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Techno-Economic Analysis of Hydrogen Production & Storage Technologies for Grid Scale Applications

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ABSTRACT :

The use of fossil fuels in energy sectors leads to harmful emissions into the atmosphere, including carbon dioxide (CO_2). This results not only in environmental pollution but also in detrimental effects on human health. Emphasis is being placed on the deep decarbonization of the energy sector to mitigate climate issues and minimize the increase in global temperatures. As fossil fuels are replaced by renewable energy sources, storage systems are needed to address the intermittent nature of renewable power outputs and to enhance the reliability of the electricity network. Hydrogen storage systems could be a potential medium for long-term electricity storage, and extensive research is currently underway to transition to a hydrogen economy. Traditional hydrogen production methods involve byproduct gas emissions; therefore, there is a strong emphasis on producing green hydrogen using electrolyzers. This study aims to conduct technical and economic assessments of both traditional and green hydrogen production and storage technologies in electricity networks.

A mixed-integer nonlinear programming model is developed, and a test microgrid is selected for the study. Wind power generation and conventional generators are considered the renewable sources for this system. Cost minimization is the objective function of the model, encompassing the capital expenditure of hydrogen storage systems and the operational expenditure of the system. Scenarios are generated based on seasonal variations in wind speed and demand, and the model is studied for different types of hydrogen production and storage technologies. Results suggest that incorporating a storage system would enable the management of seasonal wind variations and reduce operating costs by charging during demand valleys and discharging during demand peaks. Storing green hydrogen instead of grey hydrogen in compressed gaseous form is found to be the most economical option when considering long-term technology costs. Conversely, storing hydrogen in liquid form is currently too expensive for electricity storage and requires further technological advancements to reduce costs. In conclusion, using a hydrogen storage system in the electricity network would provide economic benefits and improve network reliability.

KEYWORDS: Hydrogen Production, Hydrogen Storage, Green Hydrogen, Electrolyzer, Techno-economic Analysis, Optimization

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Abbreviations

AWE	Alkaline Water Electrolyzer
BESS	Battery Energy Storage System
CCS	Carbon Capture and Storage
EU	European Union
GAMS	General Algebraic Modeling System
GDL	Gas Diffusion Layer
GHG	Green House Gases
HER	Hydrogen Evolution Reaction
HOMER	Hybrid Optimization of Multiple Energy Resources
KOH	Potassium Hydroxide
LCOE	Levelized Cost of Electricity
LCOH	Levelized Cost of Hydrogen
OER	Oxygen Evolution Reaction
P2H2P	Power to Hydrogen to Power
PEM	Proton Exchange Membrane
PSA	Pressure Swing Absorption
PTL	Porous Transport Layer
SOE	Solid Oxide Electrolysis
RHER	Regenerative Heat Exchanger
SMR	Steam Methane Reforming
TDM	Thermal Decomposition of Methane
UN	United Nation

1 Introduction

1.1 Motivation of the Study

The energy requirement will increase exponentially in the coming years as the population increases. Fossil fuels used today have a certain lifespan and availability is based on geographical locations, so alternate energy sources should be investigated. Fossil fuels such as oil, coal and natural gas contain carbons and when combusted, they produce carbon dioxide (CO_2) along with other by-products. About 85% of the world's total energy is produced from non-renewable sources which creates political unrest, and economic issues besides environmental issues (Abdalla et al., 2018). The amount of CO_2 and other greenhouse gases (GHG) have significantly upscaled in the atmosphere. Due to this, there have been negative effects on the environment including climate change, air pollution and global warming (Intergovernmental Panel On Climate Change, 2015). It is detrimental to the ecosystem as well as human health. To address the climate change issue, at the UN Climate Change Conference (COP21) held in Paris in 2015, 196 attending countries adopted an international treaty known as “The Paris Agreement” (UNFCCC, 2015). According to the agreement, the increase in global temperature should be limited to 2 °C above pre-industrial levels. In recent years concerns have been raised by world leaders to limit the average temperature to 1.5 °C above pre-industrial levels otherwise climate change may lead to severe repercussions including droughts, heatwaves and rainfall including acid rains (UNFCCC, 2015).

To tone down climate change impacts, low-carbon and zero-carbon solutions are being introduced to cut down global emissions (UNFCCC, 2015). To reduce emissions in the power sector, shifting energy production from fossil fuel to renewable sources is crucial. Hydrogen can be a promising energy carrier to enable deep decarbonization, mitigate global warming and ensure a sustainable future. It will play a pivotal role not only in the power sector but also in steel, chemicals, long-distance commutation, shipping and aviation industries where direct electrification is sophisticated (IRENA, 2020). Hydrogen is a carbon-free molecule that is a clean, sustainable, tasteless, odorless, non-toxic gas that has a high energy content per mass unit (Valente et al., 2017). It was discovered by Henry Cavendish in 1766 (IRENA, 2020d). Although it is abundant in nature, it is not directly available as molecular H_2 but rather as hydrides with a negative anion incorporated which is denoted as H- ion. The energy density of hydrogen ranges between 120 MJ/kg to 142 MJ/kg (Abdalla et al., 2018). It is the lightest, simplest and most abundant element on earth and can be found in water and other organic compounds (Dawood et al., 2020). Hydrogen can be locally produced from water, gas, biofuels, biomass, bacteria, sewage sludge etc. which empowers countries to produce energy on their own (Yue et al., 2021) (Maestre et al., 2021).

About 65% of hydrogen is used to synthesize chemicals such as ammonium, methanol, hydrochloric acid, hydrogen peroxide etc. About 25% of hydrogen is used for industrial applications such as fertilizer production, petrochemical production, petrochemical refining, oil hydrogenation, metal work, atomic hydrogen welding, electronics manufacturing and food processing (Hren et al., 2023) (Dawood et al., 2020). The remaining 10% of hydrogen is used in rocket engine fuelling, internal combustion engines, coolants, weather balloons, oxygen removal etc (Hren et al., 2023). Contemporarily, hydrogen has been deployed in numerous pertinences including hydrogen-fuelled forklifts, hydrogen-fuelled buses, fuel cells in mobile phones and electronic accessories etc (Santos et al., 2013). For heating in residential buildings, commercial buildings, industrial processes etc. hydrogen can be used as a substitute low carbon fuel (Committee on Climate Change, 2018). The use of hydrogen in multiple sectors will require a change to gas distribution networks as well. The transition from fossil fuel economy to hydrogen technologies is referred to as “hydrogen economy” and this term was first used by John Bockris in a paper entitled “The Hydrogen Economy: An Ultimate Economy?” along with John Appleby in 1972 (Infinite Energy Magazine, 2013).

The contribution of renewable sources in total European Union (EU) power generation is expected to rise to 45-60% by 2030 and over 80% by 2050 (Widera, 2020). With a continuing transition to renewable, intermittent energy sources, such as solar and wind power, it is becoming evident that energy storage systems are needed to deal with variability and intermittency (Dawood et al., 2020). Hydrogen storage can be used to deal with the intermittency of renewable sources thus aiding in decarbonization. During off-peak hours when renewable generation is abundant, demand is low and electricity price is cheaper, it can be utilized to produce hydrogen in a carbon-free way and store it. Afterward, during peak hours when demand is high, electricity prices are higher but generation is low, stored hydrogen can be converted to inject additional electricity into the grid. It evens out the difference between demand peaks and valleys thus enhancing the stability of the grid (Widera, 2020). Hydrogen storage provides flexibility and the possibility to provide support in multiple areas (power, heating, transportation, electrification etc.) otherwise known as sector coupling. This criterion singularizes it from other types of storage systems (Widera, 2020).

Traditionally, hydrogen is produced from cracking or reforming of fossil fuels (Dawood et al., 2020). These production methods contribute to GHG emissions so emphasis is given to producing hydrogen from carbon-free sources. When hydrogen is synthesized from zero-carbon sources or renewable sources, it is referred to as “green hydrogen”. The production cost of hydrogen in a green way has decreased by 40% over the last 5 years and will continue to decline in the future (Li et al., 2023). The intermittent energy produced from renewable sources can be used to electrolyze water into hydrogen. Synthesizing hydrogen by electrolysis sounds promising for a sustainable future. The produced hydrogen can be stored for future use, fed to natural gas grids, utilized in industrial applications or used in re-electrification by fuel cell technology. Fuel cell is utilized to convert hydrogen back to electricity at zero pollution with only water molecules (H_2O) as a by-product. Stationary fuel cells can be used to back up distributed power systems, independent power plants and cogeneration power plants. It enables distributed production instead of traditional centralized production. Besides location shifting, hydrogen storage provides support in different time scales such as hourly, daily and seasonally (Maestre et al., 2021).

1.2 Structure of the Thesis

Chapter 1 gives a general overview of the topic and motivation behind choosing the research topic. Chapter 2 involves reviewing of existing publications involving techno-economic analysis of hydrogen production and storage systems and mentions the research gap. Chapter 3 describes the methodology which is used to plan and study the model for analysis. Chapter 4 introduces the system which is considered for the study, how various parameters are defined and what factors are considered in the study. Chapter 5 involves analyzing the results of generated scenarios and how they impact the technical and economic parameters of the system. Chapter 6 discusses the feasibility of the proposed model and summarizes the research findings.

2 Hydrogen Production Technologies

2.1 Steam Methane Reforming (SMR)

Steam reforming is the most widely used and the cheapest option when it comes to producing hydrogen on a large scale and it accounts for 48% of global hydrogen production (Medisetty et al., 2020). Reforming is done on methanol, ethanol, methane, glycerol, toluene, acetic acid, glycerol etc (Medisetty et al., 2020). SMR is the reforming of methane to produce hydrogen which is a popular technology. Methane is a component of natural gas that can undergo through thermal reaction to produce hydrogen (Pareek et al., 2020).

The first step in this process is to remove sulfur particles from methane (Olabi et al., 2021). In the next stage, methane reacts with steam at a high temperature of about 650-1000 °C and 5-40 bar pressure in the presence of a catalyst to produce a mixture of hydrogen, carbon monoxide and carbon dioxide (Parkinson et al., 2017). This stage is referred to as the reforming stage which is highly endothermic. Nickel-based compounds are used as catalysts (Pareek et al., 2020). Afterwards, a shift reaction takes place in a water gas shift converter where CO reacts with extra steam to produce additional hydrogen and also additional CO_2 is produced in the process. Later, a pressure swing absorption (PSA) material is used to differentiate CO_2 from hydrogen (Olabi et al., 2021). Equation (1) and (2) denote the chemical reaction that takes place during SMR (Medisetty et al., 2020).

$$CH_4 + H_2O = CO + 3H_2 \qquad \Delta H = +206\ kJ/mol \tag{1}$$

$$CO + H_2O = CO_2 + H_2O \tag{2}$$

The purity of segregated hydrogen is about 99.9% (Parkinson et al., 2017). The overall efficiency varies between 65-75% for small to medium-scale reformers but extends beyond 80% for large-scale reformers (Olabi et al., 2021). More or less 9.5 tonnes of CO_2 are generated to get 1 ton of hydrogen (Parkinson et al., 2017). 60% of the generated

CO_2 is generated during the reaction process and the rest 40 % is generated when flue gasses in the reformer react with oxygen (Parkinson et al., 2017). If there is provision for a storage facility in the vicinity, then CCS technology can capture the generated CO_2 and prevent it from entering the atmosphere.

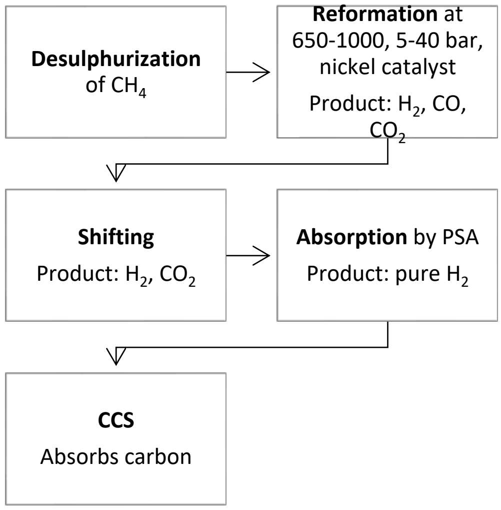

Figure 1. Overview of the SMR process

2.2 Thermal Decomposition of Methane (TDM)

TDM is an endothermic process where methane decomposes to solid carbon and gaseous hydrogen (Keipi et al., 2018). An external heat is applied to heat the reactor and the decomposition is done by taking heat from an additional feedstock heating. A regenerative heat exchanger (RHER) is the main component of the generator structure. The exchanger is cylindrical and has three zones. The middle layer is where the reaction occurs. There is an upper layer for bed material to absorb heat from generated gas as well as a lower layer where incoming methane absorbs heat from bed material. Methane flows through this exchanger in the upward direction and bed material flows in the opposite direction. The bed material can absorb and transfer heat to the gases. It has dual roles acting as a gas cooler and a methane pre-heater (Keipi et al., 2016). Equation (3) denotes the chemical reaction that takes place during TDM (Keipi et al., 2018).

$$CH_4(g) = C(s) + 2H_2(g) \qquad \Delta H = +76\ kJ/mol \qquad (3)$$

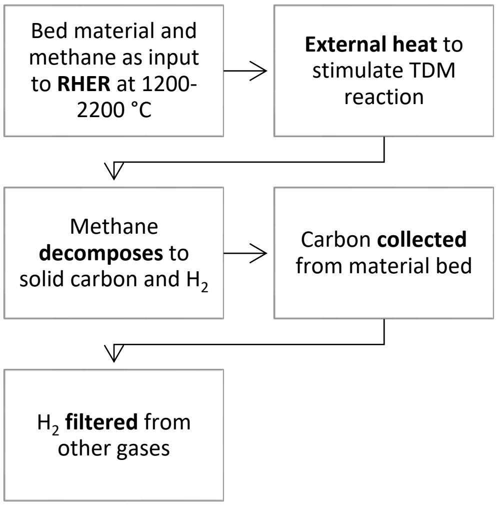

Figure 2. Overview of TDM process

The reaction can take place with or without a catalyst although a catalyst lowers the heat requirement for the reaction to take place. After decomposition, methane converts to carbon products and hydrogen. The quality of carbon depends on reaction time, temperature and catalyst properties. Generated hydrogen is separated from other gases with hydrogen-selective membranes for instance palladium membranes which have high selectivity. About 80% of the carbon product is deposited on the bed material and the rest leaves the reactor along with other gases (Keipi et al., 2018). The temperature of the carbon is decreased below its self-ignition temperature and pelletized to be utilized in other applications.

Produced carbon particles are of high quality and can be used in rubber products, paints, inks, soil amendment, materials for construction, etc (Keipi et al., 2016) (Keipi et al., 2018). After the carbon particles are removed from the bed material, it is inserted back inside the exchanger mechanically or pneumatically. Although TDM consumes 1.7 times more methane compared to SMR to produce the same volume of hydrogen, SMR produces 5 times CO_2 compared to TDM which makes TDM more favorable from an environmental perspective (Keipi et al., 2016).

2.3 Gasification of Coal

This is the oldest technique to produce hydrogen and accounts for 18% of total hydrogen production currently (Kayfeci et al., 2019). Although natural gas is the most prevalent way of generating hydrogen, they are not geographically available everywhere. Coal can be an alternative option to produce hydrogen in this case (Yamashita et al., 2005). Solid coal is first heated up to 900 °C to convert it to a gaseous state (Kayfeci et al., 2019). This gaseous form is given as input to a gasifier at high temperature and high pressure where carbon, oxygen and steam react together to produce carbon monoxide and hydrogen-enriched synthetic gas. A nickel-based catalyst with chemical denotation $FeO\text{-}CrO_2\text{-}ThO_2$ is used at this stage (Kayfeci et al., 2019). This syngas is passed through a water gas shift reactor to utilize carbon monoxide in the gaseous content to generate additional CO_2 and hydrogen (Pareek et al., 2020).

After filtering out Sulphur and CO_2, the syngas are given as input to a pressure swing absorption (PSA) unit to get pure hydrogen as an output (Yamashita et al., 2005). Residual gases can be used to spin a gas turbine to produce electricity. Cogenerating electricity alongside hydrogen yields enhanced efficiency and reduction of cost (Yamashita et al., 2005). To minimize the addition of CO_2 in the atmosphere, CCS technology can be used alongside the system. Although it is not as threatening to nature compared to production involving natural gas, it has lower efficiency compared to the steam reforming process. Equations (4), (5) and (6) describe the gasification reaction, shift reaction and purification reaction of the gasification process respectively (Pareek et al., 2020) (Kayfeci et al., 2019).

$$3C + O_2 + H_2O = H_2 + 3CO \tag{4}$$

$$CO + H_2O = H_2 + CO_2 \quad (5)$$

$$CaO + CO_2 = CaCO_3 \quad (6)$$

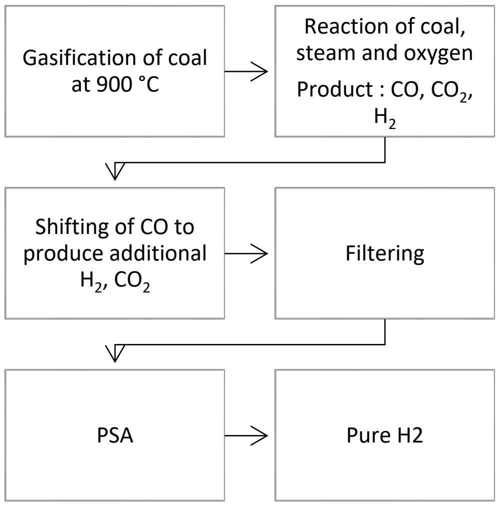

Figure 3. Overview of coal gasification process

2.4 Gasification of Biomass

Biomass originates from organic sources of energy for instance corn stover, wheat straw, forest remnants, witch grass, willow trees, and human and animal waste (Pareek et al., 2020). There are multiple products biomass can be converted to such as heat, electricity, fuels like coal, methanol, bio-oil etc (Pareek et al., 2020). The conversion can take place thermally, physically, chemically or biologically. Biomass is abundant in nature and it is environmentally friendly which makes this source suitable for large-scale production of hydrogen. Gasification takes place in a gasifier where biomass is given input along with heat, steam and oxygen (Pareek et al., 2020).

Partial oxidation takes place in biomass under high temperatures and pressure. Thus, biomass helps reduce the energy required to increase the temperature of the steam (Pareek et al., 2020). Chemical bonds inside break down to produce synthetic gas which is denoted as syngas in short form. Like the coal gasification method, a water shift reactor is used here to synthesize additional hydrogen from carbon monoxide. Then pure hydrogen is segregated from the gaseous mixture. Catalysts such as Dolomite can be used in the process to reduce tar formation and boost H_2 formation (Pareek et al., 2020). Equations (7), (8) and (9) define the gasification, shift and overall process reactions (Pareek et al., 2020) (Abdalla et al., 2018).

$$C + H_2O = CO + H_2 \quad (7)$$

$$CO + H_2O = CO_2 + H_2 \quad (8)$$

$$Biomass + Steam + Heat = H_2 + CO_2 + CO + Hydrocarbons + Tar \quad (9)$$

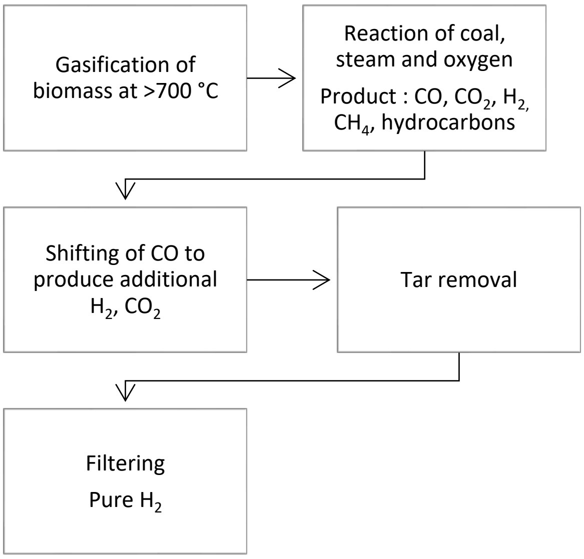

Figure 4. Overview of biomass gasification process

The advantage of this process is that it does not emit any GHG gas into the environment, additionally, it consumes CO_2 from the atmosphere during gasification (Pareek et al., 2020). Utilizing biomass or waste this way prevents the use of landfills for their disposal. The abundance of biomass makes it cost-competitive with natural gas conversion procedures (Kayfeci et al., 2019). Although the gasification process is quite similar to the coal gasification method, other hydrocarbons are produced as by-products during the reactions which makes the system sophisticated (Pareek et al., 2020). It has low thermal efficiency and the moisture content of biomass should be less than 35% to minimize tar formation (Abdalla et al., 2018).

2.5 Electrolysis of Water

Electrolysis could be a viable option to produce hydrogen in a carbon-free way. It refers to the mechanism of splitting water molecules to produce hydrogen and oxygen. Water electrolysis is a well-known technology that has been in existence for 200 years (Santos et al., 2013). Despite its popularity, only 5% of hydrogen is produced through the electrolysis technique (IRENA, 2020a). Generally, this method is applied when hydrogen needs to be generated on a small scale including spacecraft, electronics, rockets, marine, food and medical industries (Santos et al., 2013). Hydrogen generated by electrolysis can be stored in portable fuel cells and these can be used in remote areas where the main electricity grid is not accessible (Santos et al., 2013). It is particularly environmentally friendly when used in conjunction with renewable resources like solar, wind, hydro power etc.

Despite this technology being preferable considering sustainability, it is costlier than conventional hydrogen production techniques. The energy required to produce 1 mole of hydrogen in the net zero way is 7 more times than the conventional way. However, the cost of electricity produced from renewable sources has decreased significantly in recent years and will continue the downward trend moving forward and the technology will get more mature, which will make the production of green hydrogen attractive in the near future (IRENA, 2020d). EU has taken the initiative to scale up electrolyzer capacity to 40 GW in EU countries and another 40 GW in adjoining regions to produce about 10 megatons of green hydrogen per year (IRENA, 2020d). This target is set to be achieved by 2030.

2.5.1 Alkaline water electrolysis (AWE)

Electrolysis of alkaline water is a technique that separates water into hydrogen and oxygen by using electricity. This method has been used for industrial applications for a long time and was first utilized on a large-scale basis in 1939 at an electrolyzer plant with a capacity of producing 10,000 Nm^3 H_2/hr (Santos et al., 2013). The needed current density is between 200-400 mA/cm^2 and the cell has approximate efficiency of 62-82% (Wang et al., 2022). The process involves two electrodes made of nickel-coated perforated steel - an anode and a cathode - separated by a diaphragm.

The diaphragm is perforated stainless steel coated with asbestos, zirfon or nickel. A high concentration of potassium hydroxide (5M KOH/25%-30% of KOH) is used as an electrolyte. Sodium hydroxide (NaOH) and sodium chloride (NaCl) act as stimulants to the chemical reactions (Keçebaş et al., 2019). Apart from separators, other prominent components of the cell are the gas diffusion layer (GDL), porous transport layers (PTL), separator plates (bipolar plates) and end plates (Shiva Kumar & Lim, 2022).

As electricity is passed through the cell, 2 moles of water combine with electrons at the cathode to produce 1 mole of hydrogen and 2 moles of hydroxyl (OH^-) ions. The hydroxyl (OH^-) ions are transferred from the cathode to the anode through the separator. At the anode, the hydroxyl (OH^-) ions give up excess electrons and as a result, produce ½ mole of oxygen (O_2) and 1 mole of water (H_2O).

While equation (10) describes the hydrogen evolution reaction (HER) at the cathode, equation (11) describes the oxygen evolution reaction (OER) at the anode and equation (12) denotes the overall cell reaction (Keçebaş et al., 2019).

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^- \quad (10)$$

$$2OH^- \rightarrow H_2O + \tfrac{1}{2} O_2 + 2e^- \quad (11)$$

$$H_2O \rightarrow 2H_2 + O_2 \quad (12)$$

This technology has certain advantages including the usage of cost-effective transition metal catalysts instead of noble metal catalysts, the usage of low-concentrated alkaline (1M KOH) solution instead of high-concentrated alkaline (5M KOH) solution (Shiva Kumar & Lim, 2022). By using cost-effective materials, the overall cost is reduced and it can be used in conjunction with a system with load fluctuation (Nasser et al., 2022). Despite having distinct advantages, AWE has several shortcomings such as low membrane stability, low lifetime and low cell efficiency making them inapt for large-scale applications (Shiva Kumar & Lim, 2022). Table 1 summarizes the technical parameters of AWE technology.

Table 1. Technical parameters of AWE (IRENA 2020b) (Shukla, P.R et al., 2020)

Parameter	**Current**	**Long-term**
Current density (A/cm^2)	0.2-0.8	>2
Voltage range (V)	1.4-3	<1.7
Operating temperature (° C)	70-90	>90
Operating pressure (bar)	<30	>70
H_2 purity (%)	99.9-99.9998	> 99.9999
Voltage efficiency (LHV) (%)	50-68	>70
Electrical efficiency (system) (kWh/kg H_2)	50-78	<45
Parameter	Current	Long-term
Lifetime (hr)	60 000	10 000
Electrode area (cm^2)	10 000 – 30 000	30 000
CAPEX (USD/kW)	500-1000	200-700
Cost estimates (USD/kg H_2)	2.3- 6.9	0.9- 3.9

2.5.2 Proton Exchange Membrane Water Electrolysis (PEM)

Proton exchange membrane (PEM) technology was referred to by Grubbs to mitigate the problems faced by AWE and was developed in 1966 by General Electric Co (Shiva Kumar

& Himabindu, 2019). It's a mature technology well-developed for industrial and transportation applications. A sulfonated polymer membrane is used as an electrolyte. Instead of OH^- ions, protons (H^+) migrate through the membrane as charge carriers. PEM electrolysis works at low temperatures around 30-80° C, has a higher current density of around 1-2 A/cm^2 and purity of H_2 is around 99.999% (Shiva Kumar & Lim, 2022). Major components of the cell are membrane electrode assembly including PEM, cathode and anode electrodes, GDL, separator plates and end plates. Nafion, fumapem, flemion, aciplex are mainly used as PEM, among them Nafion is commonly used. Iridium oxide (IrO_2) is predominantly used as anode material and carbon-supported platinum (Pt) is used as cathode material.

During electrolysis, H_2O is segregated to O_2, protons and electrons at the anode. The O_2 flows out of the cell by a flow tube. The protons are attracted by the cathode and move through PEM. While the protons move through the membrane inside the cell, electrons move toward the cathode through an external connection. At the cathode, protons and electrons recombine to produce H_2 gas. Some of the electricity is dissipated as heat due to ohmic, concentration and activation losses in the cell and as a result temperature upsurges (Keçebaş et al., 2019). On one hand, this surge in temperature improves reaction kinetics and improves cell performance. On the other hand, it stimulates the corrosion of metallic particles. So, the optimum temperature of PEM cell is kept between 40-60 °C for better durability and performance (Keçebaş et al., 2019).

While equation (13) describes the hydrogen evolution reaction (HER) at the cathode, equation (14) describes the oxygen evolution reaction (OER) at the anode and equation (15) denotes the overall cell reaction (Keçebaş et al., 2019).

$$2H^+ + 2e^- \rightarrow H_2 \tag{13}$$

$$H_2O \rightarrow 2H^+ + \tfrac{1}{2} O_2 + 2e^- \tag{14}$$

$$2H_2O \rightarrow H_2 + \tfrac{1}{2} O_2 \tag{15}$$

The PEM comes in handy with advantages like lower gas permeability, high proton conductivity around 0.8-1.2 S/cm, wider operating temperature (20-80 °C), lower thickness ranging from 20-300 µm and high-pressure operations (Shiva Kumar & Himabindu, 2019). The produced H_2 and O_2 are ultrapure, the design is optimum, current density and efficiency are high, response and dynamic operation are quicker, the production rate is faster, the footprint is low, and handling and maintenance are smoother.

However, the noble metals used at electrodes are extravagant (Shiva Kumar & Lim, 2022). So, the main shortcoming of this technology is high production cost. Expensive coatings on PTL and bipolar plates make up a large fraction of the cost. PTLs are coated with platinum to safeguard titanium against passivation and provide superlative interference resistance. Similar to PTL, platinum coatings are used on bipolar plates. Using alternative materials to build PTL and bipolar plates as well as using alternative coatings will reduce the production cost provided new materials exhibit the same characteristics as old ones. Additionally, reducing membrane thickness, increasing electrode surface areas, and using alternative membranes and catalysts to cover those membranes will yield cost shrinkage (IRENA, 2020b).

Table 2. Technical parameters of PEM (IRENA 2020b) (Shukla, P.R et al., 2022)

Parameter	**Current**	**Long-term**
Current density	1-2 A/cm^2	4-6 A/cm^2
Voltage range	1.4-2.5 V	<1.7 V
Operating temperature	50-80° C	80° C
Operating pressure	<30 bar	>70 bar
H_2 purity	99.9%-99.9999%	Same
Voltage efficiency (LHV)	50-68%	80%
Electrical efficiency (system)	50-83 kWh/kg H_2	<45 kWh/kg H_2
Lifetime	50 000-80 000 hr	100 000-120 000 hr
Electrode area	1 500 cm^2	>10 000 cm^2
CAPEX	1100-1800 USD/KW	200-900 USD/kW
Cost estimates	3.5-9.3 USD/kg H_2	2.2-7.2 USD/kg H_2

2.5.3 Solid Oxide Electrolysis (SOE)

Solid oxide electrolysis (SOE) otherwise known as high-temperature electrolysis was first used by General Electric and Brookhaven National Laboratory in the USA in 1970 to convert electrical energy to chemical energy (Shiva Kumar & Lim, 2022). It operates at high temperatures (700-850 °C) at high pressure, which converts incoming water into steam. This improves overall reaction kinetics and reduces cell losses. Due to higher operating temperature, this technology gets preference over low-temperature electrolysis in terms of performance. A typical SOE cell contains a porous anode, a porous cathode, ion exchange membrane, GDL, PTL, end plates and a dense ceramic electrolyte that is capable of conducting oxide (O_2^-) ions. Yttria-stabilized zirconia (YSZ) is typically used as an electrolyte because it has excellent stable chemical and thermal performance at high temperatures (700-850 °C) as well as high ionic conductivity (10^{-2}-10^{-1} S cm^{-1}) (Shiva Kumar & Lim, 2022). At the anode, perovskite materials such as LSCF ($La_{0.58}Sr_{0.4}Co_{0.2}Fe_{0.8}O_{3-\delta}$) and LSM $(La_{1-x}Sr_x)_{1-y}MnO_{3-\delta}$ are used prevalently. At the cathode, usually YSZ is used along with nickel (Ni-YSZ) which acts as a non-noble metal catalyst with high electrical and ionic dynamism.

The working principle of an SOE cell is similar to a fuel cell in the reverse direction (Keçebaş et al., 2019). At the cathode, the H_2O molecule is reduced by taking in two electrons to produce H_2 and O_2- ions. H_2 is collected from the surface of the cathode and O_2- ions navigate through the ion exchange membrane to the anode. Afterwards, at anode O_2- ions are oxidized to constitute O_2 by liberating two electrons. O_2 is collected from the anode while the electrons pass through an external circuit to the cathode.

While equation (16) describes the hydrogen evolution reaction (HER) at the cathode, equation (17) describes the oxygen evolution reaction (OER) at the anode and equation (18) denotes the overall cell reaction (Keçebaş et al., 2019).

$$H_2O + 2e^- \rightarrow H_2 + O^{2-} \quad (16)$$

$O^{2-} \rightarrow ½\, O_2 + 2e^-$ (17)

$H_2O \rightarrow H_2 + ½\, O_2$ (18)

Due to operating at high temperatures, less electricity is consumed in the SOE process to produce a similar volume of hydrogen by any lower-temperature electrolysis process (Shiva Kumar & Lim, 2022). So, overall efficiency is enhanced due to better thermodynamics and conversion capability. Due to the reduction in power consumption and absence of usage of noble metal electrocatalysts, cost diminishes as well. It can be thermally integrated to produce other useful chemical compounds such as methanol, dimethyl ether and ammonia (Khan et al., 2018). On the contrary, high-temperature results in the deterioration of catalytic materials. So, it is challenging to ensure the long-term execution of these cells which acts as a hindrance to commercializing this technology. There is a possibility of hydrogen mixing with steam, so to extract pure hydrogen additional filtering is required (Wang et al., 2022). (IRENA, 2020b) recommended some improvement areas for SOE for development such as enhancement of electrolyte conductivity, equalizing thermal expansion coefficients of both electrodes, optimization of sustainability both chemically and mechanically and minimizing reactant crossover.

Table 3. Technical parameters of SOE (IRENA 2020b) (Shukla, P.R et al., 2022)

Parameter	**Current**	**Long-term**
Current density	0.3-1 A/cm^2	>2 A/cm^2
Voltage range	1-1.5 V	<1.48 V
Operating temperature	700-850° C	<600° C
Operating pressure	1 bar	>20 bar
H_2 purity	99.9%	>99.9999%
Voltage efficiency (LHV)	75-85%	>85%
Electrical efficiency (system)	40-50 kWh/kg H_2	<40 kWh/kg H_2
Lifetime	<20 000 hr	80 000 hr
Electrode area	200 cm^2	500 cm^2
CAPEX	2800-5600 USD/KW	500-1000 USD/kW
Cost estimates	4.2 USD/kg H_2	2.6-3.6 USD/kg H_2

Table 4. Advantages and disadvantages of different hydrogen production technologies (Santos et al., 2013) (IRENA, 2020d) (Keipi et al., 2016) (Abdalla et al., 2018) (Medisetty et al., 2020) (Kayfeci et al., 2019)

Production Technology	Benefits	Shortcomings
SMR	• Purity of H_2 99.99% • Mature technology • Existing infrastructure • Low operating temperature • Does not require O_2 • High efficiency	• CO_2 emission • High operating cost • Complex system

TDM	• Emits less CO_2 compared to SMR
	• Easy separation of H_2
	• Carbon can be used in
	  ○ Construction
	  ○ Inks
	  ○ Paints
	  ○ Carbon fuel cells
		• Large amount of carbon produced which could be detrimental to human health
		• CO_2 emission

Coal Gasification	• Thermally efficient • Clean process • Large scale production	• Groundwater contamination • Low efficiency • High temperature
Biomass Gasification	• Cheap feedstock • Environmentally friendly • CO_2 consumption	• Costly reactor • High temperature • Tar formation • Low efficiency
Water Electrolysis	• Environment friendly	• Low efficiency • Safety issue

Production Technology	Benefits	Shortcomings
	• Integration of variable renewable energy into the grid • High purity • System flexibility • High operating current • Low cell voltage • Economic growth	• Less durability • Complex operability • High installation and operational cost • No dedicated infrastructure

2.6 Color Codes of Hydrogen

Hydrogen is categorized into different colors depending on production techniques.

2.6.1 Blue hydrogen

Hydrogen is referred to as "blue" when it is produced from fossil fuels but the CCS system is appended to the process to offset its effect on the environment. It is cheaper than green hydrogen (Yu et al., 2021). Deployment of green hydrogen may take time considering cost and capacity so blue hydrogen can be used in the meantime to back up the current needs of hydrogen for example in the steel industry. It can use existing infrastructure and assets for implementation and has the potential to act as a substitute for grey hydrogen emitting lower CO_2. Popular technologies to produce blue hydrogen are SMR, auto thermal reforming (ATR), dry reforming of methane (DRM), partial oxidation (POX) etc (Dvoynikov et al., 2021). Synthetic gas production technology has been the forerunner of sustainable and safer use of hydrocarbons in recent years (Dvoynikov et al., 2021). Although blue hydrogen can facilitate the use of current infrastructure, it has several shortcomings. CO_2 storage and transportation require additional costs (IRENA, 2021). Moreover, CCS can capture only 85-95% CO_2 and the remaining portion still dissociates into the environment (IRENA, 2021). It uses scarce resources and is affected by price fluctuations of fossil fuels. So, it should be deemed a short-term solution to facilitate the transition towards a green economy (IRENA, 2021).

2.6.2 Grey Hydrogen

Grey hydrogen is produced from fossil fuels such as natural gas, coal etc. Some of the existing technologies are reforming, gasification etc. 1 tonne of hydrogen produced in these methods accounts for 10 tonnes of CO_2 (Dvoynikov et al., 2021). This CO_2 is released into the atmosphere so it is deemed unsuitable for net zero emission goals (IRENA, 2021).

2.6.3 Turquoise Hydrogen

Similar to grey hydrogen, turquoise hydrogen is generated from fossil fuels but the generation technique is different. Pyrolysis or decomposition methods are used for production which has a lower carbon footprint. When methane goes through a pyrolysis process, the carbon is converted to solid particles (soot) instead of gaseous CO_2 which is easier to store (IRENA, 2021). In this way, no CO_2 will be ultimately released into the air. Moreover, solid carbon can be marketed for proper utilization like in carbon nanotubes and fullerenes that generate revenues (IRENA, 2021) (Dvoynikov et al., 2021). However, proper long-term storage of carbon soot and the use of renewable energy for the operation of the reactor is necessary to ensure zero CO_2 footprint in the process (Dvoynikov et al., 2021).

2.6.4 Green Hydrogen

If hydrogen is produced from renewable sources like wind, hydro, solar etc., it is referred to as green hydrogen. Excess electricity produced by renewable sources can be stored in chemical bonds of hydrogen through electrolysis (Dvoynikov et al., 2021). For electrolysis, typically electrolytes, separators, metal electrodes coated by catalysts and vast of pure water are needed. Out of all the hydrogen production procedures, this is the most crucial technology to ensure a sustainable and zero carbon footprint and thus it is a hot topic right now (IRENA, 2021). Although it is a costly process at the moment, decreasing the cost of renewable electricity and improving in maturity of the technology will lead to curtailment of production costs in coming years (IRENA, 2021). However, there is an area of improvement in the transportation of stored hydrogen to remote areas (Dvoynikov et al., 2021).

3 Hydrogen Storage Technologies

3.1 Physical Storage

Hydrogen can be stored in its original form in the liquid or gaseous state without any physical or chemical bond with other elements. While compressed gaseous or liquid storage is preferred for small to medium-scale applications, underground storage is preferred for large-scale applications (Yue et al., 2021).

3.2 Compressed Gas

Hydrogen can be compressed at 700 bars in cylinders made of metal for instance steel, the compression making it possible to store large volumes of hydrogen in smaller spaces (Yue et al., 2021). This type of hydrogen storage in pressure vessels has been in existence since 1880 (Abdalla et al., 2018). Compressing hydrogen increases its volumetric density up to 36 kg/m3 (Yue et al., 2021). As the pressure increases, the density decreases volumetrically. Pressure vessels are generally used when transporting hydrogen through hydrogen pipelines and hydrogen tube trailers (Yue et al., 2021). Typical characteristics of a hydrogen container are high tensile strength, shallow density and lack of chemical reaction with hydrogen (Hren et al., 2023). There are four types of pressure tanks in use. Type I metallic tanks are made from steel or aluminium and used for industrial applications, they are the cheapest but heaviest option (Moradi & Groth, 2019). Type II metallic tanks are blanketed by resin composite glass fibers (Hren et al., 2023). They have the highest pressure tolerance, they are 50% costlier than type I vessels but 30-40% lighter compared to type II (Moradi & Groth, 2019).

Type III metallic tanks have fully composite wraps with metal liners (Hren et al., 2023). The composite part is made from carbon fibers and carries 95% of the mechanical load (Moradi & Groth, 2019). The remaining 5% load is supported by the aluminium liner which mainly serves as a sealant. They are two times costlier than type II vessels but 50% lighter compared to type II (Moradi & Groth, 2019). Type IV composite tanks are made from carbon fiber composites with polymer liners (Hren et al., 2023). These types of tanks are the lightest yet the cost is higher compared to other types (Moradi & Groth, 2019). Despite its benefits, there are a few shortcomings in using the compressed hydrogen method. The gas cylinders are heavy contributing to transport limitations. Due to the poor heat conductivity of cylinder material, when temperature increases inside the tank due to compression, there is a possibility of composite degradation (Yue et al., 2021). The production cost of the tanks is high and the storage capacity and dimensions are limited (Hren et al., 2023).

3.3 Liquid Hydrogen

Storing hydrogen after liquifying at its boiling temperature of -253 °C has been conventionally used. The storage efficiency and liquid density are high. Density can reach up to 70.8 kg/m^3 which is even greater than solid hydrogen (Yue et al., 2021). But a lot of energy is consumed during the phase conversion process and the cooling process is also lengthy concerning time. Acutely low boiling point of hydrogen as well as difficulties in the cooling process during throttling account for significant energy consumption during conversion (Andersson & Grönkvist, 2019).

While 10% of energy is lost in the process of storing hydrogen in the compressed mode, 40% of energy is lost when it is stored as liquid (Hren et al., 2023). The tank needs to be engulfed by an external protective jacket as well as an inner pressure vessel to minimize thermal conductivity (Hren et al., 2023). Due to high energy loss, this method is used for medium to large-scale applications as a distribution medium such as intercontinental hydrogen delivery and truck delivery (Moradi & Groth, 2019). It is also used in flight and space applications such as rockets (Hassan et al., 2021). These applications require high volumetric and gravimetric storage systems regardless of intense energy loss. Irrespective of energy demand, liquefication plants require a large investment and constitute almost 40-50% of total cost conversion (Andersson & Grönkvist, 2019).

3.4 Underground Storage

Storing gaseous particles at a depth of several hundred meters below the earth's level is possible to produce artificially (Tarkowski, 2019). Hydrogen is stored in the same way any other gases such as natural gas or CO_2 are stored. This type of storage has a roundtrip efficiency of 30-40% and with proper initiatives, it can be increased up to 50% (Olabi et al., 2020). When the gas is injected into the confined space, it is referred to as working gas and when it is extracted out of the confined space, it is known as cushion gas (Tarkowski, 2019). One kilogram of hydrogen occupies 11 m^3 of space at ambient temperature and pressure (Tarkowski, 2019). Storing at default pressure and temperature would require huge space. To increase its density so it can be stored in a relatively smaller space, it needs to be compressed or cooled down below critical temperature which is -253 °C (Tarkowski, 2019). Depending on geographical structures, hydrogen can be stored either in aquifers, depleted hydrocarbons or salt caves. Certain parameters need to be considered while choosing a storage location such as depth of reservoir, thickness, tightness, pressure of reservoir, porosity and permeability, geomechanical characteristics etc (Tarkowski, 2019). The structure should be secured by insulation of roof rocks and under no circumstance should hydrogen leak beyond storage space (Tarkowski, 2019).

3.4.1 Deep Aquifers

Aquifers consist of porous rocks that are permeable and at greater depth, empty spaces between pores are occupied by fresh or salt water (Olabi et al., 2020). They are mostly situated near major energy consumers or cities and are regarded as a suitable alternative to hydrocarbon deposits or salt caverns in case they are not available (Tarkowski, 2019). Four criteria need to be fulfilled for aquifers to work in a storage facility. The first criterion is that the porous media consists of a permeable container such as sandstones (Olabi et al., 2020). The second criterion is that the rocks should have great storage properties and should be surrounded by impermeable roof rocks to avoid leakage of hydrogen (Olabi et al., 2020). The third criterion states that the porous media should act as a trap for side inclusion (Olabi et al., 2020). The last criterion states that the porous media should be located at a reasonable depth ideally between 500-2000 m (Olabi et al., 2020).

The liquid water occupying pore space should move downward and sideways to make up space for storage. When gas is injected into the storage space, it displaces water and later can be extracted for use. But all of the stored gas can't be recoverable. The capacity of storage depends on the pressure and temperature of the storage as well as the volume and permeability of the tank (Tarkowski, 2019). Difficulties exist in determining the tightness of storage, so the creation of such storage is expensive (Tarkowski, 2019). However, the possibilities of hydrogen leakage to the surface and flammability are quite low (Tarkowski, 2019).

3.4.2 Depleted Oil & Gas Fields

Natural gas and petroleum get deposited in pore spaces of geological traps. The rocks surrounding the seal have low permeability and concrete structure to avoid leakage of deposited hydrocarbons (Tarkowski, 2019). Depleted gas storage sites are readily available and have got necessary surface and subsurface infrastructures. These infrastructures just need to be modified to act as hydrogen storage sites which lowers the overall cost (Tarkowski, 2019). Besides infrastructure, some technical aspects like casing type in boreholes, materials used and safety level have to be taken into consideration (Tarkowski, 2019).

One of the benefits of using depleted gas storage includes guaranteed tightness of storage (Tarkowski, 2019). As gas remains in that confined space for ages, it ensures the robustness of the storage space. The maximum pressure of the adapted depleted storage site is mostly greater than the original maximum pressure making it possible to store a greater volume of hydrogen than the volume of the original natural gas (Tarkowski, 2019). While storing hydrogen in depleted gas storage seems relatively easier, storing hydrogen in depleted oil reservoirs is more challenging. Stored hydrogen may chemically react with residual oil inside the reservoir and may get converted to some other unwanted compound in the process (Tarkowski, 2019).

3.4.3 Salt Caverns

Salt caverns are created by the penetration of fresh water within salt deposits to create large cavities and the stored gas can be utilized during peak gas hours (Tarkowski, 2019). There should be a necessary water supply to infiltrate the salt mine (Tarkowski, 2019). The salts that blanket the cavities have extremely low permeability therefore leakage proof. Ideally, salt cavities are created within 6000 ft of the earth's surface and with a volume of up to 1,000,000 m^3 (Lord et al., 2014) (Olabi et al., 2020). The required pressure should be at least 200 bars for large-scale storage (Olabi et al., 2020). Creating reservoirs deeper than 6000 ft would make the storage space unstable due to increased temperature and pressure (Lord et al., 2014). Factors to consider while choosing salt cavern sites for hydrogen storage are the depth and thickness of salt beds, the composition and distribution of rocks, and rock solubility (Tarkowski, 2019). Caverns can be created inside salt domes or bedded salt deposits. Bedded salt deposits have a thinner structure therefore the cavities created within are less stable. About 33.33% of the storage volume should be cushion gas (Lord et al., 2014). The benefits of using salt caverns include injection and withdrawal of hydrogen gas multiple times per year (Tarkowski, 2019).

Table 5. Technical parameters of underground storage types (Lord et al., 2014) (Tarkowski, 2019)

Parameters	**Aquifers**	**Depleted hydrocarbon fields**	**Salt caverns**
Formation pressure (Pa)	1.3755×10^7	1.3755×10^7	1.3789×10^7
Formation temperature (K)	315.1	315.1	310.9
Well depth (m)	1403	1403	1158
H_2 storage (tonnes H_2)	2868	2868	2486

Parameters	Aquifers	Depleted hydrocarbon fields	Salt caverns
LCOH ($/kg)	1.29	1.23	1.61
Boreholes	A few	A few	One
Injection and withdrawal cycles (/year)	Up to 2	Up to 2	Up to 10
Impurity	Average	High	Low
Cushion Gas	80%	50%	33.33%

3.5 Solid State Storage

In solid-state mode, hydrogen atoms or molecules react with other substances to create a compound (Tarhan & Cil, 2019).

3.5.1 Metal Hydride

Metal hydrides consisting of lithium, magnesium, boron, nitrogen and aluminium are regarded as promising storage materials for hydrogen (Hassan et al., 2021). The chemical bonds between metal and hydrogen are stronger than physical bonds and able to be stored at high density even at room temperature and moderate pressure (Andersson & Grönkvist, 2019). Hydrogen can be revived from hydrides in two ways. The first way is by thermolysis where the solid hydride is decomposed at high temperature and the reaction is endothermic (Andersson & Grönkvist, 2019). The second way is by hydrolysis where the solution of the hydride reacts with water to produce hydrogen as a product. This process is exothermic and therefore can take place at room temperature as well (Andersson & Grönkvist, 2019). Due to its working temperature being low, it is considered the safest hydrogen storage method (Hassan et al., 2021).

3.5.2 Chemical Hydride

Chemical hydrides are similar concerning composition to metal hydrides. However, as they are not as heavy as metallic elements, resulting hydrides are in a liquid phase instead of a solid phase endothermic (Andersson & Grönkvist, 2019). This makes the storage and transportation of hydrides as well as the heat and mass transfer process easier. These are cheaper than liquid-stored hydrogen and at the same time, the gravimetric densities are higher as well. Methanol is a simple liquid alcohol that is synthesized either by a reaction of hydrogen and carbon dioxide or from methane and has a storage density of 99kg/m^3 (Andersson & Grönkvist, 2019). Stored hydrogen can be released either by reaction with water by SMR method or by reaction with oxygen in partial oxidation or by thermal decomposition.

Another important chemical hydride is ammonia with a high storage density of 123 kg/m^3 (Andersson & Grönkvist, 2019). To produce ammonia from green hydrogen, existing production plants can be used with some modifications instead of implementing a new one from scratch. While the production of ammonia may seem relatively easier, dehydrogenation is difficult with the most common method being thermolysis in the presence of a catalyst. These chemical hydrides are already being used in multiple industries and applications, so they have adequate infrastructure for production, handling or transportation (Andersson & Grönkvist, 2019).

Crucial advantages and disadvantages of various hydrogen storage techniques are highlighted in Table 6.

Table 6. Advantages and disadvantages of different hydrogen storage technologies (Yue et al., 2021) (Hren et al., 2023) (Andersson & Grönkvist, 2019) (Tarkowski, 2019)

Storage Technology	Benefits	Shortcomings
Compressed tank	• Mature technology • Simplicity	• Poor heat conductivity of tank • Leakage risk

Storage Technology	Benefits	Shortcomings
		• High production cost of a tank • Low storage capacity • Limited dimension
Liquid hydrogen	• High energy density • High storage efficiency • Large scale applications	• High investment cost • Energy loss • High flammability
Underground storage	• Safety of storage • Cost effective • Availability of geographical structure	• Leakage risk
Solid state storage	• Moderate temperature and pressure • Large scale storage	• Heavy

3.6 Grid-scale Applications of Hydrogen Storage

Hydrogen storage can be used for peak shaving. During off-peak periods when the renewable source has excess generated electricity but demand is not enough to utilize the produced electricity, this excess electric energy can stored as chemical energy in a hydrogen tank. Later during peak time, when the electricity price is high, the storage can be discharged to fulfill the demand instead of buying it at a higher price from the grid. This helps mitigate the intermittent nature of renewable sources as well as a decline in electricity usage costs.

4 Literature Review

Cruz-Soto et al. (2022) carried out techno-economic feasibility studies for a standalone microgrid system located in a rural area of Mexico. Green hydrogen was produced by electrolysis using excess electricity produced by solar and wind resources integrated with the grid. Produced hydrogen was stored in a compressed tank to be used later in the summer season using fuel cells. The simulation and analysis of the system were performed in HOMER Pro and the results suggested the possibility of using stored hydrogen to meet seasonal demand instead of using a diesel generator. Using such a P2G2P system would reduce carbon emission by up to 27% but to be cost competitive, the capital cost of the electrolyzer, storage tank and fuel cells need to be reduced by half.

Sevik (2022) conducted an assessment of the integration of on-grid PV systems and hydrogen storage with conventional energy sources like gas engines for a vocational university campus located in Turkey. The hybrid system was considered to reduce transmission and distribution loss as well as to support sustainability and reliability. The results suggested integrating a hydrogen storage system in the model would increase the cost but it could be brought down to a minimal level provided minimal use of hydrogen production and storage facilities. AWE was estimated to be a cheaper technology than PEM in electrolyzing technique and due to increasing natural gas prices, LCOH appeared to be lower in the case when it was generated from electricity. LCOH was calculated to be lower when hydrogen was produced from grid electricity rather than from PV panels. On the other hand, hydrogen production from renewable sources was deemed advantageous due to their cost insensitivity to electricity prices.

Hasan and Genc (2022) assessed the economic feasibility of electricity as well as hydrogen production from renewable sources using PEM technology in Iraq. Different scenarios were generated based on the number of solar panels and wind turbines, power ratings of wind turbines and solar panels and the number of electrolyzers to investigate their effects on hydrogen production cost. The analysis suggested among all the studied cities in Iraq, Basrah seems to have the most potential for hybrid generation of electricity and hydrogen. Moreover, hydrogen production could be reduced by selling excess energy to the grid during peak demand.

Chen et al. (2021) conducted a feasibility assessment of compressed hydrogen storage along with a traditional Lithium Trinate battery energy storage system to support the variability of renewable sources. The battery system was assumed to have charging and discharging efficiencies of 90% and hydrogen was stored at 172 bars in the tank. Two case studies were simulated in GAMS, one case study was located in Kramer Junction in the USA and the other case study was located in Norderney in Germany. The results revealed economic performance and cost structure of hydrogen ESS are better than BESS for the particular scenarios. Overall, the LCOE of the whole system was found to be competitive with the current market electricity prices.

Okonkwo et al. (2022) assessed the feasibility of green hydrogen production in Salalah Oman using HOMER. This study was conducted to figure out the best methods for producing both electricity and hydrogen that would be beneficial for private and governmental investors. The studied model consisted of flat plate mono-crystalline PV modules, wind turbines, a bidirectional inverter with an efficiency of 92%, a bipolar alkaline-type electrolyzer, a hydrogen tank with a storage capacity of 100 kg and a proton exchange type fuel cell. Three types of scenarios were studies comprising PV-FC-HT, WT-FC-HT and PV-WT-FC-HT. Results implied PV-WT-FC-HT has the highest capital and replacement cost but yields to least LCOE, hence it would be the most preferred option for parallel electricity and hydrogen production. A deeper analysis of cost showed both PV-WT-FC-HT and WT-FC-HT combinations would be favorable in the event of frequent excess production of electricity exceeding demand.

Pal and Mukherjee (2021) evaluated the technical and economic performance of an off-grid renewable system consisting of PV modules and fuel cells in northeast Indian states. This study was intended for policymakers to facilitate renewable energy generation in remote areas where main grid connection is not feasible using fuel cell technology. Eight different scenarios were generated based on eight different states and based on solar irradiation data and ambient temperature, the optimum size of the system components was calculated. Connected 10 kWp load was satisfied the electricity generated from PV cells during daytime and during time energy was extracted from the stored hydrogen tank and resupplied in the form of electricity. Results implied the proposed system was ideal in terms of cost-effectiveness and optimal performance for all chosen locations.

Alonso et al. (2024) studied the feasibility of using BESS, hydrogen energy storage or a combination of both for on-grid and off-grid systems. The case study was assumed to be located in a research park in Belgium and the model was designed and simulated in HOMER for three time scales: 2019, 2022 and 2030. The results suggested BESS would be the most economical option out of the three configurations provided there is a grid connection. In this case, the configuration of the storage system was heavily dependent on grid electricity price along with carbon tax. On the other hand, a hybrid energy storage system would be preferred over a standalone hydrogen storage system regardless of the availability of grid connection. Hydrogen storage would be particularly beneficial for long-term and large-scale storage to increase the flexibility and reliability of the power supply. Moreover, it would enable decarbonization by facilitating renewable sources integration with the grid and enabling off-grid operation. However, the major barrier to implementing a hydrogen storage system was found to be the high capital cost of electrolyzers and fuel cells.

Li et al. (2022) investigated the techno-economic feasibility of a renewable-based energy system that would meet the demand of a food factory in the form of electricity, heat and hydrogen. The authors initiated a two-step optimization process using two simulation software to determine the best solution from combined economic, energy and environmental perspectives. The results suggested using both PV and wind resources would be more advantageous than using only one of them when the sunlight and wind availability are copious. Although SMR technology was estimated to be cheaper than electrolyzer technology, an electrolyzer would be preferred considering no fossil fuel consumption or CO_2 emission is involved.

Ghenai et al. (2020) designed an optimized off-grid hybrid renewable energy system to fulfill the demand of a residential community consisting of 150 houses located in Sharjah, United Arab Emirates. The proposed system was assumed to be green energy enriched, has low energy curtailment, low LCOE and low emissions of CO_2. As the case study was located in a desert region, the effect of dust accumulation and temperature on system performance were taken into consideration. PV cells and fuel cells were considered to be the source of energy and the best performance was observed when the sources worked in cycle charging mode. In cycle charging mode, fuel cells worked at full capacity providing energy to the load, rest was provided by the PV cells and the surplus energy generated by PV cells was given as input to the electrolyzer. 52% of power was estimated to be generated by PV cells and the rest was estimated to be generated by fuel cells and the system was able to fulfill the demand.

Skordoulias et al. (2022) investigated how green hydrogen can contribute to decarbonization or low carbon footprint for both electricity and heat generation. The proposed system consisted of renewable sources such as PV modules, wind turbines, hydropower and biomass, a compressor, a hydrogen storage unit, an open cycle gas turbine that can work on blended natural gas and hydrogen mixture and a heat recovery boiler. The referred system was independent of geological constraints and was comparable to large-scale seasonal energy storage. During high heat and power demands, stored hydrogen was used to rotate the gas turbine to produce power and heat concurrently. The blending of hydrogen and natural gas was changed from 0% to 100% to observe the effect on system performance. For all scenarios, the substitution of natural gas with hydrogen resulted in better conversion efficiency. If the natural gas was completely replaced by hydrogen, CO_2 and CO emissions dropped to zero while the heat and power conversion efficiency increased by 0.59%. On the other hand, NOx emissions increased by 4.2% compared to the situation when 100% natural gas was used. The results suggested if the electrolyzer cost decreases by 50% and renewable electricity gets cheaper, green hydrogen would be cost-competitive with fossil fuel hydrogen by 2030 provided a carbon tax of 90 €/t_{CO2} is applied.

Shahid et al. (2022) studied the economic, technological and environmental impacts of incorporating battery and hydrogen storage systems in a RES-P2P energy system for 21 small islands located in France. This research was intended to present a viable solution for providing cheap, clean and unceasing energy for European islands. Three combinations of storage systems were studied: standalone battery, standalone hydrogen and hybrid storage combining both. Studies revealed for an installation capacity of 41 MW of PV modules and 122 MW of wind turbines, a hybrid storage system would be the most optimal option with an LCOE of 420 €/MWh. A hybrid storage system would come in handy, especially for long-term storage capability that is required for high demand season. The referred system would prevent the usage of 34 liters of diesel per annum thus aiding in more than 99 thousand tons of CO_2 reduction.

Takatsu and Farzaneh (2020) researched about feasibility of renewable energy and hydrogen storage implementation to fulfill the energy demand of a standard household in Japan. The proposed system was supposed to not only bridge the gap between energy supply and demand but also contribute to waste management. The system considered producing hydrogen both from electrolysis and gasification of biomass. While an electrolyzer was used to utilize surplus solar energy, in the biomass gasification method, residential waste food was given as a feedstock to generate extra hydrogen to fill up the hydrogen tank completely. Two scenarios were considered for simulation, the first one was in islanded mode with an objective function of cost minimization and the second one was in grid-connected mode with an objective function of profit maximization by selling excess solar energy to the grid during peak time using a feed-in-tariff scheme. The calculated LCOE for grid-tied mode was a bit higher than off-grid mode but for both scenarios, the system was able to satisfy the defined demand.

Hernandez and Gencer (2021) investigated how hydrogen and battery storage systems can balance seasonal fluctuations of renewable energy resources in California, USA. Large-scale PEM electrolyzers were assumed to be built in areas with solar generation plants to work alongside. LCOE generated from lithium-ion batteries was compared against that of hydrogen tanks when they are used to balance the bulk power grid. Results illustrated energy production from hydrogen-fueled turbines or lithium-ion batteries would be costlier than natural gas-fueled turbines in the current era. However, to enable decarbonization in seasonal storage, operating the turbine with blue hydrogen instead of green hydrogen would make it more cost-competitive with conventional technology. Additionally, a comparison of two types of storage suggested lithium-ion batteries would be a cheaper option but for long-term storage where the heat rate of the plant would be higher, hydrogen storage would be a more feasible option.

Samy et al. (2020) performed a techno-economic analysis on a remote area in the Beni-Suef province of Egypt consisting of 450 homes for a combination of carbon-free sources and fuel cells. The research was conducted to increase the share of renewables as well as using hydrogen storage instead of battery banks to act as a backup. Hydrogen storage was assumed to provide electricity during the evening, instantaneous imbalance or unfavorable weather. Three algorithms named firefly algorithm, shuffled frog leaping algorithm and particle swarm optimization methods were used for optimization to assess three types of configurations: PV cells with fuel cells, wind turbines with fuel cells and both sources with fuel cells. The simulation revealed the best configuration of the system would be a hybrid combination of PV cells, wind turbines and fuel cells with an LCOE of 0.47 $/kWh. 70% of the green energy was supplied by solar panels, followed by wind turbines with a contribution of 16.5% and the rest was provided by fuel cells. Electrolyzers were the costliest component in the system and wind turbines were the cheapest component in the system. Moreover, using the firefly algorithm resulted in minimal NPC compared to the other two algorithms.

Wu et al. (2022) developed a techno-economic framework for a hydrogen storage system for multiple configurations and multiple grid services. Five case studies were considered with a vertically integrated grid system, a third-party investor, a distribution system grid or a large-scale industrial or commercial customer. The first case study considered the production of hydrogen from grid electricity and directly deploying it for use in transportation or industry. The second case study had similar configurations as the first case study but an electrolyzer and fuel cell were added to the system to address frequency regulation and demand response. In the third case study, besides previous configurations, integration with the natural gas grid is also considered. The fourth and fifth case studies considered an underground salt cavern for long-term storage of hydrogen to provide additional ancillary services such as capacity and curtailment of demand charge to the grid. The scenarios were simulated to get the best configuration and component sizing for different use cases. Results suggested that not only do on-site hydrogen storage systems and fuel cells considerably increase the flexibility of the system, but they also make the system cost-competitive compared to the cases where they were not considered. Moreover, using hydrogen storage to generate electricity locally seemed to be more cost-effective compared to injecting it into the natural grid system.

Palys and Daoutidis (2020) investigated the feasibility of deploying ammonia and hydrogen storage systems for off-grid systems located in 15 cities in the USA. Both solar panels and wind turbines were considered as sources of energy while for hydrogen production, both AWE and PEM technologies were considered. The pressure swing absorption method was used for nitrogen production and it was stored in gaseous format just as hydrogen. Generated ammonia was assumed to be stored in the liquid state and converted back to electricity either by internal combustion engines or solid oxide fuel cells. Results suggested using a combination of ammonia and hydrogen storage facilities would yield in lowest cost. Hydrogen storage would be favorable if short-term storage was required whereas ammonia storage would be favorable if seasonal storage was required.

(Zghaibeh et al., 2024) analyzed the techno-economic feasibility of a power station powered by hydroelectric and photovoltaic sources located in Oman. The study aimed to propose a system that could decrease carbon footprint, particularly in the transport sector. Electricity generated from hydropower and PV panels was used to generate green hydrogen via electrolyzer and the system could operate in standalone mode. A battery storage system was also considered in the event of no hydropower supply or the absence of sunlight. The robust system was able to produce energy independently as well as contribute to grid power by selling excess energy through grid-tied connections. The total cost of the system and LCOH were calculated using Homer Pro and it was deemed to be an effective system for farms and small communities.

Hoseinzadeh and Astiaso (2022) conducted feasibility studies for a photovoltaic and wind power system in the Mediterranean climate region of Sicily Island of Italy. PEM technology was chosen to be used in electrolyzer rather than SOE or AWE due to its high efficiency in load performing. Analysis suggested PV panels had the highest contribution in regard to energy supply as well as efficiency, followed by wind turbines and fuel cells. Hydrogen was estimated to be produced the most during noon as solar radiation was highest at that time and also the energy consumption during this time was too low for the fuel cells to function. When renewable production was not enough to satisfy demand, fuel cells were activated to provide deficient energy and the hydrogen storage system was able to satisfy peak demand. Using both power sources instead of one would lead to better energy security and reduction of the effects of climate change on system performance.

Xiang et al. (2021) investigated the techno-economic benefits of incorporating hydrogen storage systems, battery storage systems, auxiliary power units of aircraft, and electric vehicles into an electrified airport microgrid system. Integration of the hydrogen system would decrease the system cost by 41.6% and reduce the CO_2 emissions by 67.29%. Five scenarios were generated of which only one option considered the hydrogen system which is used as a fuel cell generator at remote stands of aircraft. Fuel cells were designed to act as mobile power sources rather than connecting with the DC grid. The PV cells, battery storage system and grid were assumed to provide electricity to aircraft at contact stands. The system was designed in such a way so that excess energy generated by photovoltaic units would first charge the battery system, remaining energy would be used to produce hydrogen by electrolyzing. Integration of the hydrogen system would enable increasing PV capacity and decreasing battery system investment costs. The proposed system would reduce dependency on the grid as well as reduction of infrastructure expansion and carbon emissions. Results showed the integrated system would be cost-effective as well as environment-friendly. The additional cost of hydrogen systems could be compensated by offsetting emission costs and generating revenues from selling oxygen. Higher solar irradiance and oxygen price as well as lower hydrogen production unit investment cost would increase the economic and environmental benefits.

Alsagri et al. (2021) performed a technical and economic assessment on an off-grid health clinic consuming energy from a battery storage system, electrolyzer, fuel cells and diesel generator. The study was conducted to investigate the necessity of an excess energy management system for a remote region and propose a viable solution. Since the availability of fuels for diesel generators would be limited in desert regions, the effect of this limitation on the hybrid system was also analyzed. Less fuel availability would have to be offset by an additional installation of PV panels and battery banks leading to an upsurge of cost as well as electricity. The involvement of an electrolyzer would lead to a reduction of excess electricity from 32.5% to 6%. It was also established that the proposed system would work best for small loads considering the grid extension lines.

Nadaleti et al. (2020) studied the possibility of utilizing excess hydropower and wind power in Brazil to produce green hydrogen. The electricity produced by hydrogen would meet all commercial and residential loads in the country except for the southeast region where the demand was assumed to be the highest. While the production cost of hydrogen was estimated to be expensive, the authors believe with the maturity of technology the cost would shrink making it easier for a safe and diversified energy network.

LiJ et al. (2022) conducted a techno-economic assessment on a remote energy system in west China for both electric and hydrogen loads. Besides traditional solar and wind resources, biomass was used to generate electricity by converting abundant manure found in the village into biogas through anaerobic fermentation. The load profile was divided into essential primary loads that were measured for three different seasons throughout the year and constant deferrable loads. Part of the electricity was utilized to synthesize hydrogen mainly from 10.00 to 18.00 over all seasons of the year. The generated hydrogen was used to refuel two electric buses for local transportation. Investigation revealed building up an off-grid system would be more economical compared to grid extension when the breakeven grid distance was 16.15 km. Additional hydrogen load implied an increase of net present value and cost of energy but a decrease of LCOH due to the scale effect of hydrogen generation. The system would enable independent rural electrification as well as a declination of carbon emissions.

Patel et al. (2022) investigated the possibility of transporting electricity over a long horizon using a hydrogen network instead of high-voltage DC cables. The concept was based on harnessing electricity generated from remote renewable sources, converting it to green hydrogen, transporting it by pipelines to demand location and converting the chemical energy of hydrogen back to electric energy. Energy was stored in hydrogen pipelines by controlling the operating pressure and the intended flow rate of hydrogen was achieved by pressure loss between inlet and outlet of pipelines. Hydrogen was reconverted to electricity either by hydrogen-fired gas turbines where direct AC electricity was generated or by fuel cells where a DC-to-AC converter was needed to provide AC electricity to end users. It was deducted from the evaluation that the hydrogen interconnection system would be more cost-effective compared to high-voltage DC lines in 2050 provided the distance between supply and demand was more than 350 km.

Marocco et al. (2020) proposed a hydrogen storage-based renewable energy system for islanded microgrids to evade establishing grid extensions. The system contained both electrochemical and chemical storage solutions but the efficiency of battery storage was assumed to be higher than hydrogen storage. To avoid quick start-up and shutdowns of the electrolyzer and to equalize the renewable output battery storage was used as support. Results showed for all case studies, renewable systems would be more cost-competitive compared to the current system regardless of the short or long timeframe. The contribution of diesel generators to total demand fulfillment was calculated to be between 4-5% only.

Rad et al. (2020) performed a case study to find an optimal renewable energy system for a small village in Iran. Besides conventional renewable sources, biogas produced by sheep and chickens were used to generate electricity. One scenario involved producing hydrogen from natural gas from a reformer while the other scenario involved producing hydrogen using fuel cell technology. While hydrogen storage was intended to be used for long-term applications, battery storage was included in the system to support immediate fluctuations of supply. The system was analyzed based on whether electrolyzer or reformer was used for hydrogen generation both for grid-tied and islanded mode. The results revealed in standalone mode, using a biogas generator along with PV modules and battery storage would be the most optimal option while in grid-tied mode, only the sources were enough to fulfill the demand. Using fuel cells would increase the cost by 33-37% but it would increase the flexibility. Using a reformer instead of an electrolyzer would lower the system cost but increase the pollution cost.

Vendoti et al. (2021) modeled a renewable hybrid energy system for an islanded village in India to analyze the best combination of energy resources to fulfill the end-user demand. The system was assumed to have an AC grid connecting all generators except photovoltaic sources while the DC grid was connected to photovoltaic cells as well as the storage facilities. Four scenarios were generated based on energy sources for designated off-grid hybrid systems. Results suggested the most economical option would be to use all available renewable sources along with both hydrogen and battery storage systems.

Hussam et al. (2024) studied the feasibility of local hydrogen production using the renewable resources available at a power plant in Kuwait City. Three scenarios were generated, while in the first one, the electricity supply was solely dependent on grid connection, in the second and third scenarios battery and hydrogen storage systems were considered respectively. Results showed an on-grid connection with a combination of renewable sources along with an electrolyzer, hydrogen tank and inverter would be the most economically viable option considering both electricity and hydrogen loads. Sensitivity analysis suggested the cost of electricity is more perceptive to PV panel costs than wind turbine costs. Table 7 points out the main characteristics of existing literature relevant to this study.

Table 7. A systematic review of related work to this study

Reference	**Case Study Location**	**Energy Source**	**Grid Connection**	**Production Technology**	**Storage Technology**	**Optimization Software**	**Model**
Alonso et al. (2024)	Belgium	PV, WT	On-grid	Alkaline Electrolyzer	Compressed H_2, BESS	HOMER	
Alsagri et al. (2021)	Saudi Arabia	PV, Diesel	Off-grid	PEM electrolyzer	Compressed H_2, BESS	HOMER	
Chen et al. (2021)	USA, Germany	PV, WT	Off-grid	PEM electrolyzer	Compressed H_2, BESS	GAMS	LP
Cruz-Soto et al. (2022)	Mexico	PV, WT, Diesel	Off-grid	PEM electrolyzer	Compressed H_2, BESS	HOMER Pro	
Ghenai et al. (2020)	UAE	PV	Off-grid	Electrolyzer	Compressed H_2		
Hasan and Genc (2022)	Iraq	PV, WT	On-grid, Off-grid	PEM electrolyzer	Compressed H_2		

Reference	Case Study Location	Energy Source	Grid Connection	Production Technology	Storage Technology	Optimization Software	Model
Hernandez and Gencer (2021)	USA	PV	On-grid	PEM electrolyzer	BESS, Compressed H_2		
Hoseinzadeh & Astiaso (2022)	Italy	PV, WT	Off-grid	PEM electrolyzer	Compressed H_2	HOMER	
Hussam et al. (2024)	Kuwait	PV, WT	On-grid, Off-grid	PEM electrolyzer	Compressed H_2, BESS	HOMER Pro	
LiJ et al. (2022)	China	PV, WT, Biogas	Off-grid	PEM Electrolyzer	BESS, Compressed H_2	HOMER	
LiX et al. (2022)	China	PV, WT, PV+WT	Off-grid	SMR, PEM Electrolyzer	BESS, Compressed H_2	HOMER, VIKOR	
Marocco et al. (2020)	Italy, Greece, Norway	PV, Hydro, Biomass, Wind, Diesel	Off-grid	PEM Electrolyzer, Alkaline Electrolyzer	BESS, Compressed H_2		
Nadaleti et al. (2020)	Brazil	WT, Hydropower	On-grid		Compressed H_2		
Okonkwo et al. (2022)	Oman	PV, WT	Off-grid	Alkaline Electrolyzer	Compressed H_2	HOMER	
Pal and Mukherjee (2021)	India	PV	Off-grid	PEM Electrolyzer	Compressed H_2	HOMER	
Palys and Daoutidis (2020)	USA	PV, WT	Off-grid	Alkaline Electrolyzer, PEM Electrolyzer	Compressed H_2, Liquid Ammonia	GAMS	MILP

Reference	Case Study Location	Energy Source	Grid Connection	Production Technology	Storage Technology	Optimization Software	Model
Patel et al. (2022)	UK	PV, WT	Off-grid	PEM Electrolyzer	Gas Pipeline		
Rad et al. (2020)	Iran	PV, WT, Biogas	On-grid, Off-grid	SMR, PEM Electrolyzer	Compressed H_2, BESS	HOMER	
Samy et al. (2020)	Egypt	PV, WT	Off-grid	PEM Electrolyzer	Compressed H_2	MATLAB	
Sevik (2022)	Turkey	PV, Diesel	On-grid	PEM Electrolyzer	Compressed H_2		
Shahid et al. (2022)	France	PV, WT	Off-grid	PEM Electrolyzer	Compressed H_2, BESS		
Skordoulias et al. (2022)		PV, WT	On-grid	PEM Electrolyzer	Compressed H_2	Aspen Plus™	
Takatsu and Farzaneh (2020)	Japan	PV	On-grid, Off-grid	PEM Electrolyzer, Biomass Gasification	Compressed H_2		
Vendoti et al. (2021)	India	PV, WT, Biogas, Biomass	Off-grid	PEM Electrolyzer	Compressed H_2, BESS	HOMER Pro	
Wu et al. (2022)	USA	PV, Grid	On-grid, Off-grid	PEM Electrolyzer	Salt Cave	HESET	MILP
Xiang et al. (2021)	China	PV, Grid	On-grid	PEM Electrolyzer	Compressed H_2, BESS		MILP
Zghaibeh et al. (2024)	Oman	PV, Hydropower	On-grid, Off-grid	PEM Electrolyzer	Compressed H_2, BESS	HOMER Pro	

4.1 Research Gap

While the existing literature explored the feasibility of integration of a hydrogen storage system with the electricity network, but it has not been fully investigated which type of production or storage technologies will be economical to operate in conjunction with an electricity network in the near future. This study aims to find out which particular hydrogen production and storage technologies would be economical to use in electrical networks. Previous studies relied more on simulation-based solutions rather than mathematical solutions. Since the problem was formulated as a mixed integer non-linear programming problem, using a mathematical tool to study the system might lead to more precise results.

5 Methodology

A 33-node, 32-line standard microgrid is considered to study the effects of integrating a hydrogen system with the existing network. The system is considered to be connected to the grid and both conventional and renewable energy sources were taken into consideration. When the electricity price is cheaper, the system is assumed to buy electricity from the grid and meet the connected demand as well as charge the storage system. If the electricity buying price is higher, the storage system is assumed to discharge power back to the system to fulfill the demand.

5.1 Objective Function

Equation (19) defines the objective function of optimal operation of the microgrid. The objective is to minimize the cost incurred by the system to avail electricity (Shahbazbegian et al., 2023). The objective function consists of two terms: the operation cost of the microgrid system and the upfront cost of the hydrogen system consisting of electrolyzer, storage facility and fuel cell.

$$OF = min(\sum Operation\ cost + \sum_{C} Installation\ cost\ of\ hydrogen\ system) \quad (19)$$

Where C = number of hydrogen production and storage set

The first term is the cost of microgrid operation which includes the cost incurred to buy electricity from the grid as well as revenues earned by selling electricity back to the grid. Fixed and variable costs associated with the non-renewable generators are also considered as a part of microgrid operation cost which is depicted in equation (20) (Shahbazbegian et al., 2023).

$$Operation\ cost = \sum_{G} \sum_{T} EP\ (Pbuy - Psell) + \sum_{J} \sum_{T} (VC + FC) \quad (20)$$

Where G = number of grid connections to the microgrid

J = number of fuel generators in the microgrid

T = time step

VC = variable cost of non-renewable generator

FC = fixed cost of non-renewable generator

Equation (21) represents the investment associated with hydrogen storage systems including production facilities and fuel cells (Shahbazbegian et al., 2023). A binary variable is multiplied by this term to assess if a storage system needs to be established for this system.

$$Storage\ cost\ = \left\lfloor \frac{r\,(1+r)^{j}}{(1+r)^{J}-1} \right\rfloor \frac{D^{day}}{D^{year}} C^{inv} \qquad (21)$$

Where r = number of grid connections to the microgrid

j = number of fuel generators in the microgrid

D^{day} = total energy demand for a day (kWh)

D^{year} = total energy demand for a year (kWh)

C^{inv} = total investment cost of storage ($)

5.2 Constraints

Several constraints have been defined for the microgrid system.

5.2.1 Active Power Balance

Equations (22)-(26) define the active power constraints of the microgrid (Shahbazbegian et al., 2023). In every instance, supply should equal demand. The power supply can be availed from the grid, renewable and conventional resources and storage systems. Besides consuming energy by the loads, some energy is lost as heat loss in distribution lines. At a certain time step, electricity can either be bought from the grid or sold back to the grid utilizing the energy stored in storage facilities or power generated by conventional resources.

$$P_{i,t} + P_{i,t}^{wind} + P_{j,t}^{fuel\,gen} + P_{i,t}^{buy} - P_{i,t}^{sell} - P_{c,t}^{E\rightarrow H2} + P_{c,t}^{H2\rightarrow E} - \sum_i (P_{l,t}^{line} + R_l\, I_{l,t}^2) = P_{i,t}^{load} \quad \forall i, \forall j, \forall l, \forall c, \forall t \tag{22}$$

$$P_{i,t}^{wind} \leq P_{i,t}^{wind,max} \tag{23}$$

$$0 \leq P_{i,t}^{buy} \leq P_{i,t}^{buy,max} U_{buy\, i,t} \quad \forall i, \forall t \tag{24}$$

$$0 \leq P_{i,t}^{sell} \leq P_{i,t}^{sell,max} U_{sell\, i,t} \quad \forall i, \forall t \tag{25}$$

$$U_{buy\, i,t} + U_{sell\, i,t} \leq 1 \quad \forall i, \forall t \tag{26}$$

5.2.2 Reactive Power Balance

Equation (27)-(28) depicts the reactive power balance of the microgrid (Shahbazbegian et al., 2023). Source reactive power should match sink reactive power and distribution loss.

$$Q_{i,t} + Q_{i,t}^{wind} - \sum_i (Q_{l,t}^{line} + X\, I_{l,t}^2) = Q_{i,t}^{load} \quad \forall i, \forall l, \forall t \tag{27}$$

$$Q_{i,t}^{min} \leq Q_{i,t} \leq Q_{i,t}^{max} \tag{28}$$

5.2.3 Renewable Generator Constraints

Equation (29) describes the dispatching constraint of renewable generators (Shahbazbegian et al., 2023). The maximum amount of power dispatched by the renewable sources at any time step should be equal to the capacity of the sources multiplied by the system load at the particular time step.

$$0 \leq P_{i,t}^{wind} \leq P_{i,t}^{wind,max} \quad \forall i, \forall t \tag{29}$$

5.2.4 Non-renewable Generator Constraints

Equations (30)-(32) describe the dispatching constraints of non-renewable generators (Shahbazbegian et al., 2023). While the binary variable $U_{i,t}$ in equation (30) depicts whether the sources are active or inactive, equations (31)-(32) define the ramping rate capability to keep the system stable. Since these generators are used in conjunction with renewable sources, a fast ramping rate is preferred.

$$U_{i,t}\, P_i^{min} \leq P_{i,t} \leq U_{i,t}\, P_i^{max} \quad \forall i, \forall t \tag{30}$$

$$P_{i,t} - P_{i,t-1} \leq U_{i,t-1} R_i^{maxup} \quad \forall i, \forall t \tag{31}$$

$$P_{i,t-1} - P_{i,t} \leq U_{i,t} R_i^{maxdown} \quad \forall i, \forall t \tag{32}$$

5.2.5 Voltage and Current Constraints

Equation (33) represents Kirchoff's voltage law, equations (34)-(35) define the voltage constraints at each node of the microgrid and equation (36) defines the current restriction through each distribution line (Shahbazbegian et al., 2023).

$$V_{l,t}^{in2} - V_{l,t}^{out2} = 2\,(R_l\, P_{l,t}^{line} + X_l\, Q_{l,t}^{line}) + Z_l^2\, I_{l,t}^2 \quad \forall l, \forall t \tag{33}$$

$$V_{l,t}^2 I_{l,t}^2 = Q_{l,t}^{line2} + P_{l,t}^{line2} \quad \forall l, \forall t \tag{34}$$

$$V_i^{min} \leq V_{i,t} \leq V_i^{max} \quad \forall i, \forall t \tag{35}$$

$$|I_{l,t}| \leq I_l^{max} \quad \forall l, \forall t \tag{36}$$

5.3 P2H2P System

Equations (37)-(43) describe the technical constraints of the hydrogen system integrated with the microgrid (Shahbazbegian et al., 2023). According to equation (37), excess power from the microgrid can utilized by connected electrolyzers to produce hydrogen where $\rho_{c,t}$ is the multiplication coefficient to convert the unit from MW to milliom m^3. The produced hydrogen $H_{c,t}^{in}$ is then compressed and stored in the storage tank which is described in equation (38). At time step 1, an initial amount of storage level is defined for the storage system. $\emptyset_c$ and φ_c are the charging and discharging efficiencies of the storage system respectively and the amount of hydrogen stored at the nd of each time $HL_{c,t}$ is considered as the initial hydrogen for the next time step. At peak hours when the electricity buying price is high, hydrogen $H_{c,t}^{out}$ is extracted from the storage tank and chemical energy is converted to electrical energy by fuel cells which is depicted in equation (39). ψ_c is the multiplication coefficient that is used to convert the unit from million m^3 to MW. According to equations (40)-(42), instantaneous input or output hydrogen in the storage system is constrained by the capacity of the storage facility. At each time step, the storage can either be charged or discharged, simultaneous actions are avoided for the proper functioning of fuel cells which is defined by equation (43) where $U_{charge\ c,t}$ and $U_{discharge\ c,t}$ are binary variables.

$$P_{c,t}^{E\rightarrow H2}\,\rho_{c,t} = H_{c,t}^{in} \quad \forall c, \forall t \tag{37}$$

$$HL_{c,t} = \begin{cases} HL_c^0 \quad if\ \forall t = 1 \\ HL_{c,t-1} + (\emptyset_c\, H_{c,t}^{in} - \frac{H_{c,t}^{out}}{\varphi_c}) \quad if\ \forall t \geq 2 \end{cases} \tag{38}$$

$$H_{c,t}^{out}\,\psi_c = P_{c,t}^{H2\rightarrow E} \quad \forall c, \forall t \tag{39}$$

$$HL_{c,t} \leq HL_{c,t}^{max} \quad \forall c, \forall t \tag{40}$$

$$H_{c,t}^{in} \leq U_{charge\ c,t}\, HL_{c,t}^{max} \tag{41}$$

$$H_{c,t}^{out} \leq U_{discharge\ c,t}\, HL_{c,t}^{max} \tag{42}$$

$$U_{charge\ c,t} + U_{discharge\ c,t} \leq 1 \tag{43}$$

5.4 Solver

The proposed model is a non-linear mixed integer linear programming model implemented in the General Algebraic Modeling System (GAMS) tool using the DICOPT solver.

5.5 Operation

The test microgrid considered for the study has 33 nodes and 32 lines where the microgrid is connected to the main grid at node 1. 1000 kVA is considered as the base apparent power while 12.66 kV is regarded as the base voltage. Figure 5 depicts the dispatch of microgrid components without a storage system. According to the graph, the off-peak period is from hours 1 to 7 and the peak is from hours 11 to 21. Non-renewable generators are also activated during peak periods to support the loads.

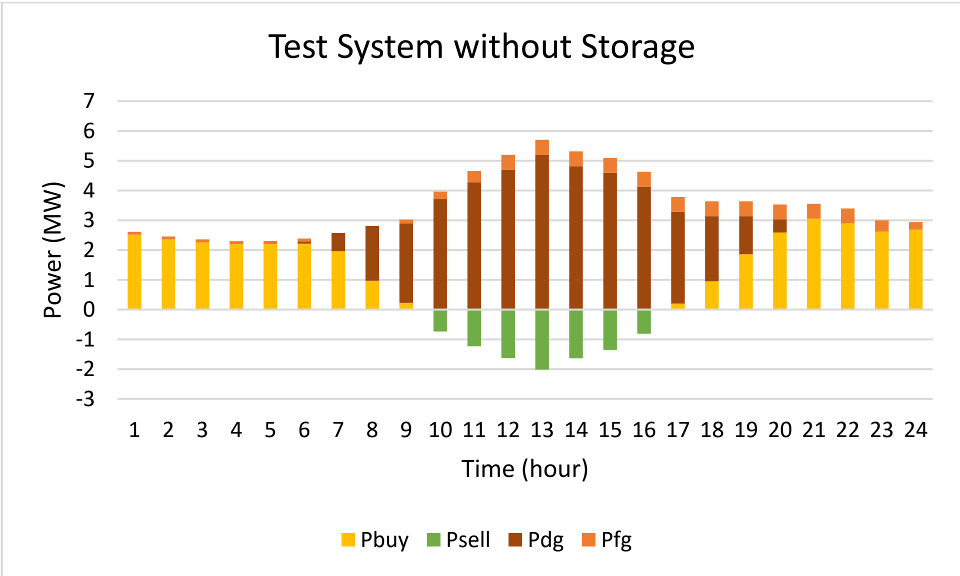

Figure 5. Dispatch of the studied system without storage

Figure 6 depicts the microgrid dispatch with a hydrogen storage system. The hydrogen storage system gets charged during off-peak hours from time periods 1 to 7 and gets discharged during peak hours from time periods 15 to 17. Adding a hydrogen storage system reduces the operation cost by $25.676 per day and reduces renewable energy spillage by 2.13 MW. So integration of the hydrogen storage system into the studied microgrid system will result in economic benefits as well as reduction of renewable energy loss.

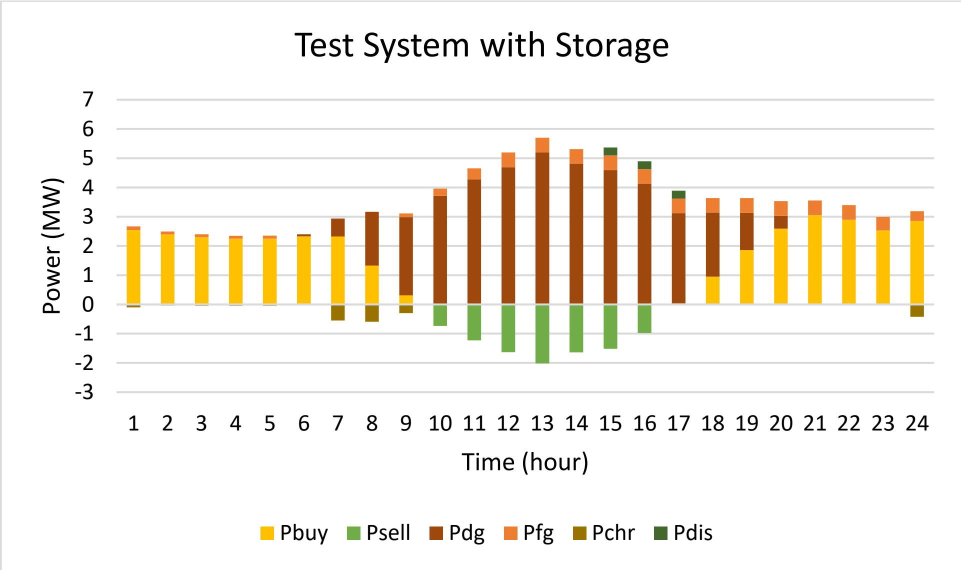

Figure 6. Dispatch of the studied system with storage

5.6 Planning

The hydrogen storage system is incorporated with the microgrid in the planning stage. In the event of excess renewable energy, the electrical energy is converted to chemical energy by hydrogen production cells like electrolyzers and then stored in storage tanks. During peak hours, the stored energy is fed into the system by fuel cells. In table 8, the location, capacity and characteristics of the components are mentioned.

Table 8. Characteristics of different systems installed in the microgrid (Shahbazbegian et al., 2023)

Components	Number of Resources	Location	Installed Capacity	Characteristics
Wind turbines	4	Node 8, Node 15, Node 21, Node 29	4 MW	$P_{i,t}^{windmax}$ = 1 MW
Dispatchable units	2	Node 2	1 MW	P_i^{min} = 0.1 MW, P_i^{min} = 1 MW, Fixed cost = 1 $/MWh, Variable cost = 250 $/MWh, $R_i^{maxup/down}$ = 0.5 MW
		Node 9	0.5 MW	P_i^{min} = 0.1 MW, P_i^{min} = 0.5 MW,

Components	Number of Resources	Location	Installed Capacity	Characteristics
				Fixed cost = 1 $/MWh, Variable cost = 40 $/MWh, $R_i^{maxup/down}$ = 0.25 MW
Hydrogen production and storage set	5	Node 25	0.0005 million m^3/10 MW	$HL_{c,t}^{max}$ = 0.0001 million m^3 HL_initial = 20% of $HL_{c,t}^{max} Hin_{c,t}^{max} / HL_{c,t}^{max} = HL_{c,t}^{max}$

5.7 Steps of Analysis

Figure 7 represents the main steps that were followed to conduct the study. As mentioned before, a 33-node standard microgrid is considered a test grid which is assumed to be connected to the grid all the time. The model is first studied without a storage system to understand how much storage would be appropriate for the system. Then the storage system is integrated with the model and two scenarios are generated based on two operating days representing two different seasons. The generated scenarios are executed based on different hydrogen production and storage techniques and the technical and economic parameters of the total system are assessed.

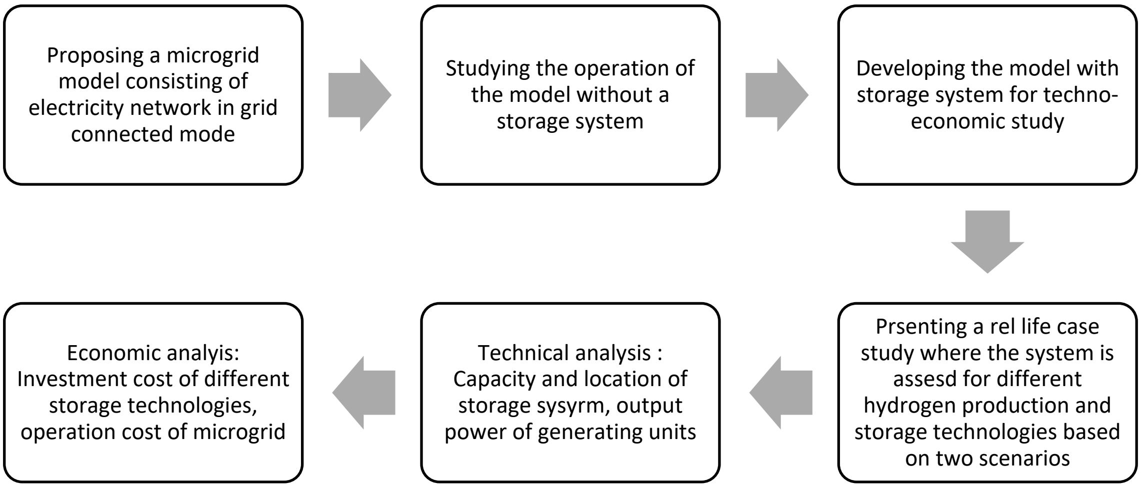

Figure 7. Analysis steps

6 Case Study

6.1 Technical Data

Real-life data has been used to study the performance of the microgrid. Table 9 describes the real and reactive power loads connected to each node in the system.

Table 9. Load connected to the microgrid (Shahbazbegian et al., 2023)

Node	Load (MW)	Load (MVar)
1	0	0
2	0.1	0.06
3	0.09	0.04
4	0.12	0.08
5	0.06	0.03
6	0.06	0.02
7	0.2	0.1
8	0.2	0.1
9	0.06	0.02
10	0.06	0.02
11	0.045	0.03
12	0.06	0.035
13	0.06	0.035
14	0.12	0.08
15	0.06	0.01
16	0.06	0.02
17	0.06	0.02
18	0.09	0.04
19	0.09	0.04
20	0.09	0.04
21	0.09	0.04
22	0.09	0.04
23	0.09	0.05

Node	Load (MW)	Load (MVar)
24	0.42	0.2
25	0.42	0.2
26	0.06	0.025
27	0.06	0.025
28	0.06	0.02
29	0.12	0.07
30	0.2	0.6
31	0.15	0.07
32	0.21	0.1
33	0.06	0.04

Table 10 describes the resistance, reactance and maximum current allowed in 32 lines connecting the nodes.

Table 10. Electricity network data (Shahbazbegian et al., 2023)

Branch	From node	To node	Resistance (Ω)	Reactance (Ω)	Maximum current (A)
1	1	2	0.0922	0.047	300
2	2	3	0.493	0.2511	300
3	3	4	0.366	0.1864	300
4	4	5	0.3811	0.1941	300
5	5	6	0.819	0.707	300
6	6	7	0.1872	0.6188	300
7	7	8	0.7114	0.2351	300
8	8	9	1.03	0.74	300
9	9	10	1.044	0.74	300
10	10	11	0.1966	0.065	300
11	11	12	0.3744	0.1238	300
12	12	13	1.468	1.155	300
13	13	14	0.5416	0.7129	300

Branch	From node	To node	Resistance (Ω)	Reactance (Ω)	Maximum current (A)
14	14	15	0.591	0.526	300
15	15	16	0.7463	0.545	300
16	16	17	1.289	1.721	300
17	17	18	0.732	0.574	300
18	18	19	0.164	0.1565	300
19	19	20	1.5042	1.3554	300
20	20	21	0.4095	0.4784	300
21	21	22	0.7089	0.9373	300
22	22	23	0.4512	0.3083	300
23	23	24	0.898	0.7091	300
24	24	25	0.896	0.7011	300
25	25	26	0.203	0.1034	300
26	26	27	0.2842	0.1447	300
27	27	28	1.059	0.9337	300
28	28	29	0.8042	0.7006	300
29	29	30	0.5075	0.2585	300
30	30	31	0.9744	0.963	300
31	31	32	0.3105	0.3619	300
32	32	33	0.341	0.5302	300

Table 11 shows the hourly buying and selling price when the grid is involved, the selling price is assumed to be the same as the buying price.

Table 11. Hourly electricity buying and selling price (Ding et al., 2014)

Time (hour)	Electricity buying price ($/kWh)	Electricity selling price ($/kWh)
1	0.025	0.025
2	0.025	0.025
3	0.021	0.021

Time (hour)	Electricity buying price ($/kWh)	Electricity selling price ($/kWh)
4	0.02	0.02
5	0.02	0.02
6	0.025	0.025
7	0.025	0.025
8	0.03	0.03
9	0.038	0.038
10	0.04	0.04
11	0.045	0.045
12	0.062	0.062
13	0.079	0.079
14	0.1	0.1
15	0.124	0.124
16	0.15	0.15
17	0.14	0.14
18	0.1	0.1
19	0.175	0.175
20	0.06	0.06
21	0.06	0.06
22	0.05	0.05
23	0.04	0.04
24	0.035	0.035

6.1.1 Parameters $\rho_{c,t}$, $\emptyset_c$, φ_c, ψ_c

There are several technical parameters with electricity to hydrogen conversion and vice versa that need to be defined. Equation (44) depicts how $\rho_{c,t}$ is calculated (Skordoulias et al., 2022).

$$\rho_{c,t} = \frac{Efficiency\ of\ electrolyzer}{LHV\ of\ hydrogen} \quad (44)$$

The value of LHV of hydrogen corresponds to 3 KWh/normal m^3 (Enapter).

For each hour,

LHV = 3 kW/normal m^3 = $(3 \times 10^{-3})/10^{-6}$ MW/million m^3 = 3000 MW/million m^3

Table 12. $\rho_{c,t}$ for different production technologies (IPCC, 2022)

Technology	**LHV of Hydrogen MW/million m^3**	**Efficiency**	$\boldsymbol{\rho_{c,t}}$
Alkaline water electrolysis	3000	76%	0.0002533
PEM electrolysis	3000	75%	0.00025
SOE electrolysis	3000	85%	0.0002833
SMR	3000	74%	0.0002466
Coal gasification	3000	54%	0.00018
Biomass gasification	3000	50%	0.0001666

Table 13. ϕ and φ for different storage technologies (Ni, 2006)

Technology	**Charging Efficiency ϕ**	**Discharging Efficiency φ (assumed to be the same as charging efficiency)**
Compressed gas	93%	93%
Liquid hydrogen	65%	65%
Metal Hydride	88%	88%

Equation (45) defines how ψ_c is calculated (Skordoulias et al., 2022).

$$\psi_c = Efficiency\ of\ electrolyzer\ x\ LHV\ of\ Hydrogen \quad (45)$$

So, ψ_c = 0.6 x 3000 = 1800 MW/million m^3 (fuel cell technologies).

Table 14. Installation cost of hydrogen storage systems

System	Component	CAPEX (per kW)
Hydrogen production	SMR reactor	(Keipi et al., 2018) $3600.00
Hydrogen production	Gasifier	(Lourinho et al., 2023) $3000.00
Hydrogen production	AWE electrolyzer	(IPCC, 2022) $450.00
Hydrogen production	PEM electrolyzer	(IPCC, 2022) $650.00
Hydrogen production	SOE electrolyzer	(IPCC, 2022) $750.00
Hydrogen storage	Compressed H_2	(Kiessling, 2021) $48.72
Hydrogen storage	Liquid H_2	(Kiessling, 2021) $110.88
Hydrogen conversion	Fuel cell	(Regmi et al., 2020) $1870.00

6.2 Scenario Generation

Two scenarios are analyzed in this study based on different wind power outputs and demand share. Wind speed and demand vary mainly based on different seasons throughout the year so two scenarios were generated based on two different seasons to analyze when the storage system would be more beneficial.

6.2.1 Scenario 1

Figures 8 and 9 represent hourly demand and wind power output for a single day in spring. Demand valley is observed between hours 1 and 8 while demand peak is observed between hours 18 to 23.

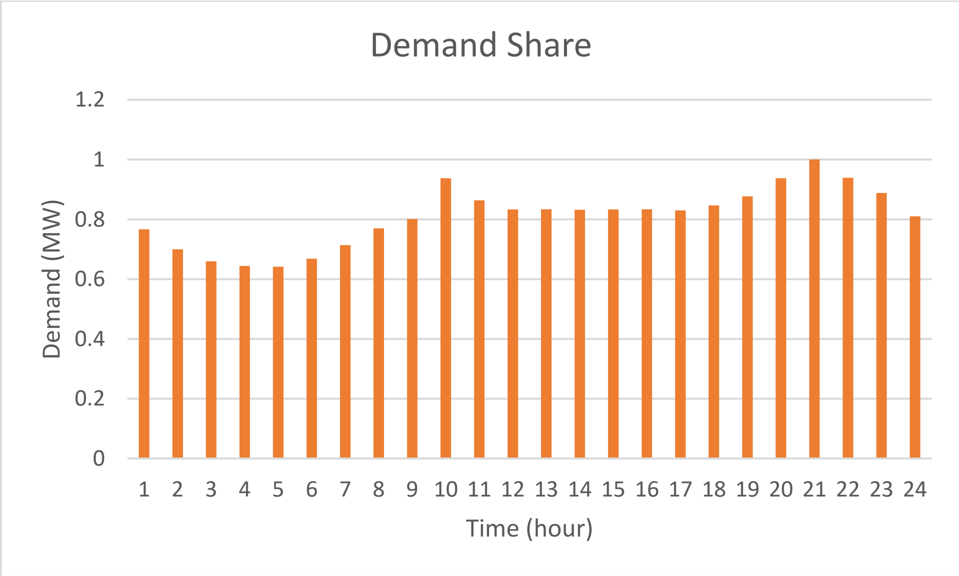

Figure 8. Hourly demand for scenario 1.

Due to low wind speed, wind turbines generate lower power in the first half of the day except hours 7 and 8. The wind turbines generate maximum power from hours 19 to 24.

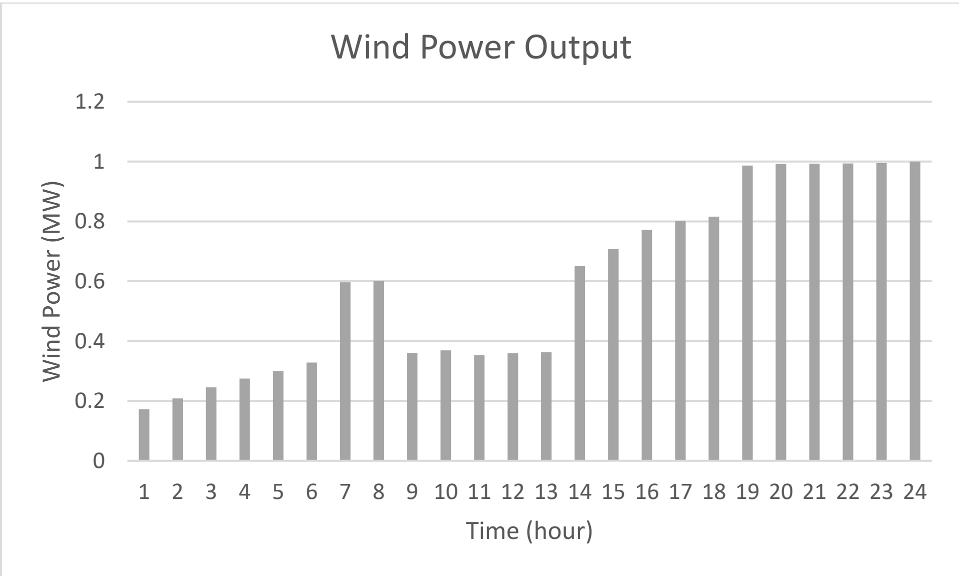

Figure 9. Wind power output for scenario 1.

6.2.2 Scenario 2

Figures 10 and 11 represent hourly demand and wind power output for a single day in summer. The demand pattern is quite similar to that in scenario 1 except the demand value is a bit higher compared to scenario 1.

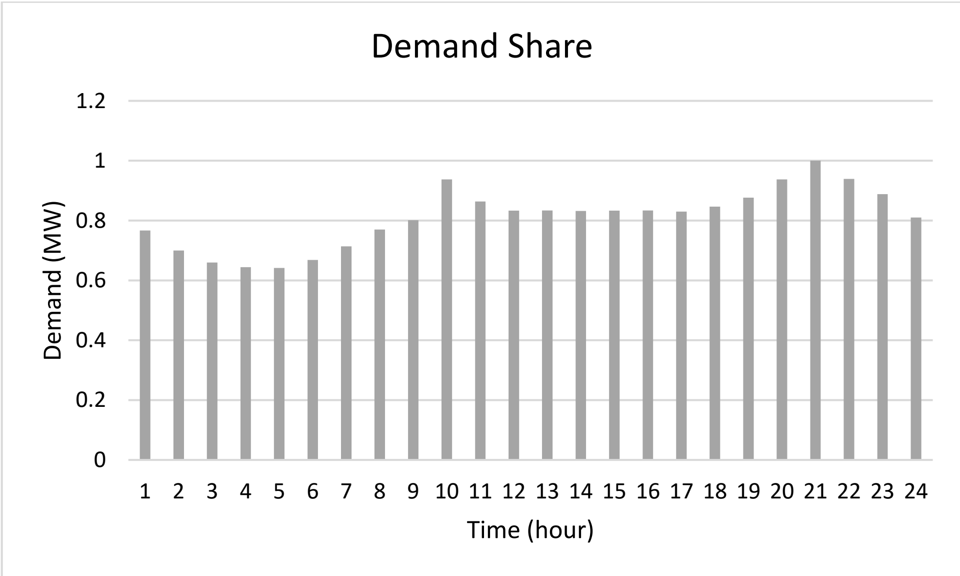

Figure 10. Hourly demand for scenario 2.

The wind power output pattern of scenario 2 is considerably different than scenario 1. The wind turbines are able to provide maximum output from hours 2 to 8. Wind speed is low from hours 13 to 24 as a result the renewable power output is low as well.

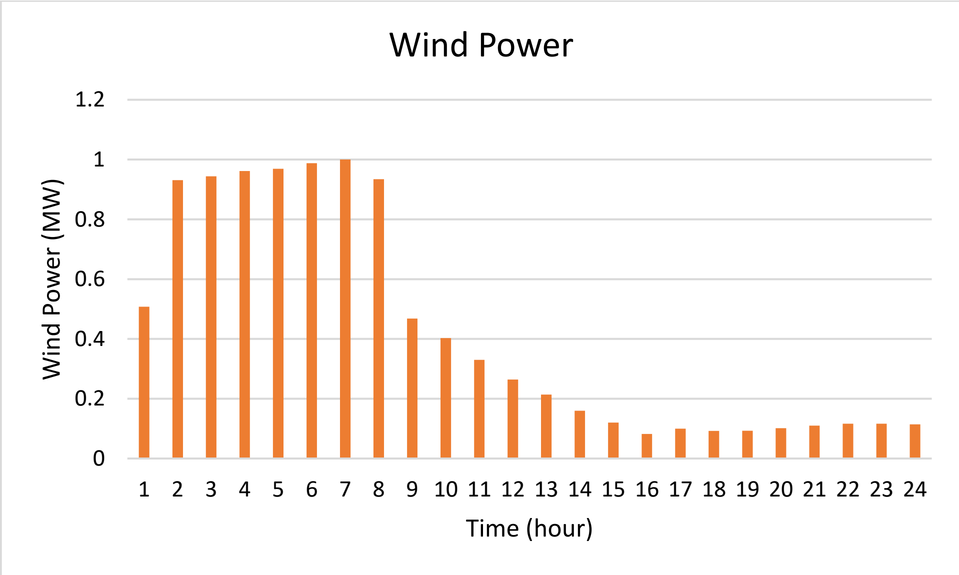

Figure 11. Wind power output for scenario 2.

7 Results and Analyses

7.1 Scenario 1

The system was first analyzed without a hydrogen storage solution and figure 12 depicts the hourly dispatch of grid power, wind power and non-renewable generators. From hours 1 to 6, the output of wind power generators is low due to low wind speed, so it is necessary to buy electricity from the grid. From hours 7 to 8, renewable power output gets a bit high so less electricity is purchased from the grid. From hours 9 to 13, fuel generators are also activated since demand starts to increase gradually hence the optimized option is to use both energy sources in this timeframe. From hours 14 to 24, the demands are high compared to hours 1-13, with peak demand being observed from hours 21 to 24 and the demands are met by both renewable and non-renewable generators.

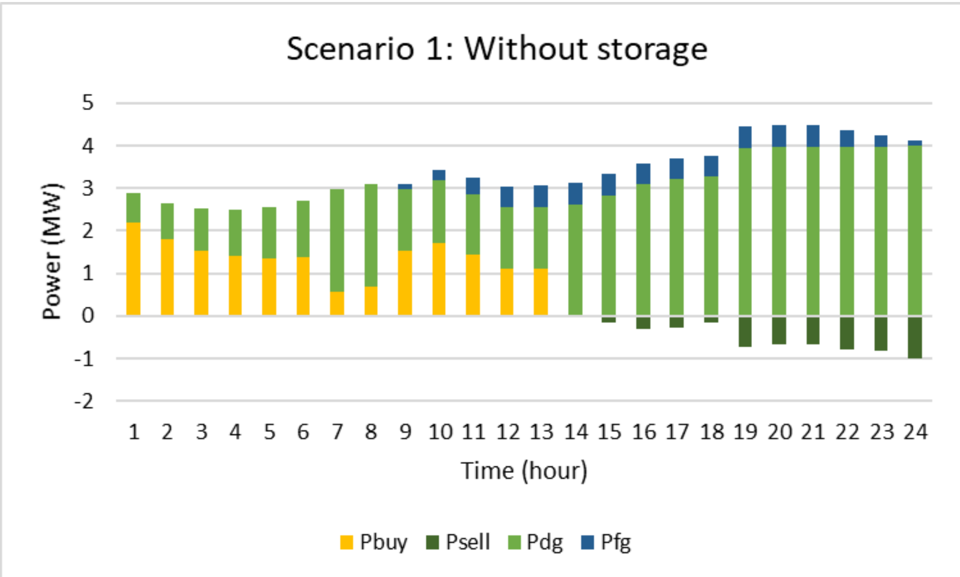

Figure 12. Scenario 1: dispatch without storage.

Figure 13 depicts the dispatch power of microgrid components when a storage system is added to the system. As the electricity buying price is lower from hours 3 to 5 ranging from \$0.02-\$0..21, hydrogen storage gets charged. Conversely, from hours 15 to 17, hydrogen storage gets discharged to provide electricity during peak demand timeframe from hours 16 to 24. The electricity selling price for hours 15 to 17 is in the range of $0.035-$0.15, this is the timeframe with the high electricity price rate as a result, the storage system is discharged to provide electricity to load. By introducing a storage system, renewable energy spillage is lessened by 2.12 MW per day.

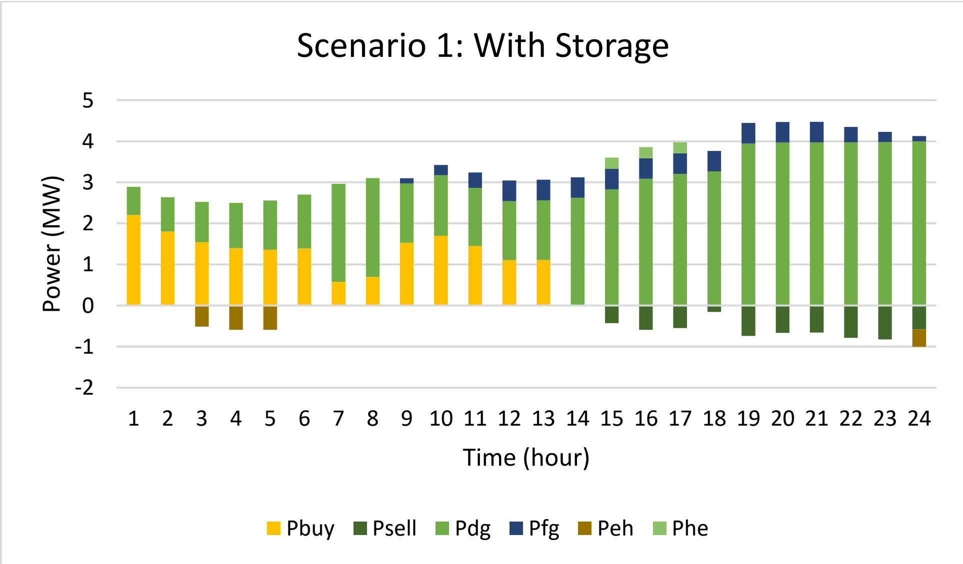

Figure 13. Scenario 1: dispatch with storage.

Figure 14 depicts the dispatch pattern of microgrid components when wind availability decreases by 10% for an operating day. In the event of low wind, the microgrid has to buy a significant amount of electricity from the grid which is almost double the amount when there is regular wind availability. This increases the daily operation cost by 70.94%, therefore hydrogen storage can be used to lower the operation cost in such extreme conditions. The charging and discharging pattern of the storage solution is similar to that of storage in normal weather which can support the load from hours 15 to 24. This proves hydrogen storage increases the resilience of the system in case of extreme situations keeping the operation cost as low as possible.

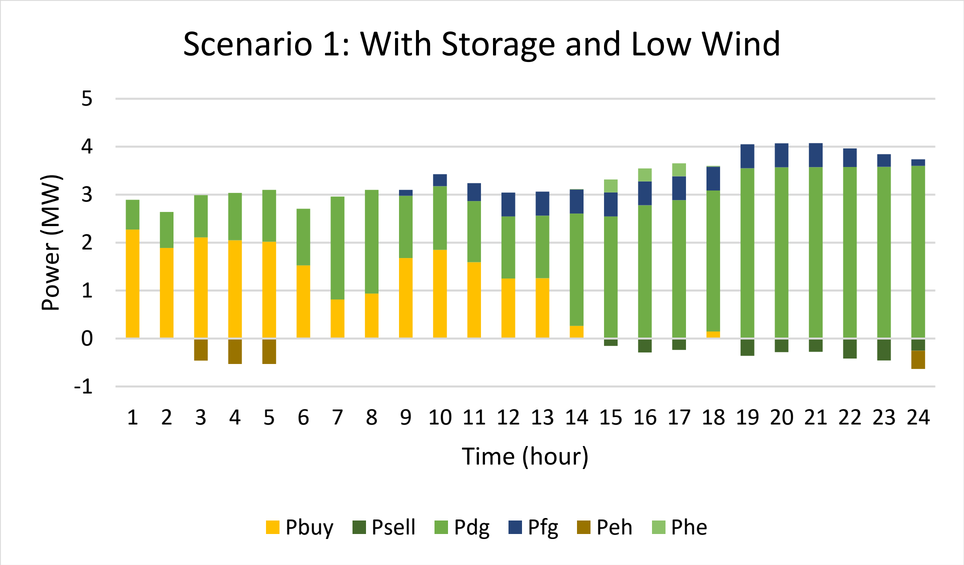

Figure 14. Scenario 1 with low wind speed: dispatch with storage.

Figure 15 illustrates the yearly operation cost of the microgrid depending on various hydrogen production and storage technologies. As per the figure, the most economical option to use in the test grid would be an SOE electrolyzer along with a compressed gas storage system which equals a daily operating cost of $ 477.97. The next best options would be to use an AWE electrolyzer, PEM electrolyzer and SMR reactor respectively along with a compressed gas storage system. For all of the instances where liquid hydrogen is used as a storage medium, the storage establishment cost seems to be too high to get them integrated with the system that would be profitable, therefore the operation cost in these cases is the same as the operation cost of the system without storage which is $ 519.36. Hence these options are not viable when the objective is to minimize the operating cost.

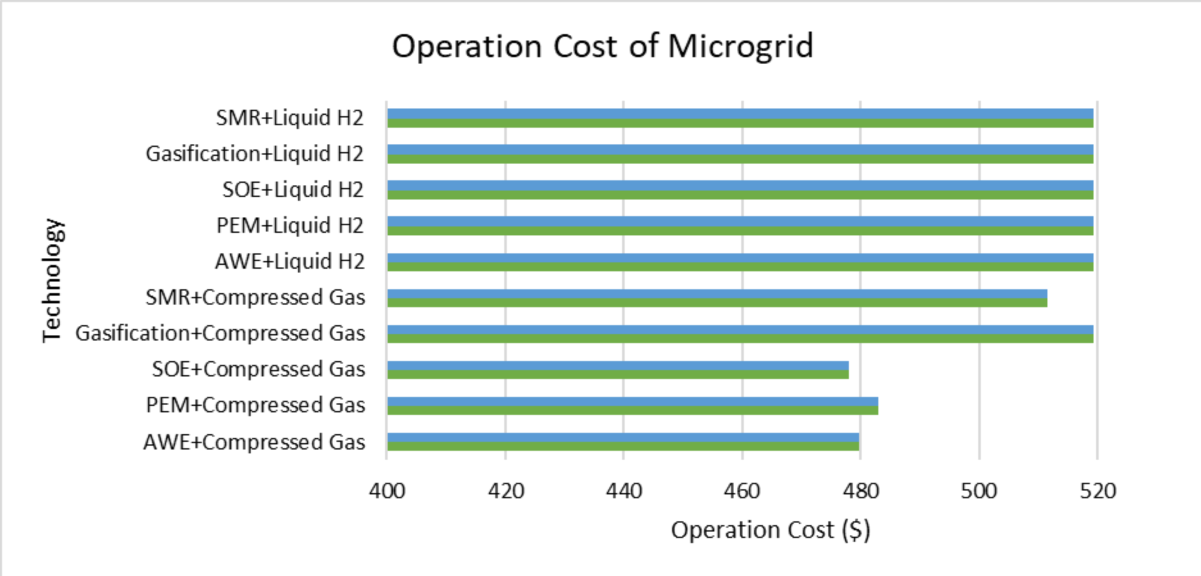

Figure 15. Scenario 1: operation cost of microgrid as per different technologies.

Figure 16 illustrates the yearly operation cost of the test system as per the number of storages when the SOE electrolyzer is considered for generating hydrogen and compressed hydrogen tanks are used for storing hydrogen. According to the figure, incorporating a storage system with the microgrid would be beneficial for the system economically and operation costs can be further reduced by increasing the number of storage solutions.

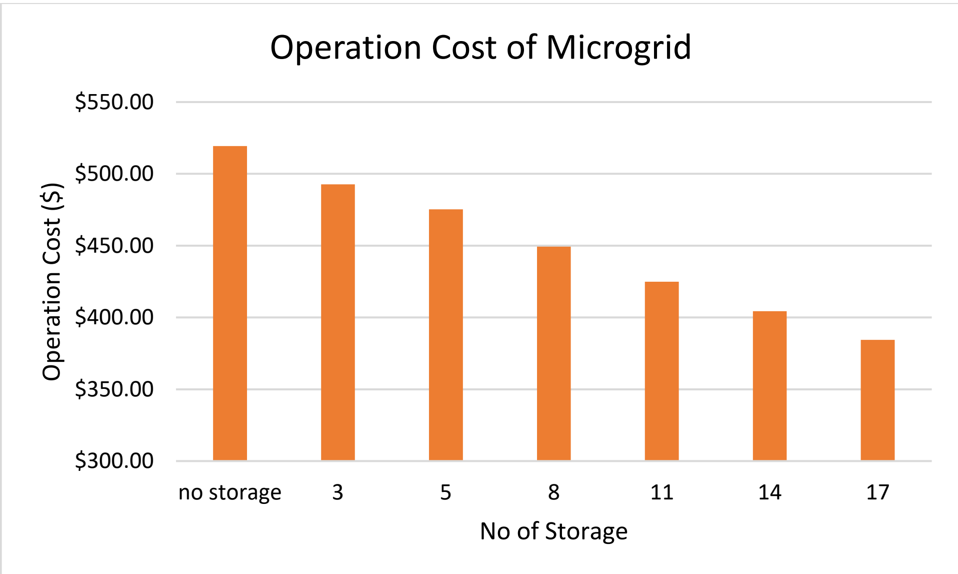

Figure 16. Scenario 1: operation cost of microgrid as per number of storage systems.

7.2 Scenario 2

In scenario 2, the demand share is almost similar to scenario 1 but the wind power output pattern is reserved. Here in the first half of the day, there is abundant wind speed while in the second half, wind power output is quite low. The system was first analyzed without a hydrogen storage solution and figure 17 depicts the hourly dispatch of grid power, wind power and non-renewable generators. Since wind output power is low from hours 10 to 24, the major portion of the demand is fulfilled by buying electricity from the grid while the contribution of renewable and non-renewable generators is smaller. From hours 2 to 9, there is sufficient renewable electricity production to fulfill the demand so no electricity is bought from the grid in this period, instead electricity produced by non-renewable generators is sold back to the grid.

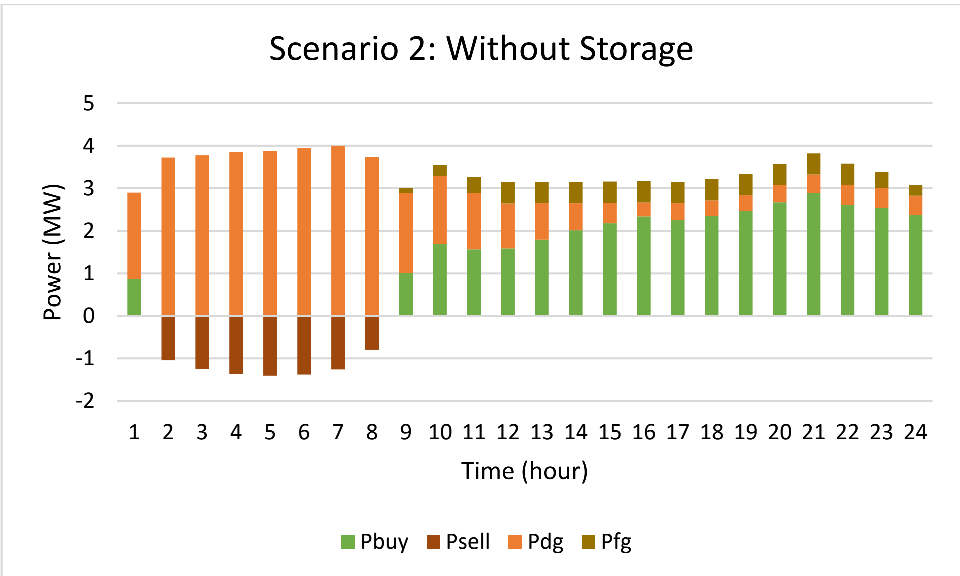

Figure 17. Scenario 2: dispatch without storage.

Figure 18 depicts the dispatch power of microgrid components when a storage system is added to the system. As the electricity buying price is lower from hours 3 to 5 ranging from \$0.02-\$0..21, hydrogen storage gets charged. Conversely, from hours 15 to 17, hydrogen storage gets discharged to provide electricity during peak demand timeframe from hours 16 to 24. The electricity selling price for hours 15 to 17 is in the range $0.035-$0.15, this is the timeframe with the high electricity price rate so the storage system is discharged to provide electricity to load partially. By introducing a storage system, renewable energy spillage is lessened by 2.59 MW per day. This proves incorporating a hydrogen storage system in this scenario would lower differences between demand peaks and valleys to minimize the operation cost.

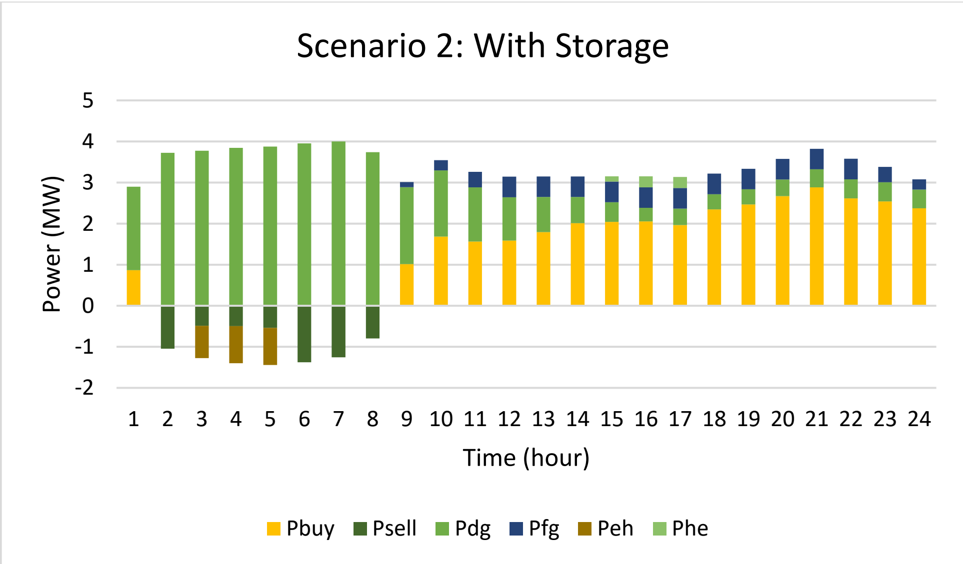

Figure 18. Scenario 2: dispatch with storage.

Figure 19 depicts the dispatch pattern of microgrid components when wind availability decreases by 10% for an operating day. In the event of low wind, the microgrid has to buy a significant amount of electricity from the grid which is 7.4% higher than the amount when there is regular wind availability. This increases the daily operation cost by 10.63%, therefore hydrogen storage can be used to lower the operation cost in such extreme conditions. The effect of low wind speed on system performance is less sensitive for scenario 2 compared to scenario 1. The charging and discharging pattern of the storage solution is similar to that of storage in normal weather which can support the load from hours 15 to 24. This shows hydrogen storage increases the system's resilience in case of extreme situations keeping the operation cost as low as possible.

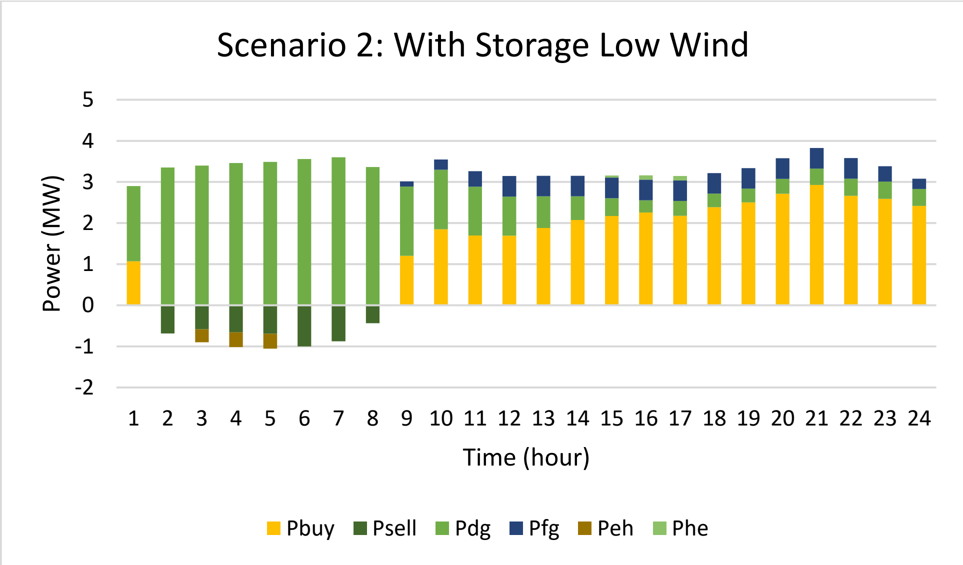

Figure 19. Scenario 2 with low wind speed: dispatch with storage.

Figure 20 illustrates the yearly operation cost of the microgrid depending on various hydrogen production and storage technologies. As per the figure, the most economical option to use in the test grid would be an SOE electrolyzer along with a compressed gas storage system which equals to an operating cost of $ 2,686.23. The next best options would be to use an AWE electrolyzer, PEM electrolyzer and SMR reactor respectively along with a compressed gas storage system. If liquid hydrogen is to be used as a storage medium, only SOE or AWE electrolyzer seems to be the production method option that would result in optimized operation. For all other instances, the storage installation cost seems to be too high to get them integrated with the system which would be profitable, so the operation cost in these cases is the same as the operation cost of the system without storage which is $ 2,736.47. Hence these options are not viable when the objective is to minimize the operating cost.

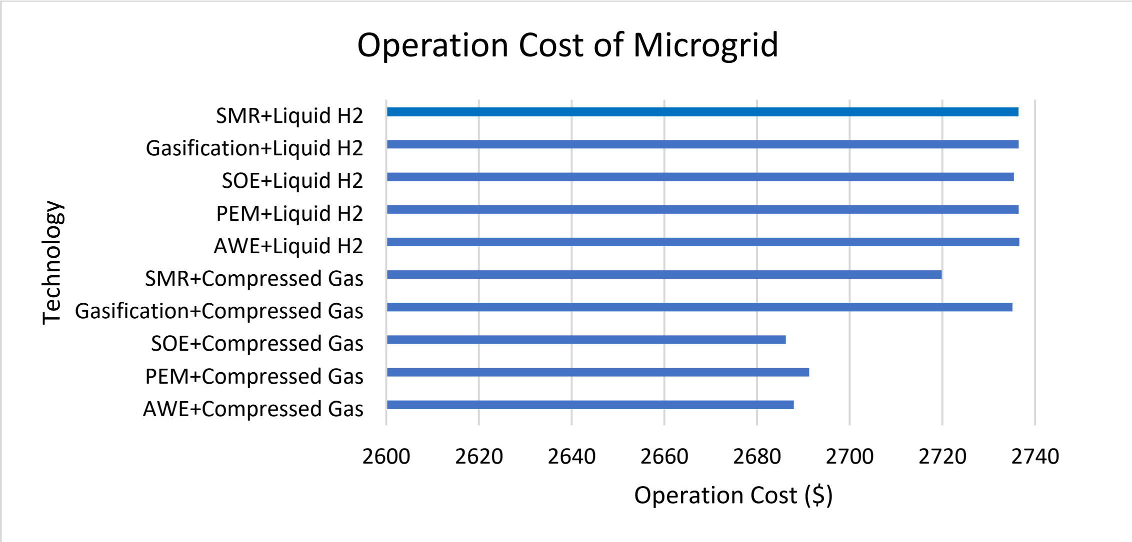

Figure 20. Scenario 2: operation cost of microgrid as per different technologies.

Figure 21 illustrates the yearly operation cost of the test system as per the number of storages when the SOE electrolyzer is considered for generating hydrogen and compressed hydrogen tanks are used for storing hydrogen. According to the figure, incorporating a storage system with the microgrid would be beneficial for the system economically and operation costs can be further reduced by increasing the number of storage solutions.

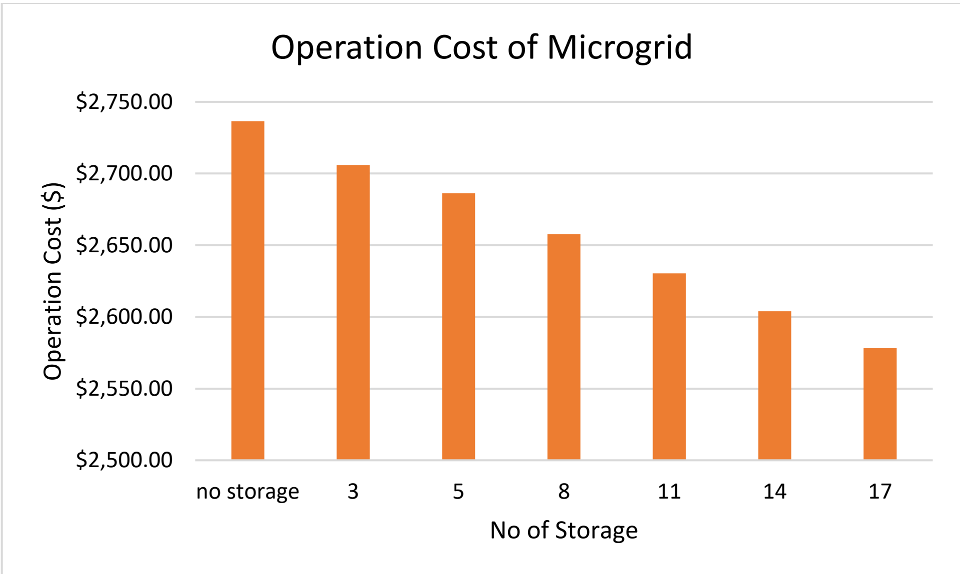

Figure 21. Scenario 2: operation cost of microgrid as per number of storage systems.

Figure 22 shows the comparison of the dispatch of different components in Scenario 1 and Scenario 2. Wind power output is lower for scenario 2 is 40% lower than scenario 1 due to low seasonal wind speed. Hence in this case, grid power availability is more crucial and the electricity bought from the grid is almost 48% greater than the electricity bought from the grid in case of scenario 1. More storage might be required in case of scenario 2 to reduce the imported power from the grid. The storage system dispatch for scenario 2 is almost 20% greater than that of scenario 1. This indicates that the storage system is more beneficial during periods throughout the year when wind speeds are low. By having a storage system in place, energy can be stored during times of higher wind speeds and then dispatched during times of low wind speeds, thereby ensuring a more consistent and reliable energy supply. This results in more efficient utilization of the storage system and highlights its importance in scenarios with variable renewable energy sources like wind.

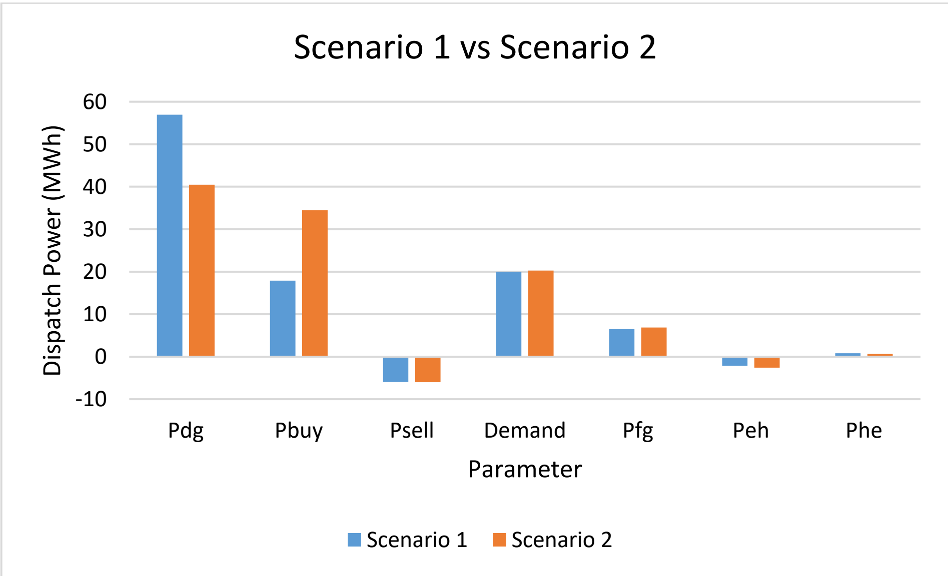

Figure 22. Dispatch power of different components in both scenarios.

8 Conclusion

This study presented a mixed integer non-linear programming model for cost optimization. The model was designed for a 33-node microgrid system with a grid-tied connection. A hydrogen storage system was incorporated with the system that consisted of production units, storage units and fuel cells. The aim of introducing a storage system was to buy electricity from the grid when the renewable power output is abundant as well as when the electricity price is low and utilize this stored energy in case of demand peak when the electricity price is high. Using the storage system in such a way would reduce the imported power from the grid as well as dependency on grid connection. Utilizing nearby resources for electricity instead of the main grid would lower the power loss as well as increase the reliability of the microgrid. Different types of hydrogen production and storage technologies were considered to see the technical and economic impact on the system performance.

Analysis revealed that integrating the storage system into the system would reduce the operation cost by 9% by including at least 5 storage sets in the system and this can be reduced further by increasing the number of storage sets. The most economical storage medium was found to be compressed gas tanks when hydrogen is produced by SOE electrolyzer followed by PEM and AWE electrolyzer. Conventional hydrogen production methods were found to be more expensive than green hydrogen production methods when long-term production costs were used in the calculation. On the other hand, using liquid hydrogen as the storage medium was found to be infeasible for the studied system. Storage systems could mitigate the renewable source variability by storing excess energy during high availability and discharging the energy during low availability. While this study shows integrating green hydrogen production and storage systems into the electricity network would be economical, there is scope for future research in this area. This can involve including maintenance and emission costs in the operation cost calculation, including gas network in the system etc.

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