean and sustainable solution for electricity generation. These devices transform sunlight directly into electricity through photovoltaic effect. This literature review aims to provide an overview of the current state of research and development in the field of solar PV cells, focusing on key findings and advancements. Green et al. [15] presented the latest version of the solar cell efficiency tables, which provided an overview of the highest recorded efficiencies for various kinds of solar PV cells. The paper discusses advancements in crystalline silicon, thin-film, and multi-junction solar cells. It also highlights the importance of materials optimization, device design, and manufacturing techniques in achieving higher conversion efficiencies. The review provides a benchmark for the performance of solar PV cells and showcases the progress made in recent years. Zhou et al. [16]focused on the emerging field of perovskite solar cells, which have gained significant attention due to their high efficiency and low-cost potential. The article discusses interface engineering strategies for enhancing the efficacy and stability of perovskite solar cells. It investigates numerous device architectures, material choices, and interface engineering techniques to improve charge transport, light absorption, and overall power conversion efficiency. This study illuminates the opportunities and obstacles in perovskite solar cell research.

This literature review highlights key findings and advancements in the field of Solar Photovoltaic (PV) cells. The reviewed papers discuss various aspects of solar PV technology, including material optimization, device design, efficiency improvements, and the exploration of new materials.

2.3: Review of wind Turbine and Oscillating Water Chamber

Wind turbines and oscillating water chambers are two prominent technologies renewable energy field. This literature review aims to provide an overview of the current state of research and development in these areas, focusing on key findings and advancements.

Jensen and Bak [17] provided a comprehensive overview of wind turbine, covering fundamental concepts and engineering principles. The book discusses various types of wind turbines, including horizontal-axis and vertical-axis designs, and explores key components such as rotor blades, generators, and control systems. It also highlights advancements in wind turbine materials, aerodynamics, and performance optimization. The review offers insights into the design and operation of wind turbines and their potential for sustainable energy generation. Falcao and Henriques [18] reviewed recent developments and future prospects of oscillating water column (OWC) wave energy converters. The article describes the fundamentals of OWC technology, which uses an oscillating chamber that is partially submerged to produce energy by causing air to pass through a turbine. The review addresses design considerations, performance analysis, and challenges associated with OWC systems. It also explores potential advancements in materials, control strategies, and integration with other renewable energy technologies. Sundararajan et al. [19]presented a comprehensive review of recent advancements in wave energy conversion technologies, including oscillating water chambers. The paper discusses various wave energy conversion principles, such as point absorbers, overtopping devices, and OWCs. It addresses the challenges associated with wave resource assessment, design optimization, and power take-off systems. The review highlights the potential of wave energy as a significant contributor to the renewable energy mix and identifies avenues for future research and development. The advancements in these technologies demonstrate their potential for sustainable energy generation and contribute to the overall efforts of transitioning to clean and renewable energy sources.

2.4: Review of Sensitivity analysis of PEM Fuel Cell

Understanding the behavior and efficiency of proton exchange membrane (PEM) fuel cells depends heavily on sensitivity analysis. It assists in determining which elements have the greatest impact on the effectiveness, robustness, and general performance of the system. This literature review aims to explore the current state of research and development in the field of sensitivity analysis of PEM fuel cells, highlighting key findings and advancements.

Aguiar et al. [20] conducted a sensitivity analysis of a PEM fuel cell model, focusing on identifying the most influential parameters affecting its performance. The study employs mathematical modeling and simulation techniques to analyze the effects of key parameters, such as membrane thickness, catalyst layer properties, and operating conditions. The sensitivity analysis provides valuable insights into the design and optimization of PEM fuel cell systems by understanding the impact of individual parameters on system performance. Hussain et al. [21] performed a sensitivity analysis of a PEMFC model to identify parameters that significantly affect its efficiency. The study investigates the impact of various parameters, including operating temperature, membrane properties, and gas diffusion layer characteristics. The sensitivity analysis helps in understanding the interplay between these parameters and optimizing PEMFC for improved efficiency. The research highlights the importance of sensitivity analysis in guiding the design and operation of PEM fuel cells. Koca et al. [22] conducted a sensitivity analysis of a PEM fuel cell model to optimize its performance. The study considers various model parameters, including kinetic and transport parameters, as well as operating conditions. The sensitivity analysis helps identify the most influential parameters and their optimal values for enhanced fuel cell performance. The research highlights the significance of sensitivity analysis in improving the efficiency and durability of PEM fuel cell systems. These peer-reviewed studies emphasize the use of sensitivity analysis approaches to pinpoint key variables and enhance PEM fuel cell system design and performance. Researchers acquire important insights into the behavior of the system and direct the optimization process by examining the effects of different parameters on performance indicators, such as efficiency and power density. Further research in this area can explore advanced sensitivity analysis methods, such as global sensitivity analysis and uncertainty quantification.

2.5: Review of RHFC system Developed in MATLAB/Simulink

The development and simulation of RHFC systems using MATLAB/Simulink provide a valuable tool for analyzing their performance, optimizing design parameters, and evaluating control strategies. By highlighting significant discoveries and developments, this literature review intends to examine the present level of research and development in the area of RHFC systems created in MATLAB/Simulink.

Jansen and Dehouche [23] presented a study on the cost-effective sizing of a hybrid Regenerative Hydrogen Fuel Cell energy storage system for remote and off-grid telecom towers. The system is designed and simulated by the authors using MATLAB/Simulink, taking into account variables like load demand, renewable energy sources, and hydrogen production. The system's size parameters, including those for the fuel cell, hydrogen storage, and power electronics, are the main subject of the study. The study sheds light on the RHFC systems' economic and technological viability for off-grid and distant applications. The technical and financial viability of RHFC systems can be evaluated by simulating and evaluating different system parameters using MATLAB/Simulink. Further research in this area can explore advanced control strategies, energy management algorithms, and integration with renewable energy sources to enhance the efficiency and reliability of RHFC systems.

Overall, this literature review provides a comprehensive understanding of the current state of research and development in renewable energy technologies, their advancements, and the potential for sustainable energy generation and storage.

Based on the literature review, one of the major potential future scopes would be the integration of control system into an advanced autonomous technology known as IoE (Internet of Energy) to support digital infrastructure that will usher in a new revolution in the energy generation industry. Also, exploration of new materials for RHFC systems, as well as the optimization of design parameters, can enhance their efficiency and reliability. Additionally, investigating the integration of RHFC systems with emerging renewable energy sources can be an area of interest.

CHAPTER 3: METHODOLOGY

3.1: Hydrogen Fuel Cell

A fuel cell is an extremely effective and environmentally responsible technology that produces electricity from the chemical energy of hydrogen or other fuels. Heat, electricity, and water are the only byproducts created when hydrogen is employed as the fuel source. Anode, cathode, electrolyte, and external circuit are main parts of a fuel cell. The separation of protons and electrons occurs as a result of the oxidation of hydrogen at the anode during the operation of the fuel cell. Oxygen is simultaneously reduced at the cathode and forms oxide species. Water is ultimately produced as a result of this chemical reaction. The method by which protons or oxide ions are carried through an ion-conducting electrolyte while insulating electrons depends on the electrolyte used in the fuel cell. The external circuit makes it easier for electrons to conduct, which enables the production of electrical power. The electrochemical reaction of a hydrogen fuel cell can be generalized as:

$$2H_2(g) + O_2(g) \rightarrow 2H_2O + \text{ energy}$$

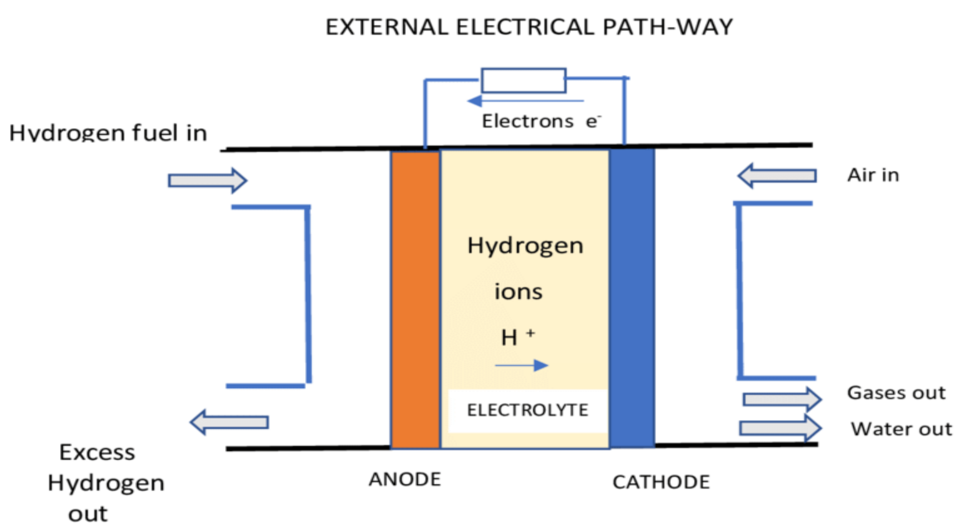


Figure 8: Hydrogen Fuel Cell [57]

3.1.1: Fuel cell technologies

Operating temperature, electrolyte type, and intended use are only a few of the criteria used to categorize hydrogen fuel cells. Hydrogen fuel cells can generally be broken down into the following types:

- **Alkaline fuel cell (AFC):** AFCs operate at elevated temperatures and uses an alkaline electrolyte, typically potassium hydroxide (KOH). Due to their weight and size, AFCs are not appropriate for mobile applications, despite their high efficiency.
- **Phosphoric acid fuel cell (PAFC):** These cells use phosphoric acid (H_3PO_4) as their electrolyte and operate between 150 and 200 degrees Celsius. They are used frequently in stationary applications and are highly efficient.
- **Solid oxide fuel cell (SOFC):** SOFCs transport oxygen ions via a solid ceramic electrolyte and typically function at temperatures between 800 and 1,000 degrees Celsius. SOFCs are extremely efficient and can use a variety of fuels, including hydrogen, natural gas, and biogas.
- **Molten carbonate fuel cell (MCFC):** Molten carbonate fuel cells (MCFCs) work at high temperatures between 600°C and 700°C and use a molten carbonate electrolyte. Despite their remarkable efficiency, MCFCs require careful electrolyte management to prevent solidification.
- **Proton exchange membrane fuel cell (PEMFC):** Polymer electrolyte membrane (PEM) fuel cells are a common form of fuel cell that use a polymer electrolyte membrane to transport protons and separate the reactant gases, which are typically hydrogen and oxygen. The low weight and reduced operating temperatures of PEM fuel cells make them suitable for use in transportation applications.
- **Direct methanol fuel cell (DMFC):** These fuel cells use liquid methanol as a fuel source and do not require an external reformer for hydrogen production. Low operating temperature and high energy density make DMFCs appropriate for portable applications.

3.1.2: Principles of Proton Exchange Membrane Fuel Cell

Proton exchange membrane (PEM) fuel cells distinguish themselves from other types of fuel cells due to their numerous advantages. These fuel cells incorporate a solid polymer electrolyte and porous carbon electrodes with a platinum or platinum alloy catalyst. The fuel cells only require hydrogen, oxygen, and water to function. Their high-power density, low weight, and compact dimensions are notable advantages. In addition, they feature comparatively low operating temperatures, approximately 80°C (176°F), resulting in quick start-up times and reduced wear on system components, which contributes to increased durability. It is essential to note, however, that the use of a noble-metal catalyst such as platinum raises system costs and makes the catalyst susceptible to carbon monoxide toxicity. auxiliary measures, such as an auxiliary reactor, may be required to reduce carbon monoxide in the fuel gas, which would increase the overall cost of the system. The PEM cell can be divided into three following layers:

- **Gas Diffusion layer (GDL):** In hydrogen fuel cells, the gas diffusion layer (GDL) is a crucial component with significant importance. The GDL is a porous and conductive material that is situated between the electrode and the bipolar plate in the membrane-electrode assembly (MEA). It performs a number of crucial functions, including the uniform distribution of hydrogen and oxygen to the electrodes and the even dispersion of reactants across the electrode surface. In addition, it serves an essential role in preventing electrode flooding and drying out, both of which can have negative effects on the operation of the fuel cell. Carbon-based materials such as carbon paper, carbon cloth, and carbon fibers are frequently used to manufacture GDLs. They possess properties such as high porosity, compressive strength, gas permeability, electrical conductivity, and hydrophobicity, allowing for optimal performance in fuel cells.
- **Catalyst layer (CL):** The catalytic layer, also referred to as the catalyst layer, is a component required for a hydrogen fuel cell to function. The anode and cathode electrodes of the fuel cell are coated with a thin layer of catalytic material via the membrane-electrode assembly (MEA). The catalytic layer's main function is to catalyze, or speed up, the chemical reactions that take place at the electrodes during fuel cell operation. The anode, which catalyzes the oxidation of hydrogen molecules (H_2) to produce protons (H^+) and electrons (e-), is typically made of a platinum-based catalyst. Similar to the anode, the cathode frequently employs a platinum-based catalyst to catalyze the reduction of oxygen molecules (O_2) to generate water (H_2O) and electrons (e-). The electrocatalytic activity of the catalytic layer is significant because it controls the amount of research required to find new catalytic materials or inventive ways to employ currently available materials in more

efficient and effective ways. In the realm of hydrogen fuel cells, research is still being done in this area.

- **Polymer Electrolyte membrane (KOH):** Polymer electrolyte membranes (PEMs) are utilized as an electrolyte membrane in hydrogen fuel cells. These membranes are composed of a polymer material that allows the transfer of protons between the anode and cathode in the fuel cell. The PEMs serve as a barrier to prevent the mixing of hydrogen and oxygen within the fuel cell, which would otherwise decrease its efficacy. PEM fuel cells are typically suitable for applications that require lower output voltage, like powering electronic devices or electric vehicles that are portable.

3.1.3: PEM cell reaction

Anode: $H_2 (g) \rightarrow 2H^+ + 2e^-$

Cathode: $(1/2) O_2 (g) + 2H^+ + 2e^- \rightarrow H_2O$

Overall: $H_2 (g) + (1/2) O_2 (g) \rightarrow H_2O$ + Electricity + Heat

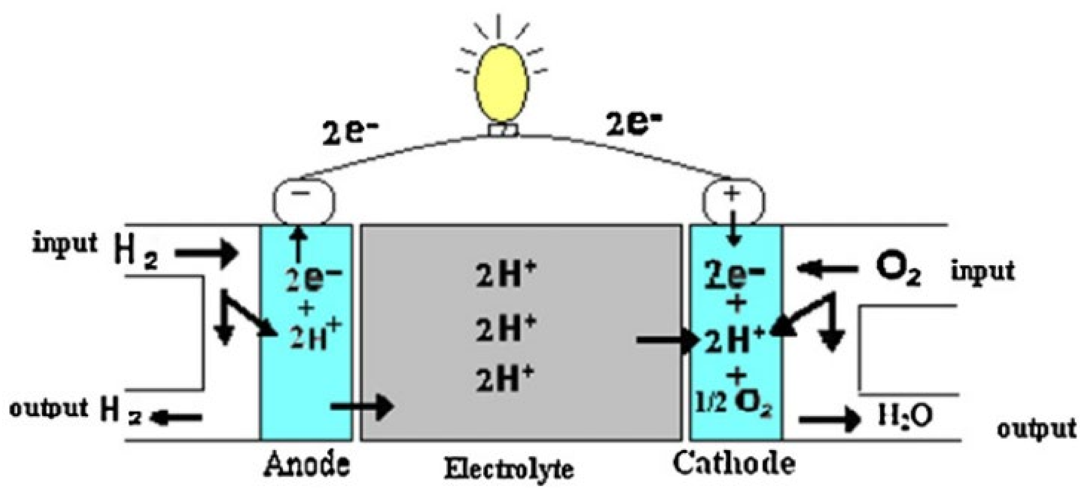


Figure 9: PEM Fuel Cell [59]

The catalyst layers present in PEMFC initiate a series of chemical reactions that result in the production of an electric potential difference between the electrodes. As long as the electrolyte allows for ionic mass transfer and both electrodes stay isolated from one another, this potential difference can be used in an external circuit. Hydrogen gas is taken in contact with the catalyst layer to be split into protons (H^+) and free electrons. Polymer electrolyte membrane only allows the protons to travel through and the free electrons that is released to the anode is forced to flow through the external circuit and it’s received by the cathode. When oxygen gas is introduced into the cathode and reacts with the proton before entering the cathode CL and the cathode's electrons, it generates H_2O, which the cathode removes.

3.1.4: Electrochemical equations

The PEM cell's operating conditions determine how much power and heat are generated. Under typical operating circumstances, a fuel cell's output voltage deviates from its standard cell voltage due to three distinct types of voltage losses (activation losses, concentration losses, ohmic losses).

$$V_{FC} = V_{Nernst} - E_{act} - E_{ohm} - E_{conc} \qquad (1)$$

Where:

V_{FC} = fuel cell voltage (V),

V_{Nernst} = Nernst voltage,

E_{act} = activation loss (V),

E_{ohm} = ohmic loss (V)

E_{conc} = concentration loss (V)

Nernst Voltage (V_{Nernst}):

According to the Nernst equation, the standard cell potential of a fuel cell varies according to the concentrations of reactants and products involved in the electrochemical process occurring inside the cell. The efficiency and performance of the fuel cell can be increased by varying the concentrations of these components.

$$V_{nernst} = E_0 + \frac{RT}{2F} \ln \frac{P_{H_2}\left(P_{O_2}\right)^{0.5}}{P_{H_2O}} \qquad (2)$$

Where:

E_0 = standard reaction potential between hydrogen and oxygen,

T = absolute temperature,

F = Faraday's constant,

P_{H_2}= partial pressure of hydrogen at anode,

P_{O_2}= partial pressure of oxygen at cathode,

P_{H_2O}= partial pressure of water at cathode.

Activation loss:

Activation loss arises in PEM fuel cells due to the energy needed to commence the reactions between the reactant gases and the catalyst at the electrode's surface. This energy requirement, known as activation energy, must be surpassed before the reactions can proceed at their standard rate. The low operating temperatures and the usage of platinum-based catalysts in PEM fuel cells pose a challenge in achieving the necessary activation energy for reactions to occur at the intended rate, resulting in activation losses. The activation loss is found by:

$$E_{act} = -2.3\frac{RT}{\alpha F}\log(i_0) + \frac{RT}{\alpha F}\log(i) \quad (3)$$

Where:

T = operating temperature (K),

α = charge transfer coefficient

F = faraday's constant (96,485 A s $mole^{-1}$)

i_0 = exchange current density (A cm^{-2})

i = operating current density (A cm^{-2})

Concentration loss:

Concentration loss is a significant problem in proton exchange membrane (PEM) fuel cells, which can reduce the cell's voltage and output power. Concentration loss is primarily caused by the depletion of reactants, namely hydrogen and oxygen. Limitations in mass transport, temperature, poisoning of catalysts, and water management are all factors that contribute to concentration loss. When the reactants cannot reach the catalyst layer rapidly enough to maintain their concentration, mass transport limitations occur, which can be affected by the electrode and electrolyte thickness, composition, and reactant flow rate. Low temperature slows the rate of the reaction, resulting in concentration loss, while impurities in the fuel or the environment contaminate the catalyst. Water management is also crucial because the presence of water can dilute reactants and prevent their transport to the catalyst layer. Concentration loss can be described by the following equation:

$$E_{conc} = \frac{RT}{nF} \ln \left(\frac{i_L}{i_L - i} \right) \tag{4}$$

Where:

i_L = limiting current density (2.2 A cm^{-2})

n= number of electrons exchanged

Ohmic loss:

Ohmic loss is a form of electrical loss caused by the resistance of a fuel cell's components to the flow of electric current. Resistance to this movement is what causes ohmic loss in a fuel cell. Several variables can affect the resistance to current flow, including the thickness and composition of the fuel cell's components, the temperature of the fuel cell, and the relative humidity of the reactant gases. Ohmic loss can be shown as:

$$E_{ohm} = iR_{in} \tag{5}$$

Where:

R_{in} = cell internal resistance (Ω cm^{-2})

Hydrogen consumption (f_{fH2}):

The equivalent amount of current corresponding to the hydrogen consumption (mol/s) into the fuel cell can be shown by the following relation [24]:

$$f_{fH_2} = S \cdot \frac{I \times N_p}{n \times F} \tag{6}$$

Where:

Np= number of cells in parallel

S= Stochiometric ratio

3.2: Electrolyser system

An electrolyser is a device that employs electricity to separate the components of a liquid or gas. This procedure, known as electrolysis, is conducted in an electrolytic cell with two electrodes, an electrolyte solution, or molten salt. Positively and negatively charged ions are attracted to opposite electrodes by the applied electric current, where they are either reduced or oxidized to produce new compounds. Electrolysers are utilized in numerous industries, such as the production of hydrogen and the extraction of metals, and play a crucial role in renewable energy technology. Through water electrolysis, it is possible to produce hydrogen of high purity without emitting greenhouse gases.

3.2.1: Electrolyser technologies

To determine the most suitable electrolysis technology for an on-site hydrogen energy storage system, the following three technologies are analyzed:

- **Alkaline electrolysis:** Alkaline electrolysers, the most prevalent form of electrolyser, use potassium hydroxide (KOH) as the electrolyte. This technology has the benefit of not requiring costly noble metal catalyst materials, resulting in a system that is cost-effective. As a result of the presence of amine contaminants in the hydrogen stream, however, the delivered hydrogen is of a relatively lower purity than the hydrogen produced. Operating at elevated temperatures and pressures, these electrolyzers are ideally adapted for large-scale hydrogen production.
- **PEM electrolysis:** In contrast to alkaline electrolysis cells, PEM electrolysis cells use a solid polymer membrane as the electrolyte and function at lower temperatures and pressures. PEM electrolysers have a wide operating range and are capable of producing high current densities.
- **Anion exchange electrolysis:** Anion exchange electrolysis is a form of electrolysis in which an anion exchange membrane (AEM) serves as the electrolyte. The AEM consists of a polymer with positively charged groups that repel negatively charged anions while permitting positively charged cations to travel through. Therefore, only negatively charged anions can travel through the membrane of an AEM electrolyzer, while positively charged

cations are blocked. It operates at a lower temperature and pressure than alkaline electrolysis, reducing the energy requirements and operating costs.

3.2.2: Principles of PEM electrolyser

Proton-conducting polymer membranes, which are frequently made of perfluorosulfonic acid polymer, are used in PEM electrolysers to separate the anode and cathode compartments. The electrolysis process takes place and the hydrogen and oxygen molecules are separated when a Direct Current (DC) power source, such as solar PV, is attached. This separation occurs concurrently as a result of the action of the DC power source on the electrolytic cell. The PEM conducts hydrogen protons (H+), while excess water is returned to the water reservoir and oxygen is either securely vented out or trapped and compressed in a tank. In the cathode compartment, hydrogen protons and electrons react to produce pure hydrogen gas.

3.2.3: PEM electrolyser reaction

Anode: $2H_2O \rightarrow O_2 + 4H+ + 4e^-$

Cathode: $4H+ + 4e^- \rightarrow 2H_2$

Overall: $2H_2O + \text{Electricity} + \text{Heat} \rightarrow 2H_2 + O_2$

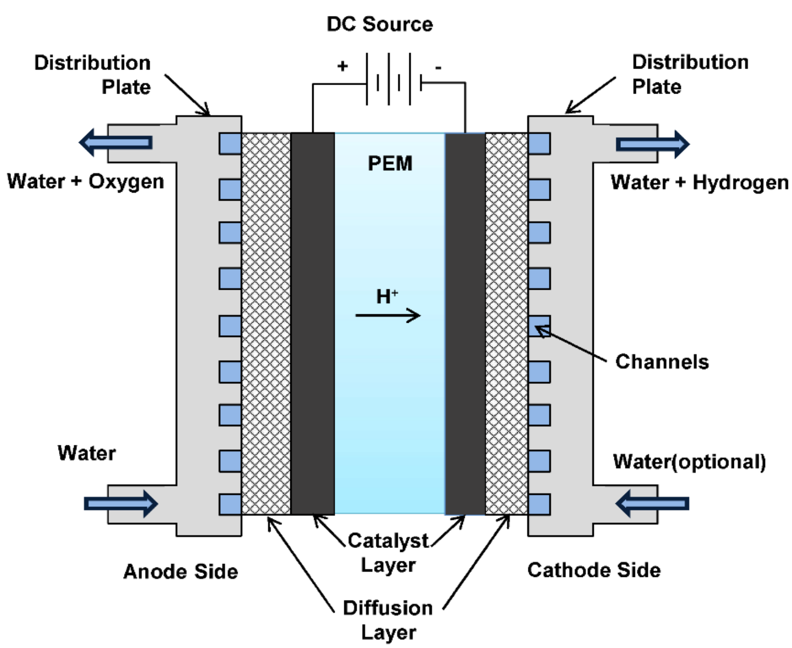


Figure 10: PEM electrolyser [58]

3.2.4: Electrochemical equations

Electrolyser voltage is directly related to the applied current to the electrolyser and due to irreversible losses it increases the electrolyser voltage as following [25]:

$$V_{el} = V_{Nernst} + E_{act} + E_{ohm} + E_{conc} \tag{7}$$

Where:

V_{el}= voltage of electrolyser (V)

V_{Nernst}= Nernst voltage (1.482V)

E_{act}= activation voltage (V)

E_{ohm}= ohmic voltage (V)

E_{conc}= concentration voltage (V)

The overpotentials are found by similar sets of equation as fuel cell according to [25]:

$$E_{act} = -2.3\frac{RT}{\alpha F}\log(i_0) + \frac{RT}{\alpha F}\log(i) \tag{8}$$

$$E_{conc} = \frac{RT}{nF}\ln\left(\frac{i_L}{i_L - i}\right) \tag{9}$$

$$E_{ohm} = iR_{in} \tag{10}$$

Hydrogen production (f_{EH_2}):

Faraday's law of electrolysis states that the amount of hydrogen produced during electrolysis is directly proportional to the amount of electric charge applied at the electrodes. The rate of hydrogen production (mol/s) can be shown as:

$$f_{EH_2} = \eta_f \frac{I_e}{nF} \tag{11}$$

$$\eta_f = 96.5e^{\left(\frac{0.09}{i} - \frac{75.5}{i^2}\right)} \tag{12}$$

Where:

η_f = efficiency of electrolysis

I_e = current applied to the electrolyser

i = current density

3.3: Hydrogen Storage system

Due to its physical and chemical properties, hydrogen storage is problematic. Its low density, high flammability, ability to diffuse through materials, and high energy content make it a hazard in the event of an accident. To effectively store hydrogen, it must be compressed to high pressures or maintained at extremely low temperatures, which requires a substantial amount of energy and expense. Handling and transporting hydrogen necessitates the use of specially constructed containers and pipelines, as well as adequate ventilation to prevent the buildup of hydrogen gas. There are a variety of methods for storing hydrogen, but each method presents its own safety, efficacy, and cost challenges. To make hydrogen storage practical and cost-effective for widespread use, additional research and development is required. There are three main methods used for hydrogen storage, which are high-pressure gas storage, cryogenic liquid storage, and solid metal-hydride storage.

3.3.1: Hydrogen storage technologies

- **Cryogenic Liquid:** Using cryogenic methods to store hydrogen requires chilling the gas to -253°C, which is a time-consuming and energy-intensive process. This storage method can result in the loss of up to 40 percent of the hydrogen's energy content [26]. Cryogenic storage of hydrogen provides a significant advantage in terms of hydrogen density, which exceeds 70 g/L [27]. Therefore, this technique is particularly useful for space exploration and specialized modes of hydrogen transportation, such as dedicated ships and vehicles that require the transport of large quantities of hydrogen.

- **High pressure Gas technology:** Compressing hydrogen at 350 to 700 bar reduces the volume required to store one kilogramme of hydrogen significantly. When the pressure is increased from 1 bar to 350 bar, the density of hydrogen reaches 22.9 g/L, and further increases to 39 g/L when the pressure is raised to 700 bar [28].

  High-pressure hydrogen storage is widely preferred because it enables rapid refuelling and provides a simple infrastructure solution. Nonetheless, retaining hydrogen at high pressures raises safety concerns due to its potential detrimental effect on the mechanical properties of metals at room temperature. This condition is referred to as high pressure hydrogen embrittlement. Additionally, high purity hydrogen at high pressure can also impact the mechanical properties of metals. [29]

- **Solid-metal hydride:** Solid metal hydride storage systems can store hydrogen at low pressures, between 1 and 10 bar, making them a safer and more practical alternative to high-pressure gas storage and cryogenic liquid storage. However, solid metal hydride storage has a disadvantage in that it may take a long time to ingest and release hydrogen, making it unsuitable for applications requiring rapid refueling or high output power. In addition, the materials used for metal hydride storage can be costly and may necessitate high temperatures for desorption, which can increase energy needs and costs.

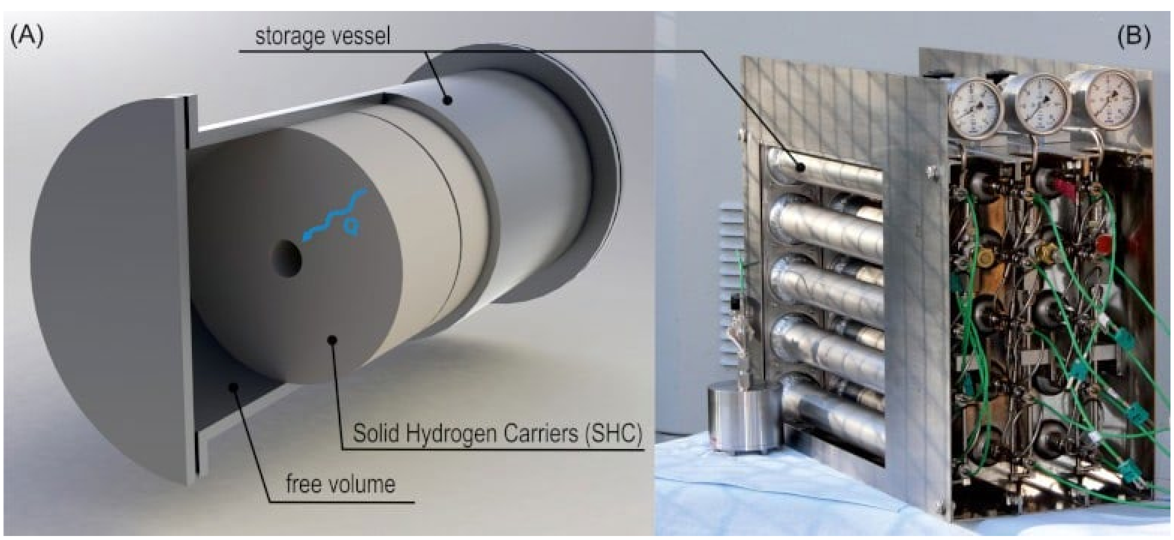


Figure 11: Solid Metal hydride storage

3.3.2: Principles of Solid Metal Hydride Storage:

Solid metal hydride hydrogen storage systems absorb and release hydrogen using metal alloys capable of producing stable compounds with hydrogen. When exposed to hydrogen gas, the interstitial sites of the crystal lattice structure of the metal retain the gas.

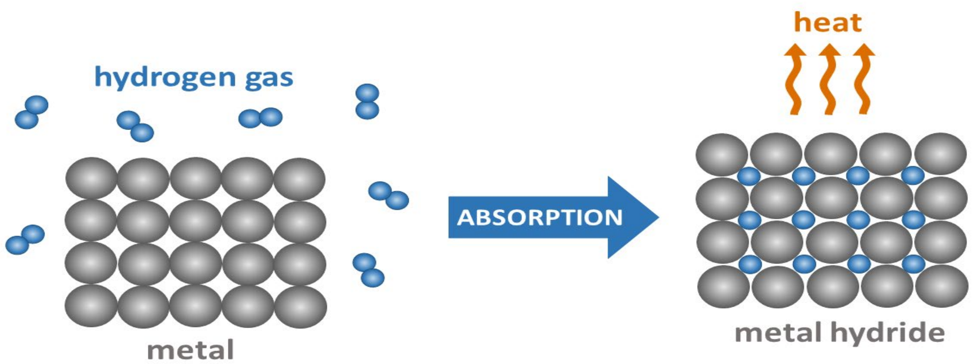


Figure 12: Hydriding process *[60]*

Hydrogen endures a molecular split when it interacts with the surface of a metal, resulting in the formation of two hydrogen atoms that become part of the metal's crystal structure, thereby forming a metal-hydride. This procedure, called hydriding, generates heat. When heat is applied to the metal-hydride, however, hydrogen is released as a gas; this process is known as dehydriding.

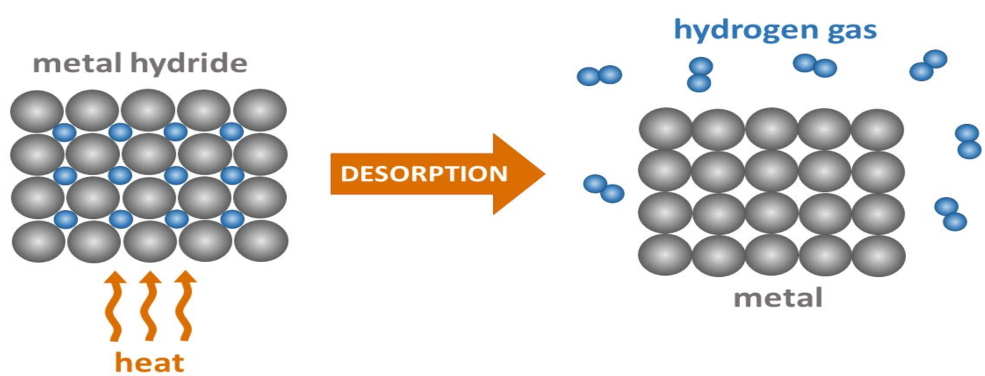


Figure 13: Dehydriding Process [60]

The hydriding and dehydriding process depend on the following reaction:

$$M + \frac{x}{2}H_2 \leftrightarrow MH_x + \Delta H$$

Where, M is the metal that is being hydrided, H_x is the amount of hydrogen that has been hydrided, ΔH is the amount of heat applied or released in the reaction.

Energy is needed to eject the hydrogen from the metal-hydride. While a portion of this energy is produced by the exothermic process in the fuel cell, additional energy is needed to heat the metal-hydride to the requisite temperature. This additional energy consumption is referred to as parasitic losses and causes a slight increase in the quantity of energy needed from the Fuel Cell. Almost 75 kJ of energy are required for the desorption of 1 mol of hydrogen. This is the same as 0.03 kWh or 3.6 MJ per mole of hydrogen released. In order to minimize parasitic losses caused by thermal energy demands, it is essential to select a metal-hydride that suits the fuel cell's operating temperature. This will maximize system integration while minimizing energy consumption.

For designing a hydride storage system Van't Hoff gas solid equilibrium equation can be used [30]:

$$\ln\left(\frac{P_{eq}}{P_0}\right) = \frac{\Delta H}{RT} - \frac{\Delta S}{R} + f(X) \tag{13}$$

Where:

ΔH= enthalpy of formation (J/mol H2)

P_{eq}= Metal-Hydride equilibrium pressure,

P_0 = standard pressure (1.013 bar),

ΔS= entropy of formation at P_0 (J/K·mol^{-1}).

f(X) can be determined by:

$$f(X) = \sum_{i=1}^{9} a_i \tan^i \pi\left(\frac{X}{X_{max}} - \frac{1}{2}\right) \tag{14}$$

The co-efficient a_i and other parameters regarding this equation can be found from [30]

3.3.3: Metal hydride storage in RHFC system:

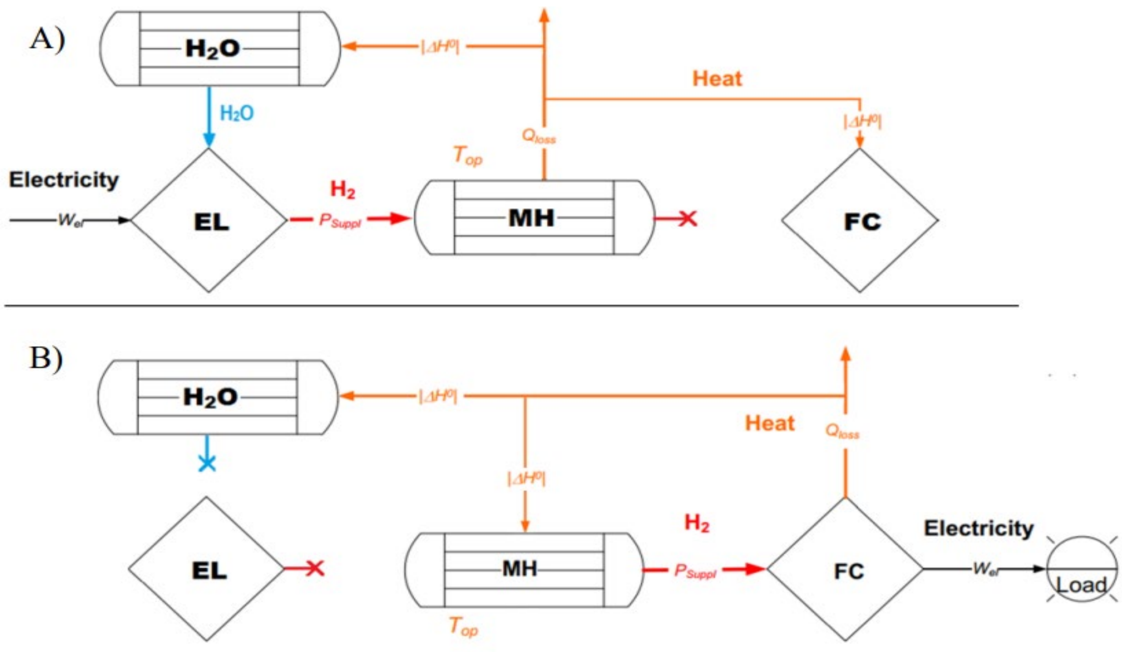


Figure 14: Heat recovery system in RHFC [61]

In the scenario A, electricity/excess power from the system and water is supplied to the electrolyser, hydrogen gas is produced and fuel cell remains turned off. Hydrogen gas coming in contact with the storage gets converted into metal hydride and due to this exothermic reaction, some heat is released that is recovered and it serves two purposes:

1. Preheating the fuel cell for fast startup.
2. Preheating the feedwater that is supplied to the electrolyser.

For the case B, in shortage of excess power/electricity, electrolyser remains turned off and fuel cell is turned on. The incoming heat from exothermic reaction in fuel cell also gets divided into two part which helps the following mechanisms:

1. Supplies the heat needed to release H_2 from metal hydride.
2. Preheats the feedwater of electrolyser.

3.4: Solar Photovoltaics

Solar photovoltaics is a technology that converts solar energy into electrical energy. This is accomplished using solar cells made from semiconducting materials such as silicon. When sunlight strikes solar cells, it dislodges electrons from atoms in the semiconducting material, generating an electrical current. Solar PV is a promising future energy source due to its sustainable and renewable nature, producing no harmful emissions or pollutants. It is expected to play a vital role in fulfilling future energy requirements, primarily due to its ability to provide renewable and clean energy while reducing carbon emissions. The need to promote sustainability and reduce dependence on fossil fuels due to growing environmental concerns further adds to the potential growth of solar PV.

3.4.1: Working principle of Solar PV

Typically, a solar cell is composed of a thin layer of semiconductor material, such as silicon, that is doped with impurities to produce two layers, one positively (P-type) and the other negatively (N-type) charged. In between the two layers, a p-n junction is created.

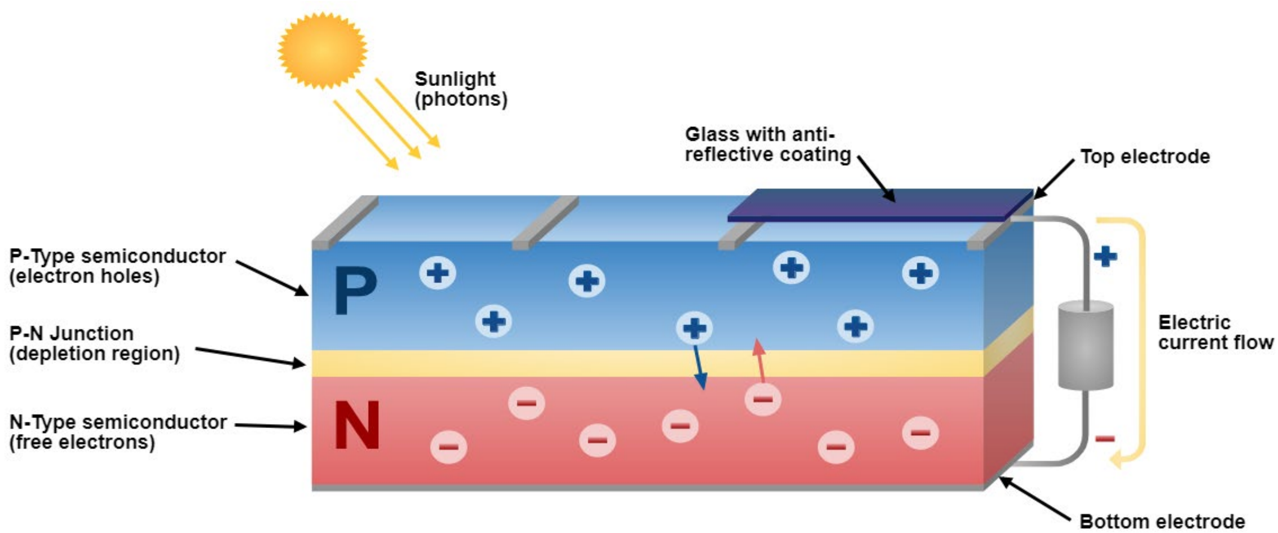


Figure 15: Working principle of Solar PV cell [62]

Sunlight is made up of particles. When a photon having energy more than bandgap energy of semiconductor, strikes the cell; an electron-hole pair is generated. When silicon atoms' outer shell electrons diffuse into the N-type layer, a hole results, which diffuses into the P-type layer. [31].

Electrons are conducted by the front electrode and travel back to the back electrode via an external electric circuit, generating an electric current. Current is collected by metal contacts on both sides of the cell and transferred to an external circuit, such as a battery or electrical device. To increase the efficiency of solar cells, multiple cells can be connected to form a solar panel, and multiple panels can be connected to form a solar array capable of producing more energy.

3.4.2: PV cell equations

The generation of current by a single solar PV cell is primarily determined by two variables: solar irradiance and temperature. The following sets of equation describes the complete solar PV system:

Current transfer (I_{PV}):

$$I_{PV} = N_P I_{PH} - N_P I_0 \left[\exp\left(\frac{\frac{V}{N_S} + IR_S}{nV_T} \right) - 1 \right] - N_P I_{SH} \qquad (15)$$

Where:

N_P= cells in parallel,

N_S= cells in series,

I_{PH}= photo current of cell (A),

I= operating current of cell (A),

I_0= dark saturation current of cell (A),

V= Cell operating Voltage (V),

R_S= series resistance (Ω),

n= ideality factor of the diode (1.2),

V_T= thermal voltage (V),

$I_{SH=}$ shunt current (A)

Module photo-current (I_{PH}):

$$I_{PH} = I_{SC} + K_i(T - T_{ref}) \cdot \frac{G}{1000} \tag{16}$$

Where:

I_{SC}= cell short circuit current (6.48A for selected cell),

K_i= short-circuit current,

G= irradiance (W/m^2)

Dark saturation current (I_0):

$$I_0 = I_{RS} \left[\frac{T}{T_{ref}}\right]^3 \exp\left[\frac{qE_{g0}}{nk}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right] \tag{17}$$

Where:

I_{RS} = module reverse saturation current (A),

T_{ref} = reference temperature (298K),

E_{g0} = band gap energy of silicon semiconductor (1.1 eV),

q = charge of electron

k = Boltzmann's constant

T = operating temperature (K),

Shunt current (I_{SH}):

$$I_{SH} = \frac{\frac{V}{N_S} + IR_S}{R_{SH}} \tag{18}$$

where, R_{SH} = Shunt resistance

Reverse saturation current (I_{RS}):

$$I_{RS} = \frac{I_{SC}}{\left[\exp\left(\frac{qV_{OC}}{N_S nkT}\right) - 1\right]} \tag{19}$$

Where:

V_{oc}= open circuit voltage of PV cell (0.68 V for selected cell)

Thermal voltage (V_T):

$$V_T = \frac{kT}{q} \tag{20}$$

3.5: Wind Turbine:

A wind turbine is a device that generates electricity using the kinetic energy of the wind. Typically, wind turbines consist of a tall structure and a rotor with two or three blades that rotate about a horizontal or vertical axis. Wind power is becoming increasingly cost-competitive with other electricity sources, making it an attractive option for many nations seeking to reduce their reliance on fossil fuels and carbon footprint. In addition, wind turbines can be installed both on land and at sea, making them a versatile renewable energy source.

3.5.1: Working principle of wind turbine

Various wind turbine components work together to transform the kinetic energy of the wind into electrical power.

Rotor blades are designed to capture wind energy by revolving around the center of the rotor as it is driven by the wind. **The rotor hub** is linked to a transmission, which raises the speed of the rotor blades and sends rotational energy to a generator. The **generator** subsequently turns the rotational energy into electrical energy, which can be utilized to power various electrical gadgets, residences, and businesses.

A **tower** is meant to lift the rotor blades to higher elevations where wind velocity is higher to maximize wind energy capture. The **pitch control system** is in charge of regulating the angle of the rotor blades to maximize efficiency and assure safety in a variety of wind speeds and directions. The **yaw control system**, on the other hand, is used to adjust the orientation of the rotor blades in response to variations in wind direction.

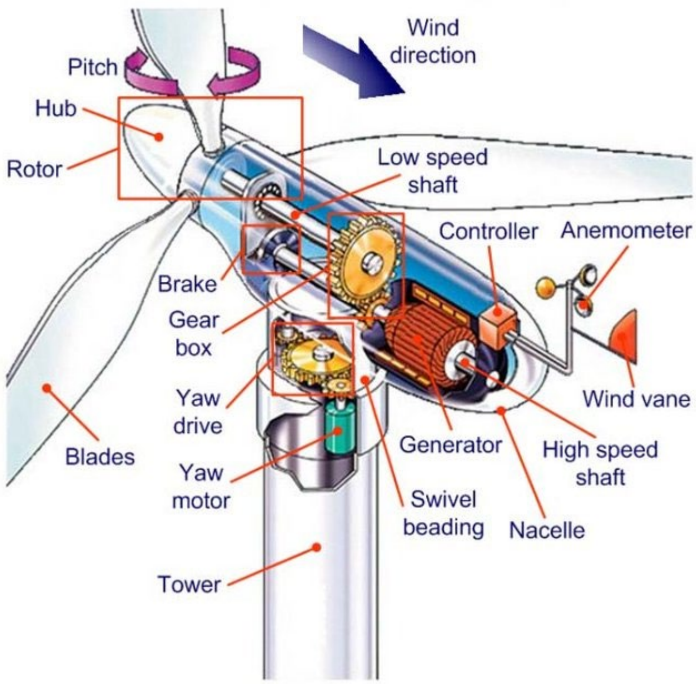


Figure 16: Components of a wind turbine [63]

Wind turbines can be installed individually or in wind farms, generating even more electricity.

3.5.2: Wind Turbine equations

Average Wind Power (P_{avg}):

The average kinetic power that can be extracted from wind:

$$P_{avg} = \frac{1}{2}\rho A(V^3)_{avg} \tag{21}$$

Where:

ρ= density of air (1.225 kg/m^3),

A= area of the rotor (m^2),

V_w= wind speed at hub height (m/s).

Actual Wind Power (P_w):

Taking the efficiencies and power coefficient into consideration, the equation can be written as:

$$P = \frac{1}{2}\rho A V_W^3 C_p \eta_{mech}\, \eta_{elec} \quad (22)$$

Where:

C_p= rotor power coefficient

η_{mech} = mechanical efficiency

η_{elec} = electrical efficiency

Mechanical efficiency measures how well a wind turbine captures and transfers wind energy to the rotor shaft. It measures the turbine's wind-to-power efficiency.

Electrical efficiency evaluates the conversion of mechanical energy to electrical energy. It gauges the wind turbine's conversion efficiency. Generator efficiency and gearbox and conversion losses affect wind turbine system electrical efficiency.

Wind Speed (V_w):

Wind speed is not typically quantified in wind turbine height. Rather, a reference height at the planned location is chosen. The following equation determines wind speed at desired height w.r.t the reference height:

$$V_W = V_{ref}\left(\frac{H}{H_{ref}}\right)^{\alpha} \quad (22)$$

Where:

V_{ref} = reference wind speed (m/s),

H = hub height (40 m),

H_{ref} = reference height (10m),

α = 0.14 (empirically derived coefficient)

The value of α may vary according to the atmospheric conditions.

Weibull Wind Power density:

The energy content of wind is constantly changing because wind speed fluctuates. Therefore, it is important to analyze the wind speed characteristics to assess the potential for generating energy at a specific location. The Weibull wind power density signifies if there is abundant amount of wind energy that can be extracted or not. This variation in wind speed can be depicted using a probability distribution function named as Weibull probability function ($f(V)_{Weibull}$).

$$f(V)_{Weibull} = \frac{k}{c}\left(\frac{V}{c}\right)^{k-1} \exp\left[-\left(\frac{V}{c}\right)^{k}\right] \tag{23}$$

where the shape factor k and scale factor c depend on the wind speed data that is generated for the selected site over a certain period (monthly/yearly) of time. These factors can be written as:

$$k = \left(\frac{\sigma}{v}\right)^{-1.086} \quad 1 \le k \le 10 \tag{24}$$

$$c = \frac{v}{\Gamma\left(1 + \frac{1}{k}\right)} \tag{25}$$

Here $\Gamma(x)$ is the gamma function of x which is defined by Stirling approximation as follows:

$$\Gamma(x) = \int_0^\infty e^{-u} u^{x-1} du$$

The mean wind speed and the variance are calculated by:

$$\bar{v} = \frac{1}{n}\left[\sum_{i=1}^{n} v_i\right]$$

$$\sigma = \left[\frac{1}{n-1} \sum_{i=1}^{n} (v_i - \bar{v})^2 \right]^{1/2}$$

And Weibull wind power density (W/m^2) becomes:

$$\frac{P}{A} = \int_0^{\infty} \frac{1}{2} \rho v^3 f(v) dv = \frac{1}{2} \rho c^3 \Gamma \left(\frac{k+3}{k} \right) \tag{26}$$

The energy density (J/m^2) can also be similarly calculated for the desired time using:

$$\frac{E}{A} = \frac{1}{2} \rho c^3 I \left[\left(\frac{k+3}{k} \right) T \right] \tag{27}$$

Wind power density is generally calculated for a month or a year in order to get a reliable value that can give a proper idea about the wind power potential.

3.6: Oscillating Water Column (OWC)

OWC is an eco-friendly and renewable energy technology that converts the energy of ocean surges into electricity. It comprises of a chamber that is exposed to the waves and partially submerged. When the waves enter the chamber, the air is displaced, causing oscillations that generate sufficient energy to drive a turbine and generate electricity. The OWC technology offers a promising strategy for harnessing the vast energy potential of ocean waves without emitting detrimental pollutants or greenhouse gases. Typically, OWC systems have a lifespan of 20 to 25 years, but this can be extended through routine maintenance and enhancements. By adhering to proper design, construction, maintenance, and monitoring protocols, the performance and durability of OWC systems can be optimized, thereby making them a crucial component of the global transition to clean and sustainable energy sources.

3.6.1: Principles of OWC

OWC comprises of a partially submerged, ocean-accessible chamber as shown in the Figure 17. As waves penetrate the chamber, the water level rises and falls, displacing the air and forming a column of moving air. Due to the movement of the waves, this column of air oscillates, and as it moves back and forth, it powers a turbine-connected generator. The bidirectional turbine converts the kinetic energy of the waves into mechanical energy, which is then transmitted to the electrical generator. The output of the OWC is primarily dependent on wave height and frequency.

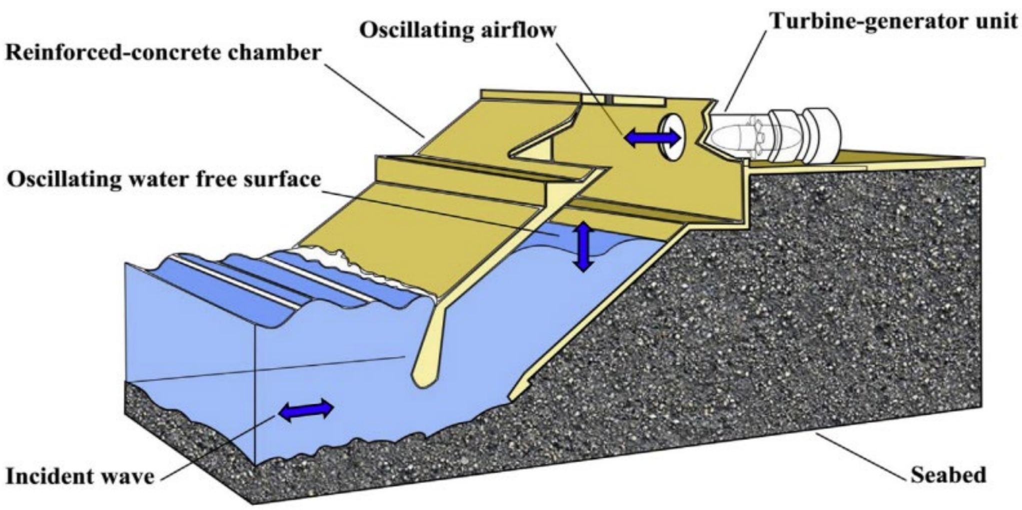


Figure 17: Schematic cutaway of Oscillating Wave Chamber [64]

5.6.2: Oscillating water column equations

Total Power (P_{total}) & Inlet power (P_{in}):

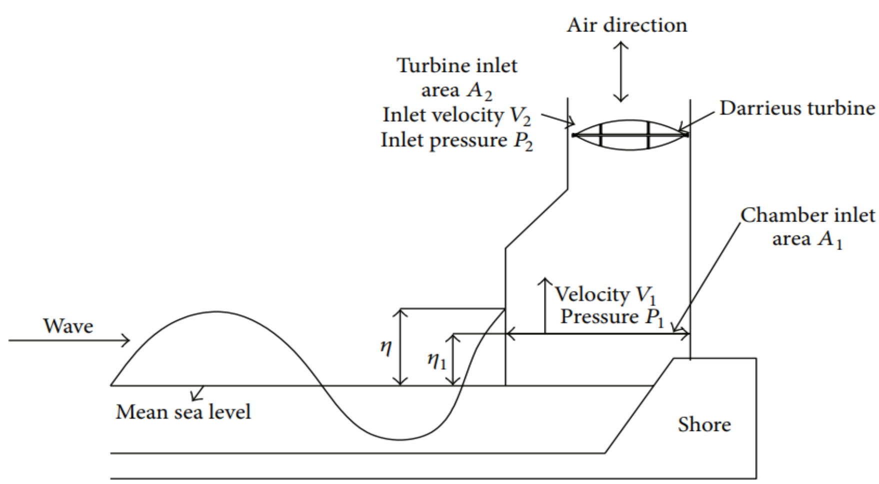


Figure 18: OWC chamber parameters [34]

The total output power of an OWC is dependent on Inlet power (P_{in}) and turbine power coefficient (C_p).

$$P_{total} = P_{in} \times C_p \tag{28}$$

Where:

$$P_{in} = (P_a + P_{pt}) \tag{29}$$

Operating principle of OWC is similar to wind turbine systems, so the power available at the wave turbine can be divided into two terms: air velocity term P_a and air pressure term P_{pt}.

The angular chamber length (θ):

$$\theta = \frac{2\pi L_{ch}}{\lambda} \tag{30}$$

Where:

L_{ch}= chamber length (1.5m)

λ= actual wave length

According to [32] this actual wave length is approximated as:

$$\lambda \cong \left(1 - \frac{\pi d}{3\lambda_0}\right) \times T_m\sqrt{gd} \tag{31}$$

d= water depth

λ_0= theoretical wave length

This theoretical wave length was formulated in [33] which was given as:

$$\lambda_0 = \frac{gT^2}{2\pi} \tag{32}$$

g= gravitational acceleration

Chamber inlet velocity (V_1):

The velocity of the air adjacent to the internal free surface (V_1) can be denoted by:

$$V_1 = \frac{d\eta_1}{dt} = -\frac{\omega H_{in}}{\theta} \sin(\omega t) \times \sin\left(\frac{\theta}{2}\right) \quad (33)$$

Where, ω = angular frequency

$$\omega = \frac{2\pi}{T_m} \quad (34)$$

Turbine inlet velocity (V_2):

Applying the continuity equation,

$$V_2 = \frac{A_1}{A_2} V_1 = -\frac{A_1}{A_2} \frac{\omega H_{in}}{\theta} \sin(\omega t) \times \sin\left(\frac{\theta}{2}\right) \quad (35)$$

Free Surface elevation (η_1):

The free surface elevation of water inside of the chamber is defined according to [33]:

$$\eta_1 = \frac{H_{in}}{2} \cos\left(\frac{2\pi}{T_m} t\right) \times \frac{2\sin(\theta/2)}{\theta} \quad (36)$$

Where:

H_{in}= averaged internal wave height (m)

T_m= wave period (s)

Air Velocity term (P_a):

Air velocity term is quite simpler than pressure term and can be described as following:

$$P_a = \frac{\rho A_2 V_2^3}{2} \tag{37}$$

Where:

ρ= density of air (1.225 kg/m^3),

A_2= inlet turbine area

Air Pressure term (P_{pt}):

The power P_{pt} mainly depends on the volume of air flow rate Q across the turbine and the pressure gradient [33]

$$P_{pt} = (p_2 - p_0) \times Q \tag{38}$$

Where:

p_0= exhausted pressure (ambient)

p_2= upstream inner pressure

The volume flow rate Q is formulated from the continuity equation:

$$Q = A_1 \times V_1 = V_2 \times A_2$$

Upstream inner pressure can be calculated by Bernoulli's equation as following:

$$p_2 = p_1 + 0.5 \times \rho \times (V_1^2 - V_2^2) + \rho \frac{\delta}{\delta t}(\varphi_1 - \varphi_2) \tag{39}$$

Here, $\varphi 1$ and $\varphi 2$ are called velocity potentials which can be denoted as:

$$\varphi_1 \approx V_1\eta_1$$
$$\varphi_2 \approx V_2\eta_2$$

Again, the pressure differences are derived from linear momentum equation theory as:

$$p_2 - p_0 \approx \rho \frac{A_1}{A_2}\frac{\delta\varphi_1}{\delta t} + \rho \frac{Q}{A_2}(V_2 - V_1) \quad (40)$$

Considering all these equations the final air pressure term was derived in [34] which is:

$$P_{pt} = [\& - \frac{A_1}{A_2}\frac{H_{in}^2}{\theta^2}\omega^2\{2\cos(\omega t)^2 - 1\} \times \sin^2\left(\frac{\theta}{2}\right) + \frac{Q}{A_2}(V_2 - V_1)\ ] \times Q \times \rho \quad (41)$$

For simplicity, the above equation can also be written as the following that is derived in this current literature:

$$P_{pt} = [\& - \frac{A_1}{A_2}\frac{H_{in}^2}{\theta^2}\omega^2\{\cos(2\omega t)\} \times \sin^2\left(\frac{\theta}{2}\right) + \frac{Q}{A_2}(V_2 - V_1)\ ] \times Q \times \rho \quad (42)$$

3.7: Control System

Control system refers to a system of interconnected device and components that collaborates, regulates and direct the performance of other systems and processes. It ensures the desired output regardless of any changes or disturbances occurring related to the system. Sensors, actuators, controllers along with the processors combine to form a control system.

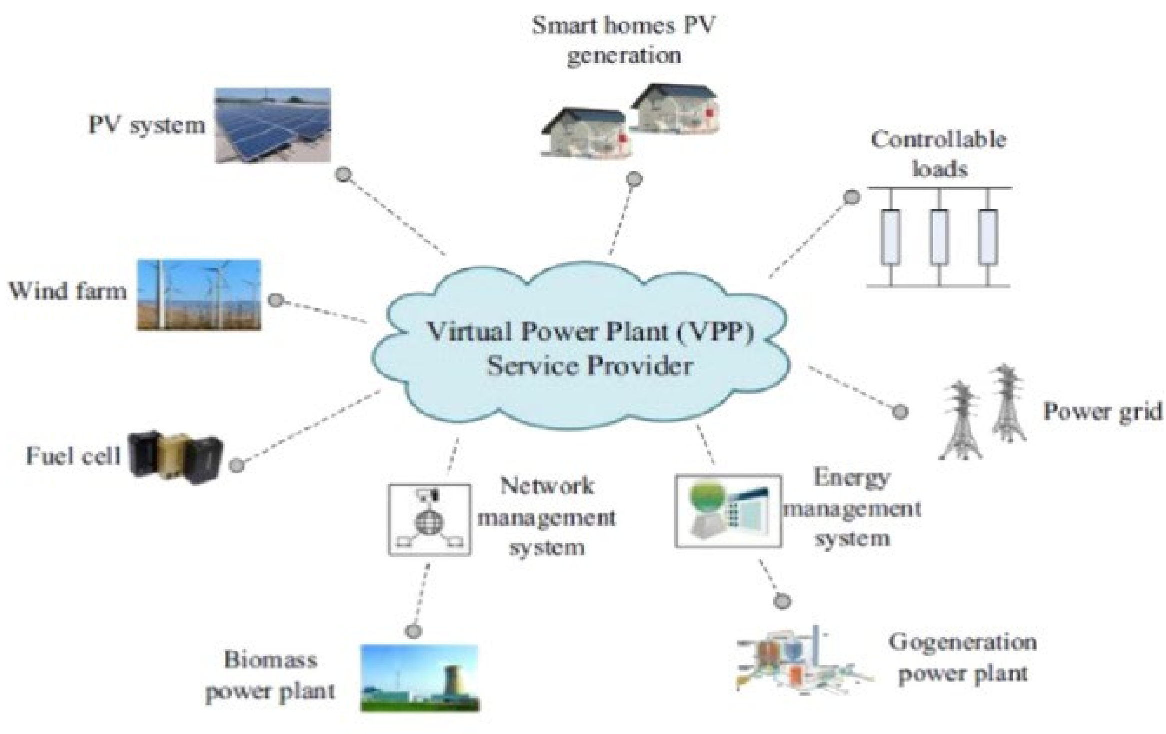


Figure 19: IoE controlled power generation [35]

In an autonomous RHFC system, a smart energy control system is required for analyzing, real-time monitoring and control of energy usage as well as optimizing the energy consumption and production which can be facilitated by an advanced intelligent technology IoE (Internet of Energy). IOE is considered as a subset of IoT (Internet of Things) created to support digital infrastructure that might bring a new revolution in the energy sector. It utilizes the internet, cloud computing, big data etc. along with different sensors to make the physical systems (Solar PV, Wind turbine, Fuel cell etc.) to be able to communicate with each other in real-time. Real-time data analytics can help the energy providers to optimize the production and distribution of energy, reduce waste of energy and promote the renewable systems as well.

IoE offers a great flexibility and efficiency in RHFC system. For example, if excess energy is produced from renewable sources and the demand is less at that instant, it directs the hydrogen storage to store the energy for later use. When an energy outage occurs, getting a command from IoE, the fuel cells get turned on to supply the required amount of energy from stored hydrogen.

In short, the following steps are to be maintained to make a communication between RHFC system and IoE:

1. Choose an IoE platform or framework such as Microsoft Azure IoT, AWS IoT, ThingWorx etc.
2. Install necessary software, drivers, and network settings to connect sensors and monitoring devices with the IoE platform.
3. Identify the required sensors for the renewable regenerative fuel cell (RHFC) system such as solar irradiance sensor, Anemometers, Wave sensors, Power meters, Energy storage sensors etc.
4. Interface the designed control system in MATLAB-Simulink into the platform.
5. Establish the connection between the system and the IoE platform.
6. Optimize energy consumption and production by utilizing the IoE platform.

While selecting IoE platforms some factors such as features and capabilities offered, cost and scalability of the platform are needed to be considered. Right communication protocol is important to transmit data from sensors to other systems through IoE platform.

3.8: Levelized Cost of Electricity (LCOE)

The Levelized Cost of Electricity (LCOE) is a useful metric for understanding the costs associated with electricity generation from various sources. It provides a transparent and standardized method for comparing the long-term costs of power generation systems, such as initial capital, operating and maintenance expenses, fuel costs, and other associated costs.

Several benefits of using LCOE include:

1. **Comparison across technologies:** LCOE standardizes the cost of generating electricity from different technologies, independent of size or capacity.
2. **Long-term perspective:** LCOE considers the lifetime expenses of a power generation system, making it a more realistic cost estimate than other measures that just examine upfront expenditures.
3. **Transparency:** LCOE estimates the cost of generating power transparently and consistently, enabling better decision-making.

LCOE computes an estimate of the cost of producing each unit of electricity by dividing these expenditures by the total amount of energy the system is expected to generate over its lifetime [36]

$$\mathrm{LCOE}\left(\frac{\$}{\mathrm{kWh}}\right) = \frac{\sum_{t=1}^{n} C_t + M_t + F_t(\$)}{\sum_{t=1}^{n} E_t(\mathrm{kWh})} \tag{43}$$

Where:

C_t = capital expenses (CAPEX),

M_t = operation & maintenance expenses (OPEX)

F_t = fuel costs

E_t = electricity generated by the system.

The lifecycle energy production of a RHFC system is highly dependent on the installation location, as solar irradiance, wind velocities, and wave characteristics vary greatly across the globe. As the average lifespan of technologies is at least 20 years, inflation rates must be considered as they affect O&M costs over time.

CHAPTER 4: MODELLING & VALIDATION

4.1: Modelling and Validation of PEMFC

The electrochemical equations of PEM cell that is described in 3.1.4 are used to create a mathematical model in MATLAB/Simulink environment. The input parameters of PEM fuel cell are described in the **Table 1**. Figure 20 shows the Simulink model of PEMFC that was designed in the current model.

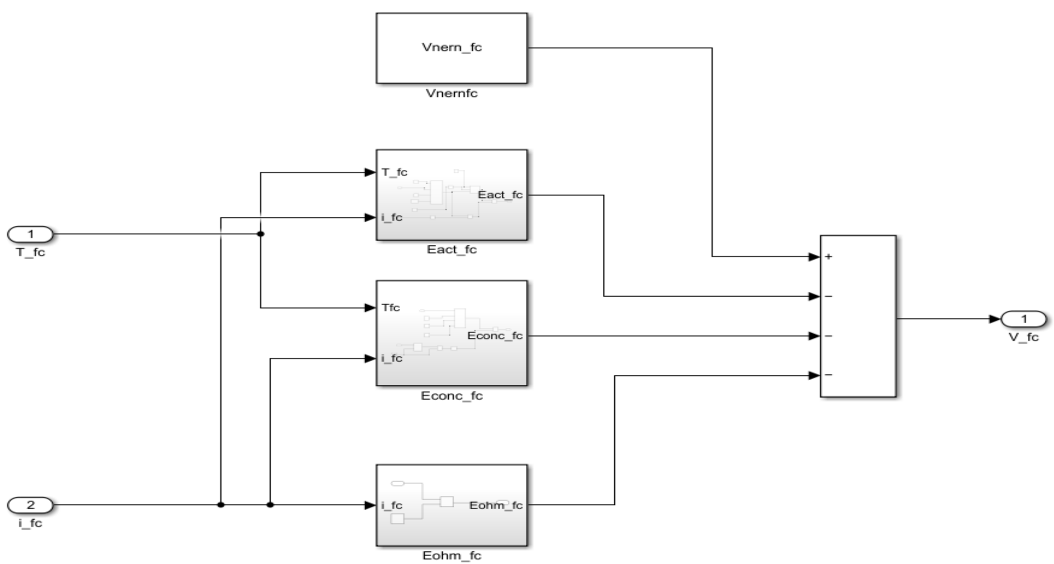


Figure 20: Simulink Model of PEMFC

Table 1: Input parameters of PEMFC

Parameter	Details
Operating Temperature	65°C
Charge transfer coefficient (α)	1
Exchange current density (i_0)	$3*10^{-6}$ A cm^{-2}
Limiting current density (i_L)	1.6 A cm^{-2}
Cell internal resistance (R_i)	0.15Ω
Number of cells in parallel (N_p)	2
Stochiometric ratio (S)	1.5
Nernst voltage	1.229V

The polarization curve (V- i) of the current Simulink model was developed and compared with the experimental literature.

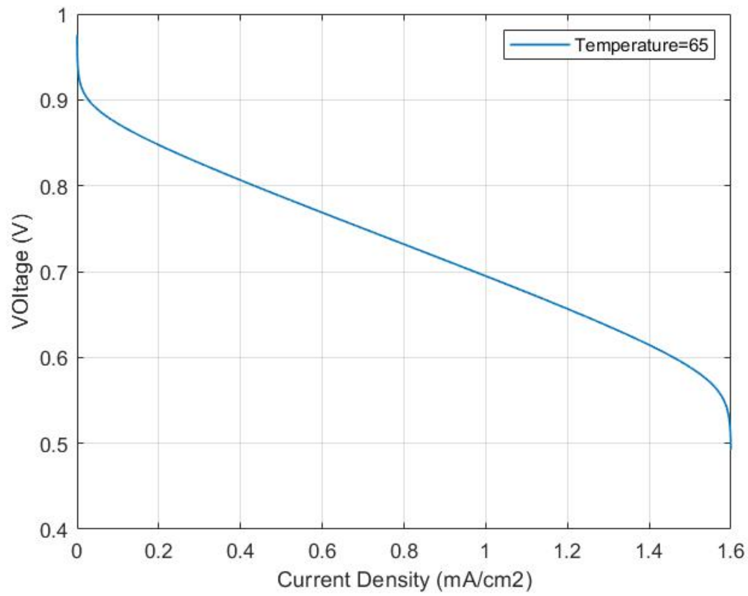


Figure 21: Polarization curve of PEMFC (current model)

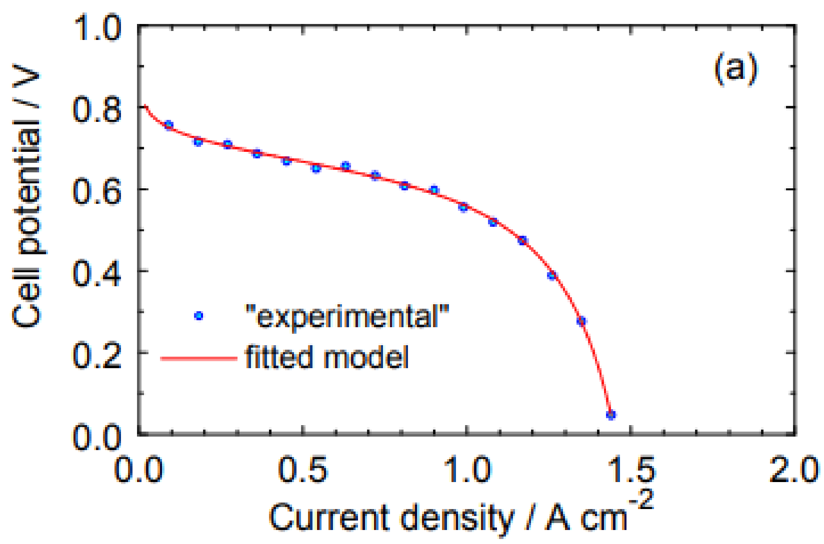


Figure 22: Polarization curve of PEMFC (experimental) [75]

4.2: Modelling and Validation of Electrolyser

Electrolyser electrochemical equations are very similar to the PEMFC which are discussed in 3.2.4. These equations along with the necessary input parameters are also modelled in MATLAB/Simulink environment. The input parameters of PEM electrolyser are given by:

Table 2: Input parameters of PEM electrolyser

Parameter	Details
Operating Temperature	60°C
Charge transfer coefficient (α)	0.23
Exchange current density (i_0)	$4.5*10^{-2}$ A cm^{-2}
Limiting current density (i_L)	2.2 A cm^{-2}
Cell internal resistance (R_i)	0.21Ω
Number of cells in parallel (N_p)	2
Nernst voltage	1.482V

The modelling and validation of electrolyser is quite similar to that of PEMFC.

4.3: Modelling and Validation of Solar PV

The equations of Solar PV are modelled in Simulink as follows:

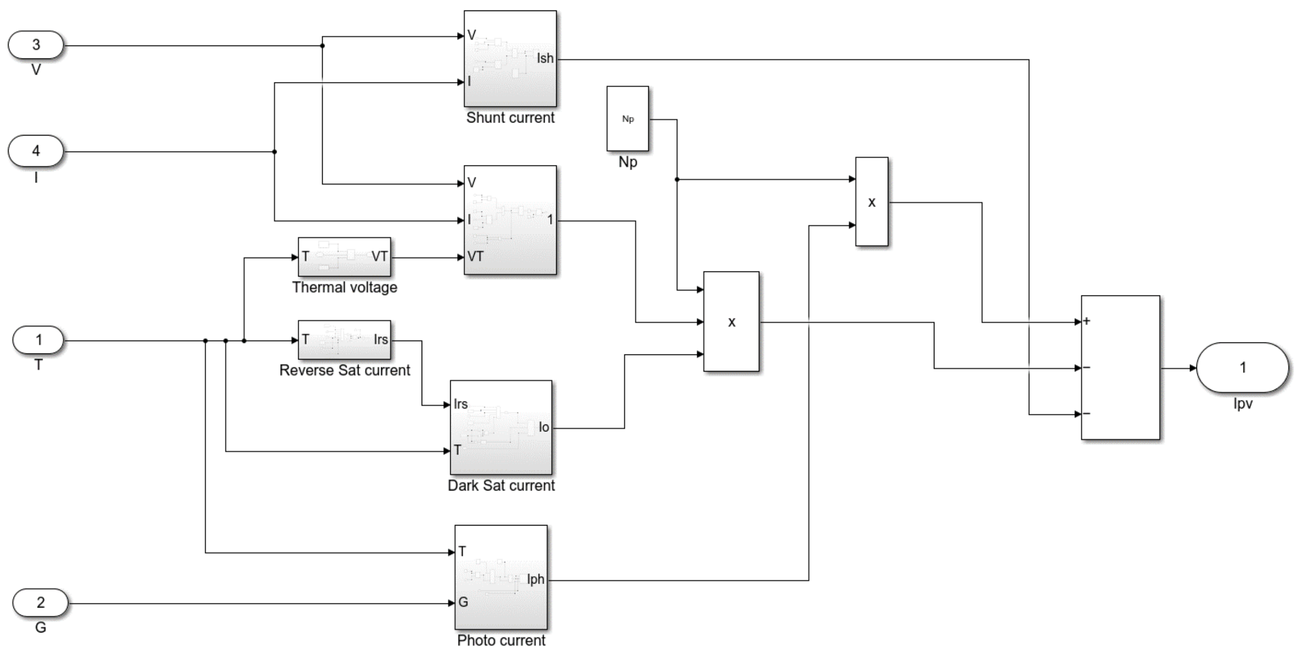


Figure 23: Simulink model of Solar PV

Table 3: Input parameters of Solar PV

Parameters	**Details**
No. of cells in parallel (N_p)	1
No. of cells in Series (N_s)	36
Series resistance (R_s)	0.0001Ω
Shunt resistance (R_{sh})	1000 Ω
Short circuit current at standard testing conditions (k_i)	0.002
Ideality factor (n)	1.2
Short circuit current (I_{sc})	6.11A
Reference Temperature (T_{ref})	25°C
Bandgap energy of silicon semiconductor (E_{g0})	1.1eV

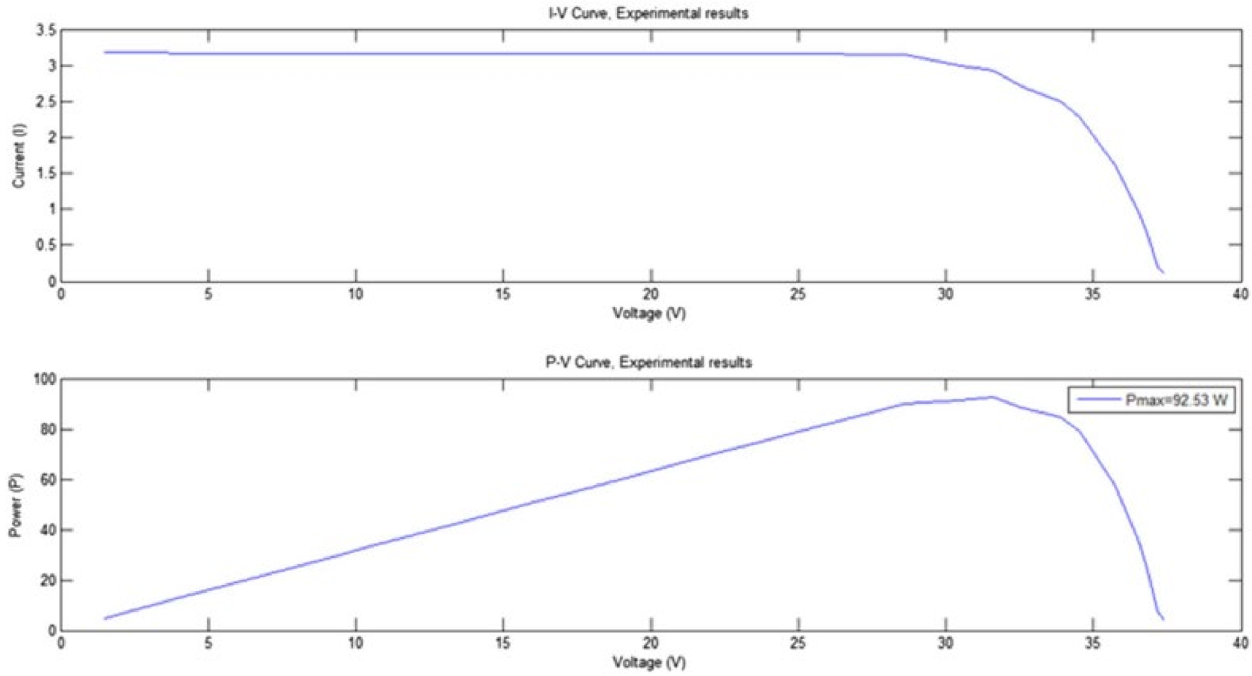


Figure 24: Experimental characteristic curve of Solar PV by Xuan Hieu Nguyen and Minh Phuong Nguyen [37]

The characteristics curve of Solar PV was generated by varying the voltage in Simulink model and corresponding output current and power were determined at three different solar irradiance which was validated against the experimental model from literature [37]

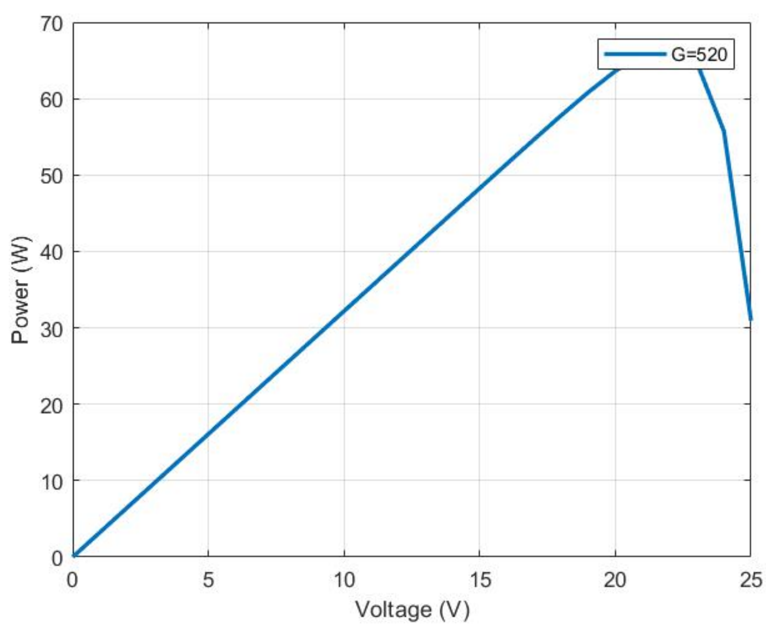


Figure 25: I-V curve of Solar PV (current model)

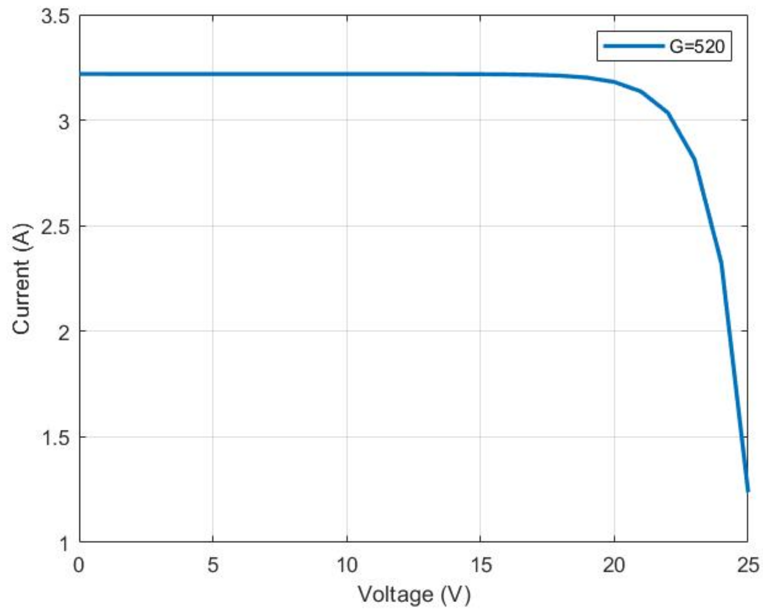


Figure 26: P-V curve of Solar PV (current model)

4.4: Modelling and Validation of Wind Turbine

The equations of Wind Turbine are modelled in Simulink as follows:

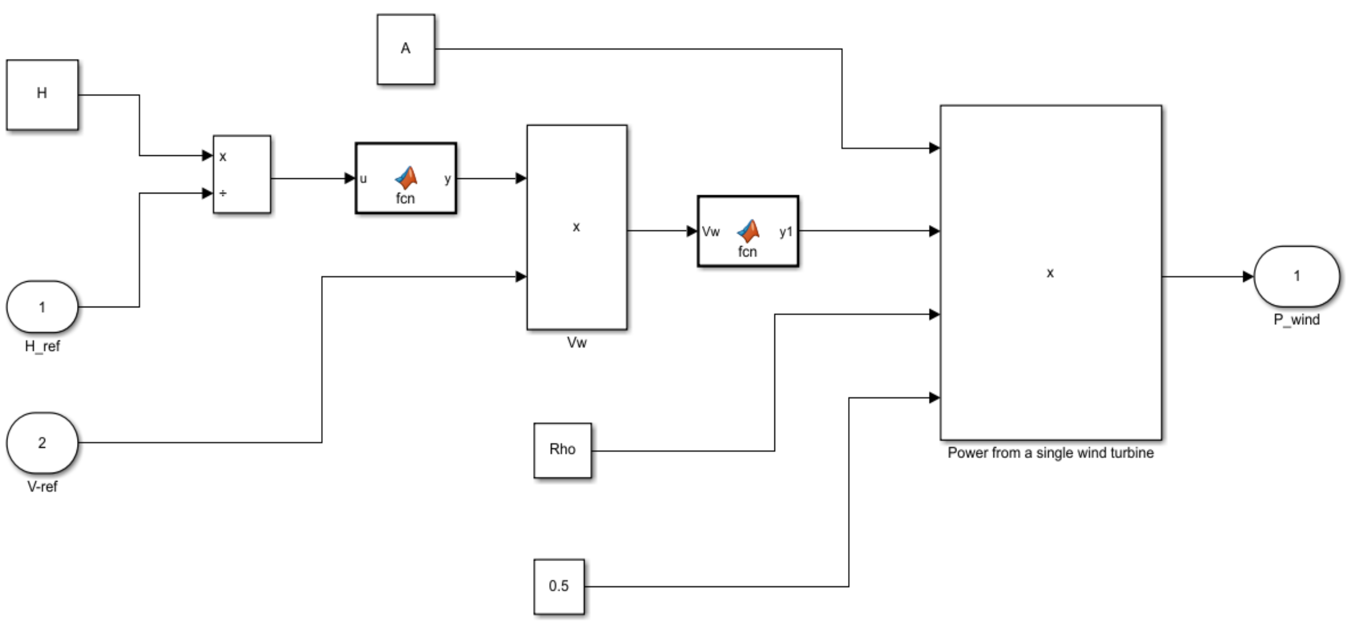


Figure 27: Simulink model of Wind Turbine

Table 4: Wind Turbine input parameters

Parameters	Details
Hub height (H)	40m
Reference height (H_{ref})	10m
Diameter of rotor (D)	20m

The characteristics curve of wind turbine was generated by varying velocity in Simulink model and corresponding output voltage was calculated. The generated curve was then validated against experimental model in literature [38].

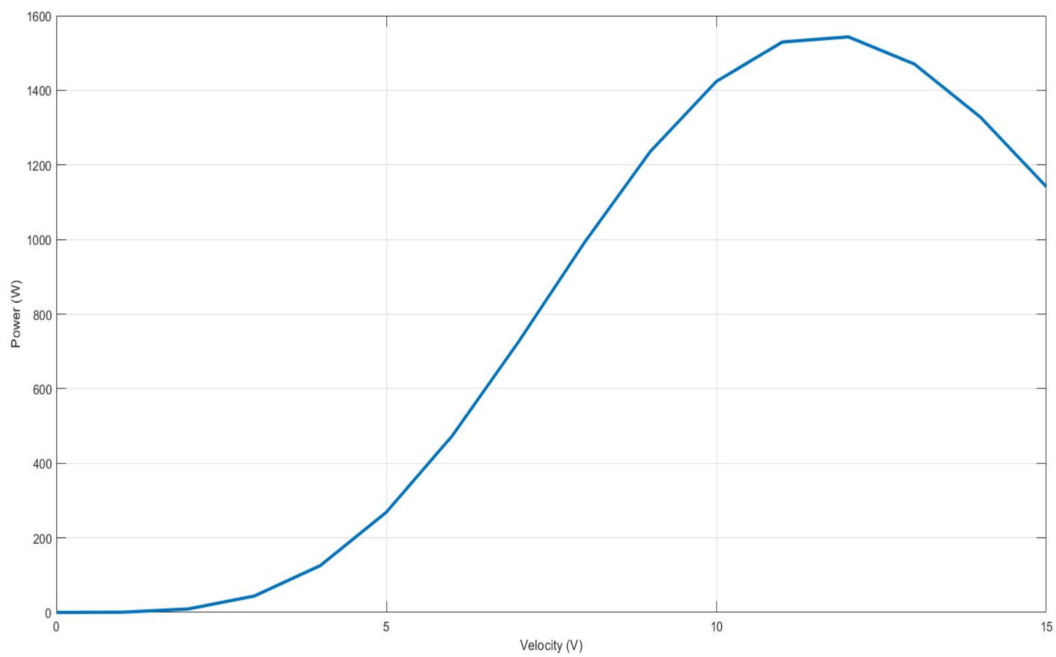


Figure 28: Wind Turbine (Weibull) characteristic curve (current model)

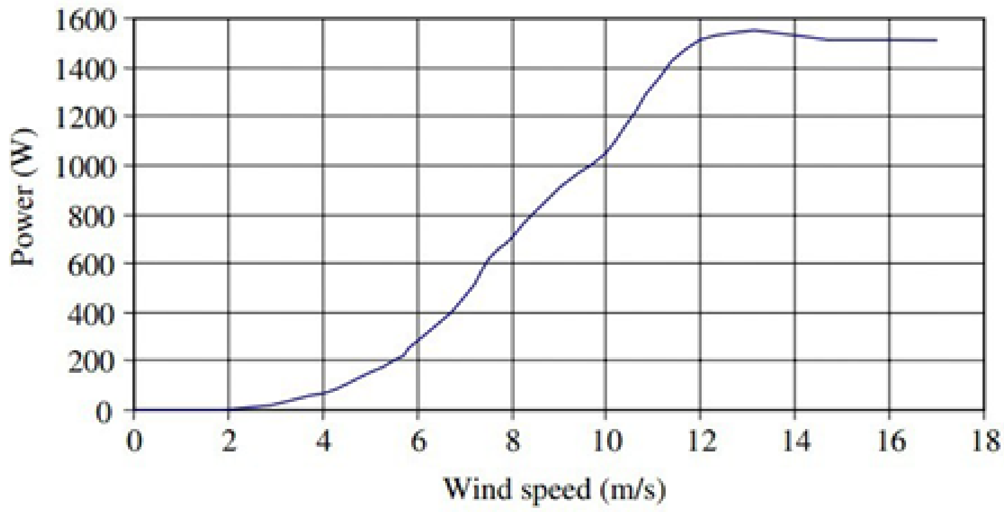


Figure 29: Wind Power characterstic curve (experimental) [76]

4.5: Modelling and validation of OWC

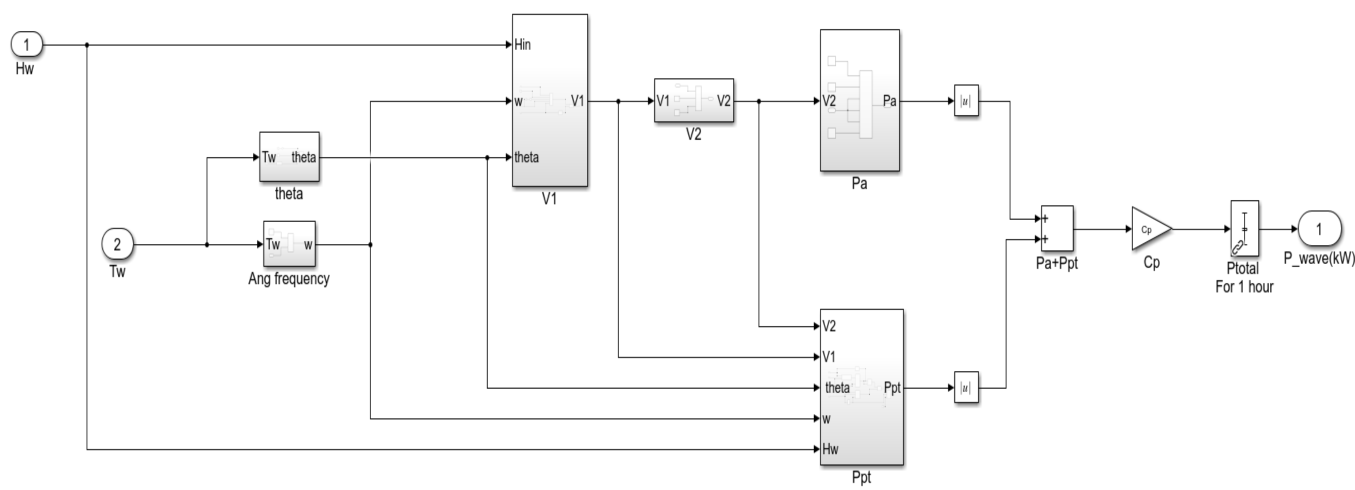


Figure 30: Simulink Model of OWC

Table 5: Input parameters of OWC

Parameters	Details
Length of Chamber (L)	1.5 m
Water surface area inside Chamber (A_1)	1.4 m^2

Turbine inlet area (A_2)	0.012 m^2
Density of air (ρ)	1.225 kg/m^3
Depth of water (d_{en})	16.47 m
Turbine performance coefficient (C_p)	0.45

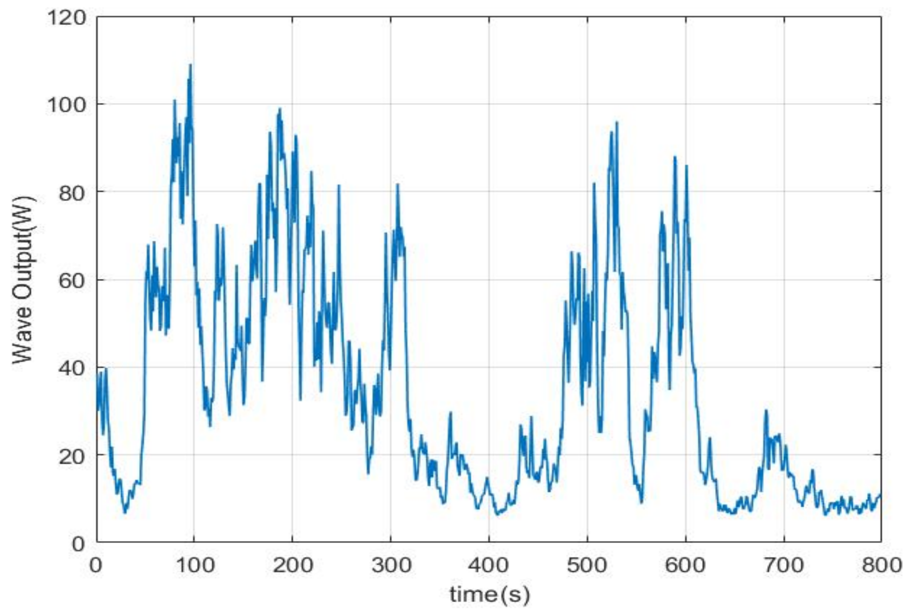


Figure 31: Wave power simulation for OWC (current model)

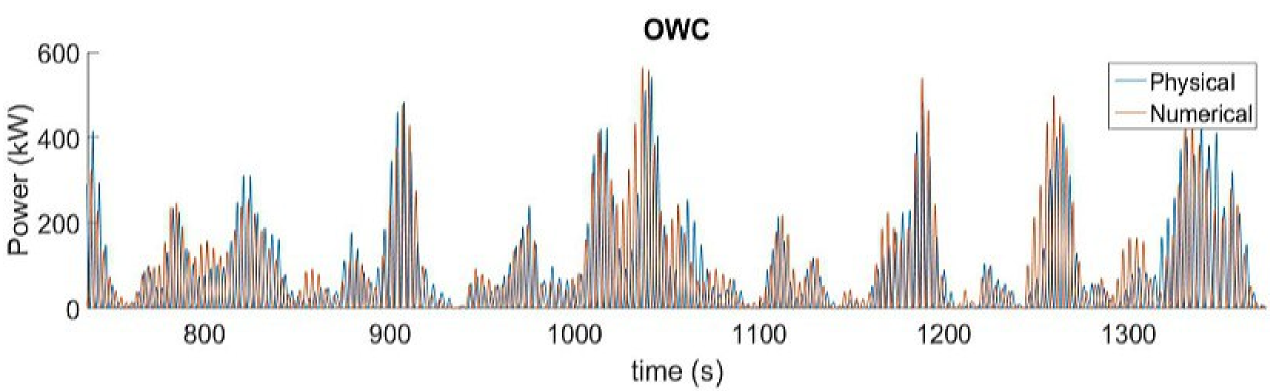


Figure 32: Wave power simulation for OWC (experimental) [77]

4.6: Modelling of RHFC system

The complete model of RHFC includes Solar PV, Wind turbine, Oscillating Water column, PEMFC, PEM electrolyser and an autonomous control system. When the generation is more than the demand of electricity, the excess power is stored as hydrogen. Again, during the shortage of power, the required amount is supplied by the fuel cell.

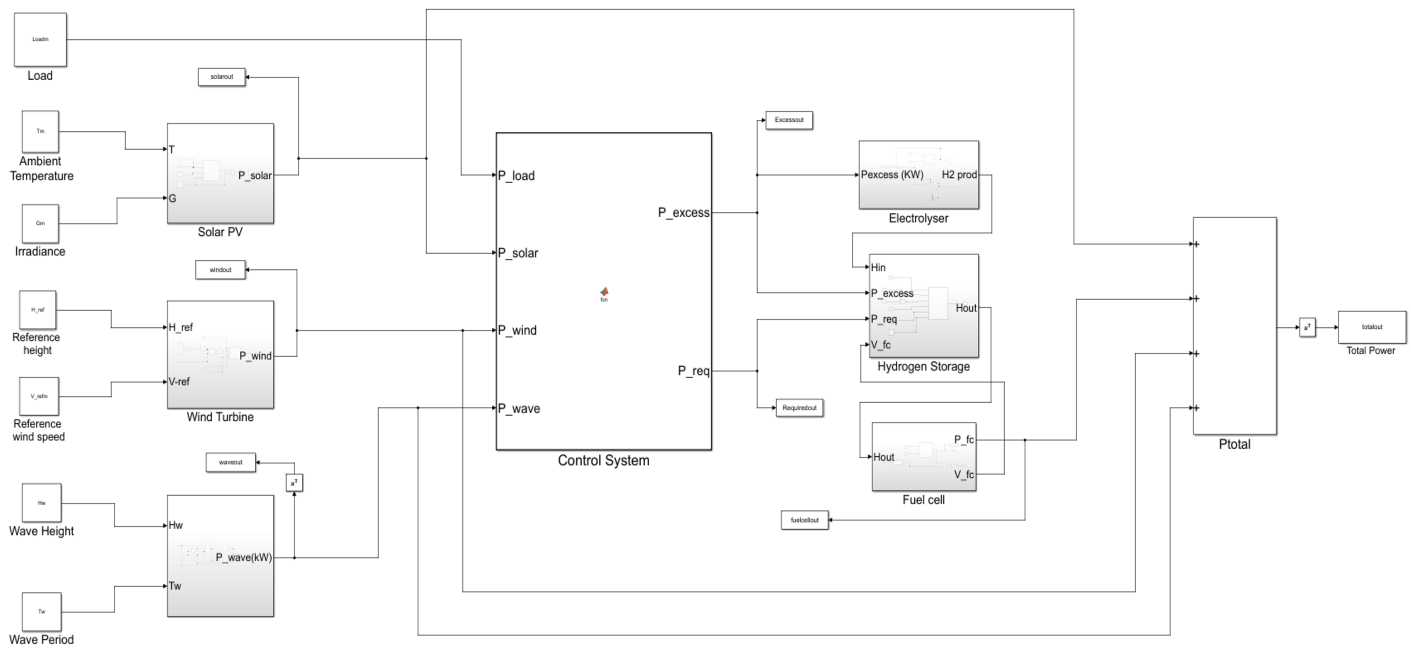


Figure 33: The Complete simulink model of RHFC system

Table 6: RHFC system parameters

Parameters	Details
Number of wind turbines (N_w)	10
Number of OWC (N_{owc})	3
Number of modules in array (N_m)	4000

Data extraction:

The major variables associated with the RHFC model are solar irradiance, wind velocity, ambient temperature, wave height, wave period and lastly the load. These parameters depend on the site that has been selected for the analysis. The values of ambient temperature, solar irradiance and wind velocity are extracted from NASA Prediction of Worldwide Energy Resources. Again, the wave parameters (height, period) are taken from National Data Buoy Center. All of the input variables were taken for the period of 2021-22.

Solar energy potential:

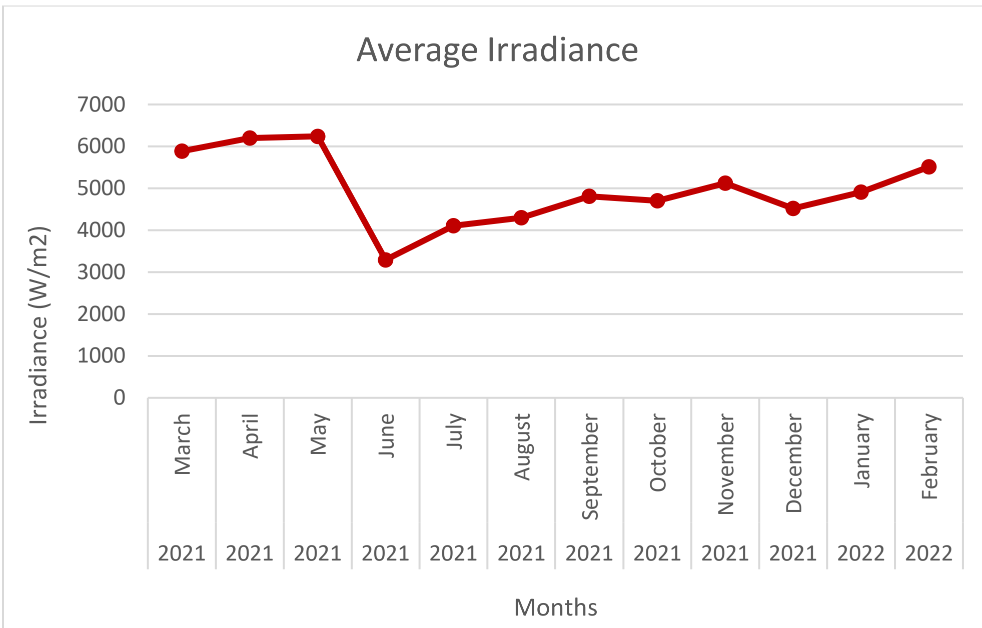


Figure 34: Monthly average irradiance at Saint Martin

From Fig.34 it can be seen that regions having more than 5kW/m^2 irradiation per day is considered to have excellent solar PV potential. Again, temperature is another factor which may affect the performance of solar PV. Typically, 25-35°C is the range where a solar PV can work at best efficiency.

In between March 2021- February 2022, the average solar irradiation of Saint Martin island was calculated and found to be 5kW/m^2 per day. The average monthly temperature was in between 20-30°C and mostly it was around 26-27°C which best suits the solar PV module.

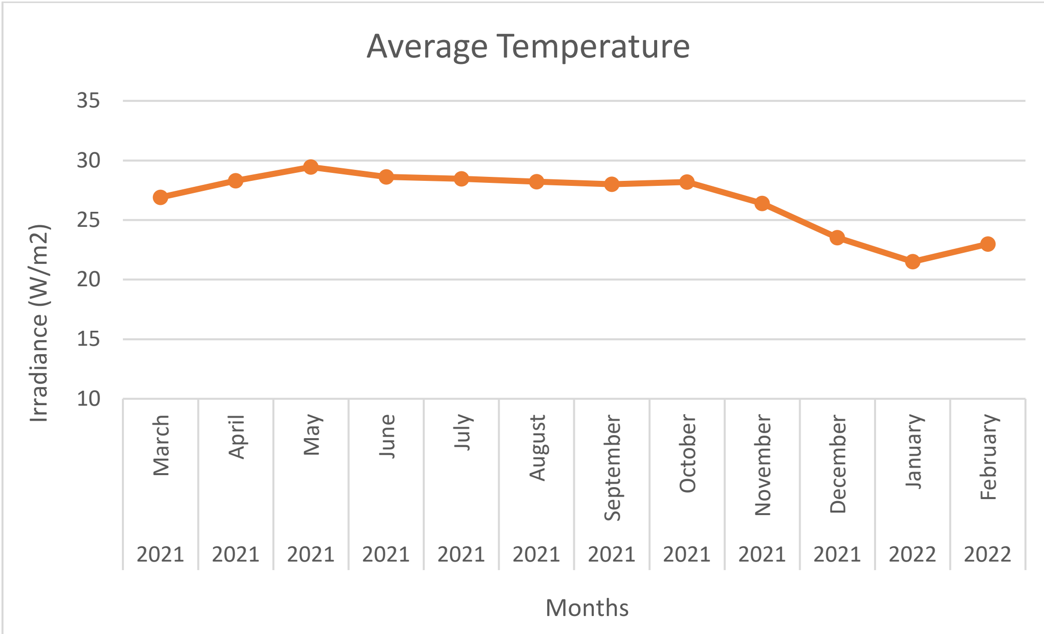


Figure 35: Monthly average temperature of Saint Martin

Wind energy potential:

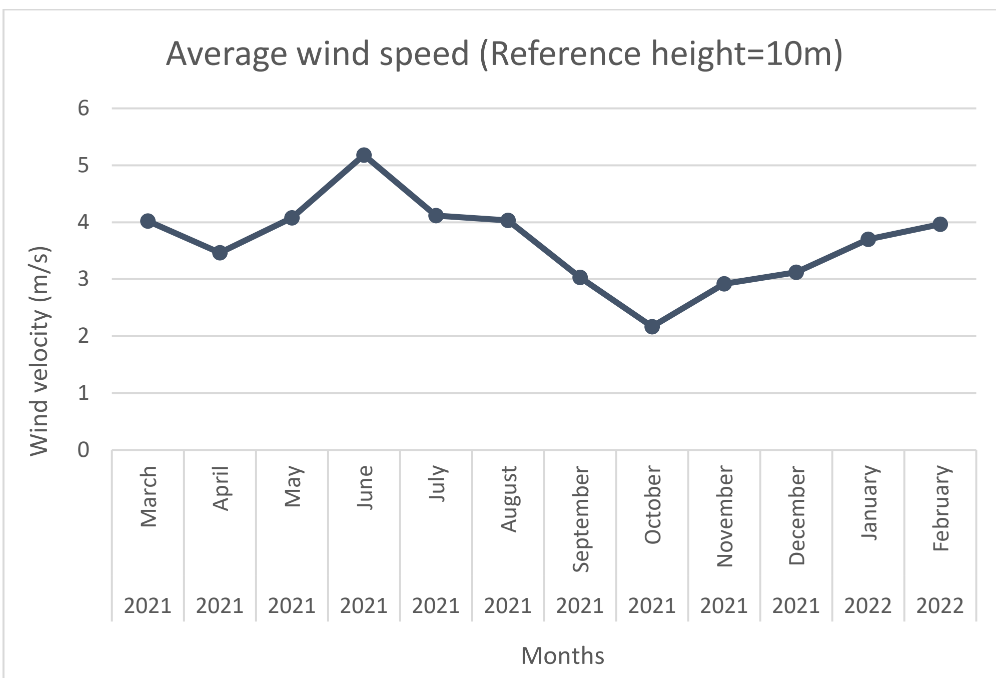


Figure 36: Monthly average wind speed in Saint Martin

Generally, wind speed around 4m/s at a reference height of 10m can typically result in more energy production and greater efficiency. In 2021-22, the monthly average wind speed from Fig.34 was found to be potentially great specially during monsoon which reached a value up to 5m/s.

Wave energy potential:

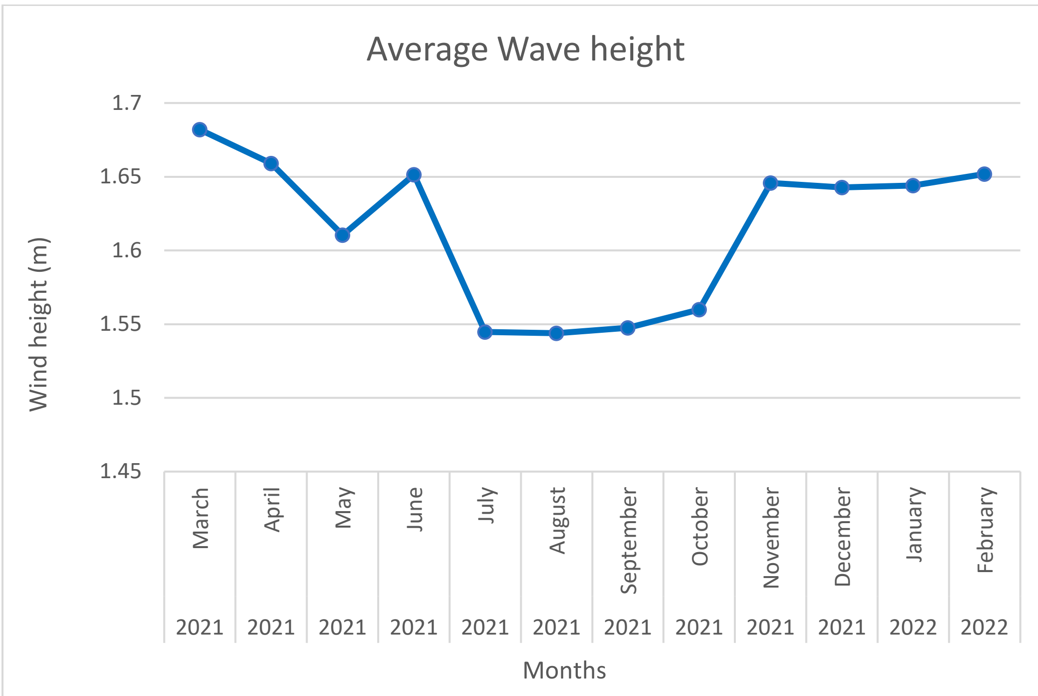


Figure 37: Monthly average wave height in Saint Martin

In an oscillating water column, the minimum height required for generating power is 0.5m but it's recommended to have more than 1.5m for extracting power from an optimum range. In 2021-22, the monthly average wave height was very consistent and varied from 1.55m to 1.7m. The average wave period was varying around 5-6 sec at shore. For an onshore water column, these can be potential values to work with.

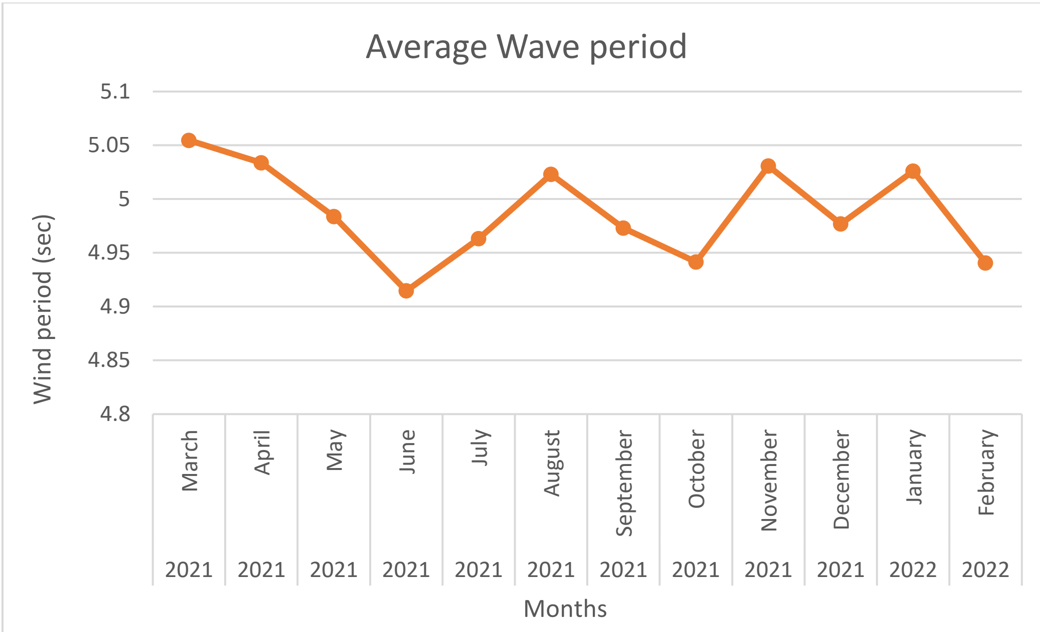


Figure 38: Monthly average wave height in Saint Martin

Load line approximation:

Table 7: Load analysis of BPDB

Parameters	Number	Unit load	Total load (kW)
Residences	100	0.5	50
Hotels/Restaurants	11	10	110
Market	1	25	25
Hospital	1	20	20
Govt. Office	6	2.5	15
Total			**220kW**

Here,

Average load = (diversity factor * Peak load)

= (0.69*220) kW

= 151 kW

According to the information regarding daily unit load demand of the different consumers of the island from a survey of BPDB, the load line was generated for three seasons which was applied in the RHFC model.

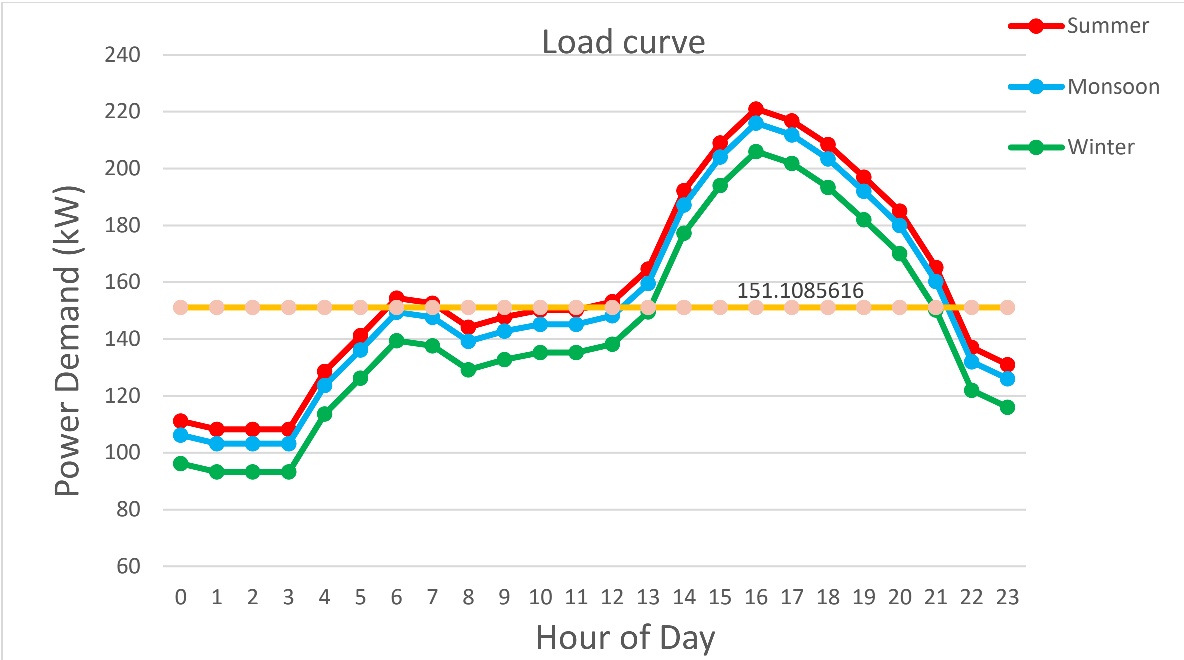


Figure 39: Daily load approximated at Saint Martin

In Saint Martin, many people are engaged in fishing and other seafood businesses, which require an early start to the day. As a result, the load readings show a gradual increase in electrical consumption from 5:00 AM to 7:00 AM, as people wake up and begin their work. During the morning hours, load readings remain relatively steady as many people are out of their homes and not using electrical appliances. However, in the afternoon and evening hours, the load readings increase rapidly, particularly from noon to 8:00 PM, as many tourists visit the area and require electricity for various activities. During this time, electrical consumption is very high, as people use lighting, sound system, charging electrical devices and other appliances to make their stay more comfortable. As the night progresses, the load readings decrease simultaneously as people go to bed early, given their early morning work requirements. This results in a relatively low electrical consumption during the night hours. Overall, these patterns of electrical consumption are influenced by the unique cultural and economic practices of Saint Martin, and the influx of tourists to the area.

Control System:

The control system is the center of this RHFC model which helps the decision-making process by which the required amount of power is generated by fuel cell and supplied according to the demand or excess amount of power is stored as hydrogen in the storage.

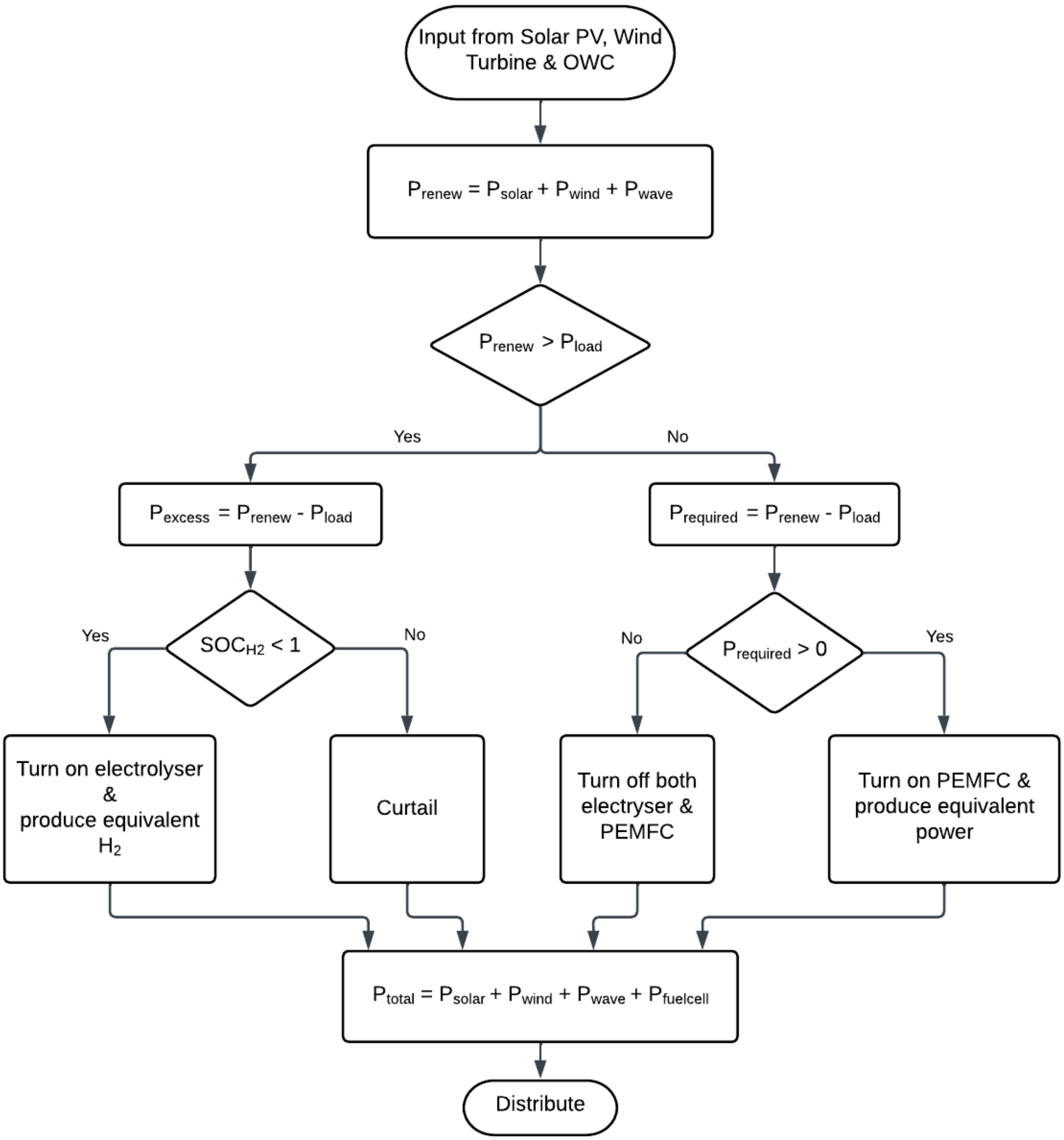


Figure 40: Decision making and hierarchy of the system

CHAPTER 5: RESULTS & DISCUSSIONS

5.1: Sensitivity & performance analysis of PEMFC

The performance and sensitivity of a PEMFC can be analyzed by varying different parameters and studying their effect on key parameters such as voltage, current, power output, and efficiency. By varying these parameters and analyzing the resulting voltage and current density curves, it is possible to determine the optimal operating conditions for the fuel cell. In addition to temperature and oxygen pressure, it is also important to consider the contributions of voltage drops and resistances in the PEMFC system. By analyzing these factors, it is possible to identify areas of the system that may be limiting performance and optimize the design and operation of the system.

5.1.1: PEMFC Performance curve & Voltage drop contributions

The performance curve of a fuel cell illustrates the relationship between voltage and current density under various conditions of operation. Typically, as the current density increases, the fuel cell's voltage output decreases, resulting in a curve with a downward slope. The term for this phenomenon is voltage loss or polarization.

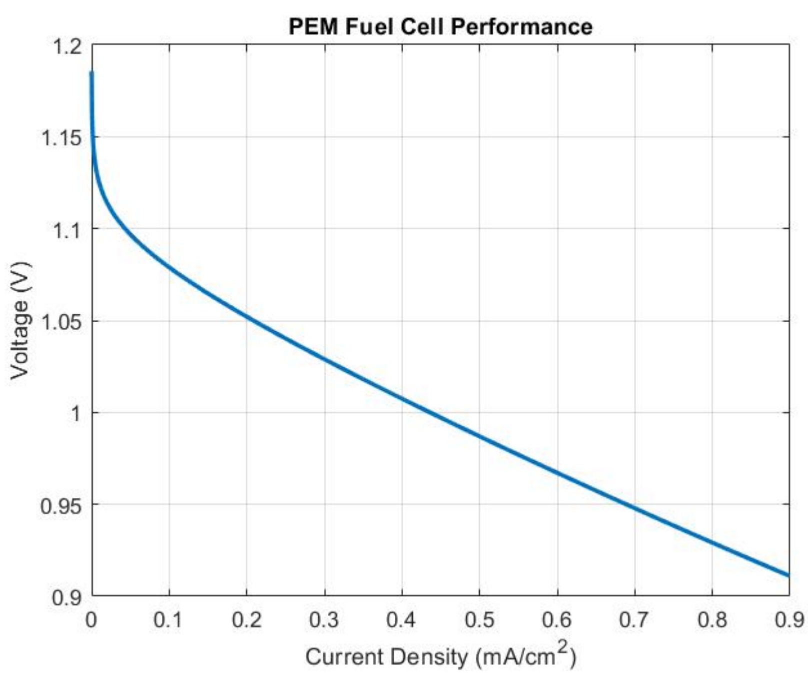


Figure 41: Performance Curve of PEM Fuel Cell

The voltage drop in a fuel cell is caused by several factors, including internal resistance, activation overpotential, and ohmic losses. These factors cause a drop in the electrochemical potential between the anode and cathode of the fuel cell, which reduces the cell voltage. Fig. 41 shows a performance curve for a PEMFC, where the voltage decreases as the current density increases. Fig. 42 shows the contribution of each voltage component to the overall voltage drop. As shown, the activation overpotential is the largest contributor to the voltage drop, followed by ohmic losses and internal resistance.

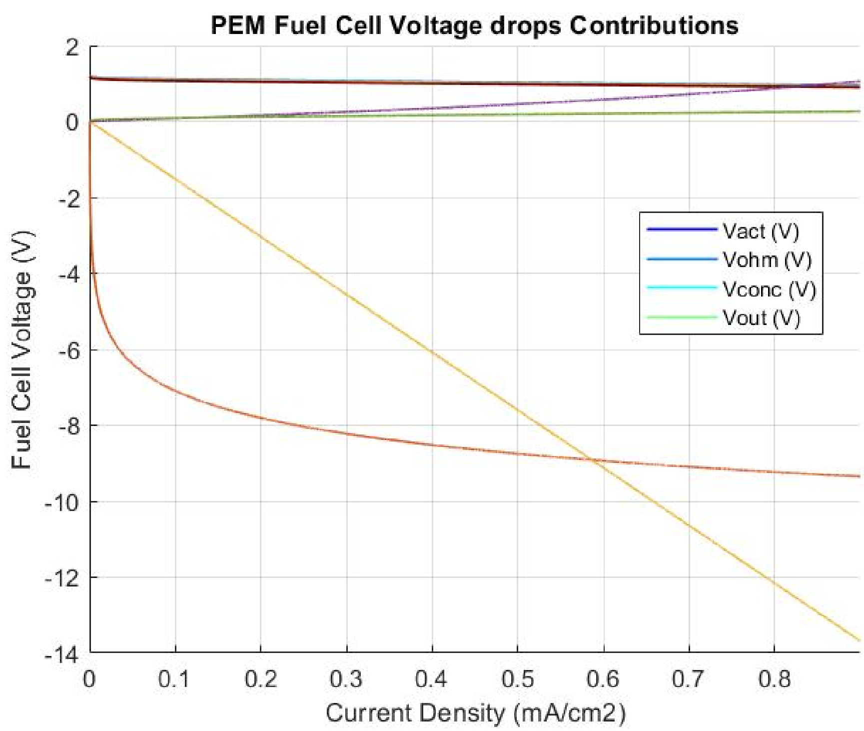


Figure 42 :Voltage Drop Contributions

5.1.2: Optimizing Fuel Cell Performance through Temperature Sensitivity Analysis

Using a sensitivity analysis, a study was conducted to determine the impact of temperature on fuel cell performance. Temperatures ranged from -50 degrees Celsius to 65 degrees Celsius, and the fuel cell performance curve (Figure 43) was analyzed to determine the impact of this variation. Temperature exerted a significant effect on fuel cell efficacy, according to the results. Lower temperatures slowed reaction kinetics, resulting in diminished efficacy. In contrast, higher temperatures led to thermal degradation of the membrane and catalyst, resulting in diminished performance and efficiency. By conducting a sensitivity analysis, a number of factors limiting fuel cell efficacy at varying temperatures were identified. For example, increasing the temperature improved the reaction kinetics and decreased the activation overpotential at low temperatures. Optimizing the thermal management of the fuel cell at high temperatures could reduce temperature gradients and prevent thermal runaway. The analysis of the fuel cell performance curve yielded valuable insights into the behavior of the fuel cell under varying temperature conditions, allowing for the optimization of its design and operation to achieve maximum power output and efficiency. In addition, the graph of the performance curve was derived from the data collected during the fuel cell testing conducted for this study.

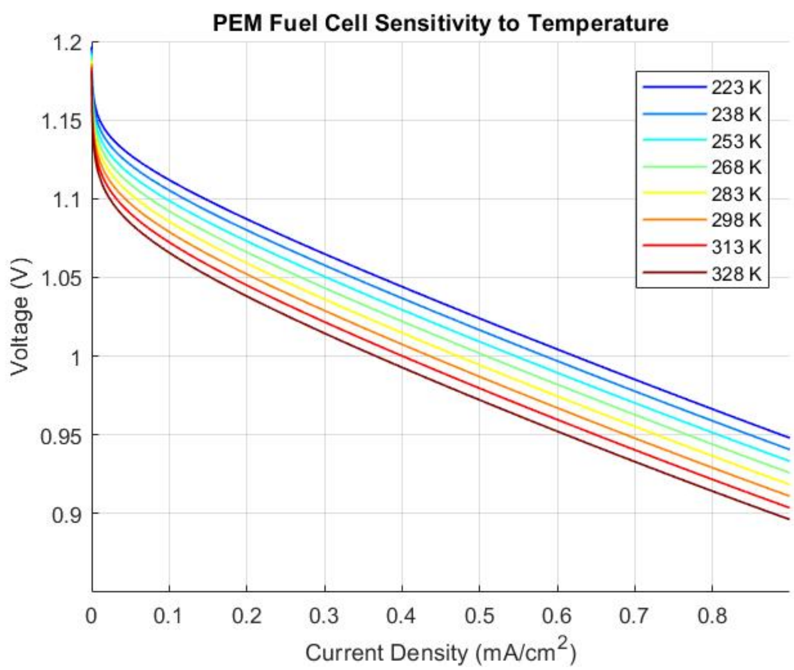


Figure 43: Performance Curve by varying Temperature

5.1.3: Effects of Oxygen Pressure on Fuel Cell Performance

The sensitivity analysis of fuel cell performance was conducted by varying the pressure of oxygen from 1 to 2 bar with some intervals. The results showed that the oxygen pressure had a significant impact on the fuel cell performance. At low oxygen pressures, the reaction kinetics were limited by the availability of oxygen, leading to reduced fuel cell performance. On the other hand, high oxygen pressures increased the mass transport of oxygen to the cathode, which improved fuel cell performance.

The sensitivity analysis helped identify the optimal oxygen pressure range for maximum fuel cell performance. The results indicated that the fuel cell performance improved with increasing oxygen pressure up to a certain point, beyond which further increases in oxygen pressure did not result in significant improvements in fuel cell performance.

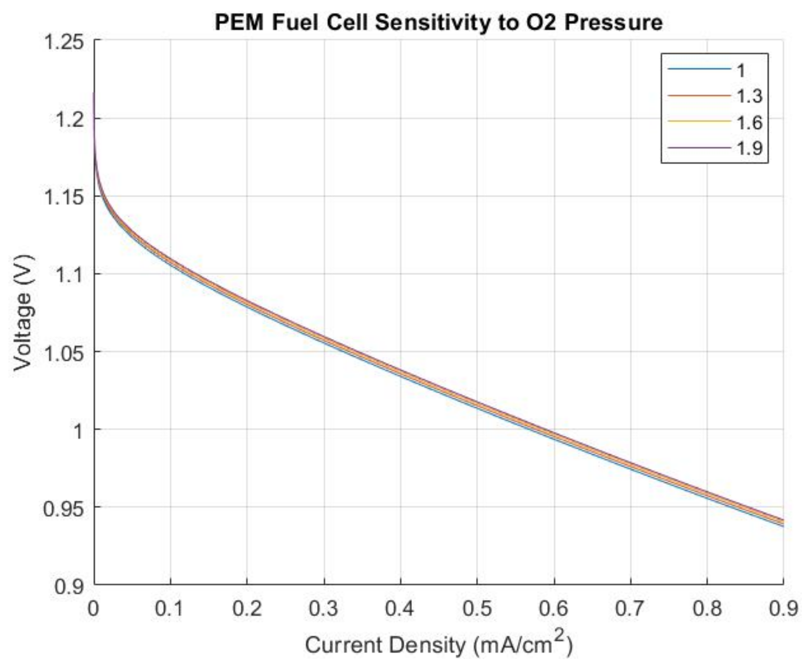


Figure 44: Performance Curve by Varying O_2 Pressure

5.1.4: Impact of Operating Current and Resistance on Fuel Cell Performance

In the study, the operating circumstances, specifically the operating current and resistance contribution, were changed in order to undertake a sensitivity analysis of fuel cell performance. The results showed that modifications to the resistance contribution had the biggest impact on fuel cell performance. Figure 45 shows the fuel cell performance curve, which shows a decrease in performance as resistance rises. Similar to this, a considerable performance shift was seen following the second iteration of the sensitivity study of fuel cell performance under varied operating current, as shown in Figure 46, with successive iterations showing similar outcomes. This shows that beyond a certain level of current density, the fuel cell performance curve plateaus.

These results enable the fuel cell's design and operation to be optimized for maximum power production and efficiency by providing useful insights into the impact of various operating conditions on fuel cell performance.

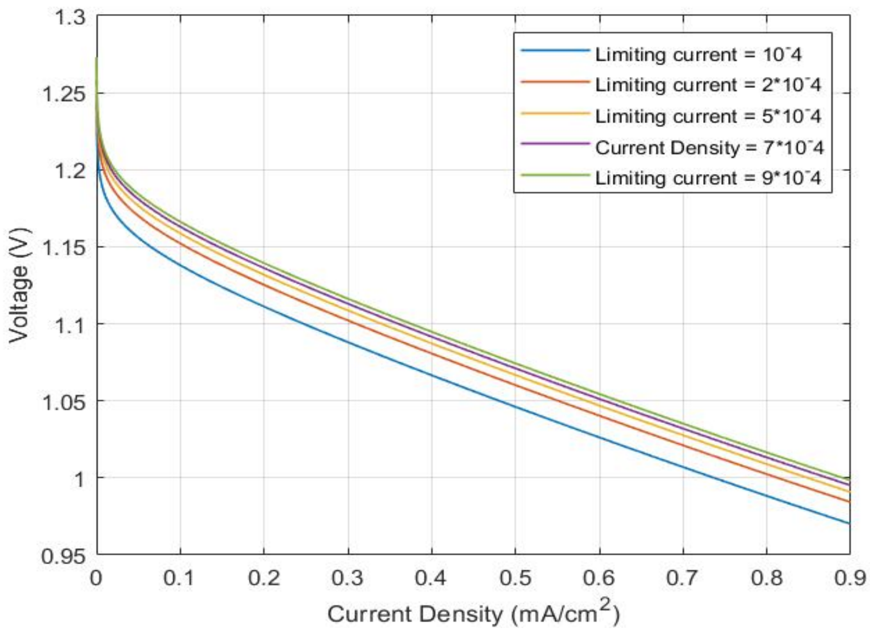


Figure 45: Effect of limiting current

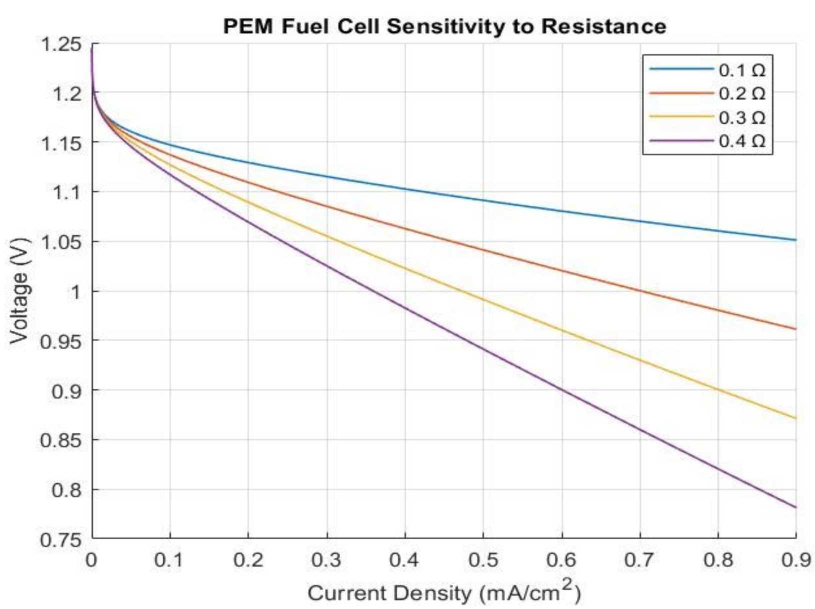


Figure 46: Effect of Resistance in Performance Curve

5.1.5: 3D Plotting of Temperature and Oxygen Pressure with Polarization Curve

3-dimensional graphs that incorporate temperature, oxygen pressure, and voltage/current density data can provide valuable insights into the behavior of the fuel cell system. By analyzing these graphs, it is possible to identify trends and patterns that may not be immediately apparent from individual 2-dimensional graphs.

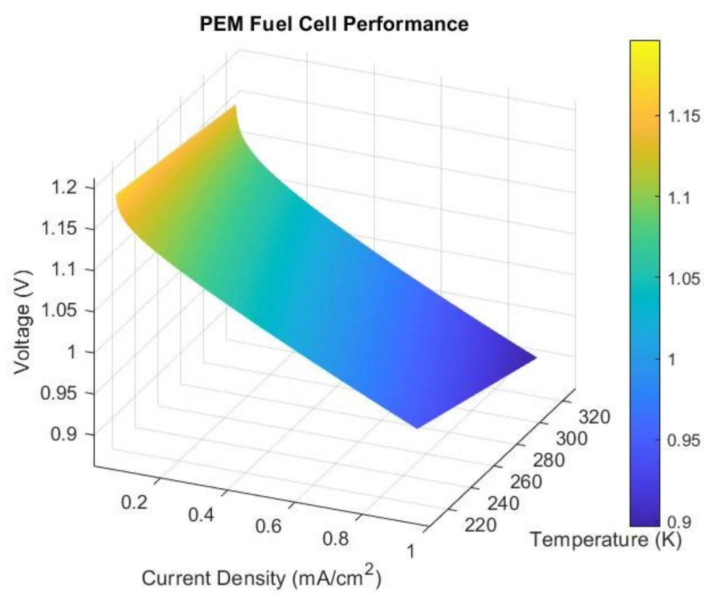


Figure 47: 3D plotting by the variation of Temperature

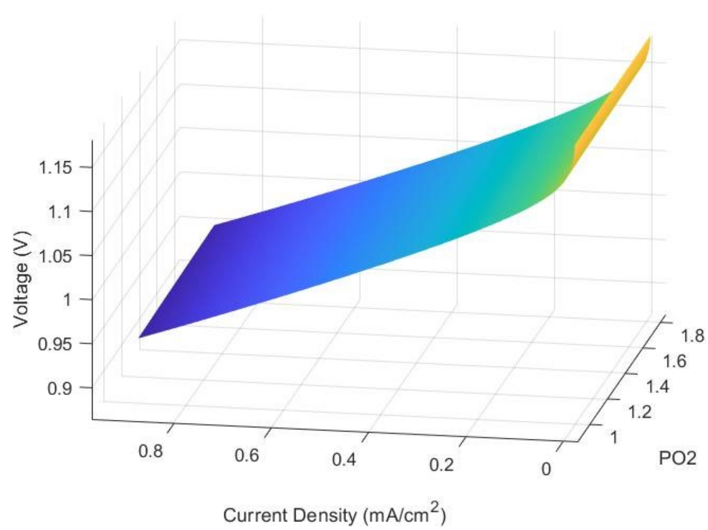


Figure 48: 3D plotting by varying O_2 Pressure

5.2: Simulation of RHFC system

The proposed model was simulated for a complete one-year period (March 2021 to February 2022) and it was analyzed for three different seasons: summer, monsoon and winter in order to observe the performance of RHFC system.

5.2.1: Result analysis of Summer

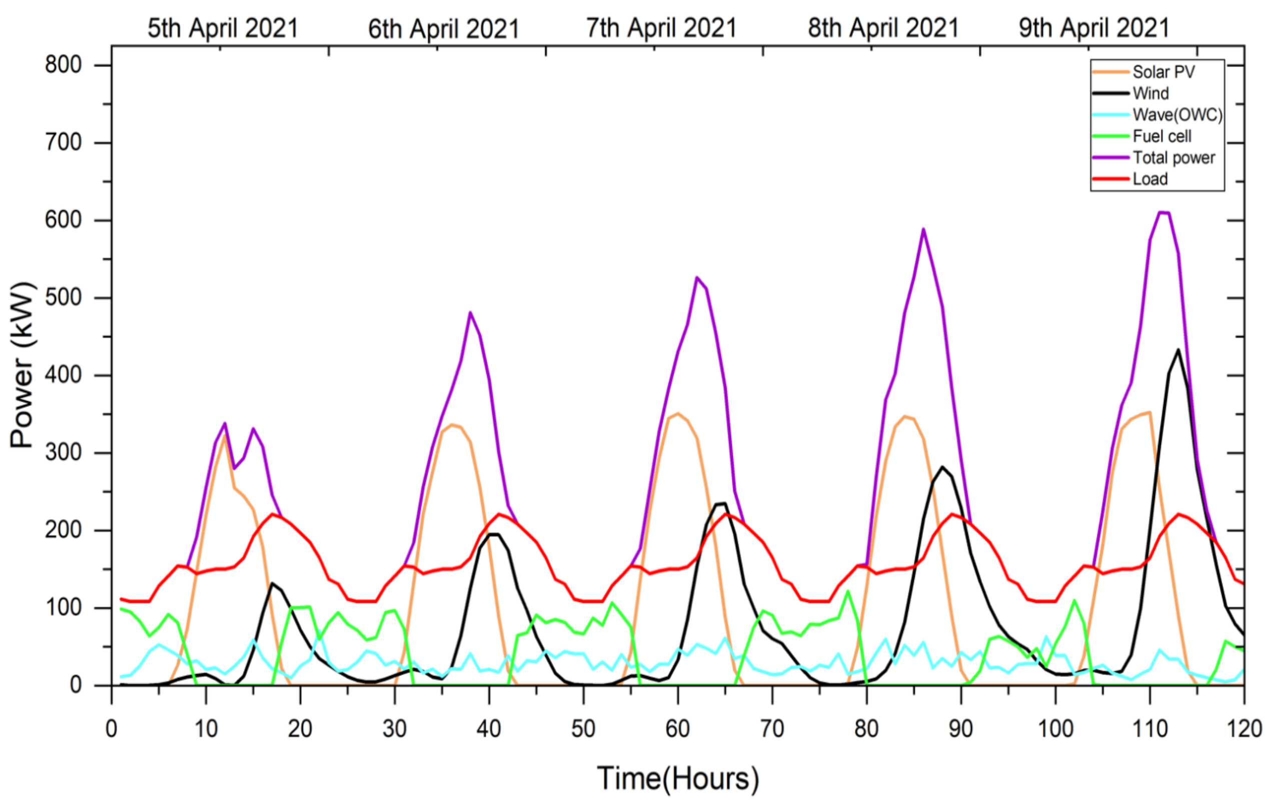


Figure 49: Performance of RHFC during Summer

Simulation results for 5th to 9th of April 2021 was analyzed in Figure 49 and the maximum solar power reached almost around 400kW during these days. So, a large amount of power can be stored as hydrogen into the storage. Here, first four days were not much windy, so during the afternoon phase, a great amount of load was supplied by PEMFC in the absence of solar power. But in summer season sometimes wind can be captured at a high velocity like 9th April, in that case fuel cell can remain turned off. Wave power that was extracted from OWC remained almost constant throughout this period.

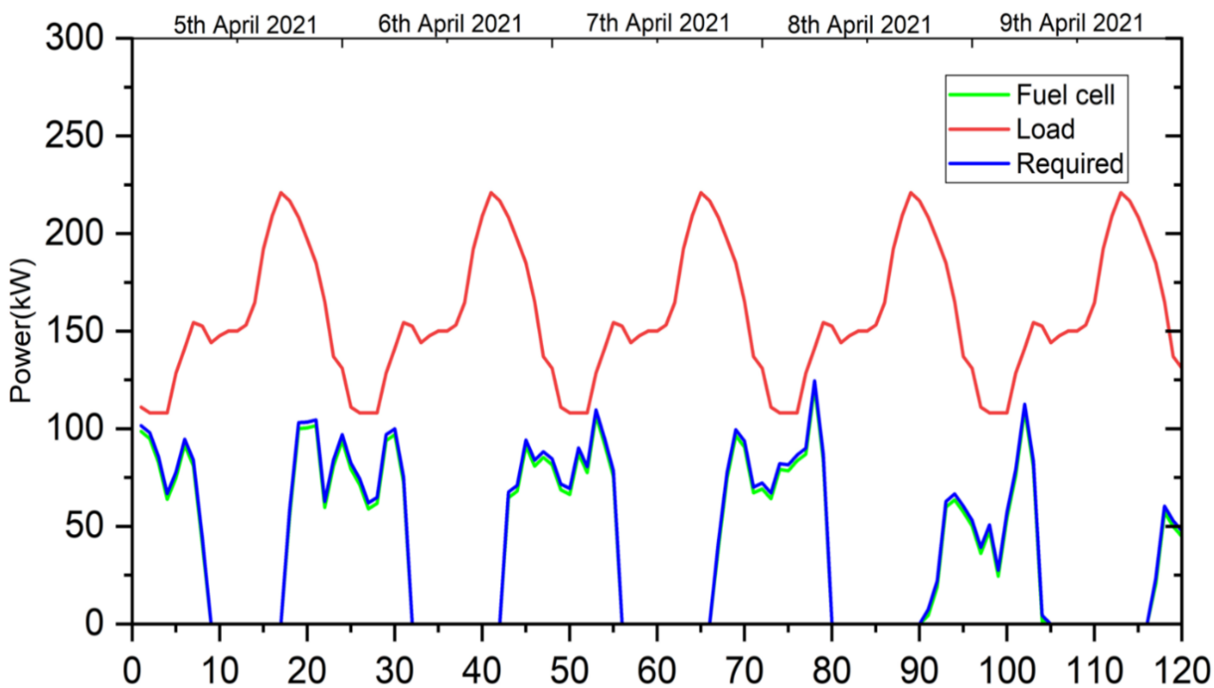


Figure 50: Performance of PEMFC during Summer

In order to test if PEMFC, can completely supply the required power or not the relation between the total load, required load by fuel cell and supplied power by fuel cell were shown in Figure 50. Required power refers to the amount of power that is to be generated by PEMFC which is actually the difference between load power and renewable power. This observation shows the complete overlapping of fuel cell power curve and the required power curve which is an indication that the storage never runs out of fuel during this interval and whenever an outage occurs PEMFC perfectly meets that part of demand.

5.2.2: Result analysis of Monsoon

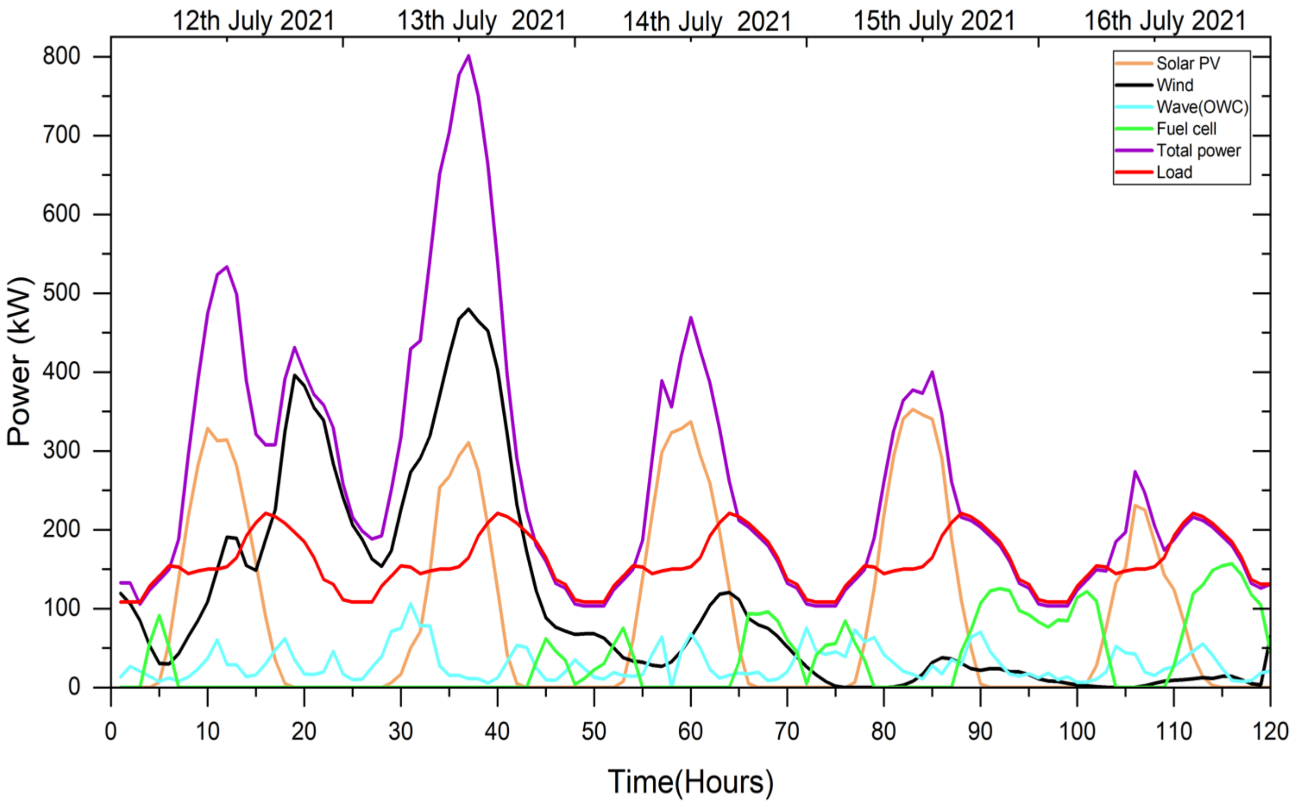


Figure 51: Performance of RHFC during Monsoon

Simulation results from 12th July to 16th July of 2021 are represented in Figure 51. The power generated by wind turbine plays the dominating role in first two days since the wind velocity remains very high sometimes during the monsoon. As a result, due to consistent wind power, PEMFC had no contribution meeting power demand for a long period of time rather a large amount of energy can be stored due to heavy wind and solar energy. But during 15th-16th July, wind power generation was less comparatively and in the afternoon since solar PV couldn't meet the demand, the fuel cell has been supplying most part of the load.

The perfect overlapping of required power and fuel cell power can be observed in this case as well which is demonstrated in Figure 52.

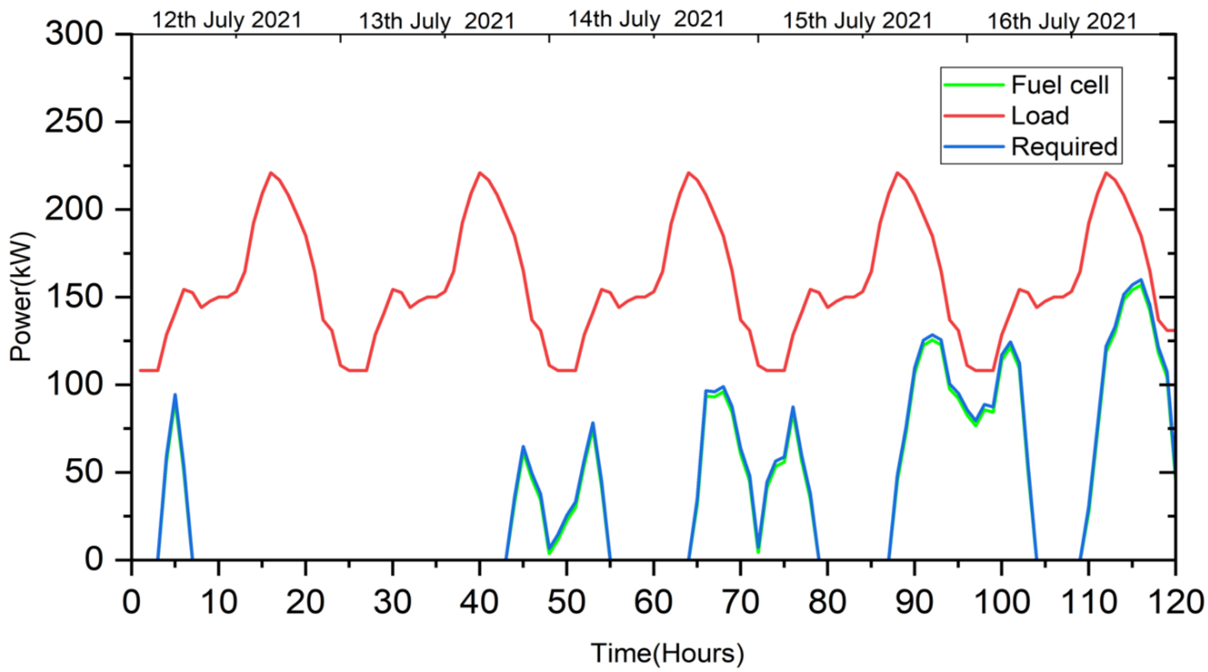


Figure 52: Performance of PEMFC during Monsoon

5.2.3: Result analysis of Winter

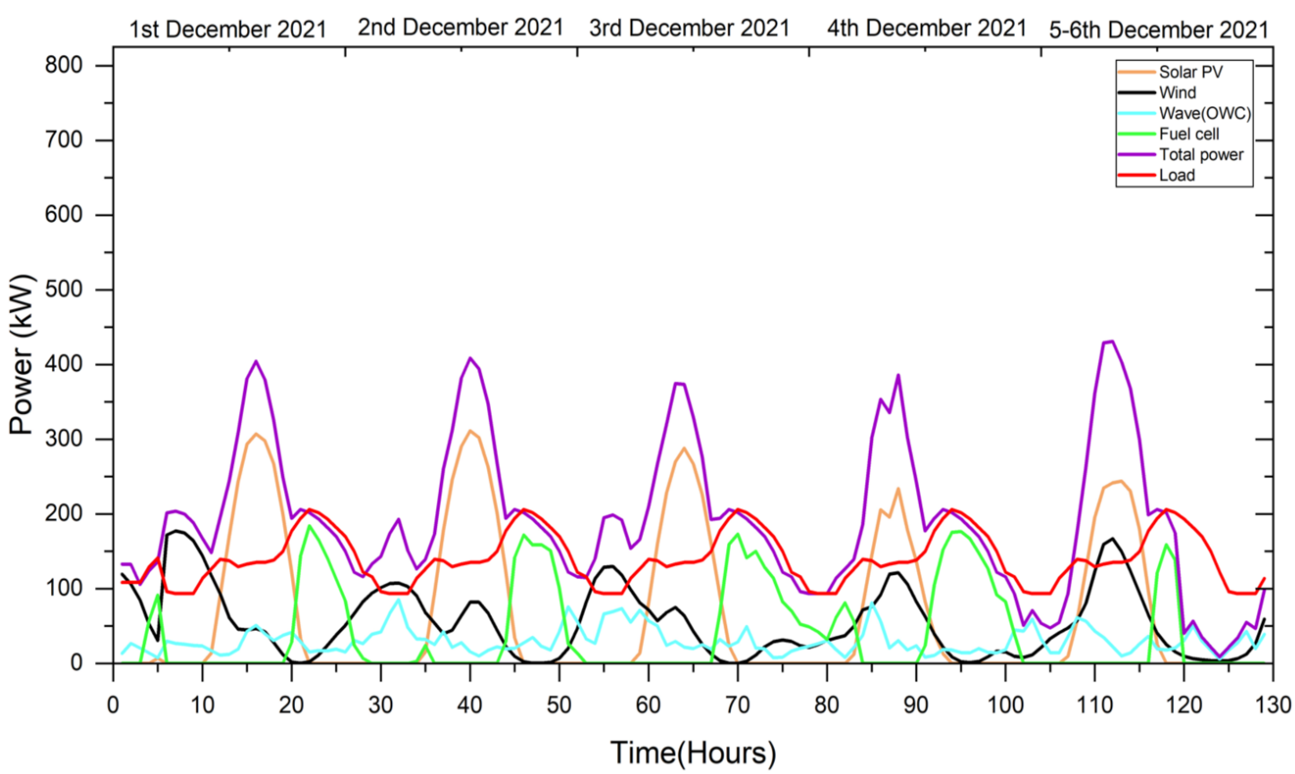


Figure 53: Performance of RHFC during Winter

During the season of winter, the wind power can't be extracted at a high range unlike monsoon and summer. Again, during winter sun sets earlier than summer. As a result, the total energy that is stored in the form of hydrogen during day time is less than summer and monsoon. Rather the afternoon time is much longer so fuel cell has to supply much more.

The outage of solar power during the afternoon is covered up by the fuel cell as it generates a large part of the load. So, the contribution of fuel cell during 1st to 6th of December was observed to be much higher than the other two cases.

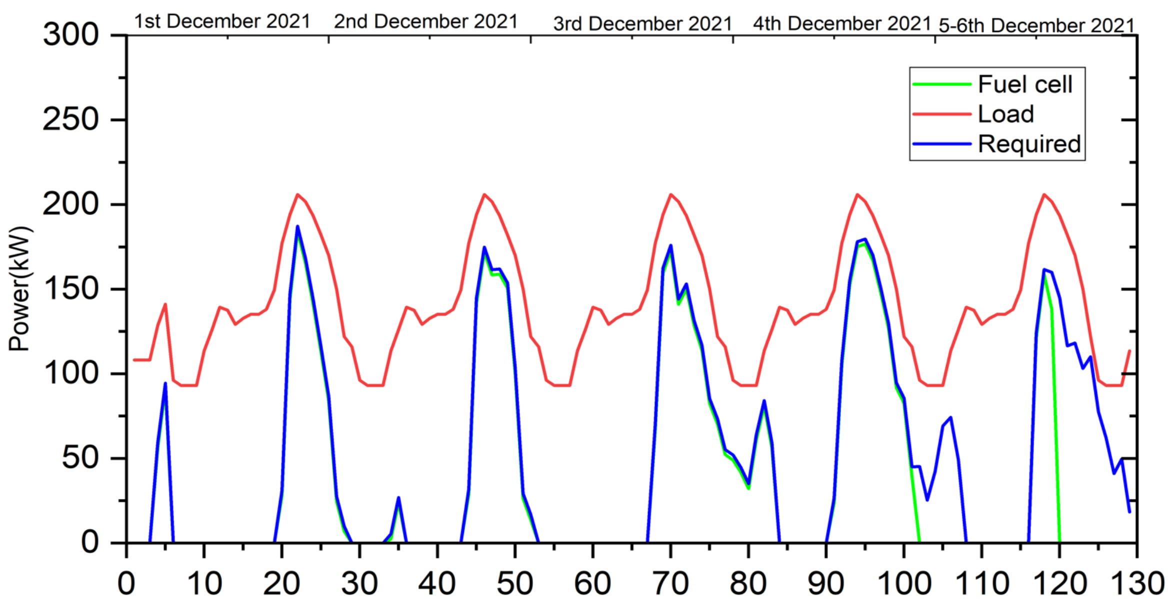


Figure 54: Performance of PEMFC in Winter

Since the storage can not store much due to lack of renewable powers and the run time of fuel cell is much higher; the storage sometimes had to face shortage of hydrogen which is shown in Figure 54. After 100th hour and 120th hour PEMFC could not generate the required amount of power because there was no hydrogen in the storage tank.

5.3: LCOE and cost analysis of RHFC system

The minimum lifespan of technology is 20 years, and it is important to consider inflation rates when estimating fuel and operation and maintenance (O&M) costs. The major factors that this cost analysis has to consider are:

- Initial investment / Capital cost
- Annual Operation & Maintenance cost (O&M)
- Import & additional cost
- Annual energy degradation rate

The initial cost of this technology is presented in Table 7.

Table 8: Capital cost for the components

Solar PV	$1410	per kW_{DCpeak}	[38]
Wind turbine	$1325	per kW_{rated}	[39], [40]
OWC	$ 1584.2	per kW_{rated}	[41]
PEMFC	$ 470	per kW_{rated}	[42]
Electrolyser	$1321.64	per kW_{rated}	[43]
Hydrogen Storage	$1780	per Kg H2 stored	[44]

In addition to the initial investment cost for installation, shipment cost, import charges and local tax were to be added in the expense. Also, as the technologies used have wear of materials and decrees in efficiency are considered in the LCOE calculations as well. The annual degradation rates are there for presented in table 8.

Table 9: Importation and additional costs for deploying in Saint-martin

Cost per Container (Shipping)	$2300	[45]
Import charges	10%	[46]
Tax	15%	[47]

Again, there are a variety of factors that can lead to annual energy loss in renewable energy systems. In solar PV systems, factors such as performance degradation, environmental conditions, and material deterioration can contribute to a decrease in energy output. In wind turbine systems, ageing turbines, wind variability, and maintenance issues can result in decreased energy production. Degradation of the catalyst and membrane, fuel quality, and system age can all contribute to energy loss in fuel cell systems. The degree of deterioration varies according to system design, maintenance, and environmental factors.

Table 10: Annual energy generation degradation rates

Solar PV degradation	0.50%	[48]
Wind turbine degradation	1.60%	[49]
OWC	0.45%	
Fuel Cell degradation	0.9%	[50]
Electrolyser	0.9%	[51]

For LCOE estimates, operation and maintenance (O&M) costs are crucial because they will rise in price over time.

Table 11: Annual O&M cost for the components

Solar PV	1.5%	of initial investment	[52]
Wind Turbine	$ 70.30	Per kW installed	[53]
Fuel cell	$0.04	Per hours of operation	[54]
Electrolyser	$0.04	Per hours of operation	[54]
OWC	2.5%	of initial investment	
Storage tank	0.25%	of initial investment	

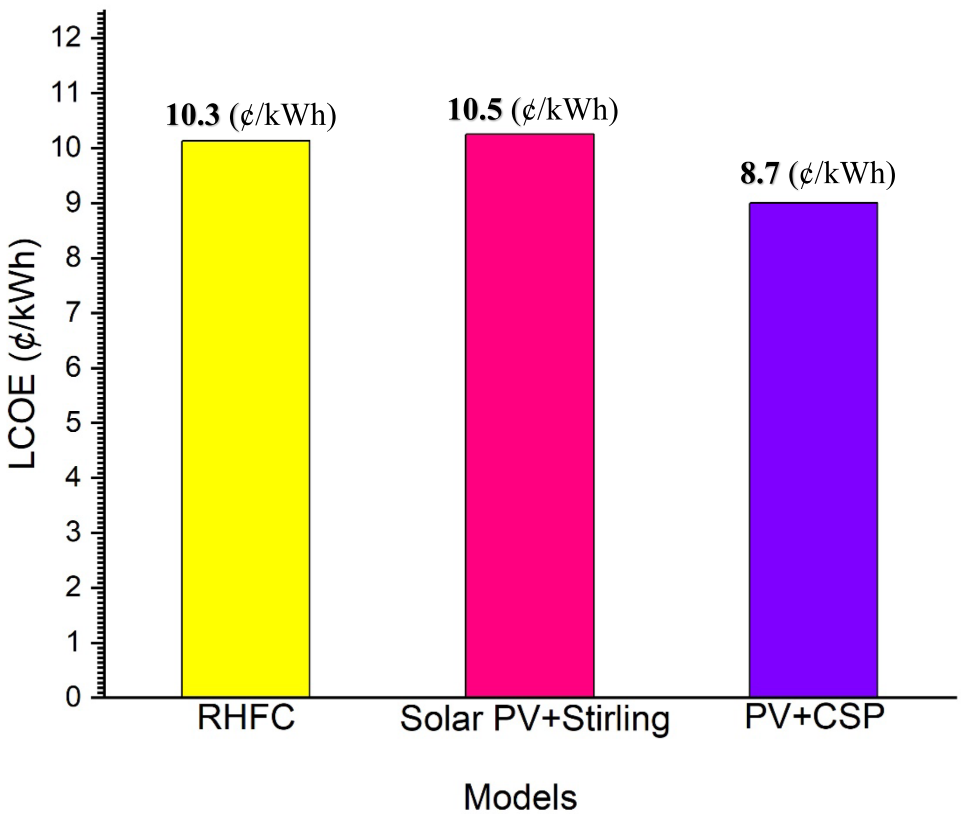
Finally, LCOE was calculated for each of the expenditure and thus total LCOE for the system was determined.

Table 12: LCOE calculation

Type of expenditure	LCOE (¢/kWh)
Capital cost	7.86
O&M	0.40
Fuel cost	-
Import charges	0.74
Tax	1.1
Shipping	0.03
Total	**10.13**

An LCOE value of 10.13 ¢/kWh lies in between the ranges of other renewable systems that are designed for off-grid power generation.

We compared our LCOE value with the Solar-driven Stirling engine System from literature [55] and the hybrid solar PV (photovoltaic) – CSP (Concentrated Solar Power) powerplant from literature [56].



We found out that our RHFC model was a better choice than a Solar PV powered Stirling engine system, but slightly higher than a hybrid powerplant made of Solar PV-CSP powerplant but these are comparable.

CHAPTER 6: CONCLUSION

The sensitivity analysis for PEM fuel cells reveals that temperature and oxygen pressure have minimal impact, while the most significant factor is the ohmic voltage drop resulting from the resistance encountered by ions in the electrolyte. Incorporating these findings into RHFC systems can lead to improved and more efficient performance of PEM fuel cells.

The modeled RHFC system is designed for supplying a peak load of 220kW and is successfully generating power whenever there is an outage due to lack of solar, wind or wave power. The capacity of hydrogen storage was fixed as 200kg that rarely runs out of fuel due to shortage of hydrogen. During all three seasons PEMFC performs perfectly and it even generates a power of 190kW at maximum. During winter season, fuel cell is generating maximum amount of power because there is shortage of renewable powers which sometimes might lead to shortage of fuel in the storage tank. But the power outage was entirely resolved over the summer and monsoon.

From the levelized cost of electricity analysis, it is found that the per kW energy generation cost around 10.13 cents which is into the range of other renewable system generation and since it has a reliable storage system that makes it a feasible option for such an island having no stable grid connection.

The current system can always be integrated with some batteries to be charged whenever the fuel cell is at a state of charge of 100% making it a more efficient one in future. Using an IoE based control system makes the RHFC system autonomous that will be a revolution for the next generation energy sectors.

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