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**HYDROGEN AS STORAGE TO
GENERATE POWER WITH THE HELP OF
FUEL CELL TECHNOLOGY**

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Master Thesis

Supervisor

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HYDROGEN AS A POTENTIAL ENERGY STORAGE TO GENERATE POWER WITH THE HELP OF FUEL CELL TECHNOLOGY

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ABSTRACT

HYDROGEN AS STORAGE TO GENERATE POWER AND WITH THE HELP OF FUEL CELL TECHNOLOGY

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This thesis presents a design of a Solar-hydrogen hybrid system (SHHS) for a domestic household. The objective is to develop a system that can provide continuous electricity throughout the year in the presence of grid and solar intermittencies. The SHHS comprises components such as Photovoltaic (PV) panels, PEM-based electrolyzers, PEM-based Fuel-cells, hydrogen-tanks, Lithium-ion batteries, controllers, and auxiliary equipment like DC/AC converters or charge controllers. This research aims to determine the optimal configuration and sizing of system components to achieve high performance at a low cost, considering different user needs and control strategies. The MATLAB SIMULINK is utilized for the full system design and simulations. The models for the PV-panels, PEM electrolyzers, control strategies, and energy management for a typical home are verified through simulations. All the developed models are integrated into SIMULINK, verifying that the household's electricity demand is met directly from the PV-arrays or with the assistance of batteries and fuel-cells when solar energy and grid power are insufficient. Key design parameters in this study include the pressure level in the hydrogen tanks and the overall system efficiency. The analysis focuses on component parameters and various control strategies that impact the pressure in the hydrogen tanks and the system's efficiency.

Keywords: Hydrogen, Renewable Energy, Fuel Cell, Energy Storage, Sustainable Energy.



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ABBREVIATIONS

FC	:	Fuel Cell
HE	:	Hydrogen Energy
HRS	:	Hydrogen Refilling Stations
PME	:	Proton Membrane Exchange
SOFC	:	Solide Oxide Fuel Cells
PEMFC	:	Proton Exchange Membrane Fuel Cell
AFCS	:	Alkaline Fuel cells
PAFS	:	Phosphoric Acid Fuel cell
MCFs	:	Molten Carbonate Fuel Cell
SH2IFT	:	Safe Hydrogen Fuel Handling and use for efficiency implement
USH	:	Underground Hydrogen Storage
SPU	:	Secondary Power Unit
HET	:	Hydrogen Energy Technology
CCS	:	Carbon Capture Storage.
LCOS	:	Levelized Cost of Storage.
LIBs	:	Li-ion Batteries
RFCs	:	Reversible Fuel Cell
ESS	:	Energy Storage System
MFC	:	Microbial Fuel Cell
PEC	:	Photo-Electric Cell

WEEE	:	Waste Electronic Electrical Equipment
MPCMs	:	Micro-Encapsulated Phase Change Material Slurry
PV/T	:	Photovoltaic Thermal
MPTT	:	Maximum Power Point Tracking
PEM-EL	:	Polymer- Electrolyte Membrane – Eletrolyser
OPCF	:	Open Pore Cellular Foam
Ta3N5	:	Tantalum Nitride
NOCT	:	Nominal Operating Cell Temperature
LCA	:	Life Cycle Assessment
COP	:	Coefficient of Performance
LOHC	:	Liquid Organic Hydrogen Carrier
SEM	:	Scanning Electron Microscopy
EIS	:	Electrochemical Impedance Spectroscopy
CV	:	Cyclic Voltammetry
MEA	:	Membrane Electrolyte Assembly
ECSA	:	Electrochemical Surface Area
HER	:	Hydrogen Evolution Reaction
UAV	:	Unmanned Aerial Vehicle
FEA	:	Finite Element Analysis
EMS	:	Energy Management Strategy
DDPG	:	Deep Deterministic Policy Gradient
HESS	:	Hybrid Energy Storage System

HEV	:	Hybrid electric Vehicle
MFC	:	Multi Stack Fuel Cell System
BES	:	Battery Energy Storage
ZSC	:	Z-Source Converters
MVDC	:	Medium Voltage Direct Current
PCMHE	:	Phase Change Material Heat Exchanger
CTHE	:	Coiled -Tube Heat Exchanger
MH	:	Metal Hybrid
HST	:	Hydrogen Storage Tank
ETC	:	Effective Thermal Conductivity
GHGs	:	Greenhouse Gas Effect
RSOC	:	Reversible Solide Oxide Fuel
RFC	:	Reversible Fuel Cell
HSS	:	Hydrogen Storage System
EES	:	Electrical Energy Storage
P2H	:	Power to Hydrogen
FBFCs	:	Flow Biomass Fuel Cells
BEHP	:	Biomass Electrolysis Hydrogen Production
LPG	:	Liquefied Petroleum Gas
PEC	:	Photoelectric Cells
MFC	:	Microbial Fuel Cells

1. INTRODUCTION

1.1 INTRODUCTION

Hydrogen energy has emerged as a significant player in the global pursuit of clean and sustainable energy solutions. As the world strives to address the challenges of climate change and transition towards a carbon-neutral future, hydrogen has gained increasing attention due to its potential as a versatile and low carbon energy carrier. This introduction will explore the significance of hydrogen energy in today's world, focusing on its benefits, policies, and roadmaps, with a specific emphasis on Turkey. Hydrogen holds tremendous promise as a clean energy source due to its high-energy density, ability to be produced from diverse renewable resources, and versatility in various sectors, including transportation, power generation and industry [1]. Hydrogen utilization offers a substantial potential for reducing greenhouse gas emissions and improving energy security through diversifying energy sources. Recognizing the immense value of hydrogen energy, several countries and international organizations have embraced proactive measures to facilitate its widespread adoption. They have established policies, roadmaps, and funding initiatives to encourage research, development, and deployment of hydrogen technologies. A notable example is the European Union's Hydrogen Strategy, launched in July 2020, which sets ambitious targets and allocates funding to foster the growth of the hydrogen economy. [2]. Likewise, nations such as Japan, South Korea, and Australia have devised comprehensive strategies and made significant investments to expedite the advancement and implementation of hydrogen technologies.

1.2 HYDROGEN ECONOMY IN TÜRKİYE

Turkey, with its strategic geographic location, substantial renewable energy potential, and growing energy demand, recognizes the importance of hydrogen energy in its transition toward a sustainable future. The Turkish government has also prioritized the development of a hydrogen-powered economy and has initiated various measures to promote hydrogen technologies. In 2021, Turkey introduced its National Hydrogen Strategy, outlining its vision, goals, and policy framework to leverage hydrogen as a driving component of its energy system. The strategy emphasizes promoting domestic hydrogen production, international collaborations, research and development, and

creating a supportive regulatory framework. Furthermore, Turkey has set ambitious targets for hydrogen deployment, aiming to establish a domestic hydrogen generation of 1 GW by 2023 and increased it to 10 GW by 2030. The country's favorable renewable energy potential, particularly in solar and wind power, provides ample opportunities for green hydrogen production. Turkey's strategic position between Europe and Asia also positions it as a potential hydrogen hub, facilitating regional cooperation and trade.

1.3 DOMESTIC HYDROGEN PRODUCTION

The significance of domestic hydrogen production and use for residential purposes cannot be overstated. It can potentially revolutionize our energy systems, making them more sustainable, decentralized, and environmentally friendly. One of the primary benefits of domestic hydrogen production is the opportunity for homeowners to achieve increased energy independence. By generating hydrogen at home, individuals can reduce their dependence on conventional energy sources and take control of their energy supply [3]. This shift towards self-sufficiency empowers homeowners to become active participants in the energy transition and reduces their vulnerability to fluctuations in energy prices and availability. Moreover, domestic hydrogen production enables the inclusion of renewable energy sources, such as solar and wind power, into residential energy systems more easily. Excess electricity generated from renewables during times of low demand can be efficiently converted into hydrogen via electrolysis process [4]. This process allows for the storage of clean energy and provides a means to utilize it when needed, even during limited renewable energy production periods [5]. As a result, domestic hydrogen production acts as a valuable tool in balancing energy supply and demand, while reducing large-scale energy storage [6].

The benefits of domestic hydrogen production extend beyond energy storage and renewable integration. It promotes the decentralization of energy generation and consumption, transforming households into potential energy producers [7]. This decentralized energy model lessens the strain on centralized power plants and transmission infrastructure, enhancing the resilience of the overall energy system. It also reduces transmission losses, improving energy efficiency and reducing wastage [8]. One of the most compelling reasons to prioritize domestic hydrogen production is its significant contribution to carbon reduction efforts. One can process Hydrogen in fuel-

cells or internal combustion engines, generating heat and electricity without releasing harmful greenhouse gases. Figure 1.1 shows the application of hydrogen in modern vehicles. This clean energy conversion process aids in mitigating climate change and improving local air quality [9]. By adopting domestic hydrogen production for residential purposes, homeowners can substantially impact reducing carbon emissions and promote a sustainable future.

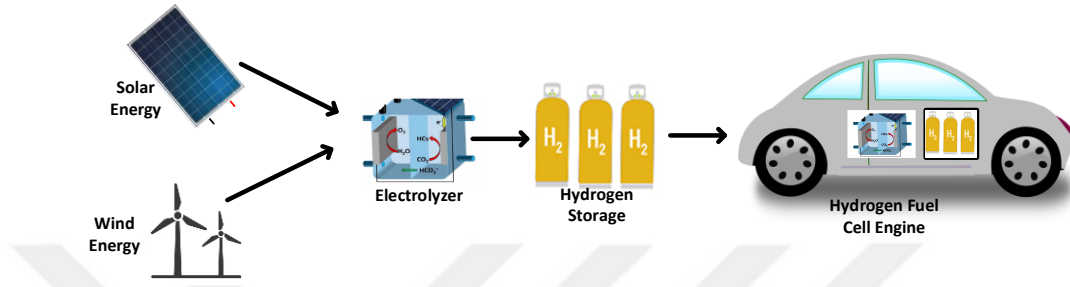


Figure 1.1: Application of Hydrogen Usage in Transport.

Furthermore, the versatility of hydrogen applications makes it an ideal energy source for residential use. It can be utilized for heating, cooking, power generation, and even as a vehicle-fuel. This flexibility offers homeowners multiple pathways to meet energy needs, promoting energy diversification and resilience [10]. It also encourages technological advancements and innovation, as the growing demand for domestic hydrogen production drives state-of-the-art research efforts to improve the efficiency, affordability, and safety of hydrogen production and utilization systems. Domestic hydrogen production and use for residential purposes have transformative potential [11]. It empowers homeowners, reduces reliance on external energy sources, integrates renewable energy, decentralizes energy generation, reduces carbon emissions, and offers versatile applications. By embracing domestic hydrogen production, individuals can actively contribute to a sustainable and low-carbon future, shaping a resilient and environmentally friendly energy landscape at the residential level [12].

1.4 PROBLEM STATEMENT

Developing a domestic hydrogen system for home use requires proper modeling of every component within the hybrid energy system. This comprehensive modeling approach ensures the efficient and effective integration of various components, such as photovoltaic (PV) panels, electrolyzers, battery converters, and other supporting equipment. Firstly, modeling the PV component involves understanding solar resource

availability, PV panel characteristics, and system efficiency [13]. We can estimate the energy production potential by accurately modeling the PV panels, including their electrical behavior and response to varying solar irradiation and temperature. This information helps determine the appropriate sizing and configuration of the PV array to meet the home's energy demands. Next, modeling the electrolyzer is crucial for understanding its operational characteristics and efficiency. The electrolyzer converts electricity from the PV panels into hydrogen through electrolysis. By developing a detailed model, we can analyze the electrolyzer's response to different electrical inputs, optimize its performance, and estimate the hydrogen production rate [14]. This information is essential for properly sizing the electrolyzer and determining its integration within the system.

Additionally, implementing the battery storage allows storing of excess energy produced by the PV panels for later use when sunlight is insufficient. Modeling the battery storage system helps assess the systems to optimize the charging and discharging cycles and maximize the overall system performance [15]. Proper modeling of each component also involves considering their interactions and system-level dynamics. We can simulate and analyze the overall system's behavior under different scenarios by integrating the models of PV panels, electrolyzers, battery converters, and other components [16]. This enables us to evaluate the system's performance, energy efficiency, and overall feasibility, ensuring that all components work together seamlessly. Moreover, modeling the hybrid energy system provides insights into control strategies and optimization techniques. By simulating the system's operation, we can develop and test different control algorithms and energy management strategies to enhance system performance and maximize the utilization of renewable energy sources. This modeling approach helps identify optimal operating points, improve system efficiency, and minimize energy waste.

Modeling every component within the home hybrid energy system with a PEM electrolyzer presents several challenges. Capturing the complex dynamics of the electrolyzer, including its response to varying electrical inputs and efficiency characteristics, is crucial. Additionally, accurately modeling the dynamic behavior of PV panels due to changing solar irradiation and temperature is essential for predicting available electrical energy. The battery storage component requires modeling its charge and discharge characteristics, state of charge, and efficiency to optimize system

operation. Integrating and controlling different components, obtaining reliable data, accounting for uncertainties, ensuring scalability and flexibility, managing computational requirements, and validating the models against real-world data are also vital aspects to consider. The identified areas to improve the PV inverters are as the following:

1.5 RESEARCH OBJECTIVES

This thesis attempts to model a complete solar-battery-hydrogen hybrid system. The proposed system focuses on solar generation as a primary electricity source combined with battery and hydrogen storage, including an electrolyze and a fuel cell to power a typical house. This system can help tackle the daily fluctuations in energy demand and resolve the renewable energy intermittency problem through battery or hydrogen storage. The variation in the load power is duly compensated either by PV generation/inverter, battery storage/inverter, hydrogen storage/fuel cell, and an energy management controller. The goal of hydrogen integrated energy system is to follow a varying power consumption profile. The system is optimally sized to meet these differing load profiles. After the comprehensive literature survey conducted in chapter two, the motivation for extending domestic hydrogen production research has led to the following objectives.

- a. To model a feasible PEM fuel cell and verify the characteristic curves (i.e., Voltage vs current density, and Power density vs Current density).
- b. To develop scenarios for assessing the hybrid energy system to fulfill electrical load, including power produced by the fuel-cell and consumed by the consumer load.
- c. To study thermal efficiency and reactant utilization of fuel cells (Hydrogen and Oxygen).
- d. To study the relationship between hydrogen consumed and the energy produced for a typical household.

1.6 THESIS SCOPE

The thesis explores the possibility of developing a hybrid energy system for a household with hydrogen storage to compensate for the solar and grid intermittencies. All calculations assume that the average household consumes around 1000-1200 kWh

monthly. Other considerations like the size, occupants, rooms, etc., are not taken into consideration. The utilized fuel cell is considered a black box benchmarked with efficiency only. It is also assumed that electrolyzer water is abundantly available, free from impurities, and ready to be used without pretreatment.

1.7 RESEARCH METHODOLOGY

Figure 1.2 represents the research methodology. The project starts with the simulation and implementation of the hybrid PV-battery-electrolyzer energy system for a household. Next, state-of-the-art techniques for direct PV coupling to the electrolyzer/ Fuel Cell are conducted and shown as white blocks. Comprehensive modeling of renewable energy systems is conducted in which the individual components are modeled, followed by a complete system modeling. The proposed improvement in the thermal management, sizing, and energy management is the novelty of the current research, shown in blue blocks, while the future work is highlighted in yellow in Figure 1.2.

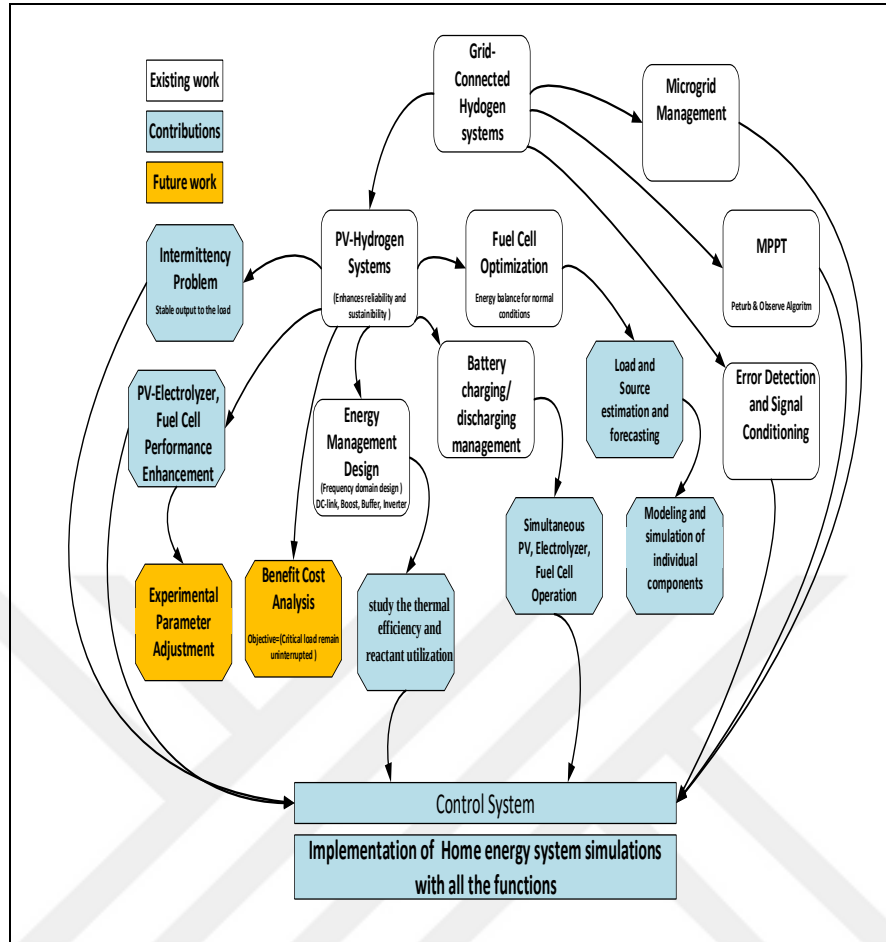


Figure 1.2: Research Methodology.

1.8 THESIS OUTLINE

This thesis constitutes five chapters. Chapter 1 presents the significance and background of the research in PV directly coupled electrolyzer, Fuel cell-based hydrogen production, storage, and utilization. Next, we define the problem statement, research objectives, and methodology. The chapter concludes by defining the thesis outline.

Chapter 2 starts introducing the challenges of producing hydrogen from renewable energy systems. The research area and the literature review are briefly explained. A section in Chapter 2 discusses different types of electrolyzers, hydrogen storage techniques, Fuel cells, integrating and coupling techniques, and household energy sizing and management. A review of the state-of-the-art techniques in designing PV-Electrolyzer/Fuel cell coupling provides a firm understanding of the improvement in controlling techniques and system modeling. The latest solutions in the literature for integrating multiple energy sources for a home energy system are discussed, emphasizing resolving the renewable energy intermittences with hydrogen storage.

Chapter 3 comprises various methods to analyze the PV-battery-electrolyzer-fuel cell system. Firstly, mathematical modeling is presented for individual components and the overall system. The effect of solar intermittencies and grid disturbance is simulated. The chapter emphasizes the novel method of direct PV coupling to the electrolyzer.

A novel control strategy compensating for intermittencies for simultaneous PV and grid disturbance is proposed. The control ensures a constant power output during rapid load change or low insolation conditions. The component sizing for each element, including the PV array, lithium-ion battery, electrolyzer, and fuel-cells, is presented. A simulation of the complete system during rapid load variation is presented to demonstrate the proposed hybridization's efficacy.

Chapter 4 reports the simulation results: efficiency, direct PV-electrolyzer/fuel cell coupling, intermittency compensation, and home energy system sizing. The result section also includes the simultaneous implementation of load variations. The efficacy of the studied system is also verified through various simulations. Finally, chapter 4 compares the proposed hybrid hydrogen-based energy system for a small household.

Chapter 5 presents the conclusion and recommendations for all the objectives individually. The chapter also highlights the contribution of the author. An overall conclusion on the complete project is presented. Finally, this chapter mentions the limitations, future research directions, and improvements in the proposed system.



2. LITERATURE REVIEW

2.1 INTRODUCTION

Hydrogen has a rich history dating back to the 18th century when it was first discovered by the British chemist Henry Cavendish in 1766. He identified the gas as a distinct substance and named it "inflammable air." Later in the 19th century, scientists such as William Grove and Christian Friedrich Schönbein conducted experiments with hydrogen and discovered its potential for use in fuel cells. Hydrogen is the lightest and simplest element, with the chemical symbol H. It is a colorless and highly flammable gas. Its high energy content is one of its key properties, making it an attractive fuel source. Hydrogen liberates water as the only byproduct when combusted with oxygen, making it a clean energy carrier. Hydrogen has a very low density; thus, it takes up a large volume for a given mass. Thus, it is challenging to store and transport it efficiently. It can be stored as liquefied hydrogen, metal hydrides or as a compressed gas.

2.2 HYDROGEN FUEL

Hydrogen is known to have a high energy to weight ratio, making it an ideal candidate for applications requiring lightweight fuels, such as space exploration. However, harnessing hydrogen as an energy source comes with certain safety considerations due to its flammability and the need for proper handling and storage. Regarding availability, it is the most plentiful element in the world but typically exists in compound form, such as water (H₂O) or hydrocarbons. However, it can be extracted from natural gas through steam-methane reforming or electrolysis, where water is split into hydrogen and oxygen using an electrical current. Understanding the properties of hydrogen is essential for its safe and efficient utilization in numerous applications, like energy production, transportation, and industrial processes. Globally, massive research is underway on hydrogen production methods, storage techniques, and infrastructure to unlock its full potential as sustainable, clean and renewable energy source.

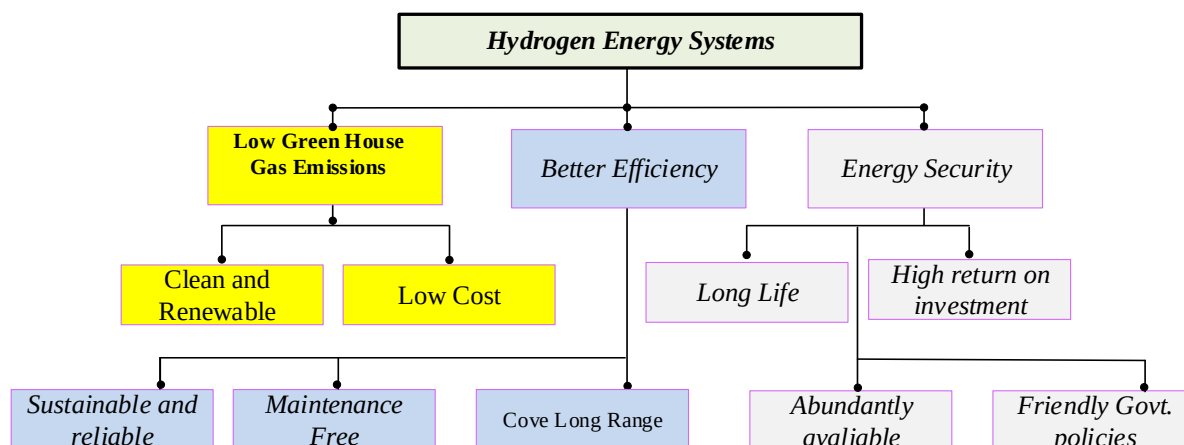


Figure 2.1: Benefits of Hydrogen Energy Systems.

2.2.1 Para And Ortho Hydrogen

Para-hydrogen and ortho-hydrogen are two different forms of hydrogen due to the different spin states of the hydrogen nuclei, also known as protons. Para-hydrogen refers to the spin state where the proton spins are oriented in opposite directions, resulting in a lower total spin value. This configuration leads to a lower energy state compared to ortho-hydrogen. In para-hydrogen, the two proton spins are aligned antiparallely, with one spin up and the other spin down. On the other hand, ortho-hydrogen refers to the spin state where the proton spins are oriented in the same direction, resulting in a higher total spin value. In ortho-hydrogen, both proton spins are either aligned in similar direction (both spins up) or in the reverse direction (both spins down). The conversion between para-hydrogen and ortho-hydrogen is governed by quantum mechanical principles and is influenced by temperature. At room temperature, hydrogen gas is typically a mixture of both para-hydrogen and ortho-hydrogen, with the ratio of ortho to para being approximately 3:1.

Energy is either released or absorbed during the conversion process, depending on the specific conditions. When para-hydrogen converts to ortho-hydrogen, energy is typically released as heat. Conversely, converting ortho-hydrogen to para-hydrogen requires the input of energy, which can be supplied through various means, such as thermal energy or catalysts. The energy released or absorbed during the para-to-ortho conversion can be quantified using thermodynamic parameters such as enthalpy, entropy, and Gibbs free energy. These parameters describe the energy changes and feasibility of the conversion process.

The para-to-ortho conversion is temperature-dependent, with higher temperatures favoring the conversion from para to ortho. The conversion is relatively slow at low temperatures, such as cryogenic temperatures. As the temperature increases, the conversion rate becomes faster. Other factors, such as pressure and the presence of catalysts, can influence the thermodynamics of para-to-ortho conversion. These factors can modify the energy barriers and kinetics of the conversion process.

2.2.2 Hydrogen Flammability

Hydrogen is a highly flammable gas and has certain properties that contribute to its flammability. Therefore, handling and storage of hydrogen requires special precautions and safety measures. Proper ventilation, leak detection systems, and adherence to safety codes and regulations are essential to minimize the risks associated with hydrogen's flammability. Here are some key aspects of hydrogen's flammable properties:

- a. **Low burning Energy:** Hydrogen has a reduced ignition energy, meaning it requires only a small amount of energy to burn. This makes it highly reactive and prone to ignition even in the presence of a small spark or heat source.
- b. **Wide Flammability Range:** Hydrogen has a wide flammability range, which means it can form an explosive mixture with air over a broad range of concentrations. The lower flammability-limit (LFL) of hydrogen in the air is about 4%, meaning that if the hydrogen concentration in the air falls below 4%, it is too lean to ignite. The upper flammability-limit (UFL) of hydrogen is about 75%, indicating that if the hydrogen concentration exceeds 75%, it becomes too rich to ignite. Within this flammability range, hydrogen-air mixtures can ignite and burn explosively.
- c. **Rapid Flame Propagation:** When hydrogen ignites, it undergoes rapid combustion and flame propagation. Hydrogen flames have a high propagation speed, which means that they can quickly spread through a mixture, leading to a rapid release of energy.
- d. **Invisible Flame:** Hydrogen flames are almost invisible to the naked eye, especially in daylight. This can make it difficult to detect a hydrogen fire visually, increasing the risk of accidental ignition.

- e. **High Heat Release:** Hydrogen has a high heat of combustion, which means that it releases a significant amount of energy when it burns. This can result in intense heat and can contribute to the severity of hydrogen fires.

2.2.3 Volumetric Energy Content

Hydrogen has a relatively poor volumetric energy content in comparison to other combustible fuels. It has a volumetric energy content of approximately 8-10MJ/liter (at standard temperature and pressure). While Gasoline has a much higher volumetric energy content, approximately 34.2-35.8 MJ/liter. Diesel fuel has an even higher volumetric energy content than Gasoline. It typically contains around 35.8-38.6 MJ/liter. Natural gas, primarily composed of methane, has a lower volumetric energy content than hydrogen. It typically contains about 35.9-39.5 MJ/liter. Also, Propane, often used for heating and cooking, has a higher volumetric energy content than hydrogen. It contains approximately 25.3-27.8 MJ/liter. Compared to Gasoline, diesel, natural gas, and Propane, hydrogen does have a lower volumetric energy content. However, it's important to consider other factors, such as energy conversion efficiency, emissions, and storage methods, when evaluating the overall suitability of hydrogen as an energy source for specific applications.

2.2.4 Characteristics Of Energy Storage System And Hydrogen Storage Potential

Energy storage systems' storage capacity, speed, and response time are essential performance features. However, when considering hydrogen to store energy, its actual properties and performance indices depend on the specific process that are utilized to convert it back into electricity. Therefore, it cannot be simply described in general terms. For example, in a local power plant that uses hydrogen in a burning engine, the performance characteristics of the gas is influenced by the engine type. A reciprocating engine with hydrogen fuel may respond relatively quickly to changes in power demand. However, the starting time may still require a few seconds if the engine is not already running. While such engines can easily adjust to fluctuations in demand, their maximum power output is typically around 10 MW and often lower. On the other hand, gas turbine processes can generate more power but are generally more complex.

Regarding responsiveness, fuel cells (FCs) generally offer the best performance. They can quickly establish themselves and effectively adapt to shifts in demand. On the other hand, burning engines become less efficient as output decreases, while their efficiency remains relatively consistent between 0-100% output. Individual fuel cells typically have a capacity of less than 1 MW capacity and can be costly, so multiple FCs are connected in high-capacity power plants. However, alternate energy storage, such as batteries, flywheels, and capacitors, can convert hydrogen into electricity much more rapidly than any other method. This makes hydrogen energy storage well-suited for arbitrary and long-term grid support storage. A hydrogen energy storage system offers a significantly larger energy storing capacity, limited only by the capacity of the gas storage container. Hydrogen could be stored underground in caverns like salt domes if high-density energy storage is desired. These underground storage facilities to store methane gas have been used for decades and can be adapted for hydrogen storage without issues. Hydrogen is usually stored at high pressure to enhance its storage capacity, similar to pressurized hydropower storage. This allows hydrogen storage to be utilized as a large-scale energy storage system. Currently, hydrogen storage systems are limited because they only operate in cycles. The best round-trip efficiency achievable is approximately 54%, significantly lower than other storage systems' efficiency. For example, an electrolyzer typically operates at around 90% efficiency, while a power plant converting hydrogen into electrical power operates at around 60% efficiency. In some instances, renewable energy (RE) storage systems like wind storage hydrogen units, where excess wind power would need to be stored, can tolerate much lower efficiency. However, in most other situations, producing low-peak energy through the grid would be inefficient, even if the option is available.

2.2.5 Hydrogen Suitability For Intermittency Problem

Hydrogen offers distinct advantages when it comes to addressing the challenges posed by the fluctuations of renewable-energy sources. Its discharge time, energy capacity, and power delivery capabilities make it an ideal candidate for integration with renewables to create a reliable and stable energy system. One key advantage is hydrogen's ability to act as an energy buffer. All the extra energy generated from renewable sources (solar, wind etc.) during periods of high production can be converted and stored as compressed

hydrogen . This stored energy can then be utilized during low renewable energy generation periods, ensuring a consistent and continuous energy supply.

Moreover, hydrogen boasts a high energy storage capacity, making it capable of storing large quantities of energy. The large storage capacity is especially valuable for renewable systems like PV-solar and wind, which may experience fluctuations in output. With hydrogen storage, surplus energy can be captured and stored for later use, enabling a more balanced and reliable energy system. Hydrogen also offers long-duration storage capabilities. Depending on the storage capacity, it can store energy for extended periods, ranging from hours to days or even weeks. This feature is particularly advantageous when renewable energy generation is low, such as on cloudy days or in calm wind conditions. Hydrogen ensures that stored energy is available when needed, bridging between intermittent renewable-energy supply and consistent demand.

Another benefit is the flexibility of hydrogen in electricity generation. It can be utilized in fuel-cells or combustion engines to convert stored hydrogen energy into electricity. This flexibility enables efficient energy conversion according to varying demand patterns, ensuring optimal power generation and utilization. Furthermore, hydrogen storage facilitates the decentralization of energy systems. By providing localized energy buffering, hydrogen allows for the establishment of reliable energy sources in remote or off-grid areas where access to a stable grid connection is limited. It enables self-sufficiency and energy independence in these regions. Finally, when hydrogen production utilizes renewable energy, such as through electrolysis powered by solar or wind energy, the entire process becomes carbon-free. This aligns with reducing greenhouse gas emissions and transitioning to sustainability. Hydrogen's discharge time, energy storage capacity, and power generation capabilities make it an ideal solution for mitigating the intermittency challenges associated with renewable energy sources. Its ability to act as an energy buffer, coupled with long-duration storage and decentralized applications, ensures a reliable and clean energy supply while maximizing the utilization of renewable resources.

2.2.6 Efficiency Of Hydrogen-Based Storage To Tackle Intermittency

Hydrogen storage has emerged as a promising solution to renewable energy intermittency problem. The renewable-energy generation is dependent on variable weather conditions,

therefore storing surplus energy during periods of high-generation and discharging it when demand is high, becomes crucial for grid stability and reliability. Hydrogen storage offers a feasible option for long-term energy storage, enabling the utilization of renewable energy on demand.

Recently, significant research advances have improved hydrogen generation, utilization and storage technologies. Different storage approaches have been investigated, including the compression of hydrogen gas, the liquefaction of hydrogen, and the utilization of solid-state storage materials. Advances in materials science, such as developing metal hydrides, carbon-based materials, and advanced catalysts, have improved the storage capacity, efficiency, and reversibility of hydrogen storage systems. Additionally, innovations in hydrogen production, transportation, and distribution technologies are being pursued to create an integrated and efficient hydrogen infrastructure.

However, several challenges still need to be addressed in hydrogen storage. One active research problem is improving hydrogen-storage capacity and density to enhance energy storage potential. Developing cost-effective storage materials and systems is also essential to make hydrogen storage economically viable. Safety considerations, including preventing leaks and addressing hydrogen flammability, also require ongoing research efforts. Furthermore, integrating hydrogen storage into current renewable energy and grid infrastructure poses technical and logistical challenges that need to be overcome.

The research presented in the article [4] explores using hydrogen and compressed air as an energy storage solution. By integrating the two subsystems thermally, it was found that small-volume pressure vessels could efficiently store a significant amount of energy. The study focused on a thermodynamic hybrid system that demonstrated high efficiency, achieving a storage capacity efficiency of 38.15% under the assumed operating parameters. The results were compared to three reference systems that utilized hydrogen generators. The first reference system employed a conventional power-to-H₂-to-power setup with fuel cells and hydrogen generators. Two additional systems were integrated into the setup, featuring storage capabilities for highly compressed air: a diabatic compressed air energy storage system and an adiabatic compressed air energy storage system. The study thoroughly examined and discussed the advantages and disadvantages of each system, providing detailed analysis on their respective characteristics[4].

The research presented in [17] focuses on hydrogen storage and addresses concerns regarding hydrogen technologies' chemical and physical properties. Although hydrogen is a clean fuel, its storage can raise conservation concerns due to the potential risks associated with tank explosions, particularly involving liquid hydrogen (LH₂) that can result in boiling liquid expanding vapor explosions (BLEVE). This study evaluates various consequences of BLEVE through theoretical and analytical models, supported by experimental results from the BMW vehicle manufacturer's protection tests in the 1990s. The Safe Use and Management of Hydrogen Fuels for Profitability (SH2IFT) project will utilize these models and select appropriate approaches for subsequent LH₂ BLEVE experiments after validation. The research also highlights the limitations of the vacuum model and the uncertainties surrounding the nature of the vacuum in LH₂ explosions. The study concludes by recommending the LH₂ BLEVE entertainment model [17].

The research presented in [8] investigates a hybrid storage system and proposes a three-layer algorithm to optimize its performance. Firstly, the capacity allocation of the hybrid storage system is determined using a fuzzy-entropy membership method. This helps efficiently distribute the storage capacity among the hydrogen and battery components. Secondly, a predictive control model combined with the Kalman filtering method is employed to allocate hydrogen and battery storage power. This predictive approach enhances the control of power flow in the system. Finally, a PID controller is utilized to generate a tracking reference signal, which aids in effectively regulating the power flow. The simulations demonstrate that their algorithm successfully manages the power allocation in the storage system, leading to improved efficiency and an extended lifespan. Additionally, excess electricity can be stored in tanks as hydrogen for future utilization, thereby ensuring better utilization of available resources [8].

The research discussed in reference [18] focuses on integrating hydrogen storage with electric vehicle (EV) charging stations to promote their usage. The study recognizes the need for studying and improving current technologies to enhance EV charging stations' efficiency. In this context, a novel energy management system (EMS) algorithm called BBO “(*Biogeography-Based Optimization*)” is proposed for hybrid Electric car charging stations that incorporate ZSC (Zero Sequence Compensation) into MVDC (Medium Voltage Direct Current) networks. The EMS optimizes the fitness function, which aims

to balance hydrogen consumption and production, using an improved BBO algorithm. The charging station comprises various components, including solar arrays, grid interface, fast battery chargers, energy storage systems, a fuel cell (FC), a battery energy storage (BES), and a complementary hydrogen energy system. The hydrogen system serves as an electrolyzer to produce hydrogen stored in the hydrogen tank, providing additional energy for the charging station [18].

The research discussed in reference [9] compares the effects of PCMHE (Phase Change Material Heat Exchanger) and CTHE (Counter-Flow Tube Heat Exchanger) on a high-capacity joint operation in the MH-CTHE (Metal Hydride-Counter-Flow Tube Heat Exchanger) hydrogen storage system. The study examines three parameters that effect the system's performance. The research findings infer that the heat transfer coefficient has a lesser impact compared to the thermal water temperature and the system efficiency at high outlet pressure. Moreover, the research presents a straightforward equation that enables the prediction and control of operating conditions based on the average dewatering rate of two other operating parameters. These findings helped in optimization of the MH-CTHE hydrogen storage system [18].

The research discussed in reference [19] highlights the importance of decarbonization in the transportation industry, specifically about the anticipated popularity of hydrogen transportation. Establishing filling stations, refueling infrastructure, and vehicles necessitates adherence to light and heavy vehicle refueling protocols. While studies have focused on refilling light vehicles with 10 kg of H_2 up to 700 times, the effort required to refuel heavy vehicles with 30 to 40 kg of Hydrogen up to 350 kg times remains unknown. This study uses a large-scale model based on real data from the “3Emotion project” to simulate a fuel flood tank to tank refueling event. The research includes predicting the refueling operation time, operating parameters during filling, and compliance with technical protection limits imposed by SAE J2601/2 standards [19].

The research presented in reference [20] focuses on addressing the issue of hydrogen leakage problem resulting from the rupture of high-pressure H_2 reservoirs. The study introduces two computational methods that simultaneously analyze the reactive fluid formation and its interaction. A unified computational strategy combines coupled particle and Eulerian methods to address the leakage of reactive hydrogen along the orifice due to crack wall propagation. The computational energy vector method is crucial in

detecting hydrogen presence within high-pressure vessels, particularly in embrittlement reactions. This method provides valuable safety insights for predicting crack propagation and hydrogen leakage. By utilizing a mathematical model, various factors such as turbulent hydrogen diffusion, concentration, partitioning, chemical reactions, thermodynamic behavior, crack formation, boundary conditions, and their impacts can be predicted and analyzed effectively. The research findings reveal that the mouth reaction is not centered on the channel near the flow axis, as it is affected by excess hydrogen fuel and the separation into upper and lower regions [20].

The research presented in reference [21] focuses on ensuring the health of storage tanks by regulating the appropriate filling temperature for efficient hydrogen vehicle refueling. The study examines heat transfer during the filling process of hydrogen tanks and establishes a balance focused on heat-transfer considerations. The model is mathematically validated when compared with rapid hydrogen filling experiments conducted on Type IV tanks, considering the gas's temperature rise. In the experiments some parameters like, temperature, nozzle diameter, and refilling time are evaluated to assess the impact of flange parameters. The collected graphs indicate that the high thermal conductivity of the shale tank interior wall reduces the peak temperature in the Type IV tank under investigation. The proposed gas over-tank model is a valuable tool for testing various parameters, including new hydrogen flange protocols and temperature rise in shale [21].

The research presented in [10] explores the practical application of hydrogen fuel as an efficient and viable alternative for transportation. One of the challenges associated with hydrogen storage is the rapid temperature rise experienced by the H₂ storage tank (HST) during high-pressure filling, which can pose issues regarding temperature protection. Several important considerations must be considered to enable rapid and safe hydrogen refueling. In this research, a system model was established to examine the high-pressure refilling process of a H₂ station storage tank using thermodynamic theory. The physical parameters of hydrogen were normalized in the analysis to bring the simulation closer to reality. The preferred temperature and pressure during filling were determined through numerical simulations of a 50 MPa compressed H₂ tank. The study compared the calculated results for adiabatic states and the simulation results for non-adiabatic filling. It further examined the influence of parameters such as pressure, initial temperature,

mass flow rate, and internal temperature. This research is a valuable theoretical basis for high-pressure hydrogen energy storage and hydrogenation technology, providing insights and understanding that can contribute to their practical implementation. [10].

In the power-to-power process, surplus renewable energy is harnessed and stored as hydrogen, a valuable chemical energy. This stored hydrogen can be utilized on-site or transported to areas of energy consumption. The H_2 may be reconverted back into electricity, ensuring a continuous and reliable energy supply. However, assessing the round-trip efficiency of these processes is crucial, which measures the energy output compared to the energy input, taking into account any losses along the way.

Calculating round-trip efficiency involves several steps. First, water undergoes electrolysis, where electrical energy produces hydrogen. The distribution of hydrogen often involves the use of compressed fuel-cell electric trucks. The hydrogen is then stored either in metal hydride or micro gas turbines [22]. Finally, the stored hydrogen is used to generate electricity when required. When studying solid-oxide electrolysis and metal-hydride storage, the maximum two-way efficiency achieved was twenty nine percent. However, when alkaline or PEM methods were employed, the efficiencies decreased to 22.8% and 21.8%, respectively. Furthermore, the two-way efficiency was even more decreased when alternative storage media like compressed or liquid hydrogen were considered.

Nevertheless, the research paper highlighted the potential for substantial improvements in power-to-power efficiency by integrating H_2 production and power generation units more effectively. The study suggests that by leveraging micro gas turbines with a 40 percent efficiency rate, a remarkable performance increase of 42 percent can be achieved in power-to-power energy storage systems over the next decade. This indicates the promising prospects for enhancing the overall efficiency and effectiveness of hydrogen-based energy storage solutions.

2.2.7 Advantages Of Hydrogen Vs Other Fuel Storage

Hydrogen offers several advantages over other energy storing techniques, e.g., supercapacitors, chemical batteries, hydropower storage, or compressed air. Here are the key advantages of hydrogen:

- a. **Energy Density:** Hydrogen has a considerable energy-density, particularly when compared to supercapacitors and batteries. H₂ systems can store a more energy per unit mass, allowing for compact storage systems and longer durations of energy supply.
- b. **Long Duration Storage:** Hydrogen store energy for longer durations, making it suitable for applications requiring extended periods of power supply. In contrast, batteries and supercapacitors have limited energy storage capacities and may require frequent recharging.
- c. **Scalability:** Hydrogen storage and distribution infrastructure can be scaled up to meet increasing demand. This scalability is advantageous for large scale storage applications, e.g., utility grid- storage or industrial energy storage.
- d. **Fast Charging and Discharging:** Hydrogen fuel cells can be refueled quickly, providing fast charging and discharging capabilities. This is particularly beneficial for applications like electric vehicles, where quick refueling is desired.
- e. **Flexibility in Energy Conversion:** Hydrogen can be reconverted into electricity via fuel cells, or it can be burned in combustion engines, providing flexibility in energy conversion. This versatility allows hydrogen to be used in various applications, from transportation to power generation.
- f. **Environmental Impact:** Hydrogen offers clean and sustainable energy storage with zero greenhouse gas emissions in fuel cells. It contributes to reducing carbon emissions and preventing climate change.
- g. **Energy Independence:** H₂ can be generated from diverse sources, including renewable energy. Thus, enabling energy independence and reducing reliance on fossil fuels, enhancing energy security and sustainability.

While hydrogen storage systems still face challenges in terms of infrastructure development, cost, and safety, they hold significant potential for utility scale energy storage and the transition to a carbon free future. These advantages make H₂ a promising option for various applications, complementing other storage technologies to form a diverse and sustainable energy mix.

2.2.8 Applications Of H₂ Storage System

Stored H₂ has various applications across different sectors. As technology advances and the hydrogen economy grows, new and innovative applications will likely emerge. Here are some notable sectors where hydrogen storage are successfully demonstrated:

- a. **Transportation:** H₂ is used as a fuel for fuel-cell powered vehicles (FCVs) and hydrogen powered vehicles engines. Hydrogen storage enables these vehicles' efficient and clean operation, offering zero-emission transportation with longer driving ranges compared to battery electric vehicles.
- b. **Energy Grid Storage:** H₂ storage is vital for balancing the intermittent nature of renewable energy sources, such as solar-PV and wind systems. Excess electricity generated during peak production periods can be stored as compressed H₂ through efficient electrolyzer. The stored hydrogen can then be reconverted into electricity using fuel-cells or combustion engines during periods of high energy demand.
- c. **Backup Power:** Hydrogen storage systems can provide backup power in areas prone to power outages or in remote locations with limited access to electricity. Fuel cells fueled by stored hydrogen are a reliable backup energy sources for critical load, such as data centers, medical facilities, and telecommunications centers.
- d. **Industrial Applications:** Hydrogen storage is essential for various industrial processes. It can be used as a feedstock for chemical production, including manufacturing ammonia, methanol, and other hydrogen-based chemicals. Hydrogen is also used in refineries, metal processing, and heat treatment applications.
- e. **Off-Grid Power Systems:** In remote areas without access to electricity grids, hydrogen storage can be combined with renewable energy sources to create self-sufficient off-grid power systems. Solar or wind power can generate hydrogen through electrolyzers, which can then be compressed, stored and later can generate electricity.
- f. **Portable Power:** Hydrogen storage enables portable power solutions for applications like camping, outdoor activities, and remote worksites. Portable fuel cell systems fueled by hydrogen can provide clean and reliable power for charging electronic devices, lighting, and other portable equipment.

- g. Residential and Commercial Energy: Hydrogen storage can be integrated into residential and commercial buildings as an energy storage solution and used for heating, cooling, and electricity generation.

2.2.9 Recent Development Of Hydrogen Powered Technologies

Recently, researchers showed keen interest in hydrogen and fuel-cell (FC) technology in the context of storing and generating electricity on demand. Numerous studies and articles have highlighted hydrogen storage systems as a solution for seasonal power storage in renewable-energy systems. Researchers like Becherif et al. [6] have emphasized the need to identify technical, economic, scientific, and social barriers to the emergence of these systems. They advocate for a comprehensive approach that considers services, technology, organization, and finance to translate hydrogen storage ideas into economic value effectively.

Kharel and Shabani [23] conducted a case study in South Australia, showcasing the benefits of hydrogen storage systems on larger scale along with long term energy storage. These storage systems are combined with renewable energy sources like wind turbines and photovoltaic cells. Similarly, [24] Liu et al. implemented a gas-solid hybrid system for stationary hydrogen energy storage in China. They stressed the importance of low cost, safety, compactness, and reliability in developing such systems. Their hybrid system achieved an impressive efficiency of 95%, making it a promising solution for hydrogen energy storage applications.

Widera's work [15] focused on the compressed hydrogen storage potential and explored the combination of hydrogen production through electrolysis driven by wind or solar energy. The paper highlights the environmental benefits of H_2 as an energy storage medium. However, the cost of the hydrogen production process remains a crucial factor, especially considering the significant electricity demand during high-demand periods.

Overall, these studies and research efforts underscore the growing recognition of hydrogen storage systems as a viable option for stabilizing energy systems during demand imbalances and reaping economic benefits through increased hydrogen and oxygen production. A systemic approach that addresses technical, economic, and social considerations will be instrumental for commercial feasibility of hydrogen storage technologies.

2.2.10 Hurdles And Probable Solutions In Adopting Hydrogen Fuel.

In the quest for carbon-free societies and a clean energy future, transforming electricity production and power generation systems is paramount. Enter hydrogen—the game-changer that holds the potential to revolutionize the landscape of renewable energy. While incorporating hydrogen into power systems is still relatively unexplored territory, its possibilities are boundless. Comprehensive research in hydrogen technologies is vital for uncovering their current capabilities and envisioning their future role for global energy and electricity needs.

The research study should shed light on electrolysis and fuel cell characterization by meticulously analyzing energy storage, gas-to-gas conversion, hybrid and triple generation, hydrogen-powered transportation, and real-world experimental data. Critical factors such as cost-effectiveness and long-term viability took center stage, bolstered by compelling statistical evidence from the literature. The findings may unequivocally emphasize that realizing a cost-effective hydrogen economy requires persistent efforts to amplify scale, enhance efficiency, foster technological innovation, and garner unwavering political support. The development of a hydrogen-based energy system faces several significant hurdles that must be solved for its prevalent adoption. These hurdles include:

- a. **Cost:** The primary challenge is the high cost associated with H₂ production, storage, and distribution infrastructure. Green H₂ generation is still relatively expensive compared to fossil fuel-based methods. The cost of establishing full H₂-infrastructure with storage facilities and refueling stations is also a barrier to its implementation.
- b. **Infrastructure:** The existing energy infrastructure is primarily designed for fossil fuel-based systems, and transitioning to a hydrogen-based system would require developing overall H₂ infrastructure, e.g., H₂ generation facilities, storage and transportation systems, and establishing a network of refueling stations. Underdeveloped infrastructure is the most challenging obstacle preventing H₂ adoption.
- c. **Storage and Transport sector:** H₂ has a low energy-density compared to conventional fuels, which means larger storage volumes are required to store the same amount of energy. Also, hydrogen has unique properties that make it challenging to handle and

transport safely. Developing efficient and cost-effective hydrogen storage and transportation methods is crucial for its viability as an energy carrier.

- d. **Safety Considerations:** H₂ is extremely combustible and has a wide flammability range. Special precautions and safety procedures must be executed to safeguard handling, storage, and hydrogen transportation. Public perception of H₂ as a safe energy source must also be addressed.
- e. **Scalability Issues:** Scaling up H₂ generation to keep up with growing energy demands is a substantial challenge. Current production methods, such as electrolysis, must be optimized for efficiency and scalability for H₂ generation on a larger scale. Additionally, advancements in renewable energy technologies are necessary to provide a sustainable and carbon-free energy source for hydrogen production.
- f. **Policy and Regulations:** Developing a hydrogen-based energy system requires supportive policies and regulations to incentivize investments, research, and development. Clear guidelines and standards must be established to ensure hydrogen technology safety, quality, and interoperability. Governments and regulatory bodies play a crucial role in creating a favorable environment for the growth of the hydrogen industry.

Addressing these hurdles requires collaborative efforts from government agencies, industry, researchers, and policymakers. Technological advancements, cost reductions, supportive policies, and public acceptance are key factors in overcoming these challenges and unlocking the full potential of a hydrogen-based energy system.

2.3 HYDROGEN GENERATION METHODS

Hydrogen can be generated through various techniques, each with its advantages, limitations, and environmental considerations. Here are the most common methods of hydrogen production:

2.3.1 Steam-Methane Reforming

SMR is the most widely used method for large scale H_2 generation globally. SMR is cost-effective and efficient but is associated with greenhouse gas emissions since it relies on fossil fuels. SMR involves reacting steam with natural gas (methane). The reaction of steam (H_2O) with natural-gas, primarily methane (CH_4), along with catalyst, produces (H_2) and carbon-monoxide (CO). The resulting gas mixture, known as synthesis gas or syngas, is then purified to obtain pure hydrogen. A basic SMR process is shown in

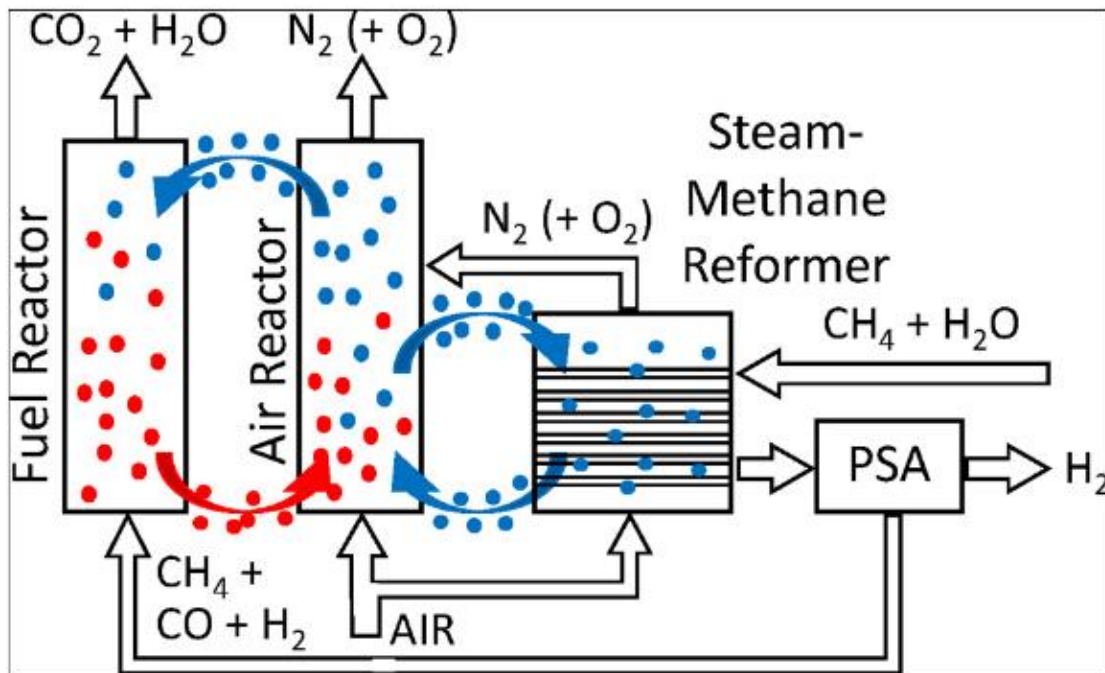


Figure 2.3: Steam Methane Reforming Method.

The process occurs in a reformer comprising several interconnected tubes filled with a catalyst material. The following steps are performed in SMR production.

- Feed Preparation:** Natural gas, typically obtained from fossil fuel sources, is the primary feedstock for SMR. The natural methane is first desulfurized to remove sulfur compounds, which can poison the catalyst. The desulfurized gas is then mixed with steam in the calculated ratio for the reforming reaction.
- Reforming Reaction:** The steam and natural gas mixture is fed into the reformer, where it meets a catalyst, commonly based on nickel. The catalyst helps to breakdown the methane and water-molecules, promoting the desired chemical

reactions. The primary reaction that occurs is the endothermic reforming reaction:
 $\text{CH}_4 + \text{H}_2\text{O} \rightarrow \text{CO} + 3\text{H}_2$.

- c. This reaction produces carbon-monoxide and H_2 gas. The reforming reaction is favored at high temperatures, typically around 700-900°C, and is enhanced by the presence of the catalyst.
- d. Shift Reaction: The resulting gas mixture from the reforming reaction contains carbon-monoxide, which needs to be converted into more hydrogen. In the shift reaction, the carbon-monoxide reacts with vapors to form more H_2 and carbon dioxide (CO_2). The shift reaction occurs in a separate reactor, typically at temperatures around 200-400°C, and with the help of a shift catalyst: $\text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2$. This reaction increases the H_2 yield and reduces the CO_2 content in the gas stream.
- e. Gas Purification Process: The gas stream from the shift reaction may still contain impurities, such as trace amounts of CO_2 , carbon dioxide, and other contaminants. Various purification processes, e.g., pressure-swing-adsorption (PSA) or membrane-separation method, are employed to separate and remove these impurities, resulting in high-purity hydrogen gas.

Steam Methane Reforming is a well-developed and established technology for hydrogen production. It offers high conversion efficiency, typically around 70-85%, and can produce large quantities of hydrogen. However, one of the main drawbacks of SMR is its association with greenhouse gas emissions. Since it relies on methane gas as the feedstock, carbon dioxide is released as a byproduct, contributing to carbon emissions unless carbon capture and storage (CCS) technologies are employed. Efforts are being made to develop cleaner and more sustainable alternatives to SMR, such as electrolysis powered by renewable energy sources.

2.3.2 Thermochemical Water-Splitting

Thermochemical water-splitting is a method of H_2 production involving high temperatures and chemical reactions to decompose water molecules into (H_2) and (O_2) gases. This process utilizes various thermochemical cycles, each with multiple chemical reactions, to achieve the desired water-splitting reaction. Here is a simplified explanation of the thermochemical water-splitting process:

- a. High-Temperature Reactor: The thermochemical water splitting process typically requires a high-temperature reactor, such as a solar furnace, concentrated solar power system, or a nuclear reactor, to provide the essential heat energy to complete the reactions.
- b. Thermochemical Cycles: Thermochemical water splitting involves several cyclic steps, each involving different chemical reactions. These cycles often utilize metal oxides as catalysts or reactive materials. Some commonly used cycles are sulfur-iodine mix (S-I), hybrid-sulfur, and copper chlorine cycles.
- c. Water Vaporization: The first step in the thermochemical cycle is the vaporization of water. The high-temperature reactor heats water to produce high-temperature steam or water vapor.
- d. Reaction Steps: In the subsequent reaction steps of the thermochemical cycle, the steam reacts with the catalyst or reactive material to undergo various chemical reactions. These reactions can involve oxidation, reduction, or other thermochemical transformations.
- e. Hydrogen and Oxygen Generation: The chemical reactions in the thermochemical cycle produce hydrogen gas and oxygen gas. These gases are then separated and collected for further processing or storage.
- f. Regeneration: After the hydrogen and oxygen gases are produced, the catalyst or reactive material must be regenerated for the next cycle. Some other reactions or processes are also needed at this stage to restore the catalyst's original state or remove any byproducts.

Thermochemical water splitting offers some advantages for hydrogen production. First, they can achieve high energy conversion efficiencies, especially when coupled with high-temperature heat sources. Thermochemical water splitting can operate continuously, allowing for a steady and reliable hydrogen supply. Also, thermochemical processes can be integrated with various high-temperature heat sources, including photovoltaic(PV) energy, nuclear energy, or waste heat from industrial processes. Thermo-chemical water decomposition has the potential for large-scale hydrogen production, making it suitable for industrial applications and energy storage. However, there are challenges associated with thermochemical water splitting, including the need for high-temperature reactors, the selection and development of efficient catalysts or reactive materials, and the overall

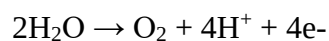
system complexity. These challenges require extensive research efforts to improve the efficacy, efficiency, cost, and scalability of thermo-chemical water splitting for commercial H₂ production.

2.3.3 Electrolysis

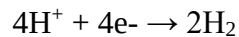
Hydrogen production from electrolysis utilizes an electric current to decompose water molecules (H₂O) into (H₂) and (O₂). It is a promising process for producing hydrogen using a complete renewable energy source (PV-solar or wind power), to generate the required electricity, making it a cleaner and more sustainable alternative to traditional H₂ production methods. The electrolysis process for H₂ production is saliently explained below:

- a. **Electrolyzer Setup:** Electrolysis of water requires an electrolyzer, comprising two electrodes (an anode and a cathode) submerged in an electrolytic solution. The electrodes are usually made of a conductive material, such as platinum or nickel, and are parted by a thin membrane that allows the passage of ions.
- b. **Electrolyte Solution:** The electrolytic solution is a dilute sulfuric-acid(H₂SO₄) or potassium-hydroxide (KOH-) solution, which provides ions for conducting electricity and enhances the electrolysis process.
- c. **Electrolysis Process:** As soon as the electric current is passed through the electrolyzer, several electro-chemical reactions take place at the electrodes:

At the anode, (positive electrode): Oxygen-evolution reaction takes place (OER)



At the cathode, (negative electrode): Hydrogen evolution reaction takes place (HER)



Applying the electric current causes the water molecules at the anode terminal to release O₂ gas and positively charged H⁺ ions (protons). The H⁺ ions migrate through the electrolytic solution to the cathode terminal, combining electrons coming from the electric current to form H₂ gas.

- d. **Gas Separation:** The resulting gases from the electrolysis process are hydrogen (H₂) at the cathode-terminal and oxygen (O₂) at the anode-terminal. To prevent the

mixture of gases, a separator or membrane in the electrolyzer helps to keep the gases separated, allowing only hydrogen to be collected.

- e. Purification: The hydrogen gas collected from the electrolysis process may still contain traces of impurities or moisture. Additional cleansing steps, such as pressure-swing adsorption (PSA) or membrane-purification, can be employed to remove impurities and ensure high-purity hydrogen.

One of the main benefits of electrolysis process for H₂ production is utilizing solely renewable energy sources. By using electricity generated from renewable sources PV-solar or wind power, electrolysis can produce "green hydrogen," which has no carbon emissions during its production. Green hydrogen technology is the only contender for a clean energy future and reducing greenhouse gas emissions. Although electrolysis offers a sustainable pathway for hydrogen-production, enabling the coupling of clean energy sources with the generation of green and versatile hydrogen gas, hydrogen production from electrolysis currently requires a significant amount of electricity. It can be less efficient compared to traditional hydrogen production methods. Current research efforts will improve the efficiency and cost-effectiveness of electrolysis technology.

2.3.4 Biomass Hydrogen Production

Biomass-gasification is a thermo-chemical process that adapts biomass feedstock, e.g., agricultural residues, woodchips, or energy-crops, into a synthesis gas, commonly known as syngas. It is a versatile and renewable energy conversion technology that can produce a (H₂), (CO), (CH₄), and other trace gases mixture. The biomass gasification process involves following steps:

- a. Feedstock Preparation: Biomass feedstock is collected and prepared by removing impurities and reducing its size into small pieces or pellets to ensure uniformity and better gasification performance.
- b. Gasification Reactor: The prepared biomass is then introduced into a gasifier (high-temperature reactor). The gasifier undergoes under controlled oxygen-deficient or oxygen-starved conditions to avoid complete combustion of the biomass.
- c. Drying and Pyrolysis: Initially, the biomass undergoes a drying process where moisture is evaporated. As the temperature increases, a thermal decomposition

process called pyrolysis occurs, converting the solid biomass into volatile gases, tars, and char.

- d. Gasification Reactions: The volatile gases and tars produced during pyrolysis react with the limited oxygen available in the gasifier. The reactions involved include:
 - a. Partial Combustion: Some of the carbon in the biomass reacts with O_2 to form (CO_2) and (CO).
 - b. Gasification: The remaining carbon reacts with steam (H_2O) or carbon dioxide (CO_2) to produce hydrogen gas (H_2) and carbon monoxide (CO) through endothermic reactions.
 - c. Tar Reforming: The tars and volatile hydrocarbons are thermally cracked and reformed into simpler gases, including hydrogen and methane.
 - e. Syngas Cleaning: The produced syngas contains impure traces such as tars, particulates, sulfur-compounds, and other minor contaminants. These impurities can be removed through various cleaning processes, such as filtration, cooling, scrubbing, and catalytic reactions to obtain cleaner syngas.
- f. Utilization or Conversion: The cleaned syngas can be utilized in various ways:
 - a. Power Generation: The syngas can be combusted in a gas engine or turbine to generate electricity.
 - b. Heat Generation: The syngas can be used as a heat source for industrial processes or district heating.
 - c. Bio methanation: The syngas can be further processed through methanation, where it reacts with additional hydrogen to produce methane, known as bio methanation or synthetic natural gas.

The main benefit of biomass is its derivation from organic sources, making it a sustainable and renewable energy resource. It provides a solution for managing agricultural residues, forest waste, and other biomass materials that would otherwise contribute to environmental pollution. Moreover, the Syngas produced from biomass gasification can be used for power generation, heat production, or further processed into biofuels and other valuable chemicals. Also, when the biomass feedstock is sustainably sourced, the carbon-dioxide released during gasification and combustion is offset by the carbon absorption during biomass growth, resulting in a relatively carbon-neutral energy

process. However, biomass gasification also faces challenges, such as the need for consistent and high-quality biomass feedstock, efficient gasifier design, syngas cleaning, and managing the ash and tar byproducts. Many research and development efforts are focused on improving the efficiency and cost-effectiveness of biomass gasification technology.

2.3.5 PV-Electrolyzer Hydrogen Production

Solar water decomposition through sunlight to drive the splitting of water molecules into hydrogen (H_2) and oxygen (O_2) gases is a promising H_2 generation method. This process involves harnessing the energy from sunlight through a photoelectrochemical (PEC) cell or a photovoltaic-electrolyzer system. Here is a simplified explanation of the solar water-splitting process:

- a. Photovoltaic (PV) or Photoelectrochemical (PEC) Cell: The solar water splitting system consists of a PV or PEC cell. In a PV cell, sunlight is directly converted into electricity, while in a PEC cell, light is absorbed by a semiconductor material to initiate the water-splitting reaction.
- b. Light Absorption: The PV or PEC cell is designed to absorb sunlight-containing photons. The semiconductor material within the cell absorbs the photons, exciting the electrons within the material to a higher energy level.
- c. Charge Separation: In a PEC cell, the excited electrons are separated from the positively charged holes within the semiconductor material, creating a flow of electrons and holes. In a PV cell, the excited electrons flow through an external circuit.
- d. Water Splitting: The electrons move towards the cathode -electrode, while the holes flow towards the anode electrode. At the cathode terminal, the electrons reduce water (H_2O) to generate (H_2) gas. The holes oxidize H_2O molecules at the anode terminal to produce oxygen gas (O_2). This process is called electrolysis.
- e. Catalysts: Catalysts are often used to facilitate water-splitting reactions, improving their efficiency and kinetics. Catalysts at the cathode promote reduction of H_2O molecules, while catalysts at the anode-terminal assist in the oxidation of H_2O to form O_2 .

- f. Gas Separation: The generated hydrogen and oxygen gases are collected separately for further use or storage. The gases can be purified and compressed for different applications, such as fuel cells, transportation, or industrial processes.

Solar water decomposition for hydrogen production uses PV-solar energy that is abundantly available and renewable, making it a sustainable source for H₂ production. The process of solar water-splitting does not release any carbon dioxide (CO₂) emissions, contributing to a cleaner and greener energy system. PV-electrolyzer systems can be scaled up to meet more extensive hydrogen production demands, making them suitable for various applications. Furthermore, the Hydrogen produced from solar water splitting can be stored and used as an energy-carrier, providing a reliable source of clean-energy even when sunlight is unavailable. However, some challenges are associated with solar water splitting, including the need for efficient and stable materials for the PV or PEC cells, improving the process efficiency, and cost reduction.

2.4 ELECTROLYZERS

The electrolyzer comprises an anode, and cathode terminals immersed in an electrolytic solution. The electrodes are separated by an alkaline or a polymer membrane. When an electric current is passed to the electrolyzer, water molecules at the cathode receive electrons and undergo reduction, forming hydrogen gas (H₂). At the same time, H₂O release electrons at the anode and undergoes oxidation, producing oxygen gas (O₂). There are different types of electrolyzer apparatus e.g., alkaline electrolyzers, proton-exchange membrane (PEM) electrolyzers, solid-oxide fuel electrolyzer cells (SOFCs), and high-temperature electrolysis (HTE) systems. Each type has its advantages, operating principles, and specific applications. Benchmarking the electrolyzer systems involves considering these factors and evaluating them in the context of specific applications and requirements. Therefore, it is essential to assess the trade-offs between efficiency, scalability, cost, and operating conditions to determine the most suitable electrolyzer technology for a particular use case. Continued research and technological advancements are driving improvements in electrolyzer performance, cost reduction, and expanding their applicability in the evolving hydrogen industry. A basic electrolyzer is shown in Figure2.3.

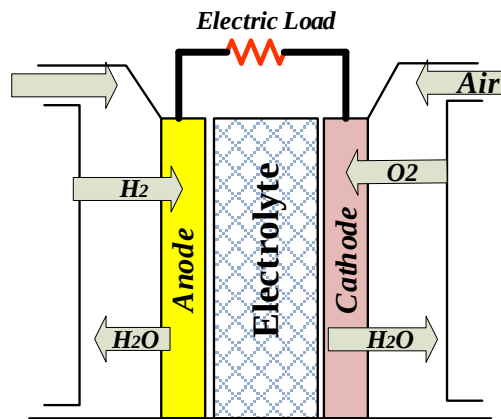


Figure 2.2: Electrolyzer Principle.

2.4.1 Alkaline Electrolyzers

Alkaline electrolyzers have been widely used for several decades and are considered one of the most mature electrolysis technologies. Alkaline electrolyzers operate using a liquid alkaline electrolyte, typically a potassium hydroxide (KOH) solution, which serves as the conducting medium for the electrochemical reactions. The main components of an alkaline electrolyzer include the electrolyte solution, an anode, a cathode, and a porous diaphragm or separator that separates the electrodes and allows the transport of ions. The electrodes are usually made of nickel or stainless steel and coated with catalyst materials, typically nickel or nickel oxide for the anode and nickel or platinum for the cathode. The electrolysis process in alkaline electrolyzers occurs in three main steps: electrolyte dissociation, hydrogen evolution, and oxygen evolution. When an electric current is applied to the electrolyzer, the electrolyte dissociates into hydroxide ions (OH^-) at the cathode and hydrogen ions (H^+) at the anode. At the cathode, the hydroxide ions combine with electrons from the external circuit to form hydrogen gas (H_2). At the anode, the hydrogen ions release electrons, which combine with hydroxide ions to form water and release oxygen gas (O_2).

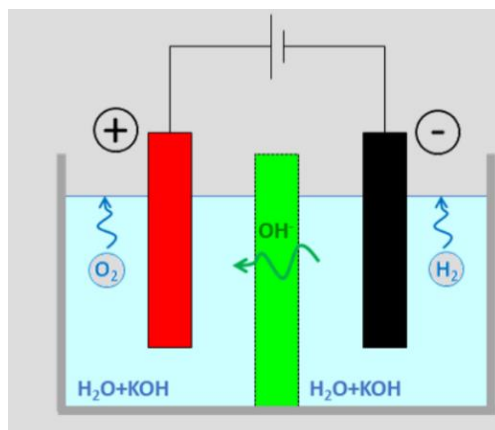


Figure 2.3: Alkaline Electrolyzer.

One of the core advantages of alkaline electrolyzers is their high efficiency, typically ranging from 60.0% to 80.0%. They also have a long life, often exceeding 10,000 hours of continuous operation. Alkaline electrolyzers can operate at relatively high current densities, enabling high hydrogen production rates. Additionally, they can handle fluctuations in electrical input, making them appropriate for grid balancing systems. However, alkaline electrolyzers also have some drawbacks. They require a stable and pure direct current (DC) electricity source for efficient operation. The liquid alkaline electrolyte in these systems can be corrosive and requires proper handling and maintenance. Alkaline electrolyzers also have slower response times than other electrolyzer technologies, making them less suitable for applications requiring rapid load changes.

Despite these limitations, alkaline electrolyzers are widely used in various industrial applications, including large-scale hydrogen production, chemical processes, and energy storage. Recent research has already begun to reduce costs and explore new materials and catalysts to enhance performance. In recent years, alkaline electrolyzers have gained renewed attention due to their potential for coupling with renewable energy sources to produce green hydrogen. The scalability and maturity of alkaline electrolyzer technology make it a promising option in achieving clean and sustainable energy systems.

2.4.2 Proton Exchange Membrane Electrolyzers

PEM (Proton-Exchange Membrane) electrolyzers are a type of electrolyzer system used for hydrogen production through the process of electrolysis. They are also called polymer-electrolyte membrane electrolyzers or solid-polymer electrolyte electrolyzers.

PEM electrolyzers operate using a solid polymer-electrolyte membrane, typically made of a perfluoro sulfonic acid polymer, such as Nafion, which acts as a proton conductor. The key components of a PEM electrolyzer include the polymer-electrolyte membrane, two electrodes, catalyst layers, gas diffusion layers, bipolar plates, and current collectors. The anode and cathode are usually made of porous carbon materials, such as graphite, coated with catalyst materials. Platinum or platinum-based catalysts are commonly used for both electrodes.

The electrolysis process in PEM electrolyzers involves several steps. Starting from an electric current application to the electrolyzer, while (H_2O) is fed to the cathode side of the membrane, where it undergoes reduction. At the cathode-terminal, hydrogen ions (H^+) from the water molecules are reduced to form (H_2), while oxygen gas (O_2) is simultaneously evolved. The proton-conducting membrane allows the transport of protons (H^+) from the anode to the cathode while preventing the mixing of hydrogen and oxygen gases. PEM electrolyzers offer several advantages compared to other electrolyzer technologies. One key advantage is their fast response time, rapid start-up and shut-down, and precise control of hydrogen production. They can operate at low temperatures, typically between 50 and 80 degrees Celsius, which reduces energy consumption and enables compact system designs. PEM electrolyzers also have high current density capabilities, enabling efficient hydrogen production. Another advantage of PEM electrolyzers is their high efficiency, often exceeding 80%. The solid polymer electrolyte membrane allows for efficient proton transport, reducing energy losses during electrolysis. PEM electrolyzers can also tolerate variations in electrical input, making them suitable for intermittent renewable energy sources.

However, PEM electrolyzers also have some challenges and limitations. They are sensitive to impurities in the water feed, requiring high-purity water to prevent performance degradation and catalyst poisoning. The platinum-based catalysts used in PEM electrolyzers are expensive, contributing to higher system costs. The membrane in PEM electrolyzers can be susceptible to degradation over time, particularly under harsh operating conditions, which can affect system durability.

Table 2.1: Types of Fuel Cell With Properties.

Type	AFCs	PEMFCs	PAFCs	MCFCs	SOFCs
Electrolyte	KOH	Perfluoro sulfonic			
Acid ionic exchange membrane	H ₃ PO ₄	Li ₂ CO ₃ -K ₂ CO ₃	Y ₂ O ₃ -ZrO ₂		
Conductible ions	OH ⁻	H ⁺	H ⁺	CO ₃ ²⁻	O ₂ ⁻
Fuel	H ₂	H ₂ .CH ₃ OH	Reformed fuel (CH ₄ .C O. H ₂)	Purified coal gas, natural gas, and reformed fuel	Purified coal gas and natural gas (CH ₄ .C O)

Despite these challenges, PEM electrolyzers have gained significant attention and are widely used in various applications, including hydrogen refueling stations, power-to-gas systems, energy storage, and industrial processes. PEM electrolyzers are particularly well-suited for applications that require high-purity hydrogen, rapid response times, and flexible operation. The ability to integrate PEM electrolyzers with renewable energy sources makes them a promising technology for producing green hydrogen.

2.4.3 Solid-Oxide Fuel Electrolyzer

Solid-Oxide Fuel Cell (SOFC) electrolyzers, also known as Solid-Oxide Electrolysis Cells (SOECs) operating in reverse mode, are a type of electrolysis technology used for hydrogen production. They leverage the same fundamental principles as SOFCs to break H₂O into H₂ and O₂ using electricity efficiently. During operation, a DC electrical current

is applied to the SOFC electrolyzer. Water vapor is dissociated at the anode into hydrogen ions (H^+) and oxygen ions (O_2^-) through the oxygen electrode reaction. The H^+ ions migrate through the solid oxide electrolyte to the cathode, while the oxygen ions travel in the opposite direction to the anode. At the cathode, the hydrogen ions combine with electrons from the external circuit to form hydrogen gas (H_2). Simultaneously, the oxygen ions at the anode react with electrons to produce oxygen gas (O_2).

SOFC electrolyzers operate at high temperatures (typically 500-900 degrees Celsius), enabling efficient electrochemical reactions and enhancing overall efficiency. SOFC electrolyzers can utilize various feedstocks, such as steam or carbon dioxide, in addition to water, enabling the co-production of hydrogen and other valuable products like syngas or carbon monoxide. Also, SOFC electrolyzers can be integrated with SOFC power generation systems, allowing for efficient energy conversion between hydrogen and electricity in a reversible manner. Another advantage of SOFC is their high-temperature operation, which enables waste heat utilization for various applications, such as space heating or industrial processes, further increasing overall system efficiency.

SOFC electrolyzers show promise in providing a clean and efficient pathway for hydrogen production, offering potential synergies with SOFC power generation systems and the ability to integrate with renewable energy sources, making them a valuable technology for advancing the hydrogen economy.

2.4.4 High Temperature Electrolysis

HTE, or High-Temperature Electrolysis, is an electrolysis process that operates at elevated temperatures to break H_2O into H_2 hydrogen and O_2 oxygen using electricity. It is a variant of electrolysis that offers certain advantages over conventional low-temperature electrolysis methods. HTE electrolysis operates similarly to other electrolysis technologies but at higher temperatures. The process involves passing an electric current through water vapor, typically in the form of steam. Steam is introduced to the anode-side of the electrolysis cell, thus splitting it into (O_2^-) and (H^+) ions. The oxygen ions migrate through the electrolyte to the cathode-side, while the hydrogen ions combine with electrons from the external circuit to produce (H_2) gas at the anode.

Advantages of HTE include high efficiency as High-temperature operation allows for more efficient electrochemical reactions, decreasing the energy required for H_2 generation.

compared to low-temperature electrolysis. Also, the elevated temperatures in HTE enable the utilization of waste heat from various industrial processes, power plants, or nuclear reactors. This heat can be utilized for steam generation, which serves as the feedstock for HTE, further improving overall system efficiency. HTE can be integrated with carbon dioxide (CO_2) sources, such as flue gases from industrial processes or power plants. The CO_2 can be combined with hydrogen produced via HTE to generate syngas, a mixture of hydrogen and carbon monoxide. Syngas has various industrial applications, including the production of synthetic fuels and chemicals. HTE can be synergistically coupled with high-temperature energy sources like concentrated solar power (CSP) or advanced nuclear reactors. The excess heat generated by these sources can be used for the HTE process, allowing for efficient and sustainable hydrogen production.

However, the high operating temperatures pose challenges if developing the electrolyzer as suitable materials that can withstand thermal and chemical stresses over prolonged periods are very rare. Developing durable and cost-effective materials is essential for the commercialization of HTE. While HTE offers improved efficiency compared to low-temperature electrolysis, it still requires significant electrical energy input. Utilizing renewable energy sources or low-carbon electricity is crucial to ensure the environmental benefits of hydrogen production through HTE.

Many recent studies have explored electrolyzer performance. Some relevant studies are briefly discussed here. In the study [25], a laboratory-scale active PEM electrolysis system was utilized to investigate the impact of various wave currents on system efficiency. The results revealed that the lag current of the wave had no discernible effect on the system. However, the average power consumption was found to increase with the coefficient of the wave and decrease with its frequency. Interestingly, the specific characteristics of the wave, such as its shape description, frequency, or lag current, did not significantly influence the average flow of hydrogen. These findings shed light on the relationship between wave currents and the efficiency of the PEM electrolysis system [25].

The research in [26] investigates PEM electrolysis preparation using OPCF (Open Parallel Flow Channel) materials. Different filling types for the electrolyzer were analyzed, including serpentine, mesh, and OPCF flow channels, while keeping other parameters constant. 3D models were created using SolidWorks to examine the

performance of each type, and computational fluid dynamics simulations were conducted using ANSYS. The results of the ANSYS simulation revealed that OPCF flow channel electrolysis was 1.5 times more effective than mesh channel electrolysis. Moreover, the experimental findings indicated a significant improvement in the performance of the electrolyzer with the OPCF flow channel, with a notable increase of 17% compared to conventional mesh flow plate electrolyzers [26].

The study [27] focused on the synthesis and characterization of 1D-spun Ta₃N₅-(O) nanofibers for electrocatalytic applications in the hydrogen evolution reaction (HER) and proton exchange membrane (PEM) water electrolysis. The researchers employed ammonolysis to produce 1D co-electrospun nanofibers of tantalum ethoxide and polyvinylpyrrolidone (PVP) at temperatures ranging from 800 to 1000 degrees Celsius. Through black-EDS and XPS analyses of the nanofibers, it was observed that increasing the nitriding temperature (from 900 to 1000 °C) led to a higher oxygen concentration on the surface. The nanofibers exhibited a low overpotential of 320 mV and demonstrated high electrocatalytic activity, achieving a current density of 10 mA/cm² in a 0.5 M H₂SO₄ electrolyte for the HER. In PEM water electrolysis, the 1D Ta₃N₅-(O) nanofibers were utilized as a novel electrocatalyst without the need for conductive support. An applied voltage of 2 V resulted in a current density of 0.1 A/cm², comparable to commonly used earth electrocatalysts like MoS₂. Furthermore, the electro-spun nanofibers exhibited excellent strength without any defects even after six hours of continuous operation. This study highlights the potential of high-performance one-dimensional electrocatalysts for the HER and underscores the advantages of nanostructured electrocatalysts in expanding the utilization of Ta₃N₅ [27].

The researchers in [28] focused on the utilization of PEM water electrolysis with ozone for in situ purification purposes. However, the application of this method relies heavily on the usage of ultra-smooth water surfaces to ensure long-term durability. The study investigated the influence of various impurity levels during standby and power operations, particularly focusing on four abundant cations (Na⁺, Mg²⁺, Ca²⁺, K⁺). The number of impurities was found to increase linearly with the current (2 ± 95 m-mol A⁻¹h⁻¹) and was distinct from ion permeation, which occurs at the water boundary through the transport of ions in the PEM/anode interface. The unstable operation of the PEM electrolyzer resulted in a pH gradient due to the formation of calcium, magnesium

hydroxides, and carbonates on the cathode surface. A novel cathode additive was introduced in the experimental chamber, leading to a reduction in single ion permeation by approximately 20%. The study also assesses the impact of feed water on the electrolysis performance of the PEM electrolyzer during ozone promotion [28].

The research paper [29] evaluated three types of electrolyzers, SOEC, PEMEC, and AEC, for converting excess renewable electricity into hydrogen for power-to-power energy storage applications. The hydrogen could be stored using three methods: compressed hydrogen, liquid hydrogen, or metal hydrides. The choice of storage technology impacts the energy costs associated with hydrogen transportation and distribution. Once the hydrogen is stored, it could be released as electrical power when the grid or end users need it as shown in Figure 8. The paper [50], specifically explored using hydrogen storage and combustion in a micro gas turbine (with a power capacity of up to 500 kWe) to convert the stored hydrogen into electrical power as shown in Figure 2.5 and 2.6. The efficiency of the overall energy storage system was assessed through the round-trip conversion efficiency, which is a crucial metric for evaluating its practicality. The research in [29] provided a comprehensive analysis of available options for power-to-power energy storage systems with micro gas turbines, it should be noted that certain limitations existed due to the study's focus and constraints. The paper did not delve into the intricate details of power and heat fluxes within each subsystem, which would require further investigation for comprehensive component analysis. Nevertheless, the research results served as an initial step toward enhancing efficiency and determining the optimal configuration for power-to-power energy storage systems with micro gas turbines. The findings contribute to narrowing down the design space and pave the way for future in-depth analyses of system components [30].

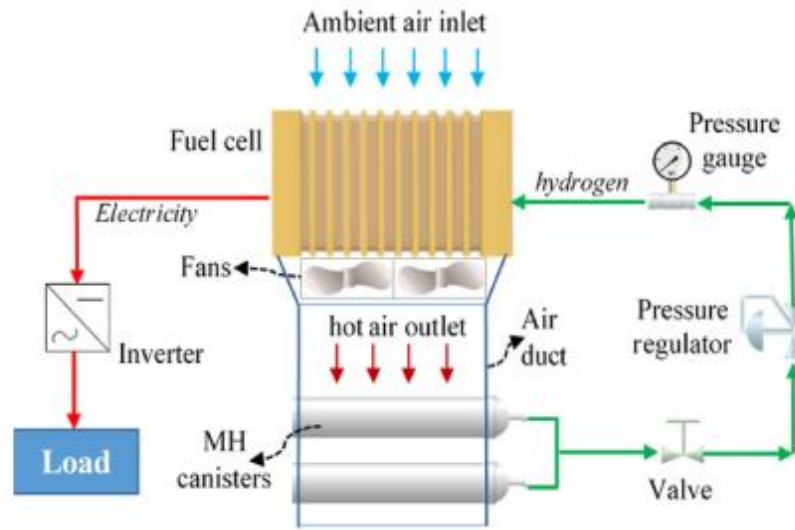


Figure 2.4: The PEMFC and Air-Cooled MH Canisters' Thermal Coupling Arrangement is Depicted Schematically [29].

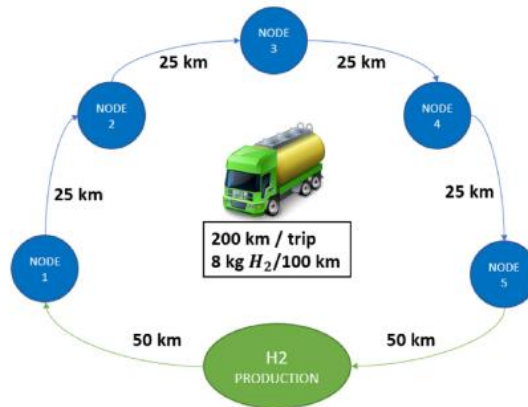


Figure 2.5: H2 Central Distribution Scheme Using Fuel Cell Electric Truck [30].

2.5 FUEL CELLS

Fuel cells are advanced energy conversion devices that have gained significant attention in research and development due to their potential to revolutionize various industries and sectors. These electrochemical devices convert the chemical energy of a fuel, typically hydrogen, into electrical energy with high efficiency and minimal environmental impact. Fuel cells offer several advantages over conventional combustion-based power generation methods, including lower greenhouse gas emissions, higher energy conversion efficiency, and quiet operation. Advanced research in fuel cells aims to enhance their performance, durability, and cost-effectiveness to enable widespread

adoption in diverse applications. One area of focus is improving the catalyst materials used in fuel cells. Catalysts play a crucial role in facilitating the electrochemical reactions within the fuel cell, and researchers are exploring novel materials and nanostructured catalyst designs to enhance catalytic activity, reduce cost, and increase durability.

Another area of advancement lies in developing innovative fuel cell architectures and designs. Researchers are exploring different types of fuel cells, such as "Proton Exchange Membrane Fuel Cells" (PEMFCs), "Solid Oxide Fuel Cells" (SOFCs), and "Molten Carbonate Fuel Cells" (MCFCs), each with its unique advantages and challenges. Efforts are being made to optimize cell and stack designs, improve ion, and gas diffusion, and enhance thermal management to maximize overall system efficiency. Furthermore, the development of advanced fuel cell components, such as membranes, electrodes, and bipolar plates, is a focus of research. Advancements in materials science, for example, developing new ion-conductive membranes with improved durability, conductivity, and selectivity, are critical for enhancing fuel cell performance and longevity.

To address the issue of fuel availability and storage, researchers are exploring alternative fuel sources and investigating methods for efficiently converting and storing fuels, such as hydrogen, methanol, and ammonia. The novel research is focused on sustainable hydrogen production through water electrolysis using renewable energy sources and developing compact and high-capacity storage solutions for hydrogen or other fuel molecules. Additionally, research efforts are directed toward system integration, control strategies, and hybridization of fuel cells with other energy conversion technologies. Integrating fuel cells with renewable energy sources, energy storage systems, and power electronics can create highly efficient and flexible energy systems capable of providing reliable and clean power in various applications, from transportation to stationary power generation. Recent fuel cell research focuses on overcoming technical challenges, optimizing system performance, reducing costs, and expanding their practical applications. Through these advancements, fuel cells have the potential to play a crucial role in achieving a sustainable and low-carbon future, addressing energy needs, and mitigating environmental concerns.

Reference [31] presents an exciting hydrogen storage method utilizing Liquid Organic Hydrogen Carriers (LOHC) within the existing fuel infrastructure. The study focuses on directly applying hydrogen bonded to LOHC in low-temperature Proton Exchange

Membrane Fuel Cells (PEMFC), which shows great potential. The research proposes an iso-propanol/acetone LOHC system to generate electricity from a condensable liquid while avoiding CO₂ emissions. Experimental tests using a commercial fuel cell test system and a vaporizer demonstrate a high-performance direct iso-propanol fuel cell, employing back pressure for the first time to improve its performance. Using a Nafion composite membrane with self-assembled Gas Diffusion Electrodes (GDEs), the iso-propanol/air fuel cell achieves a power density of 203 mW cm⁻² at 85 °C and 300 kPa operating pressure. Increasing the operating temperature by 100 °C leads to a maximum power density of 254 mW cm⁻², representing 80% of the highest reported values for air-operated iso-propanol fuel cells. This performance increase can be attributed to the reduction of acetone poisoning on the Pt-Ru catalyst under high-pressure conditions during the electrooxidation of poly iso-propanol on the anode side. Overall, the study showcases the potential of utilizing LOHC systems for hydrogen storage and highlights the promising performance of direct iso-propanol fuel cells, offering a viable and environmentally friendly approach to electricity generation without CO₂ emissions.

Recent advancement of H₂ energy and Proton-Exchange Membrane Fuel Cells (PEMFC) has faced challenges related to business barriers, hydrogen refueling systems, hydrogen-storage, transportation, fuel distribution, and commercialization. A comprehensive review in reference [32] analyzes and compares various hydrogen production, storage, transportation, and purification methods. The review explores the benefits of steam-reforming of natural gas and hydrogen-generation from industrial byproducts in PEM fuel cell systems. Utilizing hydrogen waste from industries can effectively lessen the cost of H₂ gas. Additionally, methanol is identified as a promising hydrogen carrier, as methanol steam reforming has proven to be an efficient method for hydrogen gas production, addressing storage and transportation challenges. The influence of impurities on the reformed gas is also acknowledged as an essential consideration. The review paper [32] also investigates the integration of methanol steam reforming and pre-treatment processes with PEM fuel cells. A fuel cell system and its subsystems for pure hydrogen purification and production are introduced, along with a review of key technologies for onboard reforming system pre-treatment and toxicity reduction. These technologies play a crucial role in ensuring the optimal performance and safety of the fuel cell system.

The research study in [33] consider two types of fuel cells, namely Proton-Exchange Membrane fuel cells and Solid-Oxide Fuel cells, are considered power sources for UAVs. These fuel cells generate and supply power to the propulsion system. A rechargeable battery is also integrated into the UAV's engine to support the fuel cell operation. The research paper has provided two comprehensive analyses focusing on assessing the power-consumption of the UAV during different flight-modes. In contrast, the second analysis examines the weight distribution of the UAV. These analyses help determine the power requirements and weight considerations for the successful operation of the UAV. Furthermore, the electrochemical behavior of both fuel cell types is thoroughly examined to compare their performance in the UAV propulsion system. This evaluation highlights the prime advantages and limitations of each fuel-cell technology in the context of UAV applications. Lastly, the fuel cells performance benchmarking in the propulsion system is discussed following the international standards environmental model. This ensures the UAV's power system meets the required performance criteria while considering environmental factors.

The research paper [34] introduces a potential alternative to internal combustion engines by exploring the application of fuel cells as efficient and smooth power converters. However, despite the promising attributes of fuel cells, their long-term durability poses a significant challenge. The paper presented a hybrid power source approach to address the durability issue. Fuel cells are commonly integrated into hybrid systems, incorporating additional components such as batteries, power balances, or fuel cell stacks to improve overall performance. Ensuring the sustainability of these systems requires effective diagnostics and diagnostic tools, and developing models for the system is a crucial step in implementing these tools.

The main objective of the paper [34] was to critically evaluate the existing approaches to modeling all the components of hybrid fuel cell systems, considering both their operational and degradation states. The review investigates different models used for these components, including nature-based, data-based, and hybrid models. Furthermore, the interactions between these components and the method of mass degradation are also examined. Ultimately, the paper discusses the most prominent approaches in the field, highlighting their advantages and disadvantages. By providing a comprehensive analysis

of modeling techniques for hybrid fuel cell systems, the research aims to contribute to understanding these systems and facilitate their further development.

The research in [35] shows that efficient control is crucial for fuel cells that utilize hydrogen and oxygen as their power source. The kinetic properties of gas treatment in PEMFCs and the management of fuel cell gas and electrolyte were experimentally examined to conduct a quantitative investigation. Specifically, the study focused on anode and cathode dual ejector-based fuel cells operating in spin mode. The research aimed to understand the operational effects and performance degradation. Various techniques were employed to analyze the performance degradation in-depth, including SEM images, EIS (Electrochemical Impedance Spectroscopy), CV (Cyclic Voltammetry), MEA (Membrane Electrode Assembly) scans, and scanning polarization curves. The results revealed that fuel flooding performed better with a total ECSA (Electrochemical Surface Area) of 10.61 percent compared to the dead-end mode based on spin mode with the dual ejector. The improvement achieved was 17.02 percent. The rotating mode of the ejector demonstrated its ability to rapidly remove the H₂O from fuel-cell flow channel. While preventing water flow and maintaining the fuel cell's performance over time. These findings emphasize the importance of utilizing the ejector in fuel cell systems to prevent performance degradation caused by fuel flooding and ensure optimal operation [35].

The research presented in [36] focuses on the performance of proton-exchange membrane (PEM) fuel-cells and finds that the performance is significantly affected by pressure distribution in a fuel-cell stacks. The study explores a novel approach to predicting the contact pressure-distribution in large fuel-cell stacks. The presented technique utilizes fuel cell beam model and stiffness model to access the temperature distribution leading to pressure distribution calculation. The equivalent-beam model yields improved results with an iterative calculation method for contact-pressure assessment. A three-dimensional Finite Element Analysis (FEA) model is compared with the proposed model to validate its effectiveness. The FEA equations demonstrate stress distribution on the transverse and longitudinal sides of the connection, achieving high correlation coefficients of 0.976 and 0.998, respectively. Moreover, the stiffness equation of the proposed model shows remarkable accuracy with only a 4.1% tolerance [36].

The research in [37] investigates the sluggish braking and power restoration issues of hybrid electric vehicles that utilize fuel cells as their power source. In this study, a combined fuel-cell/-battery/-supercapacitor topology has been proposed, and the research focus is on energy-management using a policy gradient based on capacity regulation for a dual-delay time scale. The design includes a topological structure, shielding capacitors, fuel-cell life, and battery-output power. The aim is to reduce fuel cell life loss, optimize fuel cell hydrogen consumption, and provide enhanced correction for maximizing the fuel's range. The DDPG, (Deep-Deterministic Policy Gradient) strategy combined with a Non-linear Programming-Algorithm has been employed in this study. This strategy effectively reduces H₂ consumption while mitigating the fuel-cell degradation and prevents excessive battery-depletion compared to other strategies. Notably, it significantly improves the lifespan of the fuel cell. The electric system also benefits from this strategy, as it gains increased utility. This research provides valuable insights for improving the performance of fuel-cells in hybrid electric cars, considering both efficacy and longevity [37].

The study presented in [38] focuses on enhancing the real-time fault tolerant control process of Fuel Cells to extend the battery's lifespan. Fuel cells are highly sensitive to operating conditions and are prone to failure. In vehicular applications, the likelihood of errors increases due to the dynamic nature of the vehicle movement. Controlling fuel cells during movement poses challenges because it involves managing the supply of reactants, thermal management, and water management, which are crucial for their proper functioning. Mistakes made in fuel cell control can lead to fuel flooding and a reduction in the remaining useful life if not handled correctly [38].

2.6 RECENT ADVANCES IN HYBRID ENERGY SYSTEMS WITH HYDROGEN STORAGE

Recent research has focused on combining hydrogen storage with various energy-sources, such as photovoltaic(PV) systems, the utility grid, battery storage, and fuel-cells, to power residential loads. This integration aims to enhance the reliability, efficiency, and sustainability of energy supply for various applications including residential buildings.

The research article [22] underscores the importance of hydrogen in decarbonization efforts and explores key technologies that enable its integration into the energy sector. The article envisions a future with large-scale renewable hydrogen installations, challenges, and probable solutions. It emphasizes the need for cost reduction, system improvement, and supportive policies for better utilization of H₂ as a sustainable energy solution.

The solution presented in [11] focuses on the thermal-management of metal-hydride (MH) storage systems in fuel-cell applications. The proposed approach utilizes the heat generated by the fuel-cell (FC) to regulate the temperature of the MH, external power source and improving energy efficiency. This thermal coupling arrangement reduces the overall footprint (volume and mass) of the system, including the thermal-management unit. The FC cooling fluids can be recirculated through various heat exchangers to control the MH temperature, with the MH requiring approximately 20-30% of the FC stack's total cooling load, as indicated by the published results.

Another energy-independent thermal management solution explored in the research [39] is using phase change materials (PCMs). PCMs offer advantages by eliminating the need for external power sources and avoiding the associated energy losses. This solution addresses the complexity of alternative thermal-management approaches discussed in the paper. However, the highlights the need of empirical and optimization studies to fully exploit the potential of PCM solutions while minimizing costs, mass, and volume. Furthermore, there is a need to compare different MH thermal management options from technical and economic perspectives. Subsequent studies should focus on filling these gaps in research, particularly in assessing the economic performance of various MH thermal management solutions.

The research presented in [29] recognizes the importance of hydrogen (H₂) as a promising energy carrier that can resolve the renewable energy intermittency problem. Due to the small size of H₂ molecules, large-scale storage is crucial to support implementing a comprehensive H₂ economy. As a result, there has been a focus on exploring the potential of storing H₂ in geological formations, enabling its extraction and reuse on a larger scale. The objective of the review is to study the underground hydrogen storage (UHS) in geological formations, encompassing both conventional and unconventional options. The review delves into the criteria for selecting suitable sites for

UHS and provides valuable insights into potential locations. It comprehensively summarizes the hydrodynamics and factors influencing UHS, including the interactions between solids and fluids. Additionally, the study examines the economic considerations and responses associated with UHS. The findings underscore that UHS, like other storage systems, is still in its early stages of development. Consequently, the research highlights the crucial need for further research and development efforts to address existing knowledge gaps and overcome barriers, particularly in optimizing effective exchange parameters.

The research in [30] addresses the thermal-management challenges associated with metal-hydride (MH) hydrogen storage systems. Well-designed thermal management is required to maintain hydrogen generation at optimal levels. However, implementing system-level thermal-management is challenging due to system mass, volume, energy-efficiency, complexity, long term stability, and high-cost. The MH substrate's low effective thermal-conductivity (ETC) (0.1 to 0.3 W/mK) further complicates the application of thermal-management strategies. The paper analyzes thermal-management solutions for M-H storage in fuel-cell systems. It focuses on methods to enhance heat-transfer and examines the heat-sources employed in various simulations and experiments. The literature suggests that for optimal MH performance, the heat-transfer coefficient between the heating/-cooling medium may lie in the range of 1000-to -1200 W/m²K, and the E-T-C of the M-H substrate may exceed 2-W/mK. The review also explores alternative heating sources, such as fuel-cell, heat-exchangers, and MH heat capture and release during charging and discharge. Furthermore, the review highlights the gaps in the thermal-management of metal-hydride-based systems and discusses potential future research directions. It underscores the need for further investigation and development to address the challenges and optimize thermal management strategies in MH hydrogen storage systems.

The article [40] reviews twenty-seven quantitative-studies that examined psychosocial factors and Hydrogen-Energy Technologies (HET) acceptance. The findings suggest that the emotions associated benchmark indices, e.g., as perceived costs, benefits/risks, and accessibility, strongly drive its adoption. However, the review identifies limitations in previous studies that studied the factors influencing HET adoption. Additionally, the review reveals a lack of research on adopting different types of HET beyond a few

specific applications. Furthermore, the article discusses the implications for future research and provides insights for policymaking and messaging. It identifies many areas that can be addressed in subsequent research. The review emphasizes the importance of conceptualizing and implementing psychological constructs more clearly and coherently to enhance the replicability and practicality of future findings. It also calls for further research on adopting HET outside the transportation industry, exploring beliefs about production, storage, and transportation methods. Lastly, the article emphasizes the need to study the evolving nature of beliefs, attitudes, and acceptance as people acquire more knowledge about HET. To ensure socially responsible development and implementation of HET, relevant stakeholders would benefit from future research in predicting public responses to HET. This would help address gaps in understanding, explore evolving beliefs and attitudes, and enhance the effectiveness of strategies to promote public acceptance.

The research discussed in [41] emphasizes the importance of investigating the potential integration of renewable-energy the small household scale, power grid and industrial scale to facilitate renewable energy-based economy. The study suggests that the solar PV can be easily installed on rooftops and can complement hydrogen energy systems as well. The study focuses on the technoeconomic evaluation of a hybrid solar energy thermal microgrid with hydrogen-energy in a typical Spanish residence. The installation includes photo-voltaic and solar-thermal energy systems, complemented by a hydrogen system consisting of a fuel cell, metal hydride bottles, an electrolyzer, and lead-acid batteries. Experimental models were developed for each microgrid component, which was then verified with actual devices to create a simulation tool. The research identifies several barriers to integrating such systems into existing buildings, including installation costs, the lack of user-friendly decision-making tools for potential users, and the complexity of retrofitting these installations in existing structures. The study aims to provide a tool that empowers the public to make informed decisions supported by empirical data, thereby facilitating wider access to renewable energy in residential settings. The research endeavors to bridge the gap between potential users and adopting renewable energy systems in homes by offering an empirical-based decision-making tool. This approach brings us one step closer to making renewable energy more accessible and viable for households, contributing to the overall transition towards a sustainable energy future.

The research discussed in [42] focuses on the anticipated role of hydrogen-energy carriers. The research promotes utilizing hydrogen carriers as an energy source e.g., ammonia and synthetic hydrocarbons. Hydrogen carriers can effectively help in reducing carbon dioxide (CO₂) emissions and aligning with the goals of the Paris Agreement. While their competitiveness and potential for fulfillment are yet to be fully established, when compared to typical electricity/biofuels or carbon capture and storage (CCS) systems. The study emphasizes the hydrogen-energy role in global energy mix. The paper proposed a detailed model encompassing various energy systems and technologies, including H₂-based energy carriers. The study concluded that hydrogen-based energy carriers are projected to contribute to less than 5-percent of global-energy demand by 2050.

The study [2] emphasizes the significant potential of H₂-based energy-carriers in offsetting residual CO₂-emissions, especially in ambitious reduction scenarios aligning with the 1.5°C target and limited CCS deployment. In such scenarios, hydrogen-based energy carriers could account for 10-to-15% of final energy-demand, while in other circumstances, their share remains around 5% or lower. The transportation industry emerges as a key sector for hydrogen utilization, followed by power generation and industrial applications. One alternative explored is using hydrogen-converted synthetic hydrocarbons and biomass, known as DAC (Direct Air Capture), for CO₂ transport instead of directly employing hydrogen or ammonia. Furthermore, the study underscores the importance of comprehensive energy and climate policies that address both energy supply and demand, emphasizing the need for strategic approaches to tackle the issue effectively.

The research presented in [43] focuses on the challenges faced by green and energy-efficient buildings regarding affordable energy-storage-systems (ESS) to mitigate the impact of power outages. These buildings often incorporate rooftop-photovoltaic PV-solar cells or other renewable-energy sources for energy conservation and electricity generation. The paper presents the comparison of three different ESS-technologies, namely Lithium-ion-batteries (LIB), reversible Proton-Exchange Membrane (PEM) fuel-cells (FCs-RFC PEM), and reversible-ESS systems (RSOC), within a techno-economic model called RSOC as shown in Figure 2.7. The evaluation considers the economic aspects of the systems using the Levelized- Cost- of- Storage (LCOS) metric, which

considers their cost decline over time. In summary, the research finds that Lithium-ion batteries offer a cost-effective solution while improving efficiency. On the other hand, FCs-RFC PEM and RSOC systems enhance the reliability and adaptability of commercial buildings in autonomous environments powered by renewable energy systems, despite their higher costs. The analysis acknowledges the uncertainty in LCOS analysis and suggests exploring other ESS and hybrid models that could offer lower capital costs and increased efficiency as future research directions. Furthermore, the research suggests extending the analysis to include comparisons across different locations to study LCOS metric variations in response to various climate zones. This broader perspective would provide valuable insights into optimizing energy storage solutions for specific geographical contexts.

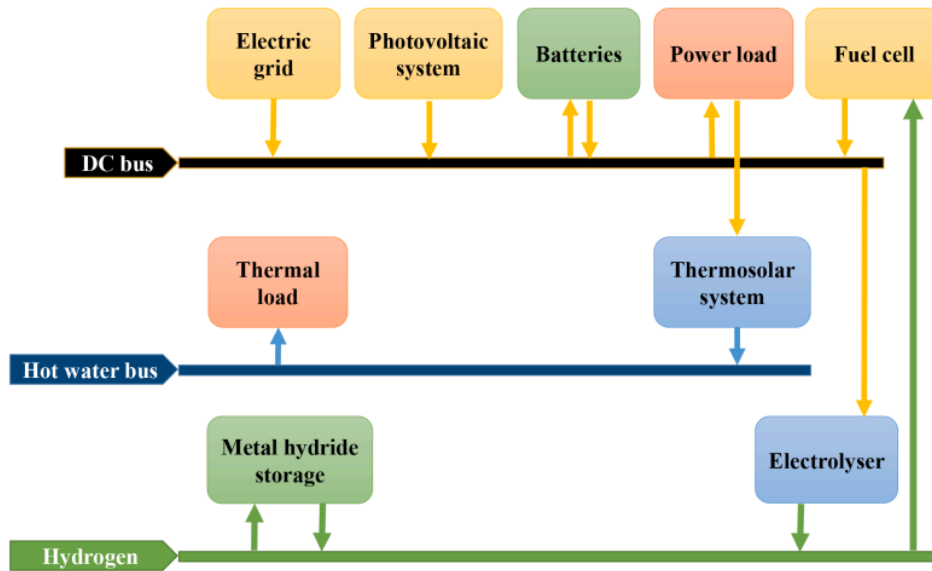


Figure 2.6: Consideration Is Given to a Solar Hybrid Scheme Block Diagram [43].

The study presented in [12] introduces a novel approach called the Hydrogen Infrastructure System (HIS) for transmitting electrical energy over long distances. The system involves the conversion of electricity from renewable energy sources into hydrogen through an electrolysis plant. The hydrogen is then transported via a pipeline to the demand center, where it is converted back into electricity using a gas-turbine or fuel-cell plant. The research examines the technological competitiveness of High-Voltage-Direct-Current (HVDC) systems. It calculates technoeconomic indicators such as the Levelized-Cost-of-Storage (LCOS) and Levelized-Cost-of-Electricity (LCOE). Additionally, the study analyzes the entire energy-system aging, considering the reduced

energy production from photovoltaic systems and increased hydrogen demand over ten years. To conduct the analysis, the researchers utilize experimental data from various components, including photovoltaic modules, fuel cells, electrolyzers, hydrogen storage, and renewable energy backup systems. They introduce a new parameter, the ratio of unit excess hydrogen consumption, which effectively describes the degradation of the analyzed system. By exploring the implications of aging on HIS, the study provides valuable insights into the long-term performance and sustainability of the system. It highlights the importance of considering degradation effects when modeling and evaluating energy systems that involve photovoltaic systems and hydrogen storage.

Battery-hydrogen hybrid systems have also gained attention. Researchers aim to achieve an optimal balance between power and energy storage by combining hydrogen storage with batteries. Batteries provide short-term energy storage for quick power delivery, while hydrogen storage offers longer-duration storage for extended power supply. This hybridization allows for better utilization of renewable energy and enhanced load management in residential settings. Furthermore, fuel cells can be integrated with hydrogen storage to provide continuous and reliable power for residential loads. Fuel-cells convert H_2 into electricity through an electro-chemical process, and when coupled with hydrogen storage, they can ensure a constant power supply during intermittency or outages.

The study in [44] addresses the environmental challenges posed by mountain huts, which operate as independent microgrid systems not connected to the electricity grid. These microgrids must be adaptable to accommodate daily and seasonal fluctuations in energy demand. Traditionally, fossil fuels have been employed for electricity and heat generation in mountain huts due to their simple on/off operation. However, there is a growing need for more sustainable energy production that strikes a balance between production and consumption. The paper explores integrating two storage systems, the Hydrogen-Storage-System (HSS) and the Battery-Storage-System (BattS), in a mountain-hut setting. This integration offers potential solutions for improving the environmental impact of energy production in these remote locations as depicted in Figure 2.8. By utilizing Renewable-Energy-Sources (RES), energy production in mountain huts can become more environmentally friendly. However, effective energy storage ensures a stable and reliable power supply. The HSS and BattS systems discussed

in the paper offer storage options that can help optimize energy utilization in the mountain hut context. The study provides insights into integrating HSS and BattS technologies, offering potential alternatives to fossil fuel-based energy generation in mountain huts. By adopting these storage systems, mountain huts can reduce their environmental impact and improve the sustainability of their energy supply.

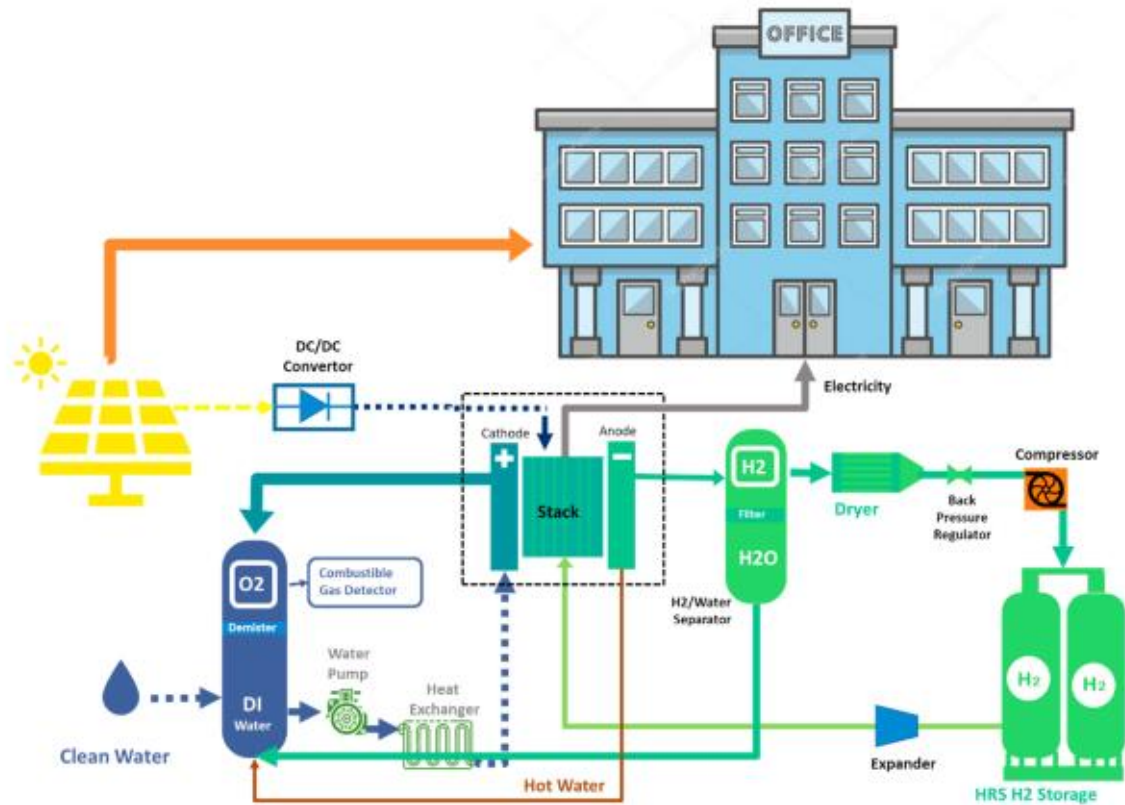


Figure 2.7: Schematic Of The System for Reversible Fuel Cells (With PEM, RFC, and RSOC) [44].

The research presented in [5] focuses on the expanding use of wind power in the Finnish grid and the need for energy storage solutions to balance seasonal variations in electricity consumption. Specifically, Finland experiences lower electricity consumption during the summer and higher demand in the winter. The study explores the potential of geological H₂-storage technology, which offers the capability to store large amounts of energy at the GWh scale for extended periods, thus resolving the imbalance issue. The research utilizes the LEAP-NEMO modeling toolbox to simulate and compare the power generation system in Finland with and without hydrogen storage. The findings reveal several benefits associated with hydrogen storage implementation. Firstly, there is a

significant reduction in carbon-dioxide-emissions, reaching approximately 69 percent. Additionally, the reliance on fossil-fuel-based energy decreases, leading to a more justifiable energy mix. Moreover, the capacity to meet electricity demand increases, resulting in lower imports of energy. The research setup in [5] is shown in Figure 2.9. The study critically examines Finland's electricity systems, considering the integration of hydrogen storage as a means to enhance renewable energy utilization and grid stability. The outcomes demonstrate the potential of hydrogen storage technology to contribute to decarbonization efforts, improve energy self-sufficiency, and enhance Finland's electricity supply's overall reliability and sustainability.

The research presented in [45] focuses on accelerating the adoption of Energy-Storage-Systems (EES) in power systems by examining their techno-economic requirements. The paper provides a comprehensive overview of various EES technologies and discusses their specific applications in power systems, offering guidance for evaluating suitable EES-technologies for different power-system services. The study delves into the scale and types of EES technologies needed in different regions. It further explores storage cost modeling and provides projections for various EES technologies. The research highlights the realizable challenges in developing scalable, cost-effective, and socio-environmentally sustainable EES-technologies, highlighting the importance of addressing these factors. Moreover, the paper analyzes the evolving role of EES in decarbonizing the electricity system and addresses the associated challenges. It offers insights, advice, and information that can be valuable for further research and development in the field of EES. The paper also emphasizes the importance of establishing storage markets and formulating policies to support the transition toward zero-carbon power systems.

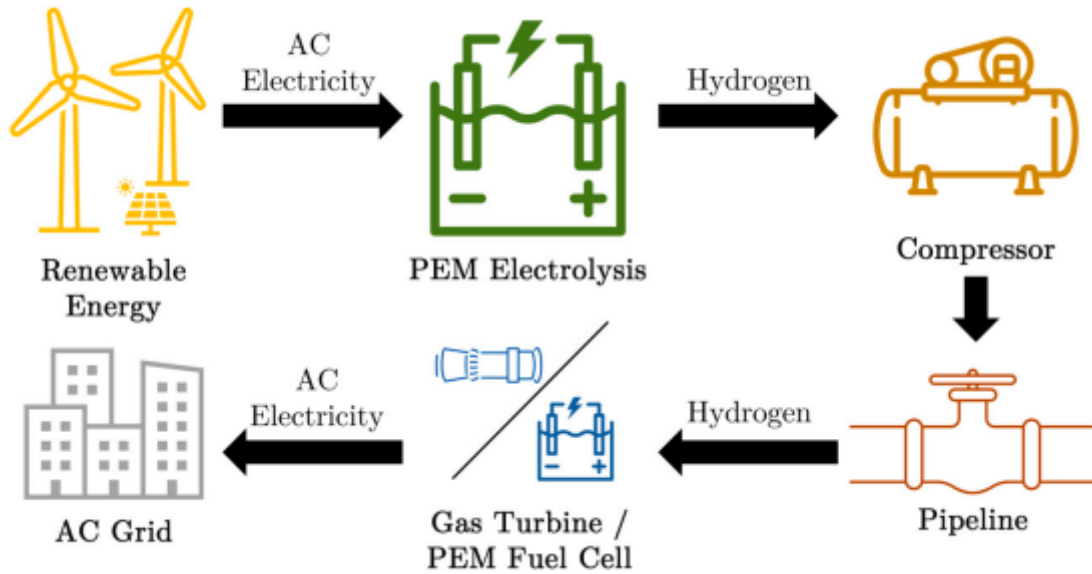


Figure 2.8: Schematic Of HIS, With Power Source And Connection To Grid [5].

The research presented in [46] explores the potential of magnesium-based materials for hydrogen storage, highlighting their advantages, such as hydrogen-storage-capacity, moderate linearity, and high Clark number properties. However, these materials limited thermo-dynamic and kinetic properties pose challenges to their engineering applications. The paper provides an overview of recent developments in optimizing the thermodynamics and kinetics of magnesium-based materials. It focuses on computational models and examines the performance parameters. The thermo-dynamics and dynamics of alloys, composites, and nano crystallization are discussed in detail, shedding light on their hydrogen storage capabilities. Furthermore, the review summarizes the correlations between different reforming strategies and the hydrogen potential, temperature, and rates of hydrogenation and dehydrogenation. Classical kinetic theories and the behavior of microscopic hydrogen transport are employed to analyze the hydrogen storage mechanism of magnesium-based materials. Finally, the paper addresses the hydrogen storage challenge and offers potential solutions for overcoming this issue. The research contributes to the understanding of optimizing the thermodynamic and kinetic properties of magnesium-based materials for efficient hydrogen storage, paving the way for further advancements in this field.

The research presented in [41] focuses on the Integrated Reformative URPEMFC (Ultra-Rapid Polymer Electrolyte Membrane Fuel Cell) system, which combines fuel cells and

electrolysis. A major technical challenge in this system is the performance loss during the transition from electrolysis mode to fuel cell mode and vice versa, known as the Proton Exchange Membrane (PEM) hydration effect (PHE). The study investigates PHE's thermodynamic and electrochemical properties through modeling and simulation to improve performance. The URPEMFC model is validated against experimental data, and parametric research is conducted to further understand the phenomenon. The study's findings indicate that PHE occurs when the number of cells is 1, 5, or 10. Moreover, the study reveals that an increase in internal leakage current density and total resistance increases the system's additional capacitance. By providing insights into the PHE phenomenon in the Integrated Reformative URPEMFC system, this research contributes to understanding the factors that affect system efficiency during transitions between electrolysis and fuel cell modes. The findings can help guide the design and optimization of URPEMFC systems, aiming to mitigate the impact of PHE and improve overall system performance.

The research conducted in [47] focuses on Power-to-Hydrogen (P2H) technology, which holds promise as a solution to address the geographic mismatch between renewable energy sources and energy markets. P2H has gained attention due to its technological maturity, adaptability, and availability of technical and economic data from numerous active demonstration projects. The study aims to provide an overview of the current state of P2H, identify technical challenges associated with its implementation, propose strategies to overcome these obstacles and suggest avenues for future research and industrial demonstrations. The research primarily focuses on two aspects: end-user refinement and the transportation of hydrogen through natural gas pipeline networks.

The study highlights compelling evidence indicating that blending approximately 10% hydrogen with natural gas in pipeline networks has no adverse impact on utilities or infrastructure. Moreover, such hydrogen integration can enhance the asset value of pipelines once natural gas reserves are depleted. By exploring the technical barriers and proposing potential solutions, the research contributes to advancing the understanding and implementation of P2H technology. Additionally, the study emphasizes the importance of further research and industrial demonstrations to refine the P2H process, optimize its integration into existing infrastructure, and explore its broader applications.

The research review in [48] focuses on hydrogen storage in solid adsorbents. The study aims to explore the potential of synthesizing optimal solid adsorbents for hydrogen storage and examine their applicability for onboard hydrogen storage in vehicles. The review process consists of two main sections. The first section addresses specific research questions related to the best adsorbents for hydrogen storage, their feasibility using coal fly ash, and their practical implementation in onboard storage systems. The second section involves an analysis that includes selecting relevant publications from databases such as Elsevier Scopus and Web of Science and reports from pertinent websites. Abstracts of the identified articles are analyzed under the research questions posed, and the connection between the research and the selected sources is thoroughly examined. The search process is repeated multiple times to ensure comprehensive coverage of relevant literature. The methodology of [48] is shown in Figure 2.10. By conducting this research review, the study aims to provide insights into the state of hydrogen storage in solid sorbents. It explores the possibilities of synthesizing efficient adsorbents and investigates their practical application in onboard hydrogen storage, particularly in vehicles.

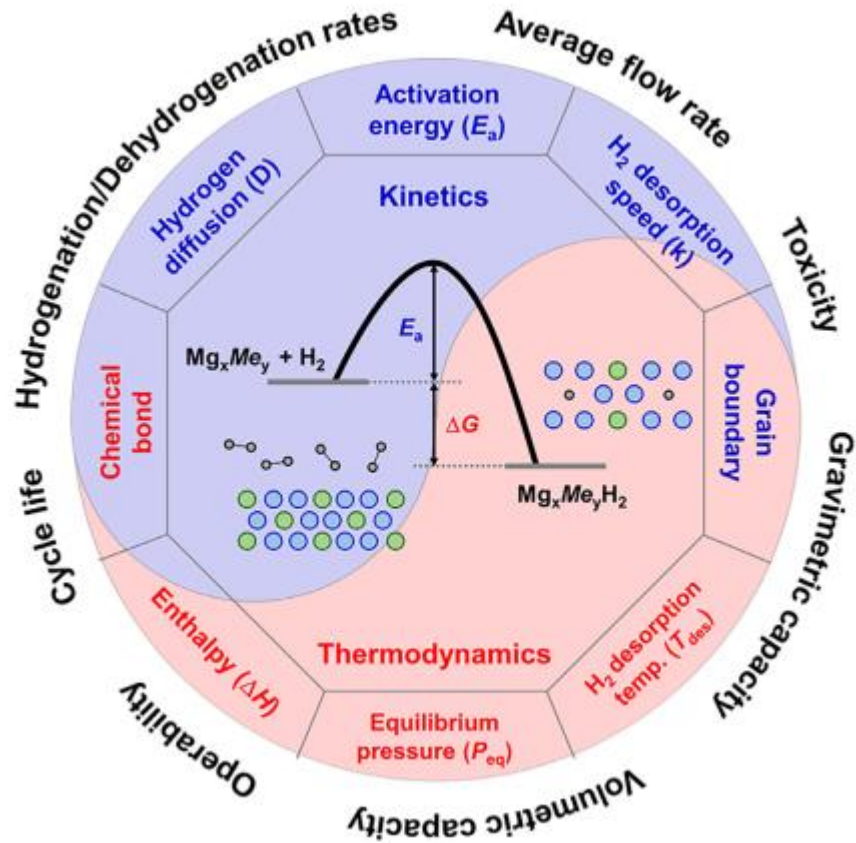


Figure 2.9: Hydrogen Storage Properties and The Reactions of Hydrogenation And Dehydration.

A notable study presented in [49] emphasizes the urgency of advancing technology in renewable energy generation, storage, transportation, and distribution to significantly reduce CO₂ emissions at a large scale as shown in Figure 2.11. In addition to electricity, there is a growing need for alternative energy carriers that are better suited for energy storage and transfer.

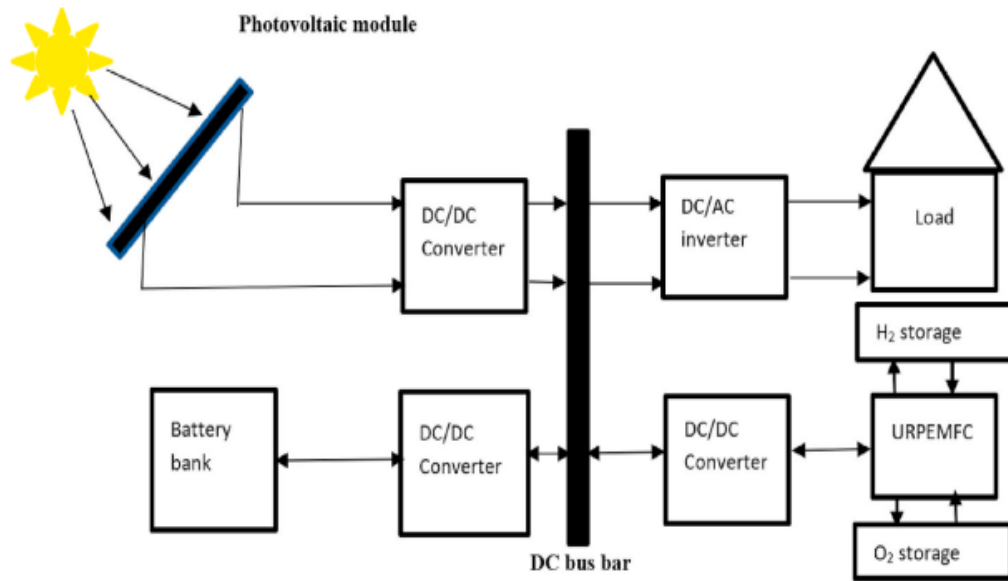


Figure 2.10: Block Illustration of A Jointed PV-URPEMFC Scheme [49].

Hydrogen emerges as a promising candidate because it can be produced and stored using renewable sources such as solar or wind power. The versatility of hydrogen enables its conversion into electricity by fuel cells, providing a reliable energy source when needed. The study also highlights the importance of sector connectivity in shaping the future energy system. Collaboration among various industries, including energy and mobility, is crucial for delivering enhanced services. Hydrogen-based fuel cells and battery-powered electric vehicles can play vital roles in this integrated system as backup and balancing power sources.

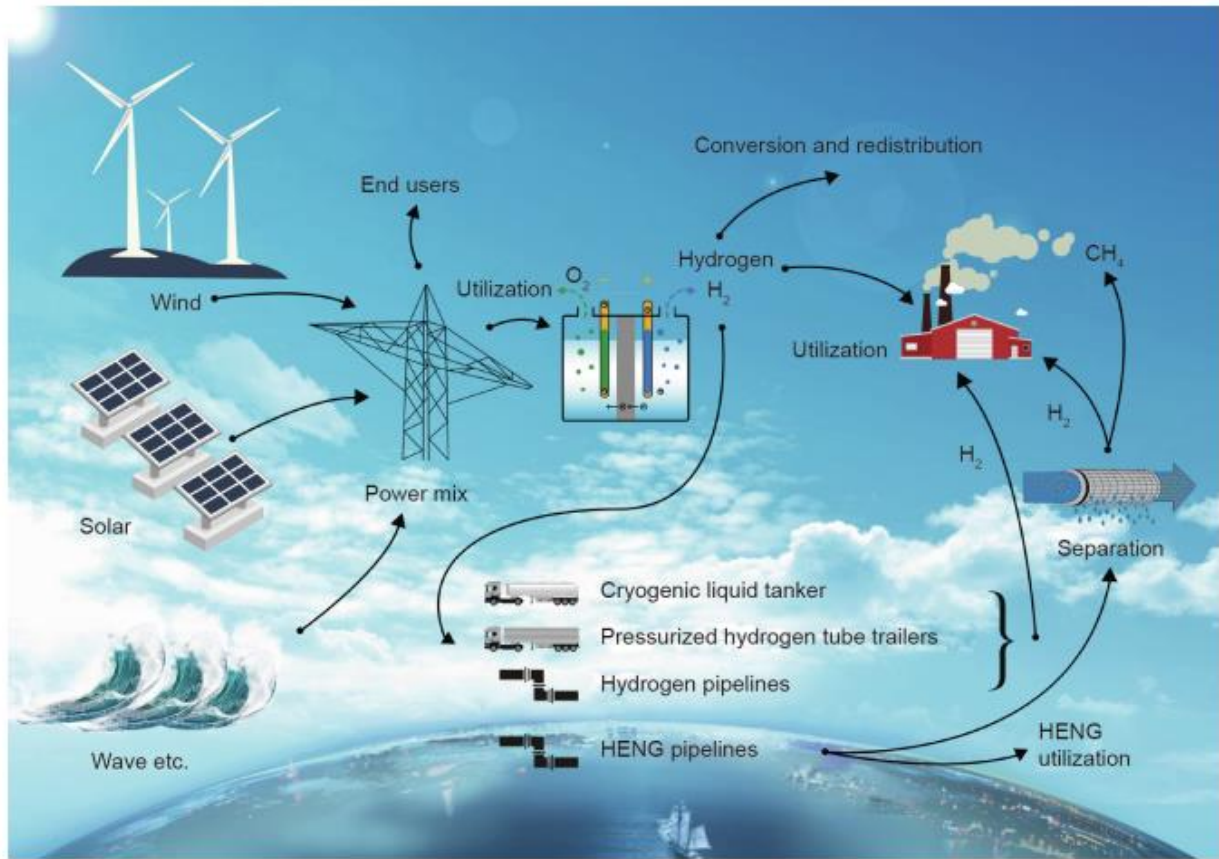


Figure 2.11: Roadmap For Energy To Hydrogen (P2H) Technology. Heng: Natural Gas Enriched With Hydrogen [32].

The study presented in [32] focused on Polymer Electrolyte Membrane (PEM) fuel cells and hydrogen energy. While these technologies have gained attention, the lack of infrastructure for hydrogen storage, refueling, and transportation hampers the commercialization of fuel cells. The review extensively examined and compared various hydrogen storage, production, purification, and transportation methods. The covered topics of review are shown in Figure 2.12. Specifically, the advantages of steam reforming gas and utilizing hydrogen derived from industrial by-products in PEM fuel cell systems were explored. Utilizing hydrogen from industrial waste could significantly reduce the cost of hydrogen. Methanol emerged as a promising carrier for hydrogen due to its potential for effective storage and transportation. Internal hydrogen production through methanol steam reforming was identified as a viable solution. However, impurities in the reformatting gas posed challenges. The study delved into the pre-treatment and steam reforming of methanol while addressing methods to reduce toxicity.

An integrated fuel cell system with subsystems for hydrogen production and purification was also discussed. The review concluded by providing recommendations for further research in the field.

The study described in [50] focused on the potential of biomass as a valuable resource for storing chemical and solar energy. Biomass, derived from animals or plants, has been widely utilized for heat generation and various industrial processes. Biomass contains a significant amount of elemental hydrogen, making it an excellent candidate for hydrogen production. Therefore, biomass is an environmentally friendly option for generating electricity and hydrogen. Despite the commercialization of biomass power plants and reforming power plants, there is still a need for more cost-effective technologies that can improve conversion efficiency and minimize the environmental impact of the process. The study highlighted two emerging areas of research that have garnered recent attention in this field. The first area explored the utilization of electrolysis technology to convert biomass into hydrogen at low temperatures. In contrast, the second area focused on the use of biomass-based flow fuel cell technology to generate electricity directly from biomass. The paper briefly discussed conventional technologies for biomass conversion into electricity and hydrogen, followed by an in-depth exploration of the advancements in Biomass-Based Flow Cells (FBFCs) and Biomass Electrolysis Hydrogen Production (BEHP). The study also highlighted the additional challenges associated with these innovative approaches.

The study in [51] focused on assessing the technical feasibility of integrating wind turbines with existing fueling stations to generate hydrogen. The objective was to utilize the produced hydrogen for fueling electric vehicles and supplying gas to local gas networks. Through GIS analysis, suitable fueling stations were identified, considering factors such as buffer zones, potential risks associated with turbine installation near built-up areas, critical infrastructure, and environmental networks.

The findings indicated that approximately 4.6% of the available fuel stations were suitable for wind turbine installation. Moreover, the land cover data from meteorological station datasets were utilized to assess the potential for hydrogen production. The results showcased the capability of these stations to meet around 2.3% of the demand in a scenario with a 30% adoption of Fuel Cell Electric Vehicles (FCEVs). Furthermore, the study conducted a case study examining the proximity of the existing gas distribution

networks to these identified fueling stations. This analysis evaluated the feasibility of integrating the hydrogen supply into the current gas infrastructure.

The study in [52] explores the potential of Proton exchange membrane water electrolysis to reduce greenhouse gas emissions in the hydrogen industry. A life cycle assessment was conducted to address this issue, comparing Proton exchange membrane water electrolysis with steam methane reforming, which served as a reference process. The findings indicated that hydrogen production through Proton exchange membrane water electrolysis could significantly reduce CO₂ emissions in the hydrogen industry, potentially reducing up to 75%. This reduction relied on the electrolysis system's ability to be powered by renewable energy sources. The study also revealed that the system components of Proton exchange membrane water electrolysis had a minimal impact on various environmental indicators associated with hydrogen production. The review highlighted that impacts such as global warming potential were primarily determined by the composition of the electricity mix used. Consequently, consumption reductions had little effect on the potential for global warming. However, critical substances were found to be significantly affected by material depletion. Furthermore, the study examined Proton exchange membrane water electrolysis in three distinct modes of operation, each requiring a unique electrical procedure. This exploration aimed to provide insights into the different operational approaches and their associated implications. The different types of energy sources discuss in [52] are shown in Figure 2.13.

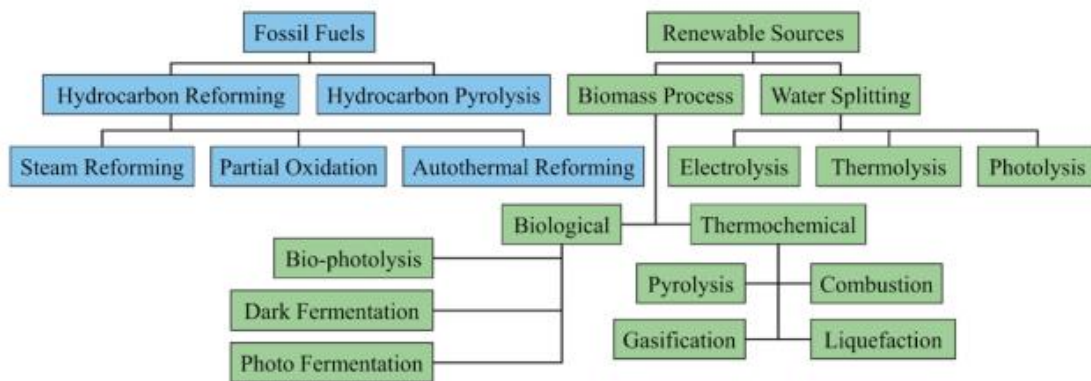


Figure 2.12: Hydrogen Making Methods [52].

The research in [53] focuses on the heating industry and its significant contribution to carbon dioxide emissions, particularly in the UK, where water and space heating demands account for a substantial portion of total energy consumption. Currently, natural

gas is predominantly used to fulfill these requirements. However, as part of a long-term strategy to mitigate carbon emissions, renewable hydrogen is a suitable alternative as a large-scale, low-carbon energy carrier that can be directly integrated into heat and power generation processes or injected into the existing gas grid. Renewable hydrogen offers advantages such as overcoming intermittency and seasonal variability of renewable energy sources through short-term storage and cost-effective transportation. A comprehensive hydrogen value chain must be established to facilitate the adoption of renewable hydrogen. This value chain encompasses various interdependent choices, including the optimal placement of wind turbines, the location of electrolyzers close to the wind resource or demand centers, the most efficient means of transferring energy in the form of hydrogen or electricity, and the strategic placement of storage facilities. The solar hybrid fuel cell model used in [68] is shown in Figure 2.14. Designing and implementing this hydrogen value chain would require the development of new infrastructure for renewable hydrogen production, transportation, storage, and utilization. Careful consideration of these choices and their interdependencies is crucial to ensure the effective integration of renewable hydrogen into the existing energy system.

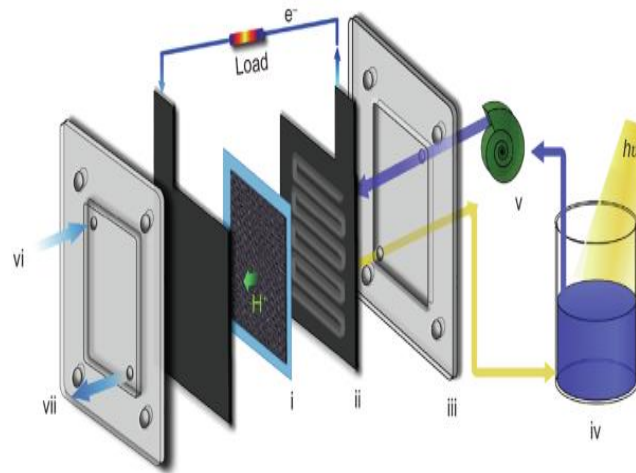


Figure 2.13: Solar Hybrid Fuel Cell Structure [53].

The research study presented in [54] investigates the competitiveness of fuel cells and proton exchange membrane (PEM) electrolyzers in the electricity utility markets of Europe. The paper begins by examining the existing framework for ancillary services, with a specific focus on ongoing European integration projects that aim to establish future frequency balancing markets. Next, the study delves into analyzing the technical characteristics of hydrogen PEM technologies and explores their potential applications

within electric power systems. The aim is to assess whether these technologies align with the requirements of sub-service markets in the electricity sector. To provide a practical context, the researchers utilize a representation of the transmission network in the northern Netherlands projected for 2030. This serves as the foundation for a case study, allowing for a more concrete evaluation of the compatibility and competitiveness of fuel cells and PEM electrolyzers within the European electricity utility markets.

The research presented in [55] explores the potential use of hydrogen as a cleaner cooking fuel in communities that rely on biomass and fossil fuels. The aim is to reduce local pollution and mitigate its adverse health effects. However, the hydrogen production process must utilize renewable energy sources and raw materials to avoid shifting environmental impacts from one stage to another within the life cycle. The paper specifically focuses on examining the environmental impacts of renewable hydrogen produced through proton exchange membrane electrolysis, using solar energy throughout its entire life cycle. The study's primary objective is to assess the environmental performance of hydrogen produced within this system when utilized as a cooking fuel. The goal is to compare its environmental impact to conventional cooking fuels commonly used in developing nations, such as LPG and coal. Additionally, the study investigates the environmental sustainability of wood and firewood, which are frequently employed as cooking fuels in these communities.

The research presented in [56] addresses the challenges associated with the optimal design and operation of multi-energy systems, particularly those involving seasonal energy storage. The complexity of the optimization problem often hinders the efficient planning and management of these systems. One of the main difficulties lies in accurately representing the seasonal cycles, while system performance requires a more granular hourly resolution. The study introduces novel mixed numerical linear programming techniques to overcome optimization challenges. These techniques offer a new approach to tackling the optimization problem by considering multiple years with an hourly resolution, thereby reducing the complexity associated with many variables, including binary variables, during system analysis. The effectiveness and validity of the proposed method are evaluated through a case study. Initially, a simplified system, which can be solved within a reasonable time frame without the need for design days, is utilized to assess the performance of the proposed method.

The research review conducted in [57] revolves around the combination of Photoelectrochemical Cells (PECs) and Microbial Fuel Cells (MFCs), with a specific focus on photosynthetic MFCs. The review explores the compatibility and performance of photocathodes and photoanodes in conjunction with photoelectronic and electrogenic microbes.

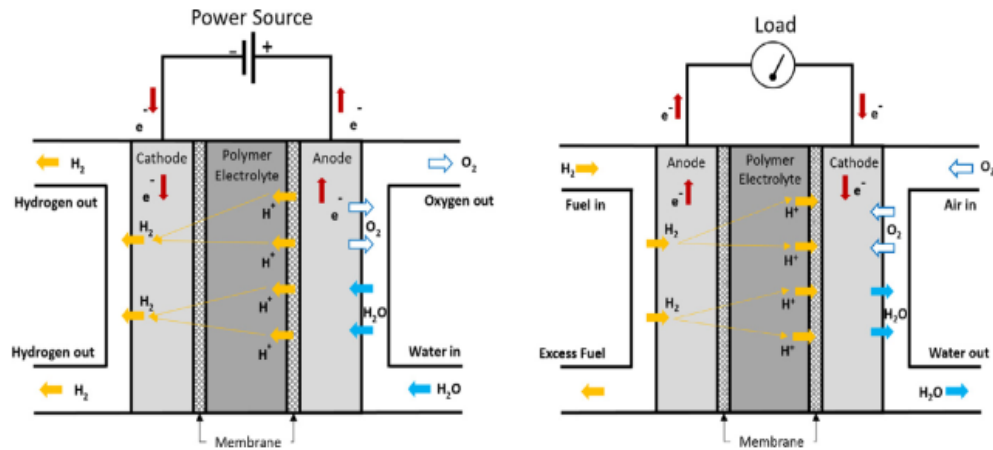


Figure 2.14: Pem Device Diagram: Fuel Cell (Right) And Electrolyzer (Left) [57].

Several studies have demonstrated the successful integration of light-to-power conversion electrodes in MFCs or the utilization of solar energy in PECs to enhance power generation compared to dark reactions alone. The advancements in this field have been driven by the hypothesis that incorporating light-based processes can significantly increase the power output of MFCs. The review highlights various manufacturing designs for photo-MFCs, including the use of both native and synthetic light-sensitive electrodes in combination with electrogenic microbes. One notable aspect is the potential of hybrid MFC-PEC reactors, which can produce solar bioelectronic fuels such as hydrogen, methane, and other valuable energy sources. As shown in Figure 2.15.

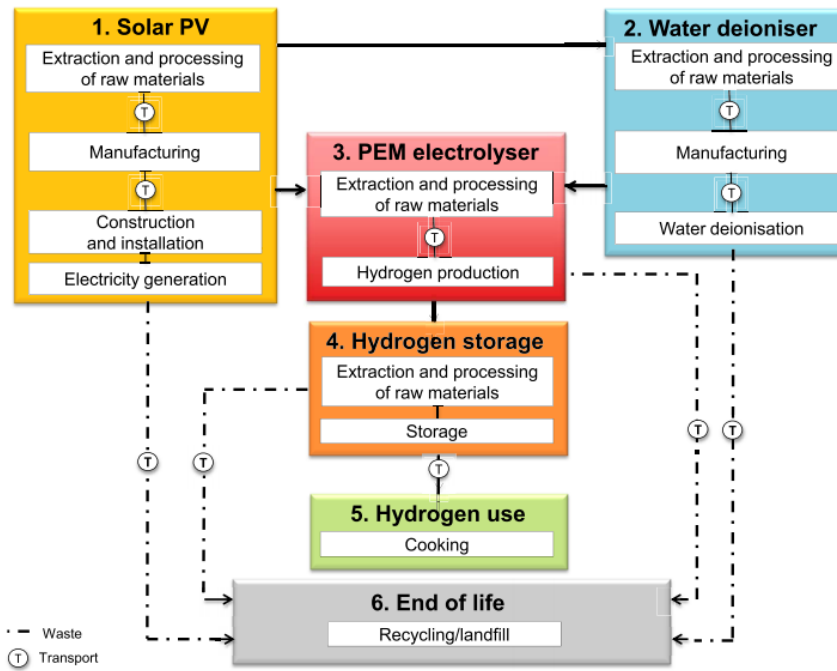


Figure 2.15: Life Cycle Analysis of A Solar PEM Electrolysis System [58].

In the research discussed in [58], it is highlighted that carbon dioxide (CO₂) emissions from fossil fuel combustion rose to 33 gigatons in 2017, surpassing the natural absorption rate of CO₂ by land and ocean sinks. The utilization of solar radiation is proposed as a viable solution to reduce dependence on fossil fuels. Solar radiation is the most abundant energy source and holds the potential to meet humanity's energy demands in the future. The key lies in converting solar radiation into stable and energy-rich liquid carriers that can seamlessly integrate into global supply chains for transportation, storage, and distribution, enabling the widespread adoption of gigaton-scale solar energy. The "Liquid Sun" concept involves producing environmentally friendly liquid fuels by harnessing solar energy, water, and carbon dioxide. This approach ensures the return of CO₂ to the atmosphere, maintaining an ecologically balanced cycle. Among the various potential liquid fuels, versatile alcohols emerge as the most promising candidates. Ethanol and methanol, in particular, are identified as the initial feasible targets due to their capacity to produce large quantities in the gigaton range. By leveraging the energy from the sun and employing these sustainable liquid fuels, a significant step can be taken towards mitigating CO₂ emissions and achieving a more sustainable energy future. The research emphasizes transforming solar radiation into high-density liquid energy carriers as a crucial pathway for transitioning away from fossil fuels and establishing a renewable and carbon-neutral energy system. The life cycle analysis of [58] is depicted in Figure 2.16.

Despite these research advances, several including the cost-effectiveness of hydrogen storage systems, system efficiency improvements, and addressing safety concerns associated with hydrogen handling and storage. Furthermore, optimizing the sizing and control strategies of the integrated system components is essential to maximize overall performance and economic viability. In conclusion, recent research has made significant strides in combining hydrogen storage with PV, grid, battery, and fuel cell technologies to power residential loads. These integrated systems have the potential to enhance energy reliability, improve renewable energy utilization, and contribute to a more sustainable residential energy sector. Continued research and development efforts are needed to overcome existing challenges and facilitate the widespread adoption of these integrated systems.

2.7 KEY FINDINGS OF THE LITERATURE REVIEW

Based on the comprehensive literature review regarding various aspects of hydrogen technologies, several key findings and recommendations can be summarized:

- a. **Hydrogen storage:** Research has focused on exploring different materials and techniques for hydrogen storage. Solid sorbents, magnesium-based materials, optimized thermodynamics, and kinetics have shown promise in enhancing storage capacity and efficiency.
- b. **P2H (Power-to-Hydrogen):** P2H offers a promising solution to the geographic mismatch between renewable energy sources and markets. Integrating P2H with natural gas pipelines is viable, with minimal impact on existing infrastructure.
- c. **Proton exchange membrane (PEM) technology:** PEM fuel cells and electrolyzers have been identified as viable options for reducing greenhouse gas emissions and improving the efficiency of the hydrogen industry. Electrolysis powered by renewable energy sources can significantly reduce CO₂ emissions.
- d. **Biomass utilization:** Biomass has great potential as a renewable resource for hydrogen production. Electrolysis at low temperatures and biomass-based flow fuel cell technology offers new avenues for sustainable electricity and hydrogen generation.
- e. **Wind turbines for hydrogen production:** Integrating wind turbines with existing fueling stations to produce hydrogen for electric cars and gas networks is technically

viable. GIS analysis helps identify suitable fueling stations, and land cover data can estimate hydrogen production potential.

- f. **Life cycle assessment:** Life cycle assessment studies emphasize the environmental impacts of hydrogen production. Renewable hydrogen production with solar energy and proton exchange membrane electrolysis is compared to conventional fuels, such as LPG and coal.

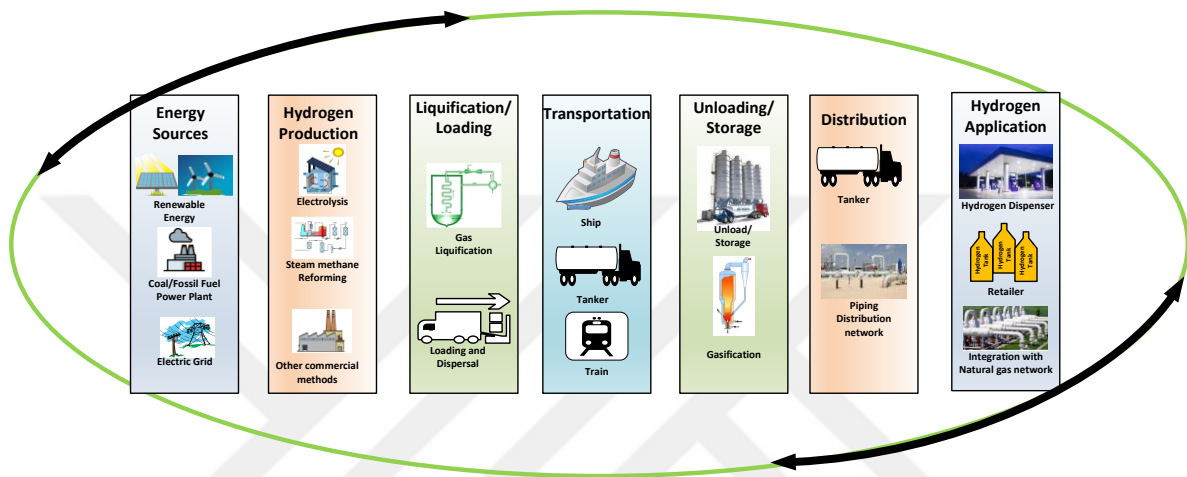


Figure 2.16: Life Cycle Analysis of A Solar PEM Electrolysis System [58].

2.8 RECOMMENDATIONS

Some recommendations are listed are given below:

- a. **Continued research:** Further research is needed to optimize the efficacy and usefulness of hydrogen-storage technologies, including exploring new materials and refining existing methods.
- b. **Infrastructure development:** Investments in infrastructure, such as hydrogen storage, refueling, and transportation systems, are essential to facilitate the widespread adoption of fuel cells and hydrogen-based technologies.
- c. **Policy support:** Governments should offer economic or tax-incentives on hydrogen-energy systems and enforce regulatory frameworks to encourage installing hydrogen technologies and foster collaborations between different sectors, such as energy and mobility.
- d. **Renewable energy integration:** Increasing renewable energy integration to produce H_2 is essential for significantly reducing greenhouse gas emissions. Regulatory

policies and incentives should promote integrating renewable energy into the hydrogen production process.

- e. **Standardization and safety:** Developing standardized protocols with safety guidelines for H₂ production, storage, and transportation will encourage its widespread adoption.
- f. **Collaboration and knowledge sharing:** Encouraging collaboration between academia, industry, and research institutions will foster innovation, accelerate technological advancements, which may lead to the commercialization of H₂ technologies.

These key findings and recommendations point towards the current state of H₂-technologies and highlight areas for further development and potential of H₂ as a clean and sustainable energy-source.

3. METHODOLOGY

3.1 INTRODUCTION

Chapter 3 presents the proposed design methodology of the proposed hydrogen-based hybrid energy system for a typical household. The chapter starts with a brief introduction of the simulative setup utilized in this research. The first section further explains step-by-step modelling and analysis of individual components of the proposed home energy system. This section includes modelling of PV array and electrolyzer. The third section deals with component sizing. The component sizing section calculates the energy requirements for the connected load. The design steps and the component selection for hydrogen-based home energy systems are also a part of this section. Simulations are the first step in testing the proposed control strategy. The simulation model of the proposed approach is developed in the MATLAB/Simulink environment. The electrolyzer is first simulated without the load to observe the characteristic curves and stability. Next, the complete system is developed incrementally, and the corresponding performance parameters are studied.

This research studies the potential of hydrogen as an energy source by developing a system that includes a renewable-energy supply (RES), electrolyzer, a Proton-Exchange Membrane Fuel Cell (PEMFC), and hydrogen-storage system(HSS). The main objective of this study is to analyze the system dynamics and achieve self-sufficiency, reducing reliance on the electrical grid. Additionally, a lithium-ion battery and a heating scheme are integrated into the system. This setup enables the storage of hydrogen generated through electrolysis during periods of excess energy production, serving as a form of short-term energy storage. This stored H_2 is then reconverted to electricity through a fuel-cell and utilized by a domestic-load when the RES output is insufficient.

3.2 PROPOSED SYSTEM AND CONTROL SCHEME

This section discusses the functions and control mechanisms of the designed hybrid-energy system. The key components of this setup include fuel-cell, electrolyzer, Li-ion battery, H_2 -storage tank, and PV-solar-panels. The block diagram (Figure 3.1) illustrates the architecture of the H_2 based home-energy system. The PV-source is the primary energy source, equipped with a power-inverter to power direct-current electric loads

within the household. Any surplus energy generated is then directed to the lithium-ion battery after passing through a DC-DC power-converter, which acts as a charge-controller. However, the system can draw additional power from the home grid via an inverter when solar energy falls short of the demand during the intermittent energy phase [29].

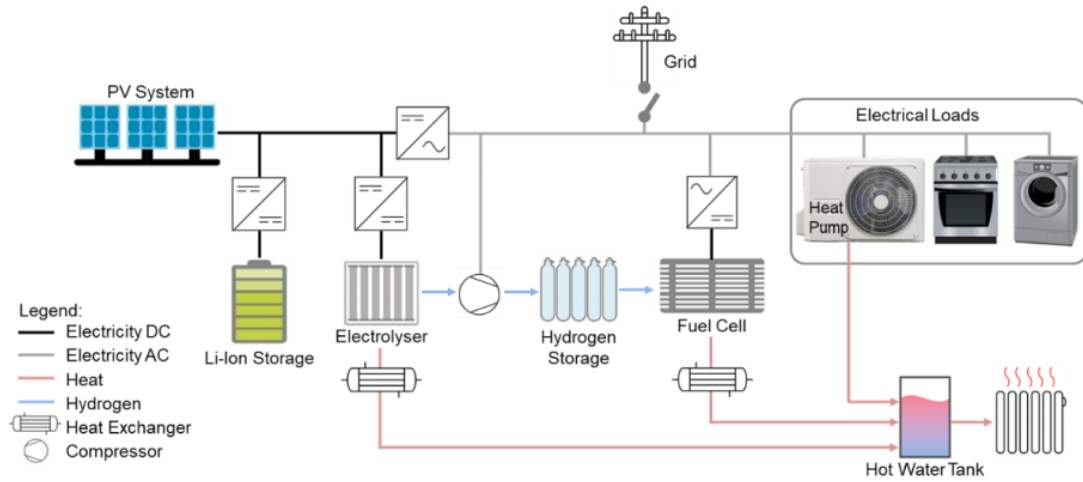


Figure 3.1: Structure of A Proposed Home-Energy System.

When Li-ion battery reaches full capacity and the PV system continues to generate excess energy, the electrolyzer is activated, allowing the surplus energy to be utilized for hydrogen production. After undergoing compression, H_2 is stored in a hydrogen tank. The fuel-cell is activated under specific conditions, such as high-power demand, low energy output, and a depleted Lithium-ion battery [8]. The fuel cell ensures a consistent power-supply to the load during load variations and solar intermittencies. The complete depletion of the Lithium-ion-battery is avoided by activating the fuel cell when the battery falls below a certain SoC threshold. Therefore, the Li-ion battery acts as a buffer i.e., (source/sink) when the energy demand is low compared to the fuel-cell. At the same time, the fuel-cell and other components maintain the battery state-of-charge (SoC). The fuel-cell delivers power, while the Lithium-ion battery remains inactive. A simple control algorithm regulates the energy flow, as shown in a Simulink diagram. Figure 3.3 illustrates the block diagram of inputs and output variables to accomplish a hybrid home energy management system.

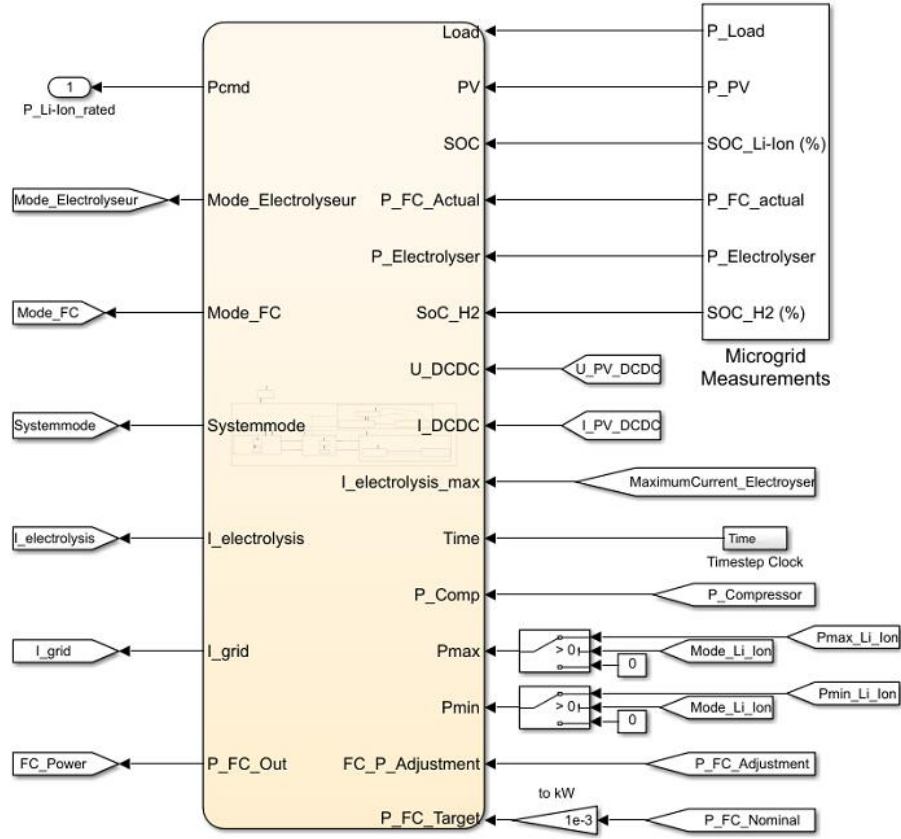


Figure 3.2: Input-Output Signals of A Multiple Sources Home Energy System.

The system generates significant residual heat; therefore, heat exchangers and heat pumps are employed for transferring excess heat into a water tank. However, since the amount of usable heat is small and there is a lack of hydrogen compressors that effectively utilize waste heat, the residual heat from the compressor is not taken into consideration.

3.3 INDIVIDUAL COMPONENT MODELLING

3.3.1 PV Modelling

For the sake of simplicity, the primary energy source is a PV array. The PV-array utilized in this thesis uses Bellini's PV model. Bellini's PV model, also known as the Bellini one-diode model, is a mathematical representation used to characterize the electrical behavior of a photovoltaic (PV) module or solar cell [59]. It is a simplified model that helps estimate the PV device's current voltage (I-V) characteristics under various operating conditions. The Bellini model assumes that a single diode parallel to a current source and a resistor can represent a PV cell. The model considers the key factors that affect the

performance of a PV cell, such as series and shunt resistances, diode ideality factor, and temperature dependence. The equation of Bellini's PV model is given as follows:

The Bellini model states that the Photo Voltaic cell current I_y is based on the Photovoltaic output voltage along with the two values K_1 and K_2 . The subsequent mathematical equivalences are:

$$I_y = I_{SC} [1 - K_1 (e^{(V_y / (K_2 \cdot V_{OC}))} - 1)] \quad (3.1)$$

Where,

$$K_1 = (1 - \frac{I_{MP}}{I_{SC}}) e^{(-\frac{V_{MP}}{K_2 \cdot V_{OC}})} \quad (3.2)$$

$$K_2 = \frac{((\frac{V_{MP}}{V_{OC}}) - 1)}{\ln(1 - (\frac{I_{MP}}{I_{SC}}))} \quad (3.3)$$

The parameters K_1 and K_2 are dependent on temperature and irradiance. The equations for the temperature dependence are specified below:

$$I_{SC}(G, T_c) = I_{SCS} \cdot \frac{G}{G_s} \cdot [1 + \alpha(T_c - T_s)] \quad V_{OC}(T_c) = V_{OCs} [1 + \beta(T_c - T_s)] \quad (3.4)$$

$$I_{MP}(G, T_c) = I_{MPS} \cdot \frac{G}{G_s} \cdot [1 + \alpha(T_c - T_s)] \quad V_{MP}(T_c) = V_{MPS} [1 + \beta(T_c - T_s)] \quad (3.5)$$

The real cell-temperature T_c (K) can be measured by the value of ambient-temperature T_a (K), the real irradiance G ($\frac{W}{m^2}$), the speed of wind ω ($\frac{m}{s}$) and the factor k_r (nearly 1.542K.s/m for single crystal applying the following formula:

$$T_c = 0.93 \cdot (T_a) + 0.031 \left(\frac{m^2 K}{W} \cdot G \right) - \omega + 3.6K \quad (3.6)$$

The two types of solar panel orientations were incorporated into the hybrid-energy system for facilitating two different radiation profiles. The configuration allows the inclusion of east/west oriented -arrays for the designed system. Further, to match the voltage of the electrolyzer, the DC/DC converter is employed to reduce the voltage output of the PV system. An efficiency parameter is applied to decrease the PV-current and power, considering factors such as conduction losses and degradation due to environmental pollution [13]. The following Figure shows the SIMULINK implementation of PV Bellini's model utilized in this thesis.

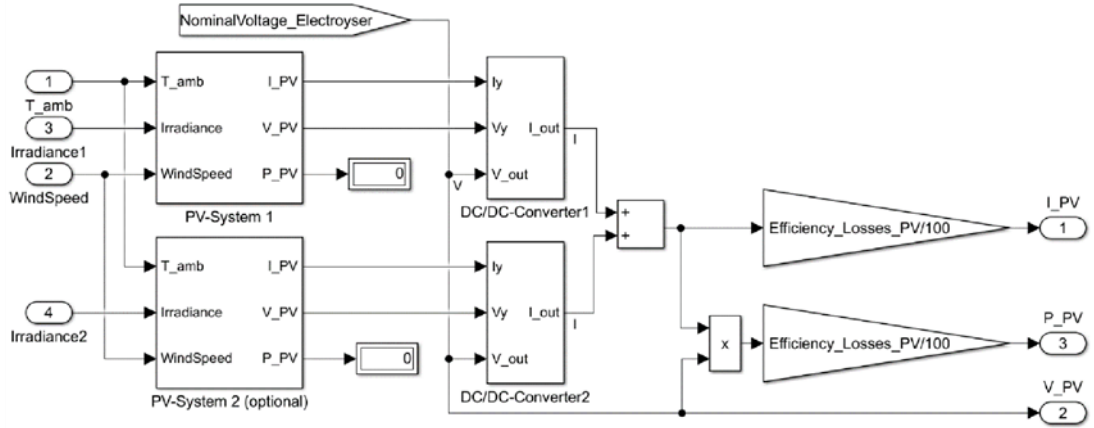


Figure 3.3: Input-Output Signals of a Multiple Sources Home Energy System.

3.3.2 PEM Electrolyzer

A PEM (Proton Exchange Membrane) electrolyzer is a compact device that utilizes an electric current to split water molecules into hydrogen and oxygen. It efficiently converts electrical energy into stored chemical energy in the form of hydrogen gas [60]. The PEM electrolyzer is well-suited for various applications with its small size, low energy consumption, and moderate operating temperature. It offers the advantage of rapid response to fluctuations in electrical input, making it compatible with intermittent renewable energy sources [26]. Additionally, PEM electrolyzers ensure high levels of safety, provide hydrogen compression capabilities, and deliver high-purity hydrogen gas output. PEM electrolyzers are selected due to their ability to handle fluctuations in electrical energy, particularly when powered by intermittent renewable energy sources, which is required for this project. Also, it is a suitable device due to its compact size, lightweight design, low energy consumption, and relatively low operating temperature [28]. Moreover, PEM electrolyzers are known for their high level of safety, hydrogen compression capabilities, and the ability to produce high-purity hydrogen gas within the system.

Mathematically, the electrolytic splitting characteristics of a PEM cell can be described as follows:

$$(T, p) = e_{rev}(T, p) - e_{rev}(T, p) e^{\frac{-5 \cdot I}{0.02 \text{ A}}} + I \cdot Ri(T, p) \quad (3.7)$$

The formulation for a whole stack is specified by:

$$V(T, p) = I \left(\frac{n_s}{n_p} \right) R_i(T, p) - n_s e_{rev}(T, p) \quad (3.8)$$

with n_s as the amount of the cells in sequence and n_p as the parallel cells, respectively. The changeable potential $e_{rev}(T, p)$ along with the resistance of PEM cell as $R_i(T, p)$ are temperature- and the pressure dependent:

$$e_{rev}(T, p) = e_{rev0} + \frac{R(273.15K+T)}{2F} \ln\left(\frac{p}{p_0}\right) \quad (3.9)$$

$$R_i(T, p) = R_{i0} + k \cdot \ln\left(\frac{p}{p_0}\right) + dR_t (T - T_0) \quad (3.10)$$

where R constant is the general gas constant, T is the inside temperature of the electrolyzer, F is as the Faraday's constant, P_0 and P are the ambient pressure, and the working pressure, correspondingly and the value k is the derivative curve-fitting limit ($k = 0.0395 \text{ VA}^{-1}$).

The production rate of hydrogen can be measured based on Faraday's law. The production rate of hydrogen within the electrolyzer cell is rightly proportional to the electron transfer rate to the conductors. It is equal to the electric current present to the circuit. The method for the production rate of hydrogen is:

$$v_{H2} \left(\frac{m^3}{s} \right) = \frac{v_m N_c I}{2F} \text{ with } v_m \left(\frac{m^3}{mol} \right) = \frac{R(273.15K+T)}{p} \quad (3.11)$$

where v_m is the one molar volume, N_c is the cells number in series of and I is the definite current to the electrolyzer. The figure displays the implemented electrolyzer model in Simulink which is linked on the work of (Beainy and Albarghot) [61] but is partly altered.

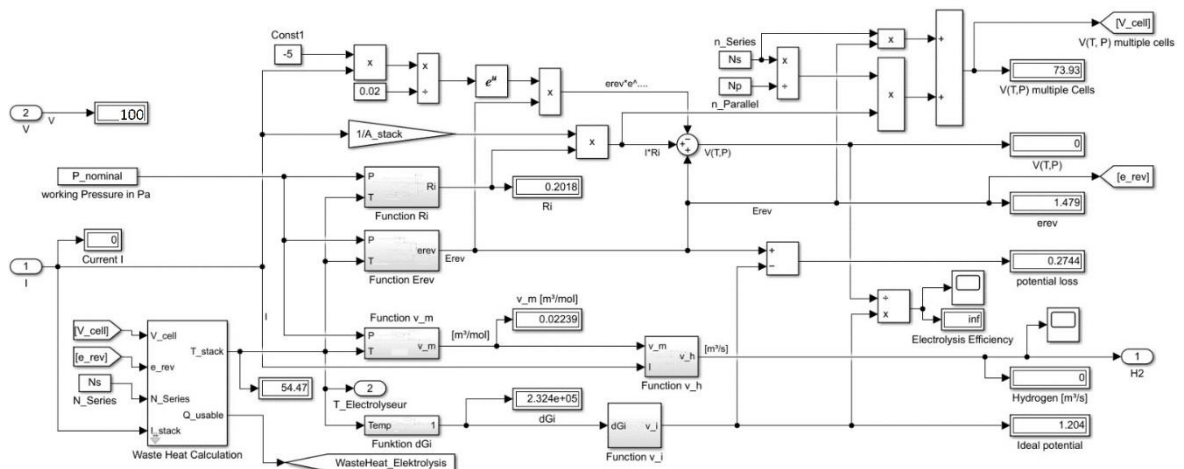


Figure 3.4: PEM Electrolyzer Implementation In SIMULINK.

3.3.3 Hydrogen Storage With Compressor

Hydrogen produced through electrolysis can be stored in hydrogen storage systems and later utilized in a fuel cell to generate electricity [1]. The generated hydrogen is supplied to the fuel cell with hydrogen during periods of low photovoltaic (PV) energy input. Several options are available for hydrogen storage, each with its advantages and disadvantages, depending on the intended use. The four typical choices for hydrogen storage are as follows:

- a. Compressed hydrogen.
- b. Liquid Organic Hydrogen Carrier.
- c. Liquid hydrogen.
- d. Metal hydride hydrogen storage.

The process of Hydrogen compression requires less energy compared to other options. Approximately 4 kW/kg of hydrogen is needed for compression at pressures ranging from 10 to 500 bars, corresponding to around 12% of the energy content of hydrogen. However, compressed hydrogen storage requires more space, which is typically not a significant concern for continuous use [62]. Therefore, compressed hydrogen is chosen as the preferred option in this specific case. However, a suitable pressure is needed for optimal storage, typically 1 to 300 bars, to achieve high storage capacity. The Hydrogen storage system dynamics can be represented using the following formula:

$$P_b - P_{bi} = z \frac{N_{H_2} R T_b}{M_{H_2} V_B} \quad z = \frac{P_b V_m}{R T_b} N_{H_2} = v_{H_2} \cdot p_{H_2} \quad (3.12)$$

Where, P_b (P_a) is the definite pressure of tank,

P_{bi} (P_a) is the initial pressure of tank,

R is the general gas constant,

T_b (K) is the working temperature,

V_B (m³) is the volume of tank,

z is the factor of compressibility,

addressing the intermittent nature of renewable sources by storing excess energy and producing hydrogen during low-demand periods. Their rapid response times and high-power output complement hydrogen fuel cells' slow startup and shutdown, ensuring a seamless and uninterrupted energy supply. With their mature and cost-effective infrastructure, lithium-ion batteries offer a practical and scalable solution for long-term energy storage in hydrogen-based systems [37]. This powerful partnership between lithium-ion batteries and hydrogen-based energy systems accelerates the transition toward a cleaner, more resilient, and sustainable energy landscape. Lithium-ion batteries are the primary storage solution for our proposed home energy system for intermittency problems. The battery stores excess energy from the PV system until the upper charging limit is reached. If the PV system's surplus energy exceeds the charging range, it is diverted toward hydrogen production. Additionally, the lithium-ion battery stores any excess power generated by the fuel cell that is not immediately required to meet the home's energy needs. Consequently, the fuel cell stops functioning once the predetermined state of charge (SoC) is reached. In situations with limited PV supply due to factors like nighttime, cloud cover, or high energy requirements, the stored energy in the lithium-ion battery is utilized to fulfill the energy demand, ensuring a smooth transition. It is worth noting that lithium-ion batteries are mainly employed for short-term energy requirements due to their lower storage capacity compared to hydrogen tanks. The ability to deliver the maximum amount of energy within a specific timeframe is a crucial parameter for achieving energy independence, influenced by the household's energy consumption preferences and the electrical load of the house.

This study used a modified version of a lithium-ion battery model, previously integrated into the Microgrid-EMS-Optimization model in Simulink, to represent the household system type. The lithium-ion battery's state of charge (SoC) limits was set at 20% and 80%, respectively, although these values can be adjusted to meet specific age and capacity requirements. The power flow in and out of the storage is governed by the power limits specified in the design, and energy calculations are performed using a simple control algorithm. Any excess energy generated by the photovoltaic system, which is insufficient to meet the load demand, is stored in the lithium-ion battery, provided it falls within the battery's rated power. When the energy demand exceeds the photovoltaic generation, the stored energy from the battery supplements the shortfall. The fuel cell is

activated when the SoC approaches the lower limit, and any excess power not required to meet the load is diverted to the storage. The fuel cell operation ceases once the SoC reaches 37.5 percent. Figure 3.6 shows the implemented Simulink model.

Figure 3.6: Lithium-Ion Battery Model.

SIMSCAPE provides a range of predefined fuel cell blocks that capture the fundamental characteristics and behavior of different fuel cells. The model's accuracy depends on the level of detail and complexity considered during the model setup [35]. Higher fidelity models may incorporate electrochemical reactions, heat transfer, and mass transport, leading to more accurate representations. However, increased complexity can also impact simulation performance. Accurate modeling often requires adjusting model parameters to match the specific fuel cell being modeled. The parameter tuning process involves modifying values such as internal resistance, polarization curves, cell voltage, and efficiency to align the simulation results with experimental data. The accuracy and performance of fuel cell modeling can also be influenced by the computational resources available. Complex models may require high computational power and memory, particularly when simulating long time frames or performing parameter sweeps [63]. Proper hardware allocation and optimization techniques can help improve simulation efficiency. When modeling fuel cells in SIMULINK, there can be trade-offs between accuracy, performance, and simulation time [31]. Increasing the model's complexity and accuracy may result in longer simulation times, impacting real-time analysis or optimization studies. Achieving a balance between accuracy and performance is essential to ensure that the model meets the specific requirements of the intended analysis.

cell current and the hydrogen flow rate, which are influenced by the cell current. The block generates a relative voltage based on the current value and other interconnected internal performance parameters. The model incorporates a heat exchanger to account for the significant amount of residual heat generated by the fuel cell. Heat exchanger modeling allows for a more comprehensive representation of the fuel cell's behavior and the associated thermal management aspects within the Simulink model.

In the context of a home energy system incorporating a PEM fuel cell, electrolyzer, and heating pump, heat exchanger modeling plays a vital role in optimizing energy efficiency and meeting heating demands. In many households, the highest energy consumption is attributed to heating purposes. The excess heat generated by the fuel cell can be utilized effectively to enhance the overall system efficiency. Additionally, during the winter season, there is a need for a hot water supply. A heat exchanger pump is employed to fulfill the remaining heat demand, as the waste heat produced by the fuel cell and electrolyzer alone may not be sufficient [64]. Heat exchangers with two separate circuits are utilized to extract and use waste heat efficiently. One circuit is dedicated to space heating, while the other is designed for hot water storage. Water serves as the heat exchange medium in both circuits since the study employs a PEM fuel cell that operates at temperatures around 60 °C. Similarly, water can be employed as a medium in PEM electrolysis cycles since the operating temperatures are also around 60 °C. By storing water and heat at a sufficiently high temperature, the fuel cell and electrolyzer contribute to meeting the home's heating demands. The heat exchanger model ensures effective heat transfer between the fuel cell system and the space heating and hot water circuits, optimizing energy utilization. The heat demand is determined based on specific heating requirements, enabling efficient control and management of the heating system without needing an elaborate model that accounts for the complex interactions with the house's structure and individual room radiators. This streamlined approach reduces complexity while maintaining the ability to meet the home's heating needs efficiently. The design equations and the temperature coefficient calculation are given by the following equations.

$$C_{t_{h,stack}} \frac{dT}{dt} = Q_{Heat, Stack} - Q_{Loss} - Q_{Cooling} \quad (3.14)$$

$$Q_{Heat, Stack} = Q_{Heat, Cell.N ELY cells} = (V_{cell} - V_{tn}).I_{Cell.N ELY cells} \quad (3.15)$$

$$Q_{Loss} = k.A_s.(T_{PEME}-T_n) \quad (3.16)$$

$$Q_{Cooling} = m_{stack} \cdot C_{p,stack} \cdot \frac{T_{out} - T_{in}}{\ln \left(\frac{T_{PEME} - T_{in}}{T_{PEME} - T_{out}} \right)} \quad (3.17)$$

3.3.6 Power Balance In Fuel Cell Electrolyzer Coupled System

In a combined fuel-cell and electrolyzer, the power balance refers to the equilibrium between each component's electrical power input and output. The electrical power input is typically supplied from an external source, such as a battery or a power grid, and it is used to drive the electrochemical reactions within the fuel cell [60]. The chemical energy of the fuel (such as hydrogen) is converted into electrical energy. The power output of the fuel cell is the electrical power generated by the cell, which results from the electrochemical reactions occurring at the electrodes. It depends on factors such as the fuel-cell's operating conditions, the efficiency of the electrochemical reactions, and the load connected to the fuel-cell. The electrical power input must equal the output and waste heat for power balance. Any imbalance can result in energy storage or discharge, affecting the overall performance of the fuel cell system [18]. Similarly, in an electrolyzer, the electrical power input drives the electrochemical process of water electrolysis. During electrolysis, electrical energy splits water into H₂ and O₂ gases. The power output of the electrolyzer is the electrical power needed for the electrolysis process. To maintain power balance, the electrical power input must equal the output and waste heat. Any deviation can lead to an accumulation or depletion of the H₂ and O₂ gases. $P_{overall}$ is the power supplied to the electrolyzer, while P_{el} is the power utilized for H₂ conversion and the power wasted in heat is P_{Heat} is explained by:

$$P_{Heat} = P_{overall} - P_{el} = I_{Stack} \cdot N_{cellsFC} \cdot (1.254 \text{ V} - V_{Cells}) \quad (3.18)$$

$$P_{el} = I_{Stack} \cdot V_{Stack} = I_{Stack} \cdot V_{Cells} \cdot N_{cellsFC} \quad P_{overall} = I_{Stack} \cdot N_{cellsFC} \cdot 1.254 \text{ V} \quad (3.19)$$

In a heat exchanger and opposite heat flow is observed denoted as interchanged heat power P_r , and can be expressed mathematically as:

$$P_{FCHE} = U_{cool} \cdot A_{cool} \cdot \left(\frac{T_{out} T_{in}}{\ln \left(\frac{T_{PEMFC} - T_{in}}{T_{PEMFC} - T_{out}} \right)} \right) \quad (3.20)$$

with U_{cool} serving as the heat exchanger-specific worldwide heat transfer coefficient and A_{cool} serving as the contact area of coolant . It is presumed that the fuel cell's output and input temperatures T_{PEMFC} remain constant. Using an efficiency parameter, heat losses, such as those caused by tubing losses, were considered. The heat exchange model and electrolyzer operating temperature calculation using equation 3.20 of the proposed system is implemented in Simulink as shown in Figure 3.7.

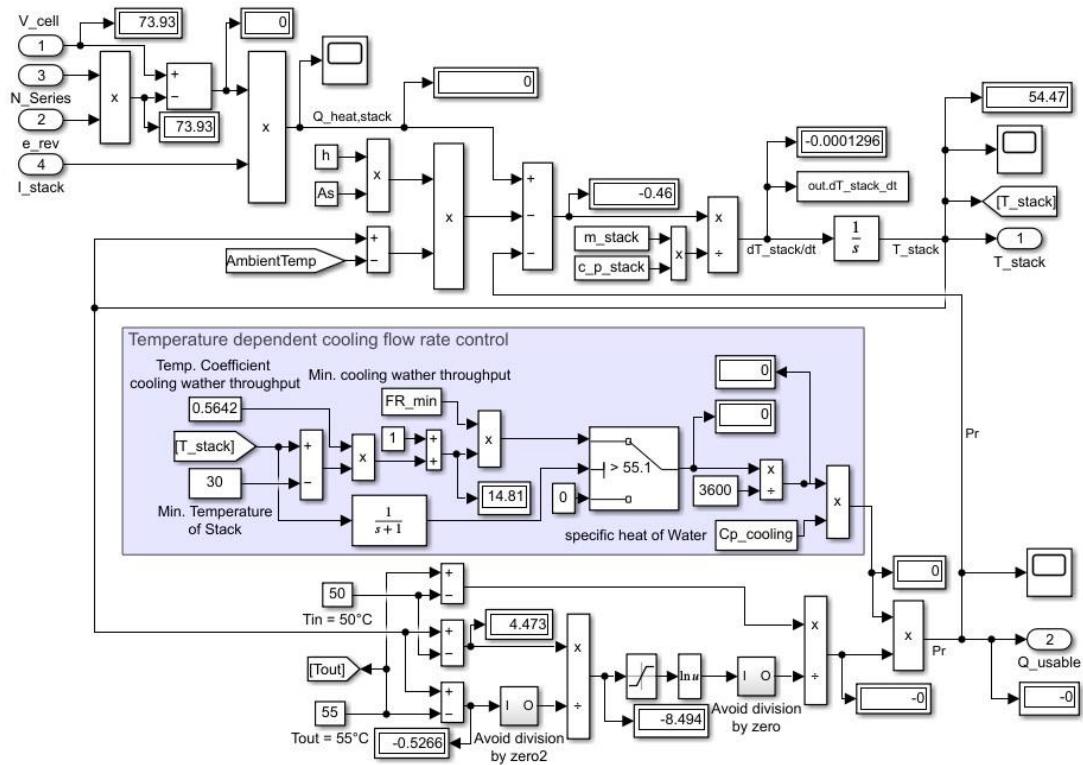


Figure 3.7: Control of The Coolant Flow-Rate and The Calculation Of The Electrolyzer Operating Temperature Are Included In The Waste Heat Calculation.

For the proposed system, the cumulative heating power for a duration of 2500 seconds is conducted. The heat energy generated by the fuel cell (FC) and electrolyzer during that time is captured by the simulations. Subsequently, the total heat demand is divided by the total heat loss. A heat exchange profile is employed to facilitate this process [37]. In a practical energy system, this approach allows for the measurement of the residual heat demand of the heat pump within 0.25-hour intervals. Consequently, the waste heat recovery potential (WHP) can be calculated to fulfill the energy requirements of the heat pump.

$$WHP = Q_{remaining}/COP \quad (3.21)$$

where the co-efficient of performance (C-O-P), or the ratio of usefully supplied heat to energy required, is influenced by the environment's actual temperature. Throughout the year, the COP is measured for each 15-minute step. As a result, the temperature on the sink side is 55 °C, and a table of C-O-P values at various ambient-temperatures serves as a reference.

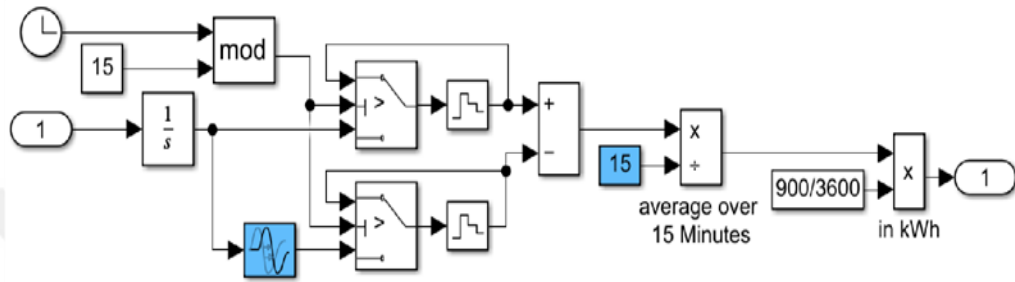


Figure 3.8: Calculation Of Heat Exchanger Waste Energy.

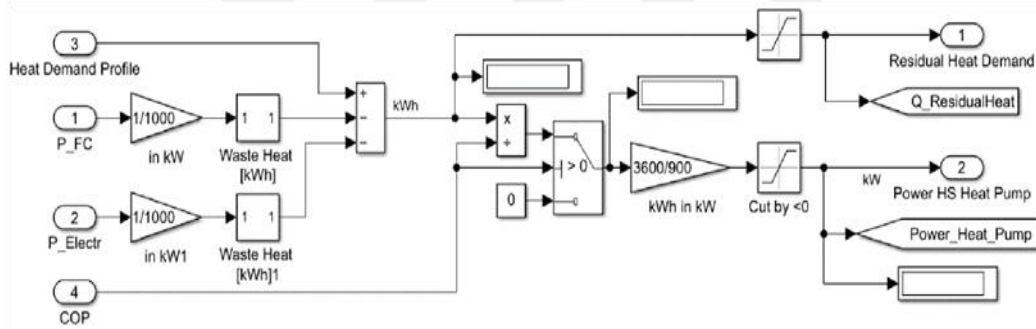


Figure 3.9: Determination of The Needed Power And Energy Of Heat Pump In Addition To The Residual Heating Demand.

3.4 CONCLUSION

This chapter sheds light on various aspects of fuel cell technology, energy systems, and modeling considerations. The chapter explored the advantages of lithium-ion batteries in hydrogen-based energy systems, highlighting their ability to store and supply short-interval power demands efficiently. Additionally, the chapter covers the modeling of fuel cells in SIMULINK using SIMSCAPE, emphasizing the importance of validation, parameter tuning, and achieving a balance between accuracy and performance. Furthermore, we examined the modeling of heat exchangers in home energy systems incorporating PEM fuel cells, electrolyzers, and heating pumps. Heat exchangers are

crucial in maximizing energy efficiency by utilizing waste-heat generated by fuel-cells and fulfilling heating demands. Using two separate circuits for space-heating and hot-water storage, along with the involvement of water as a medium, contributes to effective heat transfer and optimization of energy utilization. The chapter highlights the significance of accurate modeling, system integration, and optimization in harnessing the full potential of fuel cells, electrolyzers, and related components within energy systems. By considering power balance, heat recovery, and demand profiles, we can design and operate energy systems that are more efficient, sustainable, and capable of meeting the diverse energy needs of modern households and beyond.



4. RESULTS AND DISCUSSION

A hybrid energy system for homes integrates multiple energy sources and components to manage energy and address intermittencies efficiently. In the proposed system of Figure 4.1, a hybrid energy system for homes combines various energy sources and components to manage intermittencies and optimize energy utilization. The PV system is the primary renewable energy source, with excess electricity stored in the battery or used for electrolysis. The generated H₂ gas is stored for future use by the fuel-cell during periods of low solar generation. The grid connection acts as a backup power source, ensuring an uninterrupted electricity supply. This integrated system promotes renewable energy usage, reduces reliance on the grid, and enhances the resiliency and sustainability of home energy management.

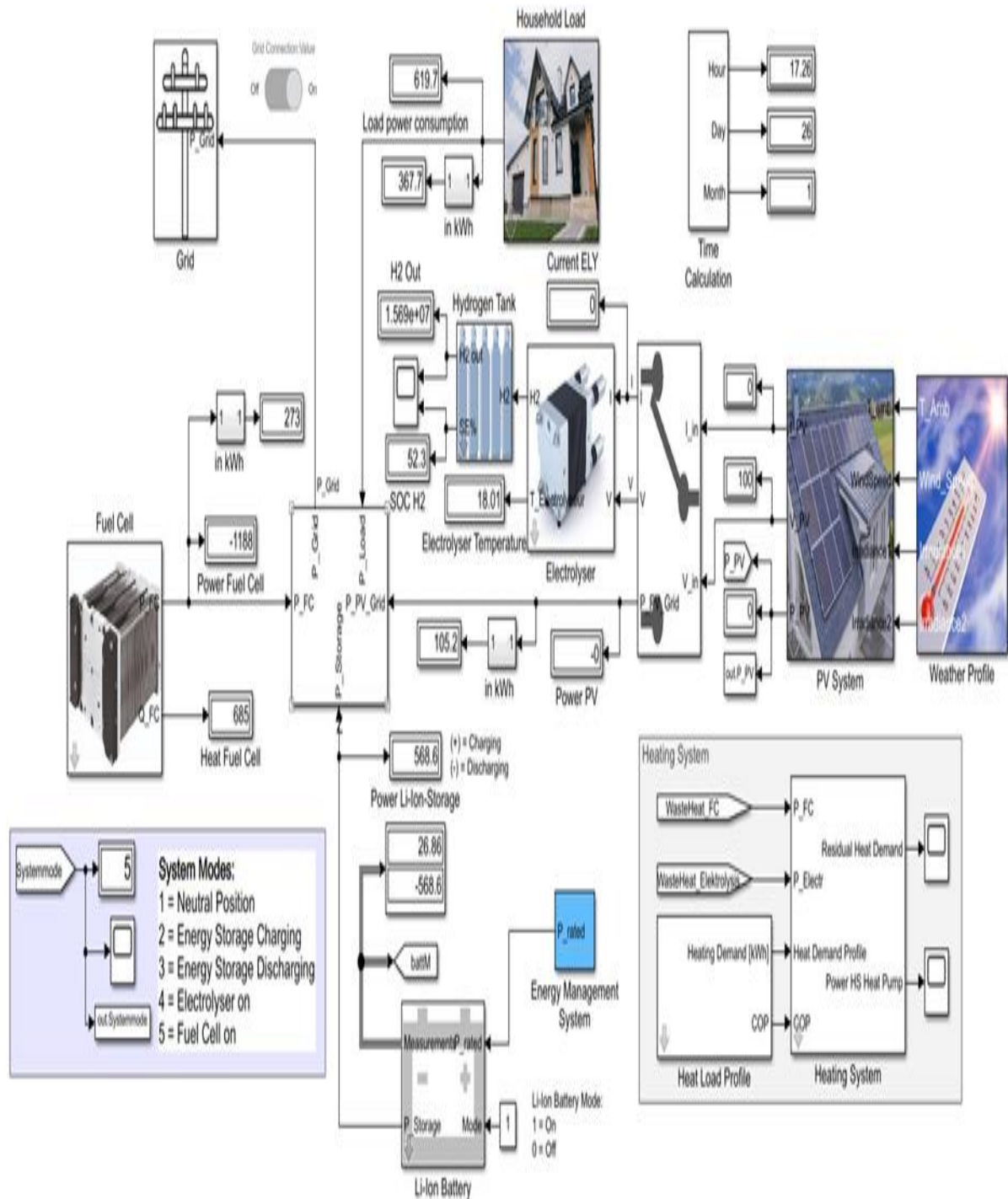


Figure 4.1: Model of The Entire Household's Energy System in Simulink.

All the components operate in conjunction to supply uninterrupted power to the load. The energy management system controls all the components, including PV (photovoltaic) panels, a fuel-cell, an electrolyzer, hydrogen storage, a grid connection, and a lithium-ion battery.

- a. PV System: The PV system comprises solar panels that convert sun irradiation into electrical energy. During periods of sunlight, the PV system generates electricity to power the home's electrical loads. The PV system is a primary renewable energy source, reducing reliance on external power.
- b. Fuel-Cell: The fuel-cell is a device that utilizes H_2 gas to generate electricity through electrochemical reactions. It acts as a backup power source when the PV system cannot meet the energy demand. The fuel-cell can operate continuously, providing a consistent power supply even during solar intermittencies.
- c. Electrolyzer: The electrolyzer produces H_2 gas through electrolysis. It utilizes surplus or excess electricity generated by the PV-arrays during periods of high production. This surplus electricity powers the electrolyzer, to produce green H_2 gas. The H_2 gas is then stored for later use, while the oxygen can be released into the atmosphere.
- d. Hydrogen Storage: The generated hydrogen gas from the electrolyzer is stored for future utilization. It serves as an energy reservoir during periods of low solar generation or high energy demand. The fuel cell can use the stored hydrogen gas to generate electricity when there is insufficient solar power available.
- e. Grid Connection: The home remains connected to the grid, providing a backup power supply during extended periods of low PV generation or depleted hydrogen storage. The grid connection ensures a continuous power supply when renewable sources cannot meet the energy demand, ensuring reliability and reducing disruptions.
- f. Lithium-ion storage Battery: The li-ion battery acts as an energy storage system within the hybrid setup. It captures and stores excess energy generated by the PV system. The stored energy can be used during low solar generation or high electricity demand. The battery enhances the self-consumption of renewable energy and reduces reliance on the grid.

During high solar irradiation, excess electricity is first directed to charging the lithium-ion battery. Once the storage battery is fully charged, the surplus electricity is then powered by the electrolyzer, producing hydrogen gas. When solar energy production is low or during high energy demand, the fuel cell can use the stored-hydrogen gas electricity generation. The fuel-cell provides continuous power, compensating for the intermittencies of solar energy.

4.1 SIMULATION CONFIGURATION

All the measurements are conducted per unit system for comprehensible modeling . The goal is to minimize reliance on the external grid and achieve optimal energy system management. The important design parameters are listed in Tables 4.2 to 4.6. A typical residential load profile is used for the simulation, which is conducted for 2500 seconds. All the selected components are suitable for small-scale applications and meet the requirements of residential households. The values in the commercially available component datasheets served as the basis for configuring the simulation parameters. The appropriate settings for all energy system components are discovered through multiple iterations of modifying and rerunning the Simulink simulation, ensuring 100% energy independence throughout the year.

Simulink offers a valuable tool for evaluating the suitability of key parameters and component dimensions for both on and off-grid performance. By adjusting the input parameters, one can tailor the analysis to match your energy consumption preferences and the specific location requirements. It's important to note that the input data values were designed for 15-minute simulations, disregarding sudden variations. The setup and ramp-up times of the components are not accounted for within the considered time scale. Although higher-resolution input datasets were not considered due to the hourly resolution of solar radiation data, these high-resolution datasets can serve as a foundation for developing more realistic solutions in future research endeavors.

Table 4.1: PV System Features.

PV/Solar energy system Features	Value
Maximum-Power Value at the STC (Pmpp)	315 Wp
Maximum-Power Value Voltage (Vmpp)	33.7 V
Maximum-Power Value Current (Impp)	9.34 A
Open-Circuit Voltage (VOC)	40.7 V

Short-Circuit Current (ISC)	9.86 A
Co-efficient of Temperature VOC	– 0.29%/K
Co-efficient of Temperature ISC	– 0.03%/K
Total units in series	12
Number of equivalent strings	2

Table 4.2: Electrolyzer Features.

Electrolyzer Features	Value
Normal rate of hydrogen production	1.11 Nm ³ /h
H ₂ production range	0.32–1.58 Nm ³ /h
Operating pressure	0 – 21 bars
Normal efficiency	76%
Normal power-consumption	5.02 kW
Max. power used	9.40 kW
Normal operating-temperature	64 °C
Current range	15–77 A
Voltage (max.)	127 VDC
Total cells in a stack	52

Table 4.3: Lithium-Ion Battery Features.

Lithium-ion Battery Features	Value
Usable Capacity	17 kWh
Power-range	12.9 kW
Peak power	18.5 kW, 6 s
Efficiency	96%
Usage	On/Off-Grid
Ambient temperature	11 °C - 51 °C

Table 4.4: Fuel Cell Features.

Fuel-Cell Parameters	Values
Kind of the Fuel-Cell	P-E-M
Power-rating	1242 W
Maximum rated power	2006 W
Voltage and maximum efficiency	24.25 V at 53 A
H ₂ pressure	1.6 bar
Normal operating-temperature	57 °C
Normal efficiency	36%
Total-Cells	36

Table 4.5: Domestic Home Features.

Domestic Home Characteristics	Value
Demand of Electricity	2353 kWh/a
Demand of Heat	4010 kWh/a
Living area	162 m ²
Extents surface area	9.2 × 9.2 m ²
Efficiency KfW	$40 \leq 25 \frac{\text{kWh}}{\text{m}^2 \cdot \text{a}}$

Table 4.6: Features of Hydrogen Storage Tank.

Hydrogen-Tank Features	Value
Extreme tan- pressure	301 bars
Tank's volume@(at 1 bar)	5.2 m ³
Primary SoC	62%

4.2 HOME ENERGY SYSTEM USING HYDROGEN FUEL CELL

The two damp air systems within the setup represent distinct gas compositions. The anode system comprises nitrous (N₂), evaporated water (H₂O), and fuel (H). The H₂stored is pressurized up to 70 MPa. When the hydrogen passes through a pressure-reducing valve, it enters the fuel cell stack at approximately 0.16 MPa. Any excess hydrogen is directed back to the boiler for reuse.

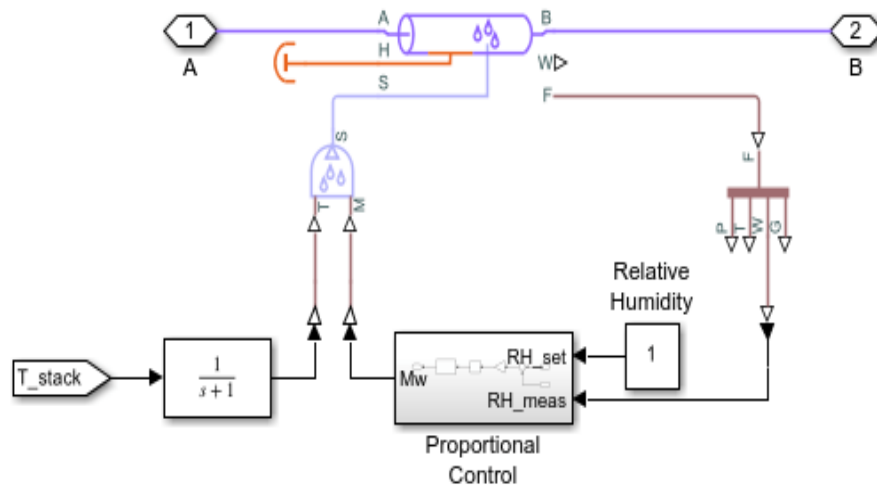


Figure 4.2: Model of Anode Humidifier.

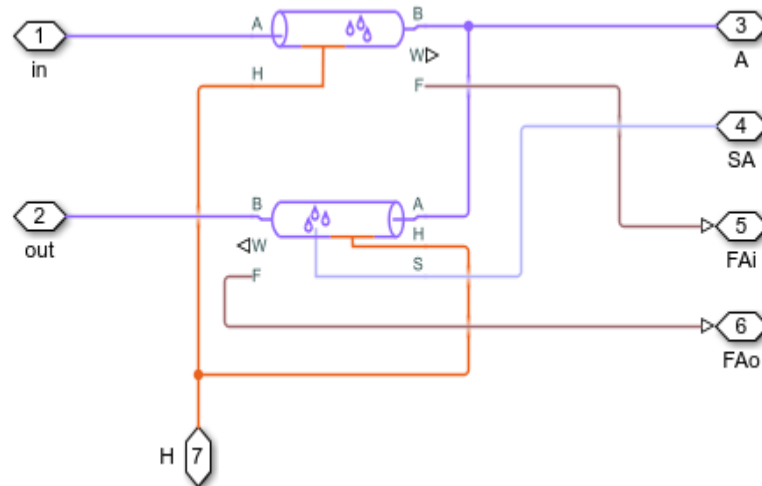


Figure 4.3: Model of Cathode Humidifier.

On the other hand, the cathode system, representing the ambient air, consists of nitrogen (N_2), evaporated water (H_2O), and oxygen (O_2). A compressor continuously supplies clean air to the stack to ensure a continuous oxygen supply, preventing oxygen depletion within the fuel cell. A relief valve shown in Figure 4.4 is installed to release excess pressure and vent the combustion gases to the outside air while maintaining a stack pressure of around 0.16 MPa. The SIMSCAPE implementation of exhaust systems are depicted in Figure 4.5, 4.6 The fuel cell stack performs best within a wide range of loads for optimal efficiency when it is maintained at a constant temperature and relative humidity.

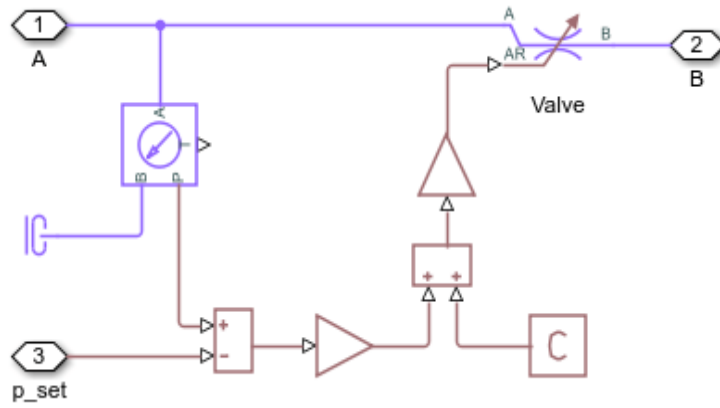


Figure 4.4: Model of Pressure Relief Valve.

When the membrane temperature increases, its resistance also rises, leading to a reduction in thermal efficiency. In this model, we ensure a steady fuel cell stack temperature of 80°C. The cooling system as illustrated in Figure 4.7 , these cooling systems remove excess heat from the interior, while the radiator releases this heat into the atmosphere. Humidifiers block for anode/cathode terminals are shown in Figures 4.2 and 4.3 add moisture to the air within the system to prevent the membrane from drying out and minimize electrical resistance. This careful temperature and humidity management ensures the fuel cell stack operates at its peak performance, enhancing overall system efficiency.

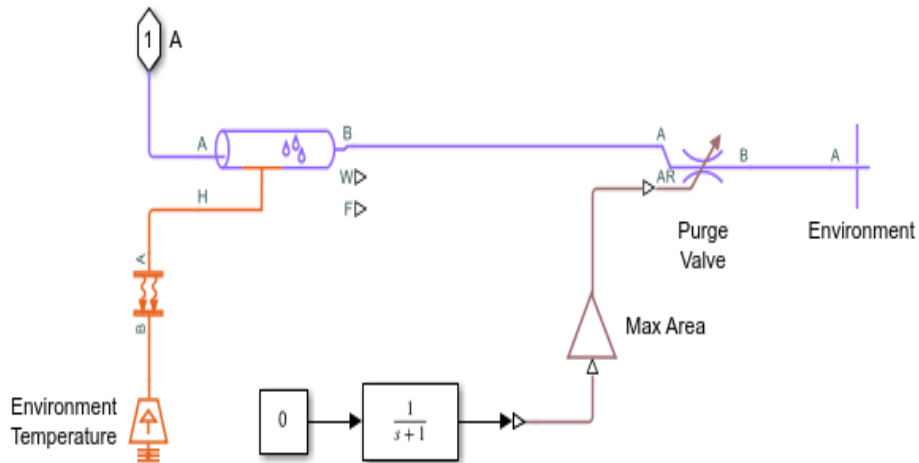


Figure 4.5: Model of Anode Exhaust Subsystem.

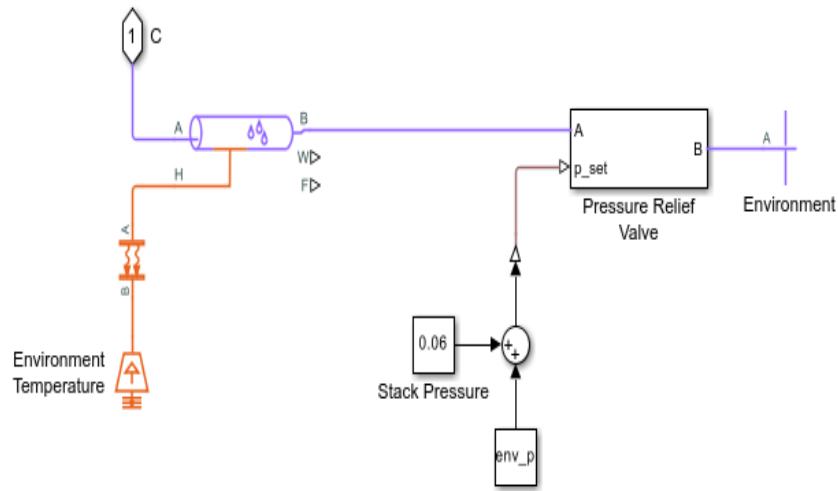


Figure 4.6: Model of Cathode Exhaust Subsystem.

The Simscape code incorporates an essential building block known as the exclusive Membrane-Electrode-Assembly (MEA). Within this MEA block, gas stream pipe blocks on both the cathode and anode sides utilize port F to discharge the gas mole fractions necessary for simulating the fuel cell reaction. Controlled Trace Energy Source (MA) blocks are employed to extract H_2 and O_2 from both the cathode and anode gas flows. Controlled Hydration Source (MA) blocks handle the production and vapor transmission of H_2O within the MEA. The reaction temperature is conveyed to the associated Thermal Mass block via the H thermal port. To better understand the implementation, you can refer to the code comments, which provide further insights.

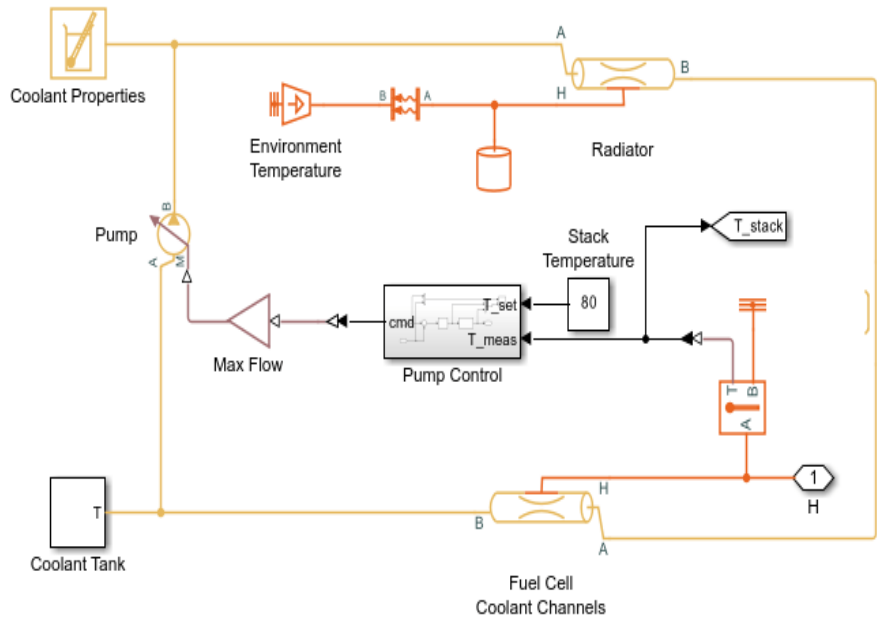


Figure 4.7: Model of Cooling Subsystem.

The following figures 4.8- 4.12 shows various implementation of subsystems utilized in the overall home energy management system.

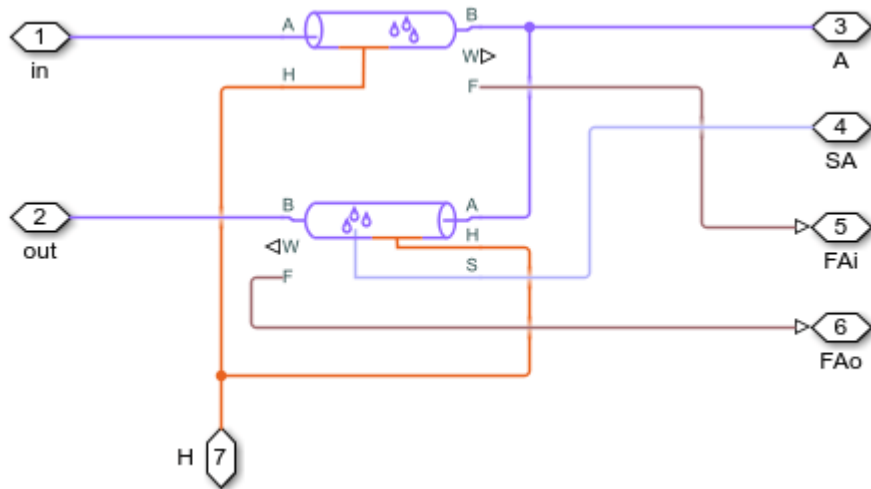


Figure 4.8: Model of Anode Gas Channel Subsystem.

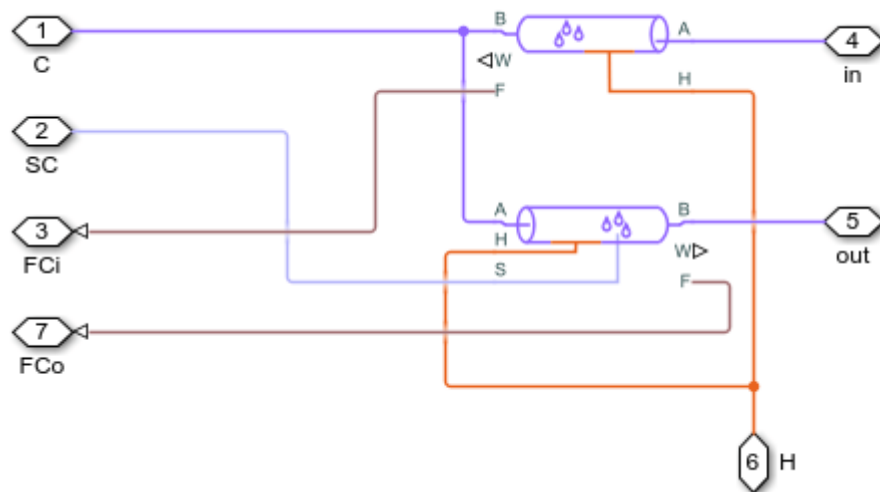


Figure 4.9: Model of Cathode Gas Channel Subsystem.

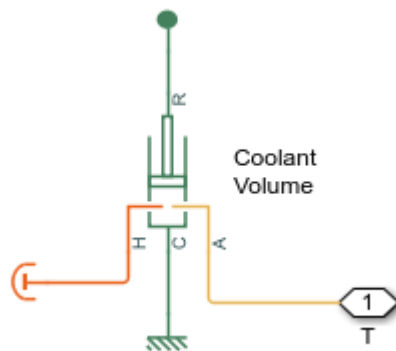


Figure 4.10: Coolant Tank Subsystem.

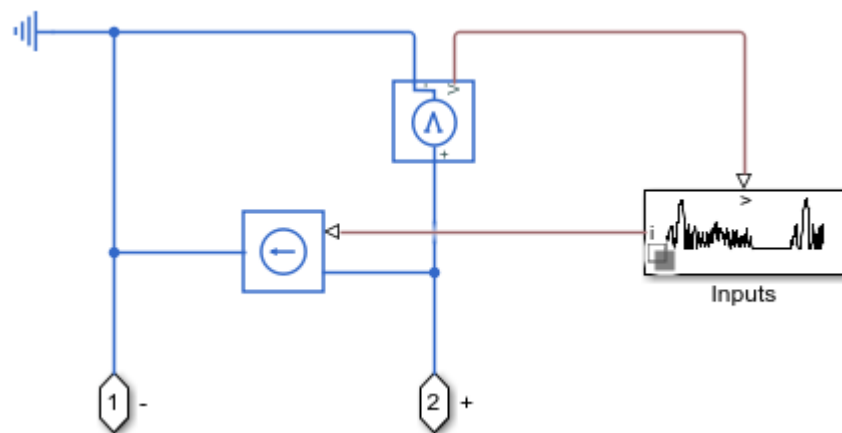


Figure 4.11: Electrical Load Subsystem.

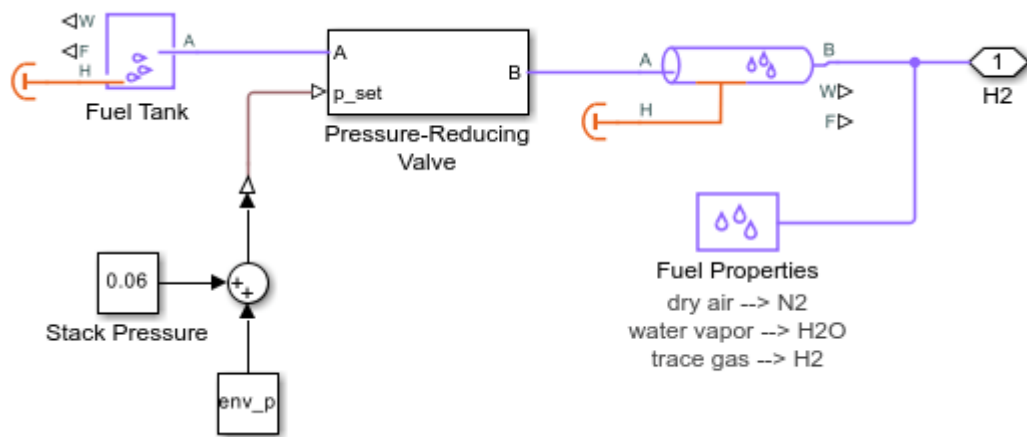


Figure 4.12: Hydrogen Source Subsystem.

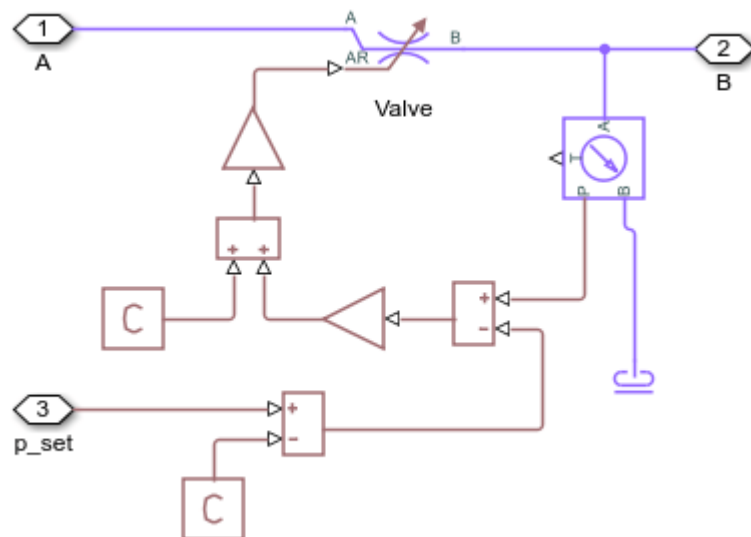


Figure 4.13: Pressure-Reducing Valve Subsystem.

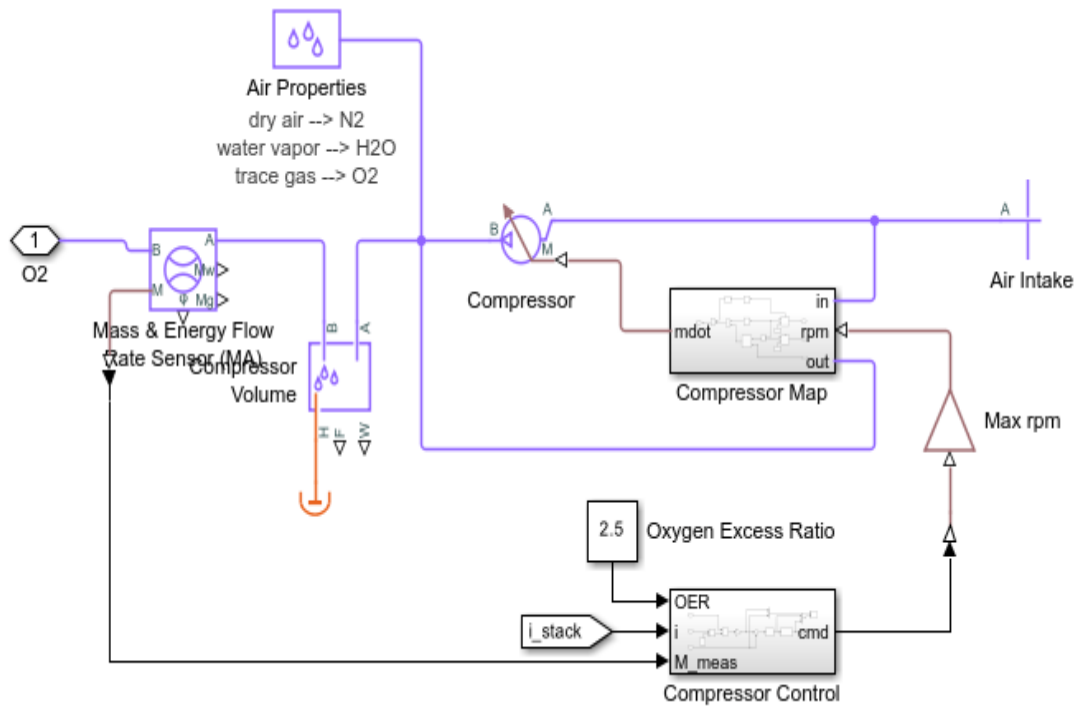


Figure 4.14: Oxygen Source Subsystem.

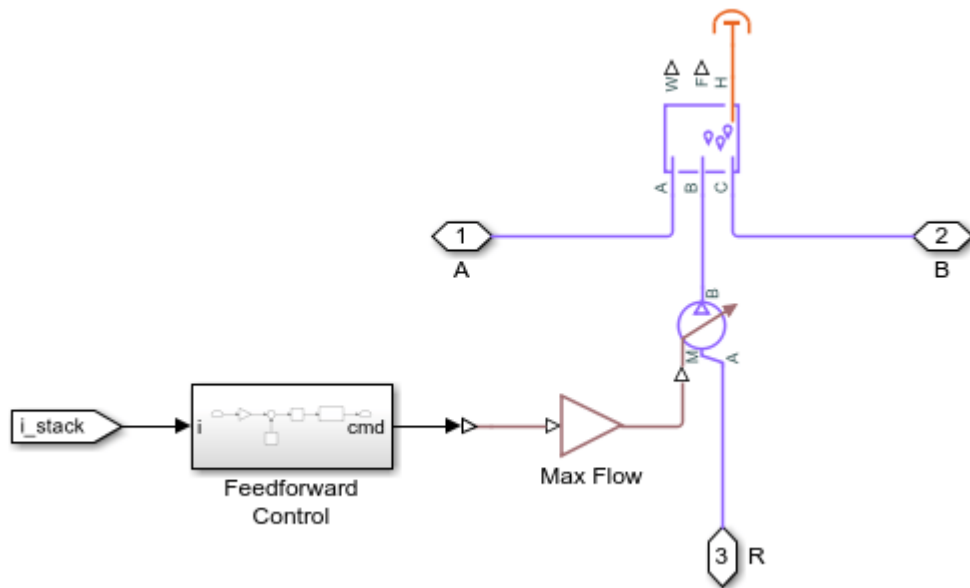


Figure 4.15: Recirculation Subsystem.

4.3 SIMULATION RESULTS

The I-V (current-voltage) diagram in Figure 4.16 illustrates the current-vs-voltage of a fuel-cell stack. As the nominal-current increases, the rated-voltage decreases, primarily

due to two factors: activation losses at the electrodes and Ohmic resistances within the fuel-cell. At higher current-levels, the corresponding voltage experiences a significant drop due to transit losses. The diagram also displays the power-output of the fuel-cell stack. In a ramp scenario, the power gradually increases until it reaches a maximum value. Afterward, the power output gradually decreases due to the substantial losses at the maximum current level. The i-v diagram provides insights into the behavior of a fuel cell stack, showcasing the voltage reduction with increasing current and highlighting the power output characteristics, including the ramp scenario where power increases and subsequently decreases due to losses at higher currents.

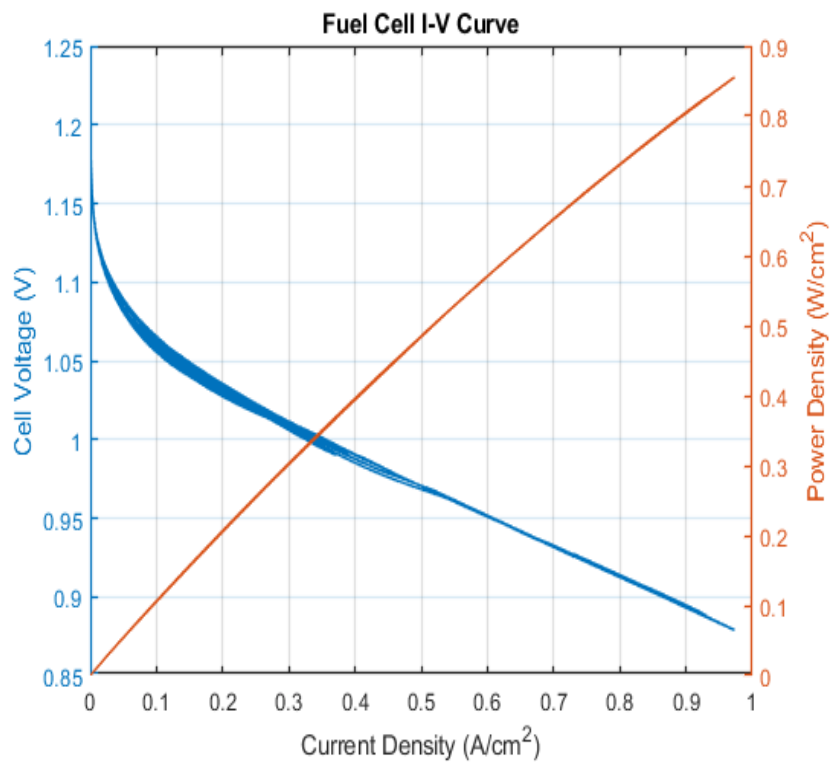


Figure 4.16: Modeled Fuel Cell I-V Curve.

The graph in Figure 4.17 demonstrates the energy consumption of the cathode air turbine, the coolant pump, and the energy generated by the fuel-cell's combustion stack. As a result, the stack's power output is slightly higher than the net power output. It's important to note that we assume an isentropic compressor in this model. However, an additional 2% would reduce the net power increase if the compressor's effectiveness was also considered. Waste-heat from the fuel-cell stack, which must be removed by the system is also shown on the graph in 4.16. The fuel cell is a stack that has the potential to produce 110 kW of electricity.

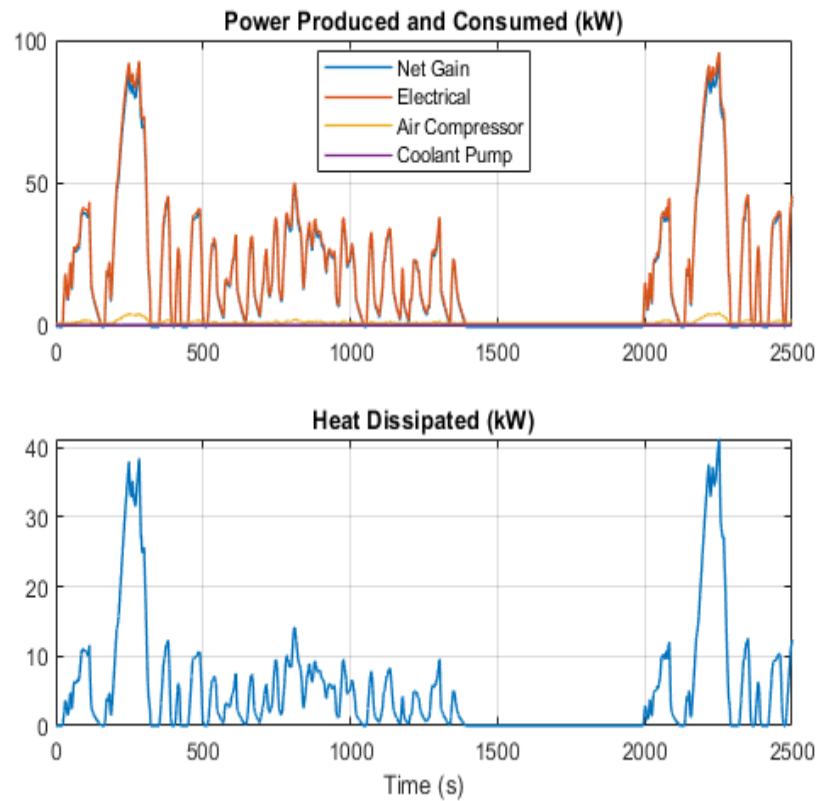


Figure 4.17: Power Produced and Consumed, Heat Dissipation in Fuel Cell.

The graph in Figure 4.18 displays the thermal-efficiency of the fuel-cell and the utilization rate of its reactants. The thermal-efficiency of a fuel-cell quantifies the extent to which the energy-stored in hydrogen fuel is effectively converted into useful electrical work. Theoretical calculations suggest that a Proton-Exchange-Membrane (PEM) fuel-cell's efficiency can reach 83%. However, due to inherent losses and practical limitations, the actual efficiency typically hovers around 60%. Moreover, efficiency further declines to approximately 45% at maximum current operation. These values reflect the fuel cell system's real-world performance, considering losses and operational considerations.

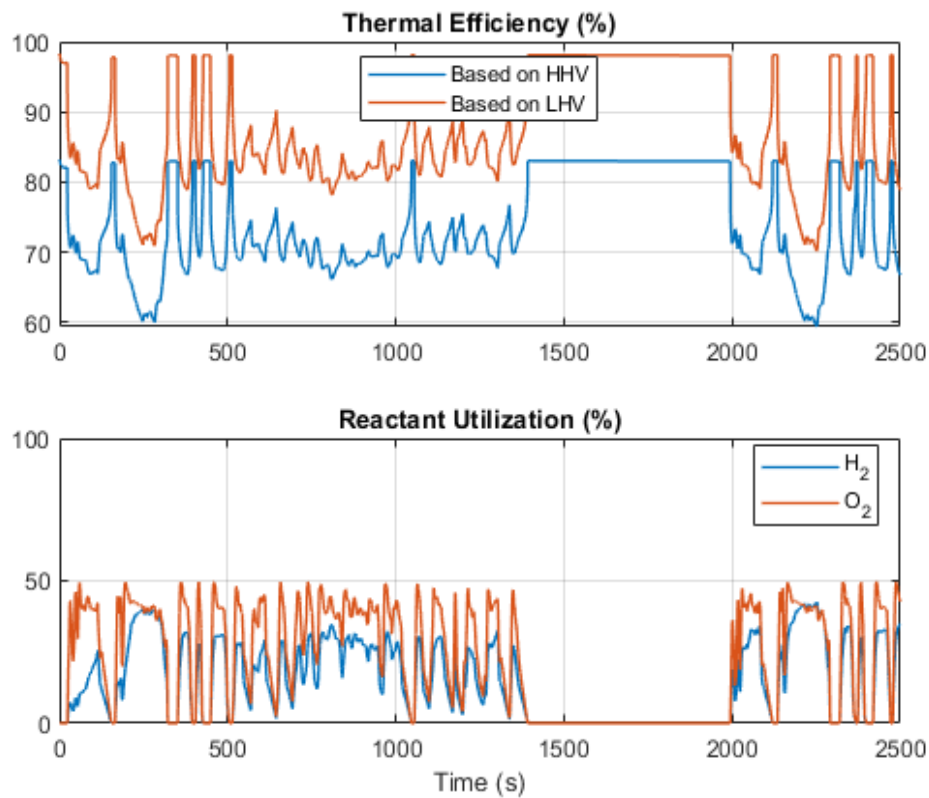


Figure 4.18: Thermal Efficiency and Reactant Utilization of Fuel Cell.

The term "Reactant Utilization" refers to the amount of hydrogen and oxygen from the incoming gas stream that is effectively converted into usable energy within the fuel cell. The concentration of the reactants influences reactant utilization. When the fuel cell efficiently utilizes the atmospheric gas passing through it, the reactants are less concentrated, resulting in a lower voltage production as shown in Figure 4.18. In cases where there is an excess of either hydrogen or oxygen, the surplus hydrogen is directed back to the electrode, while the excess oxygen is vented to the atmosphere. However, it is important to note that hydrogen (H_2) is regularly purified to remove impurities.

The temperature profiles of various nodes within the system are depicted in this visualization 4.19. The cooling system ensures that the fuel cell stack remains at a maximum temperature of 80 degrees Celsius, maintaining optimal operating conditions. The anode experiences warming through the recirculation of fuel from the fuel tank. On

the other hand, the cathode air is heated by the compressor, contributing to the overall temperature dynamics of the system.

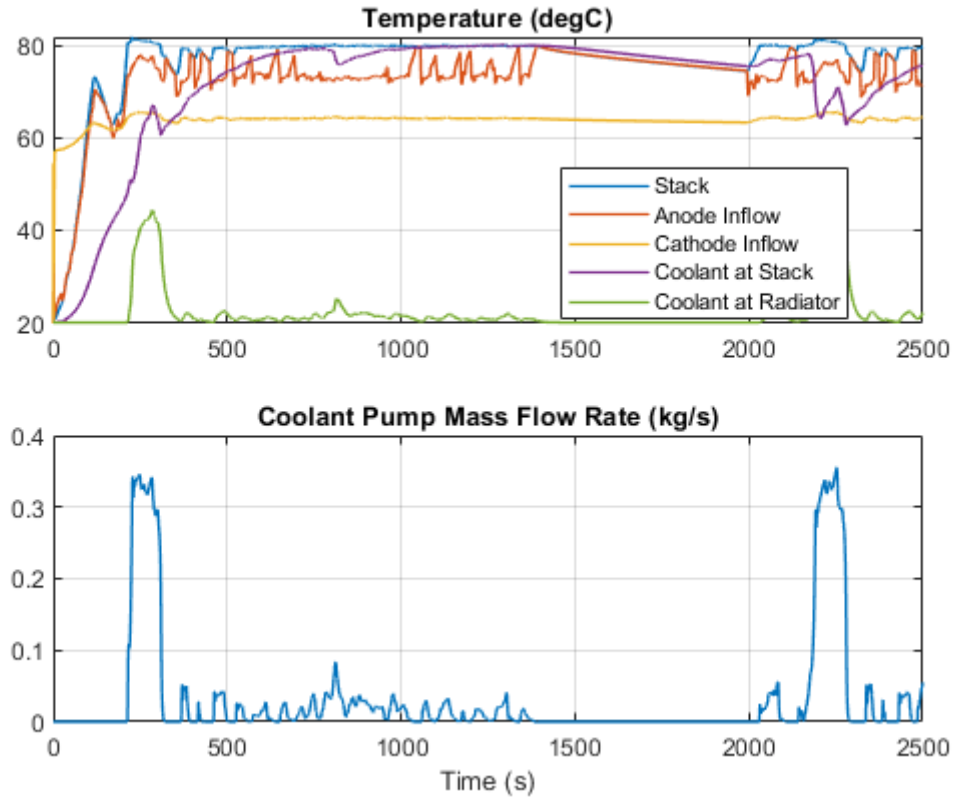


Figure 4.19: System Temperature and The Coolant Pump Mass Flow Rate (Kg/S).

Maintaining an optimal temperature is crucial for the fuel cell as higher temperatures reduce relative humidity, leading to increased membrane resistance. In this model, controlling the flow rate of the coolant pump is the primary method employed to manage the cooling system. The graph presented in 4.19 showcases the coolant temperature before and after it releases heat in the radiator, following the heat absorption from the fuel cell stack. This visual representation provides insights into the temperature dynamics

of the coolant as it passes through the cooling system, highlighting the effectiveness of heat rejection and dissipation.

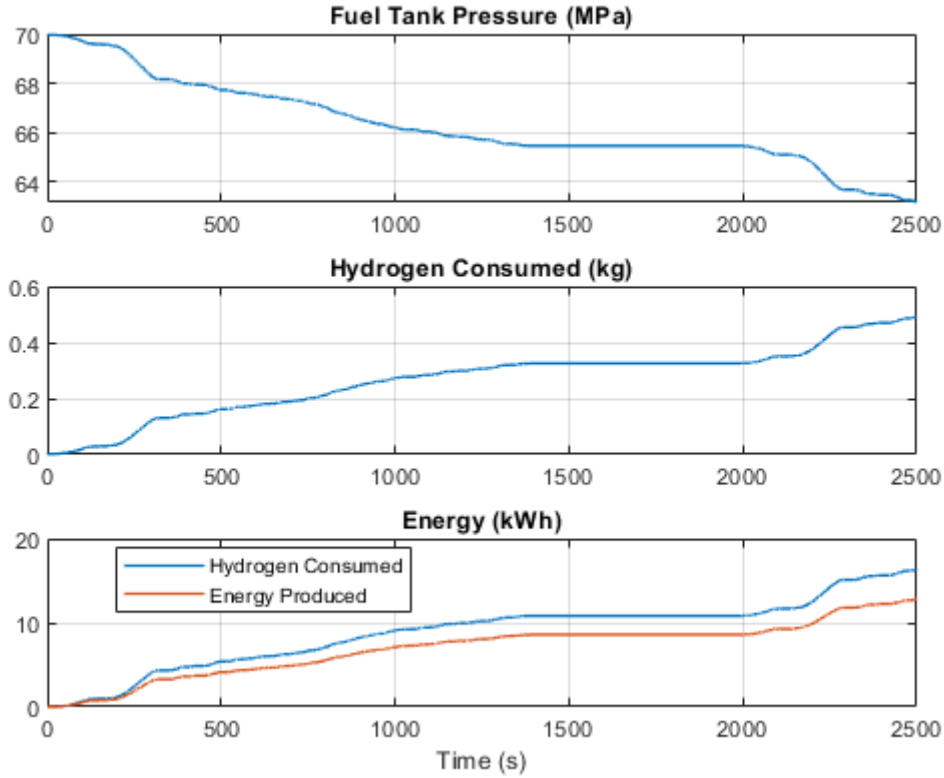


Figure 4.20: System Temperature and the Coolant Pump Mass Flow Rate (kg/s).

The visual representation in Figure 4.20 details two aspects: the mass of hydrogen consumed and the subsequent decrease in hydrogen tank pressure. This information is crucial in understanding the usage of hydrogen as a fuel-source and the dynamics of the fuel-cell system. The mass of hydrogen consumed refers to the amount of hydrogen used during the system's operation. As the fuel cell produces electrical power, it relies on the chemical reaction between H_2 and O_2 to generate this energy. The consumption of hydrogen is directly proportional to the power-output of the fuel-cell. By monitoring the mass of hydrogen consumed, one can assess the efficiency/performance of the fuel-cells. Simultaneously, the visual display also shows the drop in hydrogen tank pressure. As hydrogen is consumed by the fuel-cell, the stored- H_2 in the tank gradually decreases, resulting in a reduction in pressure. This pressure drop reflects the ongoing hydrogen fuel consumption during the system's operation. These constraints are vital in evaluating the energy-efficiency and usage of the fuel-cell system. Analyzing the mass of hydrogen

consumed and the corresponding drop in tank pressure makes it possible to assess the fuel consumption rate, estimate the remaining hydrogen storage, and plan for refueling or replenishment of the hydrogen supply.



5. CONCLUSION

5.1 INTRODUCTION

The thesis explored the possibilities of utilizing hydrogen in a home energy system alongside other energy-sources such as P-V (photovoltaic) panels, Li-ion batteries, the grid, and fuel-cells. The hydrogen energy integration into the home energy system can effectively tackle intermittencies and optimize energy management. The modeling/simulation of a home energy-system considered in this thesis comprise PV panels as a primary renewable energy source. They generate electricity from sunlight during the day. However, intermittent PV generation is affected by load variations, weather conditions, and daylight availability. By integrating hydrogen into the system, excess electricity generated by the PV panels produces H_2 through electrolysis. This stored H_2 can then be utilized during low PV or high energy demand, ensuring a continuous power supply.

The proposed model also leverages the seamless power to the home through Lithium-ion batteries which serve fast energy buffers and can store excess energy in the system. They are efficient for short-term energy storage and can provide power during PV system downtime. However, Hydrogen storage complements batteries by offering longer-duration storage capabilities, making it suitable for extended periods of intermittent PV generation or high energy demand. The proposed system model also has a grid connection that provides a backup power supply when PV generation and stored energy are insufficient. During periods of low PV generation and depleted hydrogen and battery storage, the grid connection ensures a continuous and reliable power supply. It acts as a backup to maintain energy independence and system stability. A PEM-fuel-cell is integrated into the home energy system to utilize hydrogen storage to generate hydrogen-generated electricity. During low PV generation or high energy demand, fuel cells provide continuous power by utilizing the stored hydrogen. Fuel cells offer high efficiency and can operate independently of the grid, making them ideal for meeting critical energy needs during intermittencies. The proposed system model utilizes an advanced energy management system (EMS) to optimize various energy sources and tackle intermittencies. The EMS monitors real-time energy generation, consumption, and storage levels. It intelligently manages the energy flow, switching between PV, batteries,

grid, and fuel cells based on energy availability, demand, and cost. The EMS ensures efficient energy utilization, maximizes self-consumption of renewable energy, and minimizes reliance on the grid.

5.2 CONTRIBUTION OF THE THESIS

The thesis explored various aspects of hydrogen, including its properties, applications, and experimental findings. Some of the key findings are listed as

- a. **Properties of Hydrogen:** The Thesis began by examining the fundamental H₂ properties, e.g., low-density, high-energy content, and clean combustion. Hydrogen is a versatile energy-carrier produced from diverse sources, including electrolysis, natural gas reforming, and biomass conversion.
- b. **Hydrogen-Energy-Source:** The literature review in the thesis discussed the potential of green-H₂ as a sustainable energy-source, particularly in decarbonization efforts and the transition to clean energy systems. Its use in fuel cells provides a pathway for efficient electricity generation with water as the only byproduct.
- c. **Hydrogen Production and Storage:** Different H₂ generation methods, including steam-methane reforming, electrolysis, and biomass-gasification, were explored. Additionally, the thesis provides discussion of various H₂ storage technologies, e.g., as compressed H₂ gas, liquid hydrogen, and solid-state hydrogen storage materials.
- d. **Applications of Hydrogen:** Wide range of applications for hydrogen, including its use in fuel-cells for stationary power-generation (e.g., backup power systems, home energy system) are also included in the proposed work. The thesis discussed hydrogen's potential in the industry, heating, and energy storage sectors.
- e. **Safety Considerations:** Safety aspects related to hydrogen were addressed, covering topics such as its flammability, safe handling and storage practices, and the development of safety standards and regulations to ensure the secure implementation of hydrogen technologies.
- f. **Research and Experiments:** We explored recent advancements in hydrogen-related research and experiments, including studies on improving fuel cell efficiency, investigating new hydrogen production methods, and exploring hydrogen's integration into existing home energy infrastructure.

Throughout the thesis, the importance of continued research, development, and collaboration is required to accomplish H₂ as a clean and sustainable energy solution.

5.3 RECOMMENDATIONS AND FUTURE WORK

Integrating H₂ into the home energy-system provides several benefits. It enhances energy independence by reducing dependency on the grid and increasing self-sufficiency through renewable energy generation and storage. A hydrogen-based home energy system holds significant potential for addressing renewable energy intermittencies. Moreover, hydrogen integration contributes to decarbonization efforts by enabling clean and sustainable energy usage. Some potential future areas of work that can be explored to enhance the effectiveness of the home energy system.

- a. **Efficient Electrolysis:** More research/development efforts can focus on efficiency-improvement and cost-effectiveness of electrolysis. Advancements in electrolyzer technologies, such as proton exchange membrane (PEM) and solid oxide electrolysis cells (SOEC), can lead to higher conversion efficiencies and reduced capital costs.
- b. **Better Hydrogen Storage:** Developing advanced hydrogen storage technologies is crucial for optimizing the utilization of intermittent renewable energy. Research can be directed towards improving hydrogen storage density, enhancing safety features, and exploring innovative storage methods such as hydrogen carriers or chemical storage systems.
- c. **Fuel-Cell Performance:** Enhancing the performance and durability of fuel cells used for electricity generation from hydrogen is another area of interest. Improving fuel cell efficiency, reducing costs, and extending the lifespan of fuel cell systems will contribute to the overall effectiveness of the hydrogen-based home energy system.
- d. **Hybrid Systems Enhancement:** Integrating hydrogen systems with other renewable energy technologies can create hybrid systems that synergistically combine energy sources. Integrating hydrogen with solar, wind, and energy storage systems can optimize power generation, storage, and utilization, enabling a more reliable and resilient home energy system.
- e. **Smart Energy Management:** Developing advanced energy management systems that intelligently balance energy supply, demand, and storage can maximize the utilization of renewable energy in a hydrogen-based system. Artificial intelligence,

machine learning, and predictive algorithms can enable real-time monitoring and control, optimizing energy flows and minimizing intermittency-related challenges.

- f. **Policy and Regulatory Support:** Governments and policymakers can play a vital role in promoting the adoption of H₂-based home energy systems. Implementing supportive policies, incentivizing research and development, and establishing regulatory frameworks can accelerate the deployment and integration of H₂-technologies into the energy landscape.
- g. **Demonstration Projects and Field Trials:** Conducting large-scale demonstration projects and field trials will provide valuable insights into the performance, feasibility, and potential challenges of hydrogen-based home energy systems. These projects can serve as practical examples and help identify best practices and optimize system designs.

Incorporating hydrogen into a home energy system alongside PV panels, batteries, the grid, and fuel cells offers an effective solution for intermittencies. By optimizing the utilization of different energy sources and efficiently managing energy flow through an advanced EMS, homeowners can achieve greater energy independence, resilience, and sustainability.

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