Energy, Economic, And Environment (3E) Analysis of Green Hydrogen Production

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Session 2021-23

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November 2023

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A Thesis Submitted to the U.S.-Pakistan Center for Advanced Studies in Energy in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE in
ENERGY SYSTEMS ENGINEERING

U.S.-Pakistan Center for Advanced Studies in Energy (USPCAS-E)
National University of Sciences and Technology (NUST)
H-12, Islamabad 44000, Pakistan
November 2023

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Acknowledgments

All praises are due to Almighty Allah! the Lord of the Lords, who created this world and guided us to explore its hidden secrets.

To my esteemed family, my parents and my siblings, who have been my pillars of strength and unwavering support. Their love and encouragement have been my constant motivation, pushing me to strive for excellence.

I am deeply indebted to my supervisor, **Dr. Muhammad Bilal Sajid**, for his invaluable mentorship and guidance throughout my research journey. His expertise, passion, and unwavering confidence in me have been instrumental in shaping my research and propelling me towards success.

I am also grateful to my Guidance Examination Committee Members **Dr. Adeel Waqas, Dr. Kafait Ullah, and Dr. Syed Ali Abbas Kazmi** for their insightful feedback and constructive criticism. Their expertise and guidance have helped me refine my research and strengthen my understanding of the subject matter.

A special thanks to **Dr. Syed Ali Abbas Kazmi** for his extraordinary support throughout my master's degree. His mentorship, encouragement, and unwavering belief in me have been a source of constant inspiration and played a pivotal role in my academic as well as personal growth.

I am also immensely thankful to my friends and colleagues for their camaraderie, support, and encouragement. Their presence in my life made the journey all the more memorable and enjoyable.

Abstract

Transitioning to renewable energy is crucial for achieving a net-zero emissions target by 2050. Low-emission technologies like hydrogen, ammonia, and hydrogen-based fuels show significant potential in decarbonizing hard-to-abate emission industries such as heavy industry, refineries, chemicals, and long-distance transport. Green ammonia, produced from intermittent renewable sources like solar PV or wind through water electrolysis, can serve as a versatile hydrogen carrier, energy vector, shipping fuel, or decarbonized fertilizer. This research presents a comprehensive techno-economic and emission analysis of green hydrogen production in Pakistan, comparing traditional hydrogen production methods like Steam Methane Reforming (SMR) with a proposed green hydrogen production scenario powered by Renewable Energy Resources (RESs). The energy generated from renewable sources and the produced hydrogen were calculated using an analytical model. Additionally, a parametric analysis was conducted to assess the impact of variances in several parameters on the project's profitability. The LCOH was found to be USD 5.16 per kg H_2, with electricity and capital costs significantly influencing the overall costs of renewable hydrogen. Notably, water electrolysis demonstrated significant CO_2 emissions reduction compared to Coal Gasification and SMR. The study underscores the potential of green hydrogen and ammonia in decarbonizing hard-to-abate emission industries and emphasizes the role of policy recommendations in advancing green hydrogen production in Pakistan. The research findings are pivotal in addressing climate change, achieving decarbonization, fostering a green economy, and promoting sustainable development in the country.

Keywords: Green Hydrogen, Water Electrolysis, Renewable Energy, Levelized Cost of Hydrogen (LCOH), CO_2 Emissions Reduction

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List of Abbreviations

AEC	Alkaline Electrolyzer
AEMEC	Anion Exchange Membrane Electrolyzer
BCR	Benefit-Cost Ratio
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilization and Storage
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
DPP	Discounted Payback Period
GDP	Gross Domestic Product
GHG	GHG
HB	Haber-Bosch
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
IRR	Internal Rate of Return
kW	Kilowatt
kWh	Kilowatt Hour
LCOE	Levelized Cost of Electricity
LCOH	Levelized Cost of Hydrogen
LNG	Liquified Natural Gas
MMBTU	Million British Thermal Unit
MTOE	Million Ton of Oil Equivalent
MW	Megawatt

MWh	Megawatt Hour
NPV	Net Present Value
OPEX	Operational Expense
PEMEC	Proton Exchange Membrane Electrolyzer
POL	Petroleum, Oil, and Lubricant
PPA	Power Purchase Agreement
PtA	Power-to-Ammonia
PtG	Power-to-Gas
PtH	Power-to-Hydrogen
PtX	Power-to-X
PV	Photovoltaic
RESs	Renewable Energy Sources
SOEC	Solid Oxide Electrolyzer
SPP	Simple Payback Period
WT	WT

List of Publications

1. **Saqib Ur Rehman Mughal,** Muhammad Bilal Sajid, “Energy, Economic, and Environment (3E) Analysis of Green Hydrogen: A Case Study for Ammonia Production in Pakistan,” 3rd International Conference on Water, Energy, and Environment for Sustainability (IC-WEES) 2023. Presented on 16 August 2023.

2. Noor Saleem Khan, **Saqib Ur Rehman Mughal,** Kafait Ullah, Sayyed Ahmad Ali Shah, Shahid Nawaz Khan, Ahmad Salal, Syed Ali Abbas Kazmi, “Evaluation of net metering current status, issues and way forward amid economic crisis in developing countries: A Case Study of Pakistan,” Energy Policy (Under review)

3. **Saqib Ur Rehman Mughal,** Muhammad Nauman Sajid, Muhammad Bilal Sajid, “Green Hydrogen Production: Analyzing Various Scenarios of Power Purchase Agreement and Dedicated Onsite Solar PV and Wind Power Plants,” Renewable and Sustainable Energy Reviews (Submitted)

Chapter 01: Introduction

1.1. Background

Energy stands as an essential and ever-expanding necessity for humanity, serving as a primary catalyst propelling the global economy during today's era of industrial revolution and modern civilization. According to insights provided by the IEA, a roughly 4% surge in worldwide energy demand in 2021 was anticipated as economic activities rebounded to pre-pandemic levels, with a continuous upward trajectory projected [1]. Nevertheless, the challenge of meeting this escalating energy demand, particularly through the utilization of non-renewable sources like fossil fuels, presents a formidable dilemma for humanity, especially in developing nations. Fossil fuels currently account for nearly 80% of the world's primary energy supply, and the expected annual growth rate of global energy consumption hovers around 2.3% between 2015 and 2040, heightening the risk of atmospheric concentration elevation. This concentration elevation has nearly doubled since the inception of the fourth industrial revolution [2]. Regrettably, the role of sustainable energy resources within the existing energy framework of developing nations continues to lag behind the standards set by more developed countries. In countries such as Pakistan within the South Asian region, overdependence on traditional energy sources has contributed to escalating temperatures in numerous mountain ranges and an upsurge in inflation rates within the nation [3], leading to broader repercussions like global warming and pervasive poverty across the area. Over time, POL products have been vital in fueling Pakistan's economic sector and powering electricity generation companies, representing a substantial proportion of the country's energy mix. However, the contemporary contribution of POL products to this energy blend has declined to 22 percent, a marked reduction from its peak of 35 percent in 2006.

To address the imperative demand for oil, which encompasses both crude oil and POL products, Pakistan heavily depends on imports, with only a fraction being fulfilled through domestic resources. This substantial reliance on pricier imported oil has imposed a significant economic burden on Pakistan by driving up import expenses. For a long period, Pakistan has predominantly leaned on natural gas as a primary energy source, a pivotal means of meeting energy needs across diverse sectors. The discovery of the Sui gas field in Balochistan during the early 1950s marked a significant breakthrough, yet the rapid depletion of natural gas reserves has emerged as a pressing concern. To cater to the escalating gas demand across various sectors, the government has turned to the import of LNG over the past decade. As a result, both domestically sourced natural gas and imported LNG collectively account for over 40 percent of the present energy mix in Pakistan [4].

The energy sector plays a crucial role in a country's economic development, with rising energy demand driven by economic growth, population expansion, and technological advancements. However, this sector faces challenges, notably the long-standing issue of circular debt. In FY2013, circular debt was approximately Rs 450 billion, soaring to Rs 1148 billion in 2018, and further escalating to Rs 2467 billion by March 2022, equivalent to 3.8% of Pakistan's GDP and 5.6% of its government debt. Left unaddressed, it's projected to reach Rs 4 trillion by 2025, emphasizing the need for urgent power sector reforms [5]. Despite persistent efforts, Pakistan's energy deficiency remains unresolved, aggravated by population growth and urbanization, leading to frequent power outages or load shedding. Natural gas, a vital industrial and domestic energy source, is being depleted, contributing to a worsening energy crisis. Notable breakdowns in electricity and gas supply systems have occurred since 2015 [6], partially due to the country's increasing dependence on imported LNG due to dwindling domestic reserves. Circular debt in the gas sector has surged, nearly doubling from Rs 350 billion in 2018 to Rs 650 billion. Government mismanagement hindered private sector LNG imports, exacerbating a gas crisis, particularly during winter, and affecting power plant industries and CNG stations [7].

1.2. Energy Situation in Pakistan

Pakistan, categorized as a third-world nation, has been consistently grappling with a persistent energy crisis over the past two decades. In the past decade, Pakistan faced a pronounced energy crisis impacting diverse sectors. Roughly 145 million people, predominantly in rural areas, lacked electricity access. Prolonged power outages lasting 12 to 14 hours significantly contributed to a decline in the country's economic growth

[8][9]. This energy deficit has compelled numerous industrial establishments to cease operations, resulting in a substantial loss of employment for approximately 500,000 workers due to the resultant slowdown in industrial activities [10].

To address the challenge of enhancing energy provisions, mitigating reliance on fossil fuels, and effectively combating climate change, Pakistan must undertake a significant expansion of its energy supply framework, placing a pronounced emphasis on the integration of RES. As depicted in the Pakistan Economic Survey of 2022, the country's prevailing energy composition for the same year reveals a nominal 6.2% contribution originating from renewable sources, specifically solar and wind, concerning the overarching energy generation capacity. In response to these intricately linked predicaments, the global adoption of RES has gained noteworthy momentum recently, propelled by a mounting environmental consciousness aimed at curbing GHG emissions and the ascending trend in fuel costs, thereby exerting a commensurate upward influence on energy pricing [11].

Intriguingly, amidst such a challenging backdrop, Pakistan has not yet embraced the incorporation of hydrogen within its national energy portfolio [12]. The integration of hydrogen energy into the country's energy landscape can also address the pressing concern of escalating GHG emissions, which pose a substantial threat not only to Pakistan but to the global community as a whole. Pakistan stands poised to harness its inherent capacity for substantial green hydrogen production, a resource with the capability to satisfactorily meet the energy demands of critical sectors within the nation, including the electricity and transportation sectors. This contrasts with the global trend in which several countries are progressively transitioning toward a hydrogen-based economy. The notable expansion of hydrogen's prominence can be attributed to recent advancements in hydrogen fuel cell technologies, holding the potential to supplant the necessity for fossil fuels in electricity generation. Furthermore, the growing market confidence in hydrogen-driven vehicles has further bolstered the prospects of hydrogen, with the anticipation that such vehicles will eventually replace their petroleum counterparts [13]. In the context of Pakistan's energy crisis, hydrogen energy emerges as a pivotal player with the potential to alleviate the prevailing predicament. Consequently, Pakistan's abundant reservoir of RESs positions the country favorably for efficient green hydrogen production.

1.3. Problem Statement

Despite the significant research on the economic viability of green hydrogen production in developed countries, there exists a critical gap in the knowledge base concerning developing countries like Pakistan. No comprehensive and in-depth techno-economic and emission analysis, coupled with an incorporated parametric study, has been conducted to assess the feasibility and potential of green hydrogen production in the context of Pakistan.

1.4. Aim and Objectives

The primary goal of this study is to assess the potential for transitioning Pakistan's hydrogen utilization, particularly in ammonia fertilizer production, from fossil fuels to green hydrogen derived from renewable sources. By conducting a thorough techno-economic and emissions analysis, this research seeks to fill the existing gap in understanding the implications of hydrogen usage in Pakistan's energy landscape. Specifically, the study aims to evaluate the current dependency on fossil fuels, mainly natural gas, for ammonia synthesis, which contributes significantly to annual CO_2 emissions. The ultimate objective is to explore the feasibility and viability of incorporating green hydrogen production into Pakistan's energy mix, thereby contributing to sustainable agricultural practices, reducing emissions, and addressing energy and environmental challenges. The main objectives of the study are:

1. Conduct a comparative assessment of grey/blue hydrogen production processes within Pakistan's industrial sector, with a focus on evaluating energy consumption, CO_2 emissions, and the availability of resources.
2. Perform a thorough techno-economic evaluation of green hydrogen production in Pakistan, with specific attention to analyzing electricity costs, assessing capital investments, and identifying potential avenues for cost reduction over time.
3. Quantify the environmental impact associated with green hydrogen production in Pakistan, encompassing considerations of CO_2 emissions, water consumption, and land requirements.

4. Formulate well-informed and evidence-based policy recommendations derived from research findings and analysis, with the objective of advocating for the advancement of green hydrogen production and its subsequent utilization. These recommendations are intended to be directed towards government entities and pertinent stakeholders.

1.5. Scope

The scope of the study is to comprehensively investigate and assess the techno-economic and environmental feasibility of green hydrogen production in Pakistan, specifically focusing on its integration with RESs like solar, and wind.

1.6. Limitations

While this research study presents promising opportunities and valuable insights into the potential of green hydrogen production in Pakistan, there are certain limitations that should be acknowledged. Firstly, the study relies on hourly and monthly weather data obtained from the climate database, which may have inherent uncertainties and limitations in accurately capturing localized weather variations. Secondly, the equipment specifications used in the research are primarily based on existing literature, which might not fully reflect the latest advancements or specific variations in technology available in the market. Additionally, it is essential to note that experimental validation of the proposed models and technologies is beyond the scope of this work. Consequently, while the study endeavors to offer a comprehensive analysis, the absence of experimental validation may introduce some uncertainty in the actual performance and outcomes of the proposed green hydrogen production system.

Summary

This chapter provides an in-depth introduction to the energy challenges faced by Pakistan and the urgent need to transition from fossil fuels to renewable energy resources, particularly green hydrogen. It highlights the escalating energy demand in Pakistan, the overreliance on fossil fuels, and the economic and environmental consequences of this reliance. The chapter emphasizes the growing importance of RESs and green hydrogen in addressing these challenges. The research aims to assess the feasibility and potential of green hydrogen production in Pakistan through a comprehensive techno-economic and environmental analysis, with a focus on its use in ammonia fertilizer production. The chapter outlines the objectives and scope of the study, along with acknowledging its limitations, ultimately setting the stage for a thorough investigation into Pakistan's transition to green hydrogen as a sustainable energy solution.

Chapter 02: Literature Review

2.1. Hydrogen and Energy: A Historical Nexus

Throughout history, the intricate relationship between hydrogen and energy has catalyzed remarkable advancements across various domains. The 1800s marked a pivotal era as engineers marveled at the initial manifestations of water electrolysis and fuel cell technologies [14]. Astonishingly, more than two centuries ago, hydrogen found utility as a fuel source for the earliest internal combustion engines, foreshadowing its potential as an energy carrier [15]. Moreover, the 18th and 19th centuries witnessed hydrogen's role as a lifting agent for balloons and airships, while the 1960s saw its crucial propulsion role in mankind's voyage to the moon. Beyond the skies, hydrogen's significance reverberated on Earth through its integral support of global food production via ammonia fertilizer, initially synthesized from the reaction of electricity and water, later evolving to employ fossil fuels [16]. Notably, the mid-20th century witnessed the energy sector's embrace of hydrogen, as it became a ubiquitous component in oil refining processes, exemplifying its versatility in mainstream industrial applications [17].

The trajectory of hydrogen's intertwined journey with energy traverse centuries, from early scientific curiosity to contemporary sustainable energy endeavors. Sir William Grove's groundbreaking work in the 1830s illuminated the path toward fuel cells, a technology that would later find applications in diverse sectors [18]. This historical context underscores the continuity of human fascination with hydrogen and its pivotal role in shaping the energy landscape. As the world grapples with pressing challenges of environmental sustainability and energy security, the historical tapestry of hydrogen and energy convergence provides invaluable insights into its potential to revolutionize the future energy paradigm.

2.2. Why Hydrogen?

The road to achieving net zero emissions by 2050 necessitates the rapid and widespread deployment of clean energy technologies. Among these technologies, low-emission hydrogen, ammonia, and hydrogen-based fuels hold significant promise in decarbonizing sectors with hard-to-abate emissions, like heavy industry, long-distance transport, and chemicals. However, presently, the availability of these low-emission fuels remains limited, calling for immediate efforts to scale up their production and utilization. Such endeavors would not only reduce production costs but also enable the establishment of international supply chains, supporting regions with constrained capacity to produce these fuels domestically and meeting their surging demand for clean energy. Hydrogen, as a multifaceted energy carrier, plays a pivotal role in the global quest for decarbonization. Its unique characteristics enable it to be seamlessly transported, stored, combusted, or utilized as feedstock, mirroring the functionalities of conventional hydrocarbons presently employed. In the pursuit of carbon neutrality, hydrogen's paramount importance is underscored by its indispensable application across diverse sectors. When integrated synergistically with other cutting-edge technologies, such as renewable power and biofuels, hydrogen exhibits the potential to effectuate the decarbonization of highly emitting sectors, including steel production, heavy-duty transportation, and building heating, while concurrently facilitating flexible power generation and other diverse applications [19].

Hydrogen is garnering unprecedented global interest, emerging as a vital low-carbon energy solution amid progress in renewables and batteries. Its adaptability complements electricity infrastructure, enhancing energy security by converting electricity to hydrogen and back, while diversifying sources through fossil fuel and biomass-based production. This supports economic growth, enabling nations to export or import low-carbon energy, fostering competition and stability. Hydrogen's versatility across sectors, especially alongside declining renewables costs, helps match variable energy supply and demand. As renewables become cost-competitive, hydrogen emerges as a cleaner alternative, displacing fossil fuels in transport, heating, and industry. This synergy makes hydrogen a pivotal technology for fostering low-carbon energy growth, with its economic viability increasingly compelling for sustainable development [20].

The comprehensive value chain, spanning from electricity generation to the manifold applications of hydrogen, is commonly denoted as PtX. An endeavor to precisely classify distinct PtH - HtX pathways was proffered by Dickinson et al. in 2017 [21]. An overview of the technology pathways involved in the green hydrogen and Power-to-X value chain is illustrated in Figure 1.

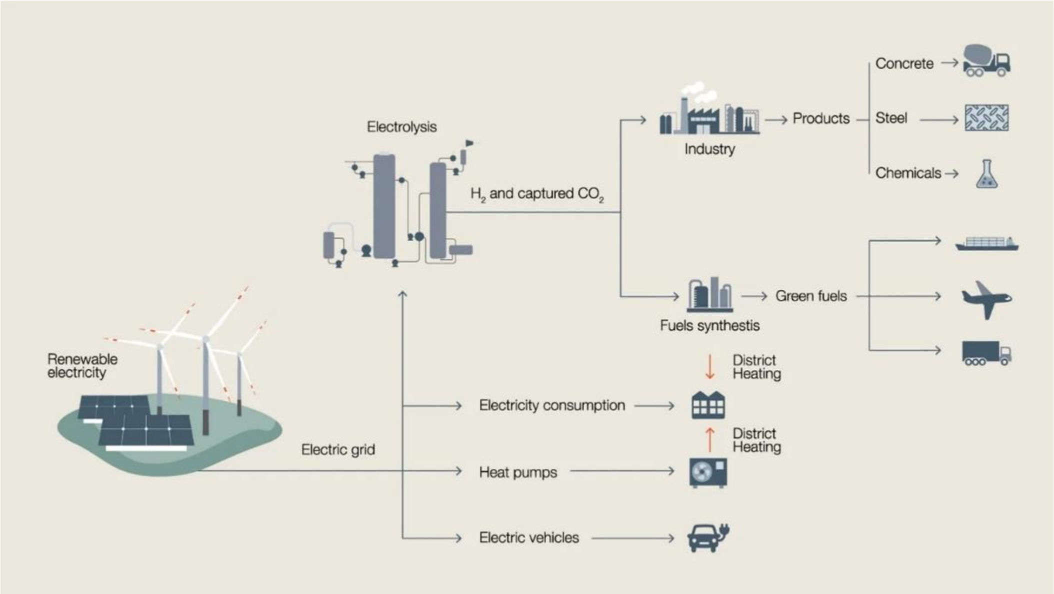
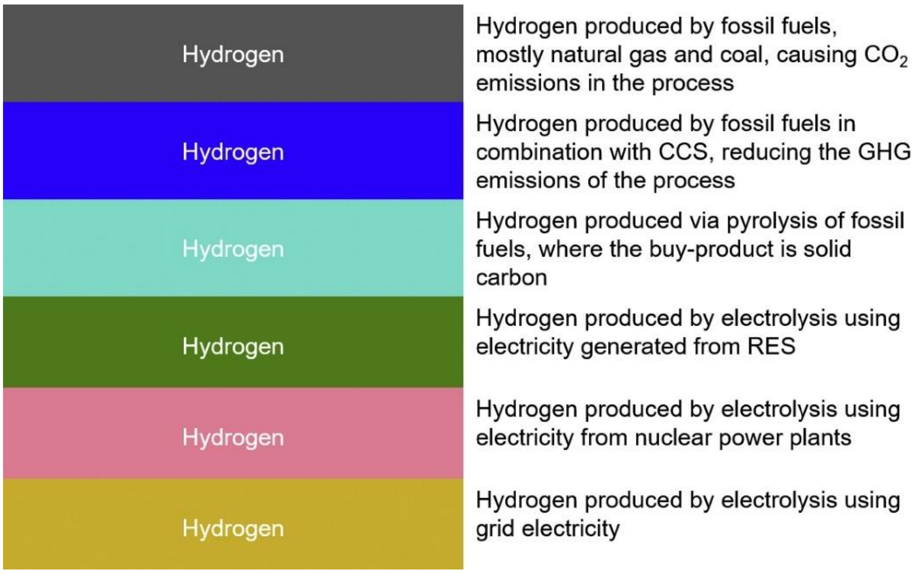


Figure 2.1: Power-to-X value chain involving different technology pathways.

The utilization of PtH principles for demand management, seasonal storage, and cross-sectoral integration among various domains (such as electricity generation, gas networks, transportation, and industrial sectors) has garnered substantial attention over the past decade. PtH plays a pivotal role in assimilating variable renewable power sources by converting electrical energy into hydrogen. These PtH systems can be deployed either within or outside the power grid and serve as a means to avert the curtailment of electricity production. They offer grid stabilization services and facilitate the incorporation of greater amounts of renewable electricity into emerging applications through the creation of environmentally friendly gas, chemicals, and fuels [22]. This functionality is enabled by the rapid adaptability of hydrogen generation via electrolysis, which can swiftly attain full-load operation within a matter of seconds [23]. Moreover, hydrogen and other chemical energy carriers hold the potential to enable extensive, cost-effective, and long-term energy storage at scale.

2.3. Different Shades of Hydrogen

Hydrogen can be derived from various primary energy sources, leading to diverse hydrogen costs and associated emissions based on the production process and energy type employed. This variability has led to the classification of hydrogen generation technologies into different categories, often denoted by colors such as grey, blue, turquoise, green, purple, and yellow (Figure 2). In the scientific literature, the prevailing classification treats hydrogen production methods reliant on fossil fuels without CCUS as grey hydrogen, aligning with the majority of references [24]–[26]. Notably, some sources acknowledge alternative designations like brown hydrogen for coal gasification and differentiate between brown and black hydrogen based on coal type [27], [28], however these distinctions are less commonly adopted. Therefore, the prevailing practice of referring to all fossil fuel-derived hydrogen as grey hydrogen has been adopted.



Hydrogen	Hydrogen produced by fossil fuels, mostly natural gas and coal, causing CO_2 emissions in the process
Hydrogen	Hydrogen produced by fossil fuels in combination with CCS, reducing the GHG emissions of the process
Hydrogen	Hydrogen produced via pyrolysis of fossil fuels, where the buy-product is solid carbon
Hydrogen	Hydrogen produced by electrolysis using electricity generated from RES
Hydrogen	Hydrogen produced by electrolysis using electricity from nuclear power plants
Hydrogen	Hydrogen produced by electrolysis using grid electricity

Figure 1.2: Different Shades of Hydrogen

Various hydrogen production techniques exhibit differing levels of technological maturity. Well-established methods include the conversion of natural gas, coal, or oil through steam reforming or gasification, which result in CO_2 emissions unless managed through CCS or CCUS. Another developed yet less widely employed technology is methane pyrolysis, a non-oxidative thermal cracking of methane that offers potential for hydrogen generation [29]. Additionally, biomass can serve as a feedstock for pyrolysis, rendering the process carbon-neutral however susceptible to hydrogen content variations due to feedstock impurities [30]. Dark fermentation, an efficient process involving microbial conversion of waste biomass, offers a promising pathway for hydrogen production despite its current low technology maturity level [31].

Electrolysis, a method involving the use of renewable electricity, is commonly associated with renewable hydrogen. Alternatively, hydrogen can be produced from RES through steam reforming of biomass. While biomass-based processes hold potential for future hydrogen production, scalability and competitiveness improvements are necessary to achieve significant volumes [32]. However, if grid-based electricity powers electrolytic hydrogen production, it cannot be categorized as green hydrogen due to its dependence on fossil fuel-powered plants (excepting Norway and Iceland). Such hydrogen generated from grid electricity is termed yellow hydrogen [33]. Various production pathways for hydrogen are illustrated in Figure 3.

Dawood et al. [34] and Nikolaidis et al. [30] provide comprehensive insights into various hydrogen production methods, encompassing a broad range of technologies and their respective maturity levels. Emerging hydrogen production technologies, such as membrane reactors and anion exchange membranes, exhibit high efficiencies of up to 90%.

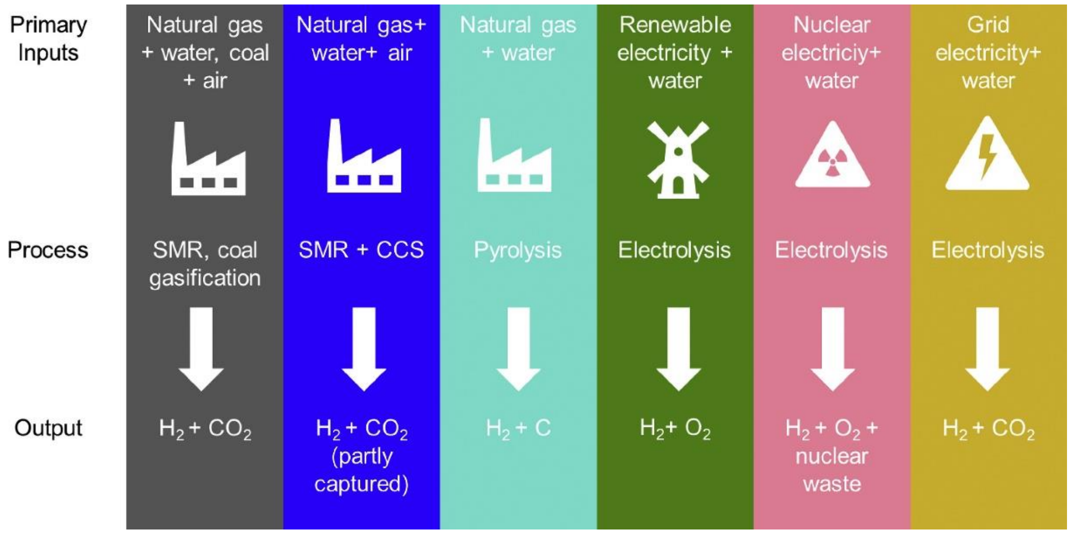


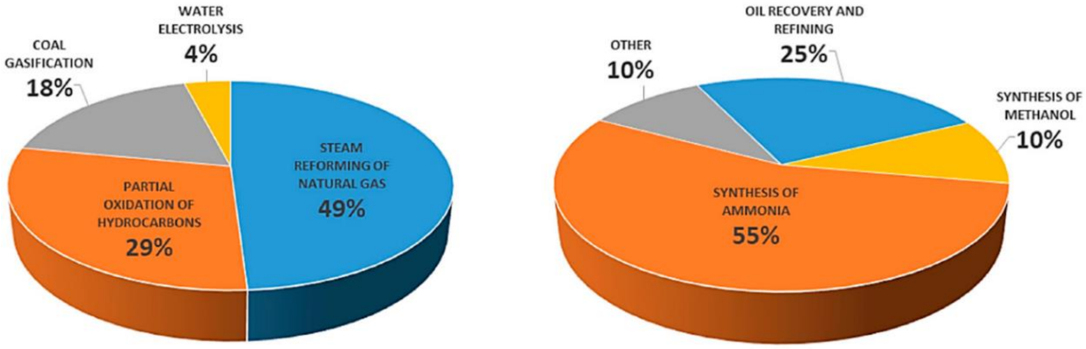
Figure 2.3: Hydrogen production pathways

In recent times, colors have been adopted to denote various origins of hydrogen generation. The terms "Black," "Brown," and "Grey," are indicative of hydrogen derived from coal, lignite, and natural gas, correspondingly. The descriptor "Blue" is commonly employed for hydrogen production from natural gas, wherein CO_2 emissions are mitigated through CCUS techniques. The label "Green" pertains to hydrogen obtained from renewable electricity sources. [35].

The industry's usage of color-based terminologies to describe different production technologies, such as "grey" hydrogen (produced from unabated fossil fuels), "blue" hydrogen (produced from fossil fuels with CCS), and "green" hydrogen (produced using renewable electricity in electrolyzer), as well as terms like "sustainable," "low-carbon," or "clean" hydrogen, has led to impracticality in forming investment contracts.

2.4. Environmental Aspects of Hydrogen

The current decade holds immense promise for hydrogen as it garners unprecedented attention worldwide and might just be the turning point for its realization as a dependable source of sustainable energy. The global demand for pure hydrogen stands at approximately 70 million tons per year (MtH_2/yr). Presently, the majority of this hydrogen is derived from fossil fuels, with hydrogen production consuming around 6% of the world's natural gas and 2% of global coal reserves. The global hydrogen production from various sources as well as global hydrogen consumption in different sectors is illustrated in Figure 4 [36]. In terms of energy consumption, the total annual global demand for hydrogen is about 330 Mtoe, surpassing the primary energy supply of Germany. Hydrogen is extracted from fossil fuels, biomass, or water, accounting for 275 Mtoe of energy use (2% of global primary energy demand) [35]. Notably, 830 $MtCO_2$/year are emitted due to hydrogen production's heavy reliance on natural gas and coal, releasing 10 tCO_2/tH_2 from natural gas, 12 tCO_2/tH_2 from oil, and 19 tCO_2/tH_2 from coal, equivalent to the combined carbon emissions of Indonesia and the United Kingdom [37].



(a) (b)

Figure 2.4: (a) Global Hydrogen Production (b) Global Hydrogen Consumption

Hydrogen plays a vital role in today's energy sector, with a demand of 94 million metric tons (Mt) in 2021 [38], primarily in refining and industrial applications. The production of hydrogen, if reliant on unabated fossil fuels, can lead to emissions of up to 27 kg CO_2-eq/kg H_2, influenced by upstream and midstream emission factors. Global hydrogen production in 2021 average emissions intensity within the range of 12-13 kg CO_2-eq/kg H_2. The IEA's Net Zero by 2050 Scenario envisions a trajectory where average emissions intensity decreases to 6-7 kg CO_2-eq/kg H_2 by 2030 and further plunges below 1 kg CO_2-eq/kg H_2 by 2050 [39].

Hydrogen production through renewable electricity demonstrates zero associated emissions, yielding 0 kg CO_2-eq/kg H_2. However, for grid electricity-based production, emission intensity varies notably between peak load and baseload hours [40], contingent on the technology harnessed to satisfy additional electrolyzer demand. Employing unabated natural gas for hydrogen generation results in an emissions intensity spanning 10-14 kg CO_2-eq/kg H_2, wherein methane and CO_2 upstream and midstream emissions from natural gas extraction contribute 1-5 kg CO_2-eq/kg H_2. Retrofitting existing assets with approximately 60% CO_2 capture capability from natural gas feedstock usage can lower emissions intensity to 5-8 kg CO_2-eq/kg H_2. Advanced technologies enable higher capture rates exceeding 90%, potentially driving emissions intensity down to 0.8-6 kg CO_2-eq/kg H_2, although operational plants utilizing these advancements are yet to be established. Notably, at elevated capture rates, upstream and midstream emissions retain dominance, accounting for 0.7-5 kg CO_2-eq/kg H_2 of hydrogen production's emissions intensity [39].

2.5. Hydrogen Via Electrolysis

Electrolyzer represents a critical technology facilitating the production of low-emission hydrogen by harnessing renewable or nuclear electricity. The electrolyzer technology landscape is dominated by AEC, which makes up 60% of global manufacturing capacity in 2021. By 2030, AEC are projected to account for 64% of manufacturing capacities, followed by PEMEC at 22%. Other emerging technologies, such as SOEC and AEMEC, hold a minimal share of the installed capacity. The cost of an installed electrolyzer varies depending on the technology used, with AEC generally cheaper than PEMEC, especially those produced in China, which can be as low as USD 750-1300/kW [38].

Commercially available technologies encompass alkaline and PEMEC, while emerging technologies such as SOEC and anion exchange membranes are maturing in the market. AEC boasts a mature status, having a substantial deployment history in the chloralkali industry. In contrast, PEM technology, although commercially viable, remains approximately 30% more expensive than alkaline systems despite significant cost reductions achieved through dedicated research and development efforts. Comparing electrolyzer capital costs across systems can be challenging due to the dearth of comprehensive information regarding system scope and key parameters. Over recent decades, cost reductions for alkaline technology have been relatively moderate, while PEM technology has witnessed substantial cost reductions primarily driven by R&D advancements. Presently, the CAPEX requirements for an installed AEC system range from USD 500-1,400/kWe, whereas PEM systems vary between USD 1,100-1,800/kWe. SOEC estimates, on the other hand, fall within the range of USD 2,800-5,600/kWe. As hydrogen production and utilization continue to evolve, ongoing advancements and investments in these electrolyzer technologies will be instrumental in fostering their wider adoption and contributing to the progression towards a low-emission energy landscape [41].

The production and value chain of green hydrogen incur substantial energy losses. Roughly 30-35% of the energy used in electrolysis to produce hydrogen is lost, and further conversion to other carriers like ammonia can result in 13-25% energy loss. Transporting hydrogen requires additional energy inputs equivalent to around 10-12% of the hydrogen's energy. Using hydrogen in fuel cells can lead to an additional 40-50% energy loss, with the total energy loss depending on the final use of hydrogen. To produce green hydrogen, electricity can be supplied from a renewable energy plant directly connected to the electrolyzer, from the grid, or a combination of both. While grid-connected electrolyzer can reduce the cost of hydrogen by producing for more hours, the sustainability of hydrogen depends on the associated CO_2 emissions from fossil fuel-generated electricity. The production cost of green hydrogen depends on the investment cost of electrolyzer, their capacity factor, and the cost of renewable electricity. Low-capacity factors and high investment costs can lead to higher green hydrogen costs, however as the facility load factor increases, the electricity price becomes a more relevant cost component in the final hydrogen production cost per kilogram [42].

2.6. Ammonia; Hydrogen's Derivative

Ammonia (NH_3) is a vital industrial chemical synthesized through the HB process [43]. It ranks as the second most produced chemical by mass, following sulfuric acid. Ammonia is a high-volume chemical, with an annual global production of ~180 megatons (Mt) [44]–[47]. Ammonia production accounts for 1.3% of global energy demand and contributes approximately 1% of global GHG emissions. It is primarily utilized as a feedstock in industry, with about 70% of its global demand directed towards nitrogen fertilizer production and the remaining 30% serving various industrial applications such as explosives, synthetic fibers, and specialty materials. Its production relies on nitrogen extracted from the atmosphere and hydrogen sourced from feedstocks [39][45], [47]. The global yearly output of hydrogen is roughly assessed to be within the range of 45 to 50 million metric tons [48]. A significant portion of this hydrogen production, specifically around 28 million metric tons, is primarily allocated for the synthesis of ammonia and methanol. The fundamental process of ammonia production, characterized by the direct synthesis of hydrogen and nitrogen, commonly referred to as the (H-B) process, is anticipated to undergo limited transformative changes in the foreseeable future.

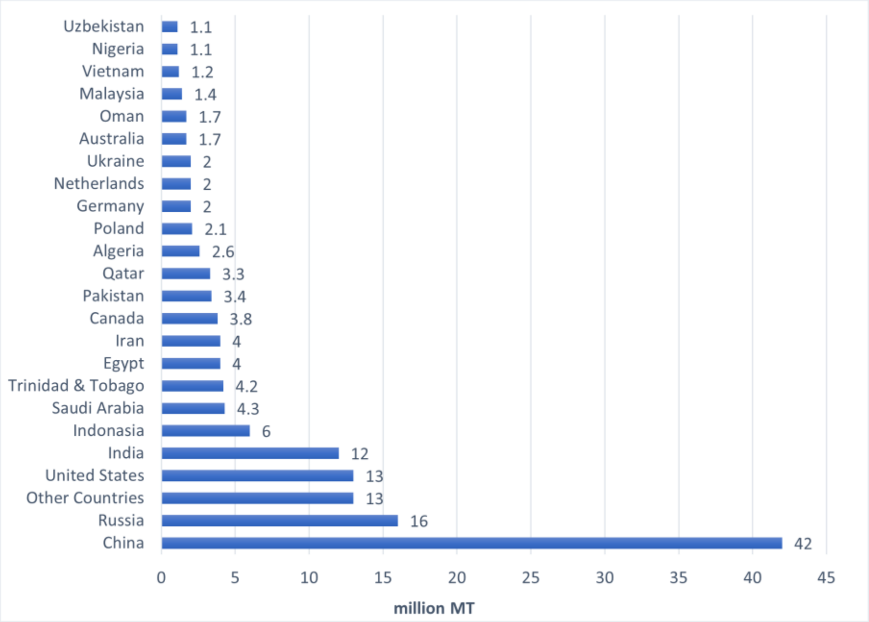


Figure 2.5: Global Ammonia Production in 2022 [49]

The chemical sector heavily relies on oil and gas to produce hydrogen and carbon for basic chemical production. Ammonia, a vital component in fertilizers, has experienced slow growth over the past decade, with production declining in Europe due to high natural gas prices. The chemical sector is expected to contribute around 5% of total CO_2 emissions to be captured by 2030 (excluding CO_2 used in urea production) and is projected to account for 11% of low-emission hydrogen consumption in the IEA's Net Zero Emissions (NZE) Scenario [50].

Present-day ammonia production is characterized by its substantial energy consumption and emissions output. Currently, ammonia production heavily relies on fossil fuels roughly 80% from methane and 20% from coal [47]. Notably, emissions from ammonia production stand at 10-15 kg CO_2-eq/kg H_2-eq for natural gas and 20-27 kg CO_2-eq/kg H_2-eq for coal, the latter being nearly twice as high. These ranges encompass both upstream and midstream emissions, accounting for variations of 4.5-28 kg CO_2-eq/GJ for natural gas and 6-23 kg CO_2-eq/GJ for coal, alongside 50-700 g CO_2-eq/kWh for grid electricity [39]. Scope 3 emissions account for over half of total GHG emissions from the ammonia sector (~0.6 Gt CO_2 eq/year). Around 80% of Scope 3 emissions occur downstream during fertilizer application, producing nitrous oxide (N_2O) and CO_2. The remaining 20% are upstream emissions from fossil fuel extraction, mainly fugitive methane. These emissions could substantially increase by 2050 if left unmitigated.

However, the ammonia production landscape could shift to net-zero-emissions routes by 2050, with green ammonia potentially accounting for 12%–38% of total production by 2030 and 69%–94% by 2050. This transformation is supported by declining costs of wind and solar power generation (expected to fall by 50%–70% by 2050) and falling electrolyzer CAPEX (reducing green ammonia costs by up to 50% relative to 2022) [51].

2.7. Global Hydrogen Scenario

In 2021, global hydrogen demand rebounded to 94 million tons (Mt), surpassing pre-pandemic levels (91 Mt in 2019). The majority of this increase came from traditional uses in refining and industry, however demand for new applications also grew, reaching about 40 thousand tons (up 60% from 2020). However, only a small fraction of hydrogen demand (less than 2 Mt) is expected to come from new uses by 2030 [38]. Meeting existing climate pledges would require around 130 Mt of hydrogen by 2030, with approximately 25% from new uses, and nearly 200 Mt would be needed to achieve net-zero emissions by 2050 [52].

Hydrogen will play a crucial role in various sectors for carbon neutrality. Forecasts indicate a soaring demand for hydrogen, projected to exceed a substantial 660 Mt by the year 2050. It is projected that hydrogen could provide a cumulative abatement of 80 Gt by 2050 equivalent to 20% of the annual emissions reductions needed to reach net zero by introducing renewable and low-carbon hydrogen [19].

As per the Global Energy Transformation report by IRENA, hydrogen is expected to have a significant impact in the energy sector, with its utilization from renewable sources projected to reach 7 exajoules (EJ) by 2050. Its primary application in the industrial sector will involve substituting natural gas and generating chemicals [53]. Global hydrogen production in 2021 stood at 94 million tons, representing about 2.6% of final energy consumption, with most usage in refining and industry. Governments' commitments to hydrogen production fall short of meeting the NZE Scenario targets, where low-emission hydrogen is expected to constitute over 50% of total supply by 2030 and almost 100% by 2050. Achieving these targets would be vital to transforming the global energy landscape and mitigating climate change [54].

However, the production cost of green hydrogen using electricity from a typical renewable energy plant in 2019 was found to be two to three times more expensive than grey hydrogen. Additionally, adopting green hydrogen technologies for various applications, such as fuel cell vehicles and synthetic aviation fuels, incurs significant costs, making them 1.5 to 2 times more expensive than their fossil fuel counterparts and up to eight times more expensive than fossil jet fuel. The economic viability of hydrogen production, particularly in its environmentally friendly form, faces a substantial challenge. The cost associated with producing hydrogen through steam reforming is approximately threefold higher per unit of energy output compared to the cost of natural gas. Similarly, employing electrolysis for hydrogen generation at an electricity rate of 5 cents/kWh results in a cost roughly double that of hydrogen production based on natural gas feedstock [55].

The production of low-emission hydrogen was limited to less than 1 Mt in 2021, primarily from plants using fossil fuels with carbon capture, utilization, and storage (CCUS). To produce low-emission hydrogen, electrolysis using low-emission electricity is crucial [38]. Given the present installed electrolyzer capacity of approximately 0.3 GW, it is evident that a substantial disparity must be addressed in order to meet the anticipated demand over the coming seven years. Bridging this considerable gap necessitates not only an ample supply of renewable energy but also a commensurate expansion in electrolyzer manufacturing capabilities [56]. Water electrolysis, which accounts for only 0.1% of global hydrogen production in 2021, is rapidly expanding, with the installed capacity of electrolyzer reaching 510 megawatts (MW) by the end of 2021, almost tripling the 2021 level expected to reach around 1.4 GW. Currently, the global electrolyzer manufacturing capacity stands at nearly 8 GW/yr, and based on industry announcements, it is projected to exceed 60 GW/yr by 2030. This scale-up in manufacturing capacities could lead to a significant drop in electrolyzer costs, potentially reducing costs by around 70% compared to today. Combined with the expected decline in renewable energy costs, this could bring the cost of renewable-based hydrogen to a range of USD 1.3-4.5/kg H2 (equivalent to USD 39-135/MWh) by 2030 [57].

A substantial body of literature exists in academic journals, spanning sustainability assessments and cost-benefit analyses of hydrogen production using RES across many countries. Notably, Sammy et al. [58] performed a comprehensive simulation and modeling of mathematical frameworks for techno-economic evaluation of power generation for rural areas in Egypt using diverse RESs. The sizing process was optimized using the Firefly Algorithm until the required outcomes were achieved. Subsequently, a comprehensive comparison of these results was carried out with those obtained from two other algorithms, namely Particle Swarm Optimization and Shuffled Frog Leaping Algorithms. Gökçek et al. [59] examined the technical and economic viability of a hydrogen refuelling station in Turkey driven by a battery-backed hybrid power plant (Wind-PV), with a predicted LCOH at USD 7.526 per kilogram and a LCOE at USD 0.16 per kWh. The projected surplus electricity production was estimated to be 41.1 percent. In a similar vein, Mojtaba et al. [60] employed the HOMER software to scrutinize the techno-economic viability of a Solar-Wind hybrid power system for hydrogen generation in Hendijan, Iran. Their hybrid facility yielded approximately 31,680 kilograms of green hydrogen and 31,53,762 kWh of electric power. Ma et al. [61] suggested a high-pressure hydro retention technique to supply off-grid electricity to Hong Kong, demonstrating its viability for solar energy integration, particularly for micro-automated systems in remote regions. The calculated optimal LCOE for this system was USD 0.289/kWh. A critical aspect of these mathematical frameworks is their construction, which addresses system stability and economic constraints as fundamental benchmarks for improvement.

Glenk [62] conducted a techno-economic comparative study between renewable hydrogen produced through the PIG route and conventional fuels, focusing on functional collaboration, sustainability, and competitiveness. His study established architectural frameworks that offer essential insights for private equity firms and policymakers. Furthermore, Glenk formulated four propositions supported by relevant equations and subsequently performed LCOE calculations for an off-grid wind power system and an off-grid PtG facility in Germany and Texas, respectively. Additionally, LCOH values of 2.54 €c/kWh and 2.47 Ec/kWh were determined, highlighting the potential impact of demand on the break-even cost of hydrogen. The economics of hydrogen production using PtG technology were explored from three perspectives: sustainability, operational synergies, and competitiveness with fossil-based alternatives. Al-Sharafi et al. [63] evaluated electricity generation possibilities and capacities through

PV and WT across various cities in Saudi Arabia, considering different climatic conditions. The lowest LCOE was found in Yanbu at USD 0.609 per kWh, utilizing solar, WT, and battery storage, while LCOH for the wind-rich city of Abha, with an electrical energy storage and hydrogen storage infrastructure, was calculated at $1.208 per kWh. A comparison was also drawn with similar facilities installed in Toronto and Sydney. Viktorsson et al. [64] explored a grid-connected Renewable Hydrogen Fueling Station in Halle, Belgium, powered by a PV-WT hybrid system, determining an LCOH estimate of 10.3 €/kg, with potential further reduction through government subsidies. To ensure the enduring viability of clean hydrogen fuel within future energy policies, the investigation of RES-fueled hydrogen filling terminals is crucial for developing a practical and cost-effective approach. Rahmouni et al. [65] utilized GIS software to map sites in Algeria and explored hydrogen production potential from RES, estimating significant potential from wind and solar resources.

Temiz et al. [66] presented and assessed a system for hydrogen production using a floating dock of solar cells that reducrd unmet power load from 49.34 percent to 0.57 percent. Kalinci et al. [67] modeled standalone wind-only and WT Generator-PV hybrid systems using HOMER, critically analyzing power generation and assessing system feasibility. Sizing, optimization, and economic analysis were carried out to identify the most effective system. Selamat et al. [68] detailed the construction steps for a highly efficient PEMEC package, enhancing performance through a single-cell electrolyzer and optimizing a ten-cell stack for improved performance. Hernández-Gómez et al. [69] analyzed existing models to elaborate on the electrical spectrum of PEMEC functioning, including dynamic operating problems and simulations of kinetics. Koponen et al. [70] investigated the SEC (kWh per m^3) of a PEMEC at different hydrogen exit pressures, finding a minimal impact on SEC from doubling the exit pressure. Lee et al. [71] compared the economics of water electrolysis and Steam Methane Reforming (SMR), concentrating on per unit hydrogen production costs, profitability, and market sensitivity. Various electrolysis methods, including PEM and Alkaline electrolysis, were compared. Tjarks et al. [72] analyzed energy consumption in the gas compression phase of an electrolyzer and refined net power requirements for a PIG facility, considering hydrogen drying by temperature swing adsorption and pressurization. Parra et al. [73] developed a dynamic PtG model and assessed the impact of electrolyzer aging on

ΠOVERALL, considering polarization curve and studying potential, LCOE, and financial gains from gas sales. Saba et al. [74] projected economic parameters for the next decade, comparing CAPEX and conducting cost analysis between PEM and AEC. Ghalavand et al. [75] examined systems predominantly used in seawater desalination, evaluating techniques based on SEC and OPEX per m^3.

D. Bellotti et al. [76] compared various energy storage media for hydrogen and found that ammonia exhibited the highest energy density by volume, with 108 kgH_2/m3 of storage. The study revealed that electricity purchase and electrolyzer costs contributed significantly to total expenses, indicating potential cost reductions of 30% and 18% through a 50% decrease in electricity cost and electrolyzer CAPEX, respectively. Notably, ammonia production cost (5.76€/kgH_2) was nearly equivalent to that of hydrogen (5.31€/kgH_2) on a mass basis. Houssam et al. [77] introduced an innovative Techno-Economic modeling approach to enhance the optimization of design and operations for a pilot-scale G-NH_3 plant. This study assessed the plant's TE performance using two main Key Performance Indicators (KPIs): HB Load Factor and LCOA. The optimal configuration identified was a PV/Battery system, with 6 MW of PV and 11 MWh of Battery capacity, resulting in an LCOA of 774 \$/tNH_3. Projections from 2021 to 2050 indicated a potential cost reduction to 250 \$/tNH3, suggesting the economic competitiveness of green ammonia with conventional fossil-fuel-based processes by 2030. In a recent study by Al-Orabi et al. [78], the potential of green hydrogen as a viable medium for storing Egypt's renewable energy was examined. The research considered various configurations across different sites, integrating solar PV, WT, electrolyzers, hydrogen fuel cells, and storage tanks. Among the tested setups, Configuration B, situated in Ras Ghareb, demonstrated the most favorable outcomes with the lowest NPV of 1.81 M \$, a minimal Cost of Energy at 0.3085 \$/kWh, and the lowest LCOH at 3.94 \$/kg. Configuration D exhibited the highest GHG emissions, producing 7,664 kg/year of CO_2. These findings underscore the potential of green hydrogen to efficiently store and utilize Egypt's RES.

As hydrogen-based technologies mature over the long term, their overall contribution is expected to significantly increase. In the interim, a short-term priority lies in replacing unabated fossil fuel-based hydrogen with low-emission alternatives in existing applications like the refining and industrial sectors, given the relatively lower technical challenges in accomplishing like-for-like substitutions. Efforts to advance low-emission hydrogen adoption and technology must be bolstered to accelerate progress towards achieving comprehensive decarbonization goals. From such literature reviews, it is clear that there is a need for an inclusive framework that considers key electrolyzer parameters, i.e., cost aspects like direct and indirect capital costs, performance parameters of different stack lifetimes, degradation rates, operating loads, etc., to assess the cost of generating hydrogen from PEM technology under different electricity supply configurations in the near and long term.

2.8. From the Perspective of Pakistan

Currently, Pakistan lacks a coherent Hydrogen economy roadmap or policy framework for integrating Hydrogen into its Fuel supply chain. Consequently, there is a notable scarcity of literature pertaining to the utilization of renewable resources for Hydrogen production within the country. In their study, Wasim Iqbal et al. [79] introduced a novel hybrid mathematical model that integrates wind-speed range and the log law. This model was utilized to estimate wind energy potential for hydrogen production through wind power in Pakistan. The researchers also performed electrolysis on wind-generated electricity to evaluate its capacity for renewable hydrogen generation. The results indicated the ability of all examined sites to yield surplus wind-generated renewable hydrogen. Utilizing the entire national wind-generated capacity, Pakistan could potentially produce a remarkable 51,917,000.39 kg of renewable hydrogen per day.

Khalil et al. [80] designed a hybrid framework involving PVs, WTGS, and converters in Balochistan, utilizing HOMER Pro for simulations and achieving reduced criterion air pollutants and emissions. Khalid et al. [81] developed an integrated hydrogen energy infrastructure for the domestic sector, considering energy and exergy efficiency, electrolyzer and fuel cell performance, and LCOE. Yaqoob et al. [82] performed a techno-economic study for a 50 MW wind facility across various locations in the wind-rich Sindh province of Pakistan, utilizing RETScreen for feasibility analysis. Hyderabad emerged as the optimal location with a 41.8 percent capacity factor and a payback period of 7.4 years. In their study, Huang et al. [83] evaluated renewable hydrogen production from natural sources (wind, solar, biomass, geothermal) in Pakistan using the FAHP method. Economic, commercial, environmental, and social factors were assessed, with wind emerging as the top choice, followed by solar. The research highlights hydrogen costs of \$5.30/kg to \$5.80/kg in Pakistan, establishing its competitiveness as an electric machinery fuel.

In light of Pakistan's ongoing energy deficiencies and the pressing need to reduce its reliance on fossil fuels and address climate change concerns, it is imperative for the nation to embark on a strategic path towards establishing a Hydrogen supply chain. Among the viable renewable options for Hydrogen production in Pakistan, wind, solar, and biomass have emerged as the primary candidates. Figure 6 presents a depiction of projected future costs associated with the production of green hydrogen utilizing renewable electricity sources on a global scale [38]. These cost estimations are based on assumptions regarding future developments in the field. In the context of Pakistan's energy security, particularly within its industrial sector, understanding these forthcoming cost dynamics becomes crucial. This is because these cost trends can have a significant impact on the feasibility and sustainability of adopting green hydrogen as an energy source for various industries in Pakistan. Given the prevailing global trends in Hydrogen energy, this endeavor would significantly contribute to mitigating Pakistan's energy challenges.

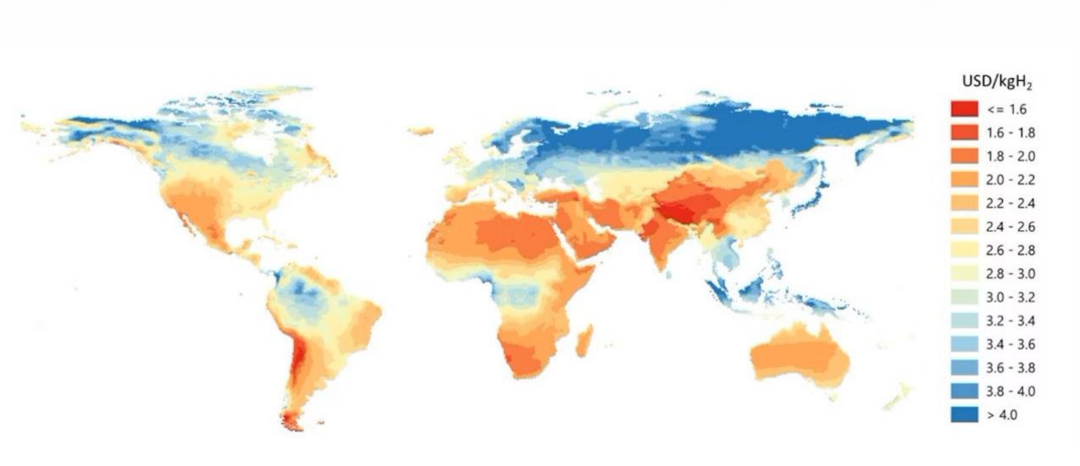


Figure 2.2: Future costs of green hydrogen production on a global scale

This study undertakes an in-depth assessment of Pakistan's renewable resources to ascertain their potential for generating Hydrogen. The country boasts a diverse range of RESs, encompassing Solar, Hydel, Biomass, Geothermal, and Wind energy [84]. These abundant resources can be harnessed to produce green hydrogen using the various conversion processes detailed earlier. Additionally, Pakistan possesses a variety of indigenous feedstocks and technologies that are well-suited for efficient hydrogen production. By examining the renewable energy landscape of Pakistan, this study provides a preliminary estimation of the feasible Hydrogen output. This assessment forms a foundational criterion for identifying the optimal resources and technologies that can serve as catalysts for initiating a Hydrogen Economy. Capitalizing on its favorable geographical and geological positioning, Pakistan is endowed with a rich assortment of renewable energy assets.

Summary

This chapter delves into the extensive literature review on the pivotal role of hydrogen in the energy landscape, explores the historical and contemporary relationship between hydrogen and energy, tracing its significance from the 1800s to modern times. Hydrogen's versatile role as a fuel source, lifting agent, and crucial component in various industrial processes is highlighted. The chapter delves into the reasons why hydrogen is gaining prominence in the pursuit of net zero emissions by 2050, emphasizing its potential to decarbonize challenging sectors like heavy industry and long-distance transport. The different production pathways and classifications of hydrogen, such as grey, blue, and green hydrogen, are discussed, considering their associated costs and emissions. The environmental aspects of hydrogen, particularly in terms of global production, consumption, and associated CO2 emissions, are outlined. Electrolysis, as a critical technology for low-emission hydrogen production, and ammonia as a derivative of hydrogen, are also examined. The global hydrogen scenario and its potential role in achieving carbon neutrality are presented, followed by a specific focus on Pakistan's perspective, assessing its renewable resources and potential for hydrogen production to address energy challenges and contribute to a hydrogen-based energy economy. Overall, the chapter provides a comprehensive review of hydrogen's historical context, its current significance, environmental implications, and the potential it holds for sustainable energy development.

Chapter 03: Methodology and System Design

In this chapter, the methodology framework is outlined for conducting a thorough techno-economic analysis and assessing the potential for emission reduction in the context of large-scale, decentralized hydrogen production infrastructure powered by renewable sources within Pakistan. Figure 7 illustrates the schematic of the research framework followed in the study. The approach is carefully tailored to the unique characteristics of the specific site. Despite the prevailing energy crisis, Pakistan exhibits strong viability for harnessing renewable energy through the establishment of solar and wind power plants.

3.1. Base Case

The case study focuses on a prominent ammonia-based urea fertilizer plant located in Pakistan, chosen as a representative example, with an annual production of 2 million tons. To meet the substantial demand, it requires more than 200,000 tons hydrogen annually which is being reacted with nitrogen to produce ammonia, a precursor of urea. The existing process employed for hydrogen generation entails SMR, wherein natural gas serves as the primary source of methane. Specifically, the production of 1 kg of hydrogen necessitates the utilization of 3.04 kg of natural gas [85]. Consequently, to generate the requisite volume of hydrogen, an aggregate of more than 30,000,000 MMBTU of natural gas is expended on an annual basis.

3.2. Proposed Case

The core objective of the proposed system under investigation revolves around the environmentally friendly production of green hydrogen. This is achieved by harnessing the power from RESs notably from solar PV and WT to generate electricity, which is then employed for a comparative analysis with the prevalent method of hydrogen production derived from natural gas, specifically in the context of ammonia manufacturing. To address sustainability concerns, a comprehensive environmental assessment is conducted with a focus on quantifying CO_2 emission reduction, water consumption, and land requirements. To ensure a realistic portrayal of the country's economic landscape, marked by elevated inflation rates and fluctuating policy rates from the State Bank of Pakistan, the analysis adopts the prevailing discount and inflation rates as set for the fiscal year 2022-2023 [86]. In the scope of this study, it was postulated that the procurement of electricity would be facilitated through the establishment of a PPA with a vendor specializing in the provision of 'green energy.' The term 'green energy' refers to electricity primarily sourced from solar PV and WT installations, benefiting from predetermined pricing structures within extended contractual arrangements. During instances of intermittent renewable energy availability, it was hypothesized that electricity procurement from the conventional grid would occur at a fixed average cost.

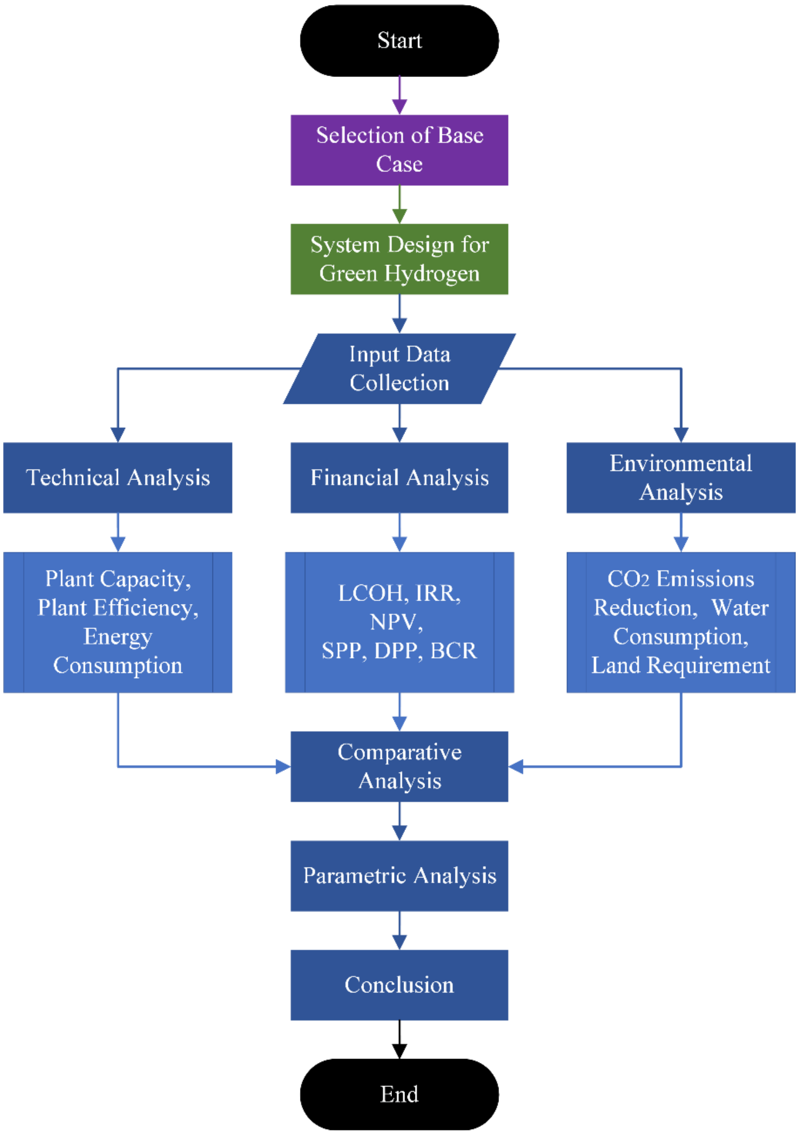


Figure 3.1: Schematic of the research framework

3.3. PtA System Description

In this section, the primary elements of the green ammonia production plant layouts and their technological aspects are discussed. The configuration for PtA setup and the key components is illustrated in Figure 8. The main components of a green ammonia plant typically include:

3.3.1. Renewable Energy Source

The renewable energy source is the foundation of a green hydrogen plant. It supplies the electricity needed for the electrolysis process. The choice of energy source depends on factors like location, available resources, and plant size. Common sources include solar PV, WT, and hydroelectric generators. Solar PV converts sunlight into electricity, WT harness the kinetic energy of the wind, and hydroelectric generators use flowing water to generate power.

3.3.2. Electrolyzer

The electrolyzer is a critical component that performs the electrolysis process, splitting water into hydrogen and oxygen. There are different types of electrolyzers, including:

- **Alkaline Electrolyzer**: AEC uses an alkaline solution (usually potassium hydroxide) as the electrolyte. These electrolyzers have been used for decades and are known for their stability and durability. They operate at higher temperatures and typically have longer operational lifetimes compared to PEMEC. AEC can handle a wide range of operating conditions however might be slower in response compared to PEMEC.
- **Proton Exchange Membrane Electrolyzer**: PEMEC use a proton exchange membrane as the electrolyte. They work by separating hydrogen and oxygen gases at the molecular level. PEMEC are known for their high efficiency, fast response times, and ability to operate at varying loads, which makes them suitable for applications with fluctuating renewable energy inputs. They also have the advantage of being compact and relatively easy to scale.
- **Solid Oxide Electrolyzer Cell**: SOEC operate at high temperatures and use a solid ceramic electrolyte. They are capable of achieving high efficiency levels, making them suitable for large-scale hydrogen production and applications where waste heat

recovery is possible. However, their high operating temperatures require careful materials selection and can result in longer start-up times.

3.3.3. Water Supply and Purification System

High-purity water is essential for efficient electrolysis. Impurities in water can lead to reduced electrolyzer efficiency and potentially cause damage. Water supply systems include water intake mechanisms and filtration processes to remove contaminants.

3.3.4. Hydrogen Compression and Storage

Once produced, hydrogen gas needs to be compressed for storage and transportation. This increases its density, making it more practical to store and transport. Hydrogen can be stored as a gas under pressure or as a liquid at cryogenic temperatures. Compression and storage systems ensure the hydrogen is available when needed, even if the renewable energy source isn't producing electricity.

3.3.5. Haber-Bosch Process (Ammonia Reactor)

The primary raw material for the HB process is atmospheric nitrogen (N_2), which makes up about 78% of Earth's atmosphere. Nitrogen gas from the atmosphere is reacted with hydrogen under high temperature (400-500°C) and high pressure (100-200 atm) conditions. The compressed nitrogen and hydrogen gases are then introduced into a reaction chamber, typically containing an iron catalyst. The iron catalyst is used to accelerate the reaction and make it feasible at lower temperatures and pressures. The core of the HB process is the synthesis of ammonia, represented by the following chemical equation:

$$N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g) \qquad (1)$$

3.3.6. Control and Automation Systems

These systems monitor and control various aspects of the plant's operation. They regulate the electrolysis process, manage energy flows, ensure safety protocols are followed, and optimize hydrogen production based on factors like electricity availability and demand.

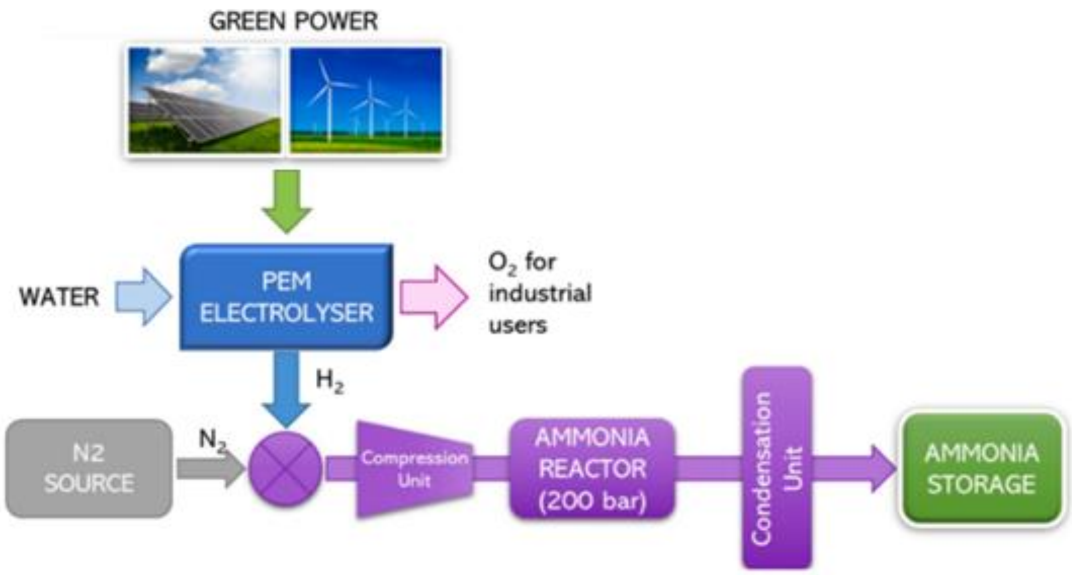


Figure 3.2: Configuration for PtA setup encompasses several key components.

3.4. Technical Model

The fundamental principle underlying water electrolysis involves the application of a direct electric current across two immersed electrodes within an electrolyte solution. This process leads to the breakdown of water molecules, resulting in the generation of hydrogen at the cathode and oxygen at the anode. The quantity of hydrogen produced is directly proportional to the magnitude of the electric current flowing through the electrodes [87]. During water electrolysis, the conversion of electrical and thermal energy transpires into chemical energy, which becomes stored within the produced hydrogen.

The energy needed to facilitate this electrochemical reaction is quantified by the enthalpy change (ΔH) accompanying water formation. However, solely the Gibbs free energy change (ΔG) of the reaction necessitates supply in the form of electrical energy to the electrodes. This minimum voltage required for driving water electrolysis is termed the reversible voltage (U_{rev}). In practice, when heat is not externally introduced, the voltage required for effecting water decomposition surpasses the reversible voltage. This higher voltage level, devoid of supplementary heat, is commonly referred to as the "thermoneutral voltage" (U_{tn}). Under standard ambient conditions, the reversible voltage and the thermoneutral voltage are measured at 1.23 V and 1.48 V, respectively.

Notably, both of these voltages are thermodynamic parameters influenced by the prevalent temperature and pressure conditions [88].

The specific energy consumption E_s (kWh/Nm^3) of a water electrolysis process can be calculated from [89]

$$E_s = \frac{\int_0^{\Delta t} N_{cell} I_{cell} U_{cell} dt}{\int_0^{\Delta t} q_m dt} \tag{2}$$

where N_{cell} is the number of electrolysis cells, I_{cell} the cell current, q_m the hydrogen production rate (Nm^3/h), and Δt the given time interval. An electrolyzer's efficiency, denoted as η_E, constitutes a crucial parameter. This efficiency parameter quantifies the relationship between the energy contained within the generated hydrogen and the energy requisite for the electrolysis of the consumed water throughout the process. The efficiency, η_E, is conveniently computed as the quotient of the Higher Heating Value (HHV) of hydrogen (3.54 kWh/Nm^3) divided by the specific energy consumption (E_s) expressed in kWh/Nm^3 [90].

$$\eta_E = \frac{\text{HHV of } H_2}{E_s} \tag{3}$$

Despite being considered the cutting-edge solution in the field, AEC have gained prominence due to their well-established technology, widespread availability in the market, cost-effectiveness (< 900 $/kW for multi-megawatt systems) and extended operational lifespan (up to 100,000 hours). However, these electrolyzer exhibit certain limitations, particularly when dealing with frequent start-ups and intermittent operations, such as their integration with RES subject to fluctuations [91]. As an alternative, PEMEC are gaining traction due to their quicker dynamic response and faster start-up time. They also boast a more compact design and enable the production of exceptionally high-purity hydrogen (>99.99% as opposed to AEC 99.5%). Nevertheless, PEMEC systems come with their own set of drawbacks, including higher initial investment costs and a comparatively shorter operational lifespan (up to 80,000 hours). This shortened lifespan is attributed to the need for periodic membrane replacement [76]. For the purpose of this study, PEMEC modules operating at 30 bar pressure are under consideration. The hydrogen compression segment is responsible for elevating the hydrogen pressure from the electrolyzer's outlet pressure (30 bar) to the desired storage pressure of 200 bar in storage tank for end use facility. All the considered specifications of the PEMEC are included in Table 1.

Table 3.1: Technical Specifications of PEMEC

Specific Energy Consumption	50	kWh/kg
Operating Pressure	30	bar
Cell Degradation Rate	0.25%	Per 1000 hours
Degradation Threshold	90%	
Annual Degradation	0.66%	Per year
Minimum Turndown	10%	
No. of Stack Replacement	1	
Stack Lifetime	42,000	hours

When it comes to hydrogen compression, various technologies are accessible in the market, including diaphragm, ionic, electrochemical, and reciprocating compressors. Among these, diaphragm compressors stand out due to their high efficiency and suitability, especially when handling chemically pure hydrogen. These compressors are advantageous as they prevent direct contact between the gas and the piston, resulting in improved performance [92]. In the context of the envisaged investigation, the compressor assumes the role of an ancillary component within the HB system framework. It functions as an input auxiliary element for the aforementioned system, facilitating the pressurization of hydrogen. This pressurized hydrogen subsequently reacts with nitrogen to facilitate the production of ammonia. It is important to clarify that, within this study's scope, the compressor is distinctively excluded from the hydrogen production system, specifically the electrolyzer module.

3.5. Financial Model

The study presents a detailed financial model for the production of green hydrogen through water electrolysis using PEMEC. In order to evaluate the economic feasibility of the proposed system, mathematical formulation of following financial parameters is modelled.

3.5.1. Levelized Cost of Hydrogen

Figure 9 illustrates the economic framework developed within this study for the calculation of LCOH, building upon gaps identified in preceding literature. The primary focus of this framework centers on the electrolyzer system and the determination of its associated capital costs. These encompass both the direct expenditures involved in procuring the electrolyzer (retail cost) and the indirect expenses encompassing importation, transportation, and plant installation. Emphasis is also placed on evaluating the performance metrics of the electrolyzer, including specific energy consumption and water utilization, which are pivotal in ascertaining feedstock consumption and variable operational outlays. Additionally, the framework accounts for the cyclic maintenance requirements and substantial refurbishments during stack replacements, contributing to fixed operational charges. Moreover, the analysis incorporates pertinent factors such as inflation, taxation, depreciation, and project financing (categorized as miscellaneous costs). The examination also encompasses electrolyzer performance indicators like efficiency and stack degradation, acknowledged for their roles in determining hydrogen yield. The cost and parameter modeling draws from data acquired from commercial electrolyzer enterprises and existing literature. Another dimension of the study is the establishment of optimal electricity configurations, pivotal in shaping electricity expenses (a significant operational cost) and defining electrolyzer utilization levels (capacity factor). The PPA is employed to derive the electricity supply cost, a critical element in the calculation of the LCOH as outlined in Equation 4.

$$\mathrm{LCOH} = \frac{\sum_{n=0}^{N} \frac{\mathrm{LCC}}{(1+r)^n}}{\sum_{n=0}^{N} \frac{H_{2n}}{(1+r)^n}} \tag{4}$$

Where LCC is the Life Cycle Cost including CAPEX, OPEX, and Replacement cost of the plant, N is the plant lifetime in year, H_2n represents the hydrogen production at a year n, and r is the discount rate, reflecting the cost of capital or desired rate of return.

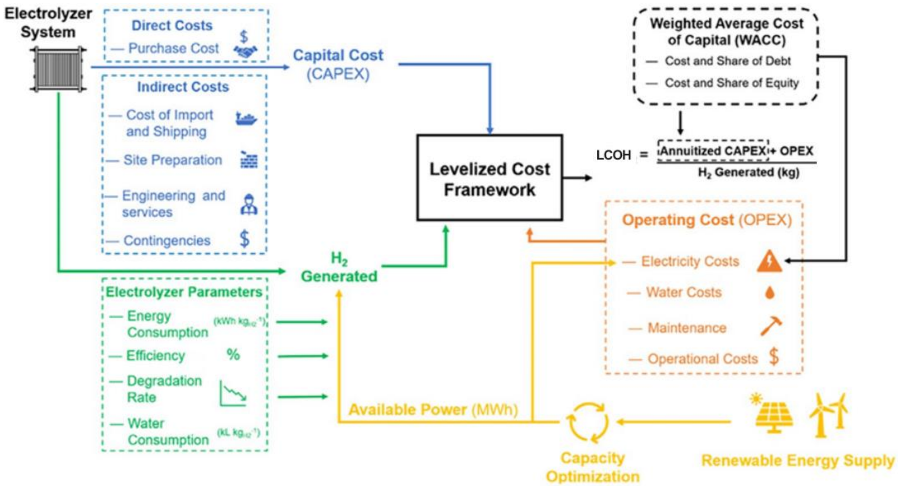


Figure 3.3: Economic Framework for Levelized Cost of Hydrogen (LCOH) [93]

3.5.2. Internal Rate of Return

The IRR is a financial metric used to evaluate the potential profitability of an investment or project. It represents the discount rate at which the NPV of all future cash flows becomes zero. In other words, it is the rate at which the project's inflows equal its outflows, making the project break even in terms of returns. The IRR is typically calculated iteratively; however, it can be represented as follows:

$$0 = \sum_{n=0}^{N} \frac{CF_n}{(1+IRR)^n} \qquad (6)$$

4.5.3. Net Present Value

NPV is a financial metric used to assess the profitability of an investment or project. It calculates the present value of all future cash flows generated by the project, considering the time value of money. In simpler terms, NPV determines whether an investment is expected to generate a positive or negative return after considering the initial investment and expected future cash flows.

$$NPV = \sum_{n=0}^{N} \frac{CF_n}{(1+r)^n} \qquad (5)$$

3.5.4. Payback Periods

The SPP is a financial metric used to evaluate the time it takes for an investment or project to recover its initial cost or break even in terms of cash flow. It measures the time it takes for the cumulative cash inflows generated by the project to equal or surpass the initial investment. It is a straightforward way to evaluate the speed at which an investment pays for itself.

$$\text{SPP} = \text{Year Before Breakeven} + \frac{\text{Cummulative Cahflow Before Breakeven}}{\text{Cahflow After Breakeven}} \tag{7}$$

The DPP is an extension of the SPP that considers the time value of money. It calculates the time required to recover the initial investment when future cash flows are discounted to their present value using a specified discount rate. This metric provides a more accurate assessment of investment risk and profitability.

$$\text{DPP} = \text{Year Before Breakeven} + \frac{\text{Cummulative Discounted Cahflow Before Breakeven}}{\text{Discounted Cahflow After Breakeven}} \tag{8}$$

3.5.5. Benefit-Cost Ratio

The BCR is a financial metric used to evaluate the attractiveness of an investment or project. It assesses the relationship between the benefits derived from the project and the costs associated with it. A BCR greater than 1 indicates that the project is expected to generate more benefits than the costs incurred, making it potentially financially viable. The BCR is calculated using the following equation:

$$\text{BCR} = \frac{\sum_{n=0}^{N} \frac{|\text{CF}_n[\text{Benefits}]|}{(1+r)^n}}{\sum_{n=0}^{N} \frac{|\text{CF}_n[\text{Costs}]|}{(1+r)^n}} \tag{9}$$

The model encompasses various aspects of project evaluation, including capital and operational costs, revenue generation, and financial metrics. By employing a formal and rigorous analytical framework, this model aims to assess the feasibility and viability of green hydrogen production in the context of renewable energy integration. The financial assumptions considered for the proposed model are outlined in Table 2.

Table 3.2: Financial Assumptions for PEMEC

CAPEX	800	\$/kW
OPEX	2.5% CAPEX	\$/kW
Water Cost	2	\$/m^3
Cost of Stack Replacement	30% CAPEX	\$
Project Lifespan	25	Years

It is important to note that hydrogen electrolysis is a modular technology, it is presumed that there are no substantial cost advantages associated with scaling up production. Therefore, a facility capable of producing a maximum of 100 kg/day is expected to be twice as costly as a facility with a maximum production capacity of 50 kg/day.

3.6. Environmental Model

Performing an environmental analysis for a green hydrogen production involves assessing the potential environmental impacts and benefits associated with the project. Following methodologies provide a structured approach to calculate the annual CO_2 emission reduction, water consumption and land requirement associated with a green hydrogen production project, aiding in environmental impact assessment and reporting.

3.6.1. CO_2 Emissions Reduction

The proposed study focuses on analyzing CO_2 emission reductions through the utilization of renewable energy for green hydrogen production compared to the conventional method of producing grey hydrogen using natural gas in SMR. The study examines the specific metric of kg CO_2 emission reduction per kg of green hydrogen. The carbon intensity of conventional grey hydrogen production using SMR, as determined by the Department of Energy's Argonne National Laboratory's GREET 2022 Model (which is the official tool for carbon intensity assessment), is 11.7 kg CO_2 eq/kg H_2 in the well-to-gate emissions analysis.

The research employs a systematic approach to quantify the annual reduction in CO_2 emissions resulting from the implementation of the green hydrogen production project. This methodology involves gathering data from diverse sources, starting with the determination of baseline CO_2 emissions associated with conventional hydrogen production methods, notably SMR and coal gasification.

3.6.2. Annual Water Consumption

To assess the annual water consumption associated with the green hydrogen production project, a rigorous scope was defined, focusing on the hydrogen production facility and related processes. The study considers a specified time, typically one year, during which the project's water usage is evaluated. To calculate the net annual water consumption, the volume of wastewater discharged was subtracted from the total water usage. The findings, outlined in subsequent sections, elucidate the project's impact on water resources and its contribution to sustainable water management practices.

3.6.3. Land Requirements

In this research, an integral aspect under consideration is the land requirement associated with the PEMEC system. Land requirement assessment plays a pivotal role in evaluating the feasibility and environmental implications of deploying PEMEC for green hydrogen production. It involves a comprehensive analysis of the physical space needed for the installation, operation, and maintenance of PEMEC systems. By thoroughly examining the land area necessary for the project, the research aims to provide critical insights into the spatial demands of PEMEC, which is essential for site selection, land use planning, and addressing potential environmental impacts. This analysis contributes to the overall assessment of the project's sustainability and its compatibility with available land resources, fostering informed decision-making and sustainable deployment of green hydrogen technologies.

3.7. Reference Scenario

In the context of the proposed plant layout, which relies on RESs for its electrical energy supply, the accurate determination of three crucial parameters holds paramount significance. These parameters significantly influence the feasibility and functionality of the solutions, namely the Installation Cost, the Capacity Factor and the LCOE. The IRENA systematically evaluates and updates these parameters for various technologies considering the pertinent geographical and economic conditions under which RES facilities operate, cited in Table 3. The dynamic interplay between these metrics is particularly salient for multiple renewable plant types: increased availability of RES raises the CF, consequently exerting a favorable influence on LCOE by driving it downwards, rendering it more competitive.

In a recent publication, IRENA has provided comprehensive ranges for LCOE and CF values associated with diverse RESs, reflecting a prevalent trend of diminishing costs for RES installations in recent years [94]. This trend has effectively positioned these technologies on par with, and even superior to, the LCOE of conventional fossil fuel power plants. Derived from the CF definition, the Equivalent Operating Hours (EOH) for each RES type can be readily computed as the product of CF and the annual count of operating hours. For the reference scenario, the ensuing parameter values are adopted:

- **Levelized Cost of Electricity (LCOE):** The expense associated with the electric power consumed for driving the operations, valued at a rate of USD 50 per MWh.
- **Equivalent Operating Hours (EOH):** The count of hours during which the process functions at its rated capacity over the course of a year, amounting to 2630 hours (@30% CF).
- **Weighted Average Cost of Capital (WACC):** A parameter employed in the determination of the IRR, set at 10%.
- **Hydrogen Sell Price:** The desired selling price of the produced hydrogen, used for calculating the IRR, is set at USD 4 per kg.

Table 3.3: Global weighted average total installed cost, capacity factor and levelized cost of electricity trends of different renewable technologies in 2022.

Technology	Installed capacity cost (USD/kW)	Capacity factor (%)	LCOE (USD/kWh)
Solar PV	876	17	0.049
CSP	4274	36	0.118
Onshore wind	1274	37	0.033
Offshore wind	3461	42	0.081
Hydropower	2881	46	0.061
Bioenergy	2162	72	0.061
Geothermal	3478	85	0.056

This study considers another scenario where the electrolyzer operates using only renewable solar and wind electricity. This is achieved by negotiating PPA with grid-connected solar PV and wind farms. By securing these PPA, the electrolyzer can obtain electricity at the same cost as the connected solar or wind farm. As new solar PV and wind farms are expected to have a lower LCOE, the cost of PPA will also decrease. Additionally, the capital cost of electrolyzer is also decreasing every year. When combined with lower PPA pricing, these cost reductions will significantly reduce the LCOH. Moreover, it is important to note that the capital investment is assumed to be

100% equity, and the economic analysis is carried out at a corporate tax rate of 29%, which is based on the fiscal year 2023 in Pakistan.

3.8. Parametric Analysis

Parametric analysis has been systematically conducted to assess and contrast the influence of distinct technical and economic parameters on LCOH and other critical determinants. The parametric analysis underscored the project's vulnerability to variations in key parameters, emphasizing the importance of carefully managing these variables for the project's economic and environmental sustainability. This comprehensive evaluation involves an array of selected parameters, encompassing a defined range as outlined in Table 4.

Table 3.4: Assumptions for Parametric Analysis at Defined Range

Parameter	Reference Value	Range	Frequency
Power Price	50 \$/MWh	10-80 \$/MWh	10
PEMEC CAPEX	800 \$/kW	400-1200 \$/kW	100
Capacity Factor	30%	15-45 \$/ton	5
WACC	10%	2.5-20 %	2.5
Specific Energy Consumption	50 kWh/kg H_2	40-70 kWh/kg H_2	5
H_2 Sell Price	4 \$/kg H_2	2-6 \$/kg H_2	1

Summary

This chapter outlines the methodology and system design for conducting a comprehensive techno-economic analysis of large-scale decentralized hydrogen production infrastructure powered by renewable sources in Pakistan. The study focuses on assessing the potential for emission reduction in the context of a representative ammonia-based urea fertilizer plant. The base case uses natural gas for hydrogen production, while the proposed case aims to produce green hydrogen using RESs, particularly solar and wind power. The chapter describes the technical model, financial model, and environmental model for evaluating the feasibility, economic viability, and environmental impact of the green hydrogen production system. The key components of the green ammonia production plant, such as renewable energy sources, electrolyzer, water supply, hydrogen compression, and the Haber-Bosch process, are detailed. The chapter also includes a financial model that calculates the LCOH, IRR, NPV, payback periods, and BCR to assess the economic feasibility of the proposed system. Furthermore, the environmental model evaluates the annual CO_2 emission reduction, water consumption, and land requirements associated with green hydrogen production. It also discusses a reference scenario and parametric analysis to assess the influence of various parameters affecting the project's viability. The research aims to provide valuable insights into the transition to green hydrogen in Pakistan's energy landscape.

Chapter 04: Results and Discussion

In this chapter, the comprehensive results of the research on the techno-economic and environmental analysis of green hydrogen production in Pakistan are presented. The study focused on comparing a base case scenario, where hydrogen is generated through SMR, with a proposed case involving environmentally friendly green hydrogen production powered by RESs. The prominent ammonia-based urea fertilizer plant in Pakistan, with an annual production of 2 million tons, served as the representative example. Additionally, this chapter explores the outcomes of the parametric analysis employed to evaluate the repercussions of variations in various input parameters on LCOH and other critical determinants influencing green hydrogen initiatives in Pakistan.

4.1. Technical Analysis

This section provides a concise overview of the findings and delves into the technical facets of the proposed green hydrogen plant. To evaluate the plant configurations in terms of energy considerations, a comprehensive technical analysis was conducted to determine the PEMEC plant size (i.e., plant capacity), assess the overall efficiency, and ascertain the annual energy consumption of the plant. The results are elucidated in Table 5.

4.1.1. Plant Capacity

The proposed green hydrogen production plant would require a capacity of 3,995.4 MW PEMEC system to meet the annual hydrogen demand of 2 million tons operating at 50 kWh/kg H_2 and a 30% capacity factor. The substantial capacity requirement in the proposed green hydrogen production scenario represents a significant shift from conventional hydrogen production methods like SMR. While SMR plants are typically designed to meet hydrogen demand with a relatively lower capacity, the renewable energy driven PEMEC plant necessitates a larger capacity due to the intermittent nature of solar PV and WT electricity generation. This increased capacity signifies a considerable upfront investment and potentially higher operational costs. However, it is a crucial step towards reducing GHG emissions associated with hydrogen production.

Comparatively, SMR and Alkaline electrolysis technologies often have smaller capacities, making them more suitable for steady hydrogen production. However, the proposed green hydrogen plant aims to mitigate environmental impacts, offering a more sustainable alternative. The feasibility of this model depends on several factors, including the availability of RESs, the cost of electricity, and government incentives. Additionally, advancements in energy storage and grid management will play a pivotal role in ensuring the reliability of such high-capacity, intermittent power plants.

4.1.2. Plant Efficiency

The overall efficiency of the PEMEC plant for green hydrogen production is determined to be 78.8%, under the conditions of 50 kWh/kg H_2. This efficiency accounts for the energy losses associated with the conversion of renewable electricity into hydrogen through electrolysis. The overall efficiency of 78.8% (HHV based) for the PEMEC plant in green hydrogen production is a promising metric, especially when compared to the lower efficiencies often associated with traditional hydrogen production methods like SMR. SMR, for instance, typically achieves lower overall efficiencies due to energy losses during the conversion of methane into hydrogen. Alkaline electrolysis also faces efficiency challenges. This higher efficiency of the PEMEC plant implies that a substantial portion of the renewable electricity is effectively utilized in hydrogen generation.

In the context of feasibility, the higher efficiency of the PEMEC plant is advantageous as it contributes to reducing the operational costs per unit of hydrogen produced. However, it's essential to consider that the intermittent nature of RESs can affect the plant's overall performance. To ensure feasibility, strategies for energy storage and grid integration must be carefully designed. Additionally, the economic viability of the project hinges on the cost of renewable electricity, which should ideally be competitive with or lower than traditional energy sources.

4.1.3. Energy Consumption

The proposed green hydrogen production plant would consume approximately 10,500,000 MWh of electricity annually. This significant energy consumption is attributed to the high-capacity requirement of the plant, driven by the need to compensate for the intermittent nature of RESs. This level of energy consumption places considerable stress on both the electricity grid and the renewable energy generation infrastructure, underscoring the paramount importance of a resilient energy supply strategy.

To mitigate these challenges, it is imperative to establish robust PPA with green energy providers. These agreements should facilitate a consistent supply of renewable electricity while also incorporating contingency plans for periods when renewable sources are unavailable. Additionally, this annual energy consumption surpasses the requirements of conventional hydrogen production methods, such as SMR, which are typically recognized for their energy efficiency but may not match the carbon emissions reduction potential of green hydrogen production plants. To assess the feasibility of such high energy consumption, it becomes imperative to evaluate the regional availability of RESs and the cost competitiveness of green electricity. To enhance feasibility, optimizing the PEMEC plant's operations and integrating energy storage solutions will be essential. Government support and policies that encourage the use of green energy and carbon reduction can also enhance the economic viability of such projects.

Table 4.1: Technical Results

Parameter	**Value**
Plant Capacity	3995.4 MW
Plant Efficiency	78.8% (HHV based)
Annual Energy Consumption	105,000,00 MWh

4.2. Financial Analysis

The financial analysis was carried out in order to assess the economic viability of green hydrogen production in Pakistan. The following results are summarized in Table 6.

4.2.1. Levelized Cost of Hydrogen

LCOH, a pivotal economic metric, was determined to be USD 5.16 per kg H_2. This cost encapsulates various factors associated with the green hydrogen production system. As shown in Figure 10, the cost breakdown for LCOH highlights several key components contributing to the overall cost structure. The most substantial cost item is the electrical energy cost, accounting for approximately 50% of the total costs. This component reflects the expense associated with procuring and utilizing renewable electricity from sources such as solar PV and WT to power the electrolysis process. The second most significant cost factor is the CAPEX of the PEMEC plant, constituting approximately 37% of the total production costs. This reflects the upfront investment required to establish and maintain the PEMEC plant, which harnesses renewable energy for hydrogen production.

OPEX represents nearly 10% of the total costs, encompassing various ongoing operational and maintenance expenditures including water cost essential for maintaining the efficiency and functionality of the PEMEC plant. These expenses are crucial for ensuring the longevity and effectiveness of the green hydrogen production process. The cumulative contribution of these three primary cost components—electrical energy cost, electrolyzer CAPEX, and OPEX—comprises approximately 97% of the total production costs for green hydrogen generated through the PEMEC plant. This indicates that optimizing these key factors is essential for managing and potentially reducing the LCOH. Notably, the analysis projects stack replacement occurring at the 16th year of operation, constituting approximately 3% of the total LCOH. This planned replacement cycle is essential to maintain the system's efficiency and reliability, mitigating the risk of performance degradation over time.

Comparatively, when assessing the LCOH of green hydrogen produced via the PEMEC plant with RESs, it is evident that this cost is higher than that associated with traditional SMR methods. The higher LCOH for water electrolysis is primarily a consequence of the investment in electrolyzer system, renewable energy infrastructure and the associated electrical energy cost, which contributes significantly to the total production costs.

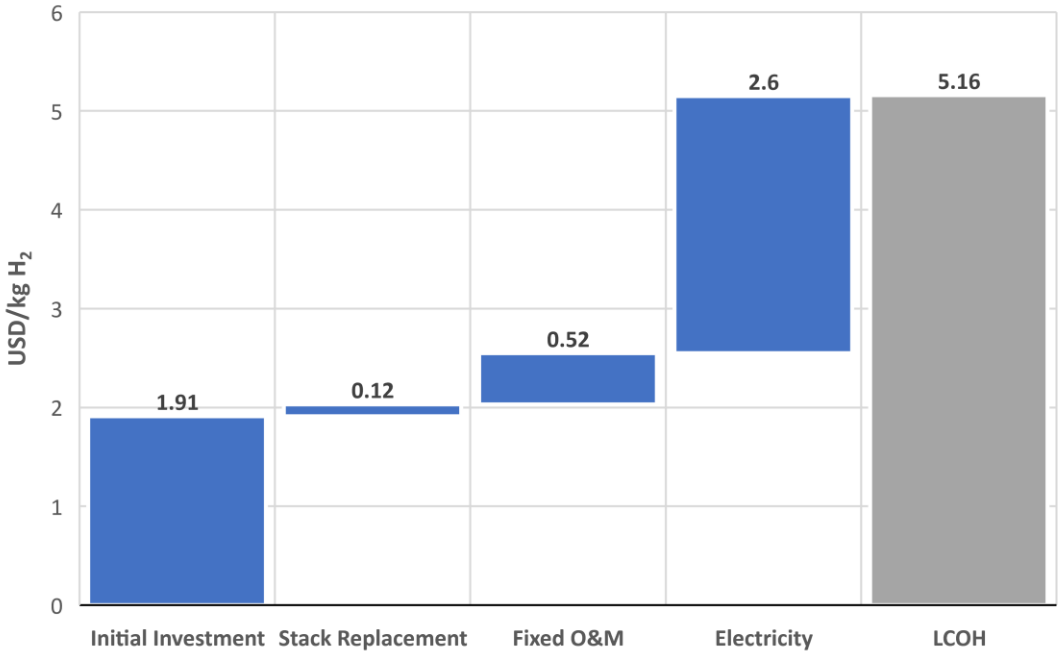


Figure 4.13: LCOH Breakdown

However, it is crucial to consider the broader environmental and sustainability benefits associated with green hydrogen production. The substantial reduction in carbon emissions and the use of RESs align with long-term sustainability goals and environmental stewardship, making green hydrogen an attractive option despite its higher LCOH.

4.2.2. Internal Rate of Return

The financial analysis yielded an IRR of 0.4% when the selling price of hydrogen was set at USD 4 per kg. The IRR signifies the profitability of the green hydrogen project, with a positive value indicating the potential for financial gains. The IRR obtained in this study is relatively modest compared to typical commercial projects. In a commercial setting, IRR is often expected to be higher, ideally surpassing the cost of capital or hurdle rate to ensure a financially competitive project. A higher IRR signifies a more lucrative investment opportunity and better potential for generating profits.

However, the IRR of 0.4% in this case aligns with the economic landscape and financial realities of the specific context, notably the prevailing conditions in Pakistan. Economic factors, including inflation rates, fluctuating policy rates, and energy market dynamics, can influence the IRR. Additionally, the transition to renewable energy infrastructure and the associated initial capital investments impact the IRR.

While the IRR for this green hydrogen project may seem relatively low, it's crucial to emphasize that the project aligns with sustainability goals, significantly reducing carbon emissions and promoting the use of renewable energy. This aspect adds immense non-financial value to the project, supporting a sustainable energy transition.

4.2.3. Net Present Value

NPV is a pivotal financial metric indicating the economic feasibility of transitioning to green hydrogen production via the PEMEC plant with RESs. The calculated NPV, approximately USD 1,384,052,520, signifies the project's positive net value over its operational lifetime. This reflects its strong financial viability, driven by factors like a competitive LCOH, prudent stack replacement strategies, and the use of RESs, which reduce long-term operational costs.

While the IRR is relatively modest at 0.4%, aligning with Pakistan's economic context, the positive NPV highlights the project's ability to generate substantial value. This economic assessment, combined with its significant environmental benefits and contribution to sustainability goals, underscores the compelling case for green hydrogen production.

4.2.4. Payback Periods

The SPP of 4.422 years indicates that it would take approximately 4.422 years to recoup the initial capital investment in the green hydrogen production project. This period reflects the time it takes for the project's generated cash flows to cover the upfront costs without considering the time value of money. The DPP, longer at 6.565 years compared to the simple payback period, considers the time value of money by discounting future cash flows to their present value. This metric provides a more conservative estimate of the time required to recover the initial investment. In this case, it takes approximately 6.565 years to recover the capital costs when accounting for the opportunity cost of the invested capital.

It is essential to interpret these payback periods in the broader context of the project's goals and the specific economic landscape. While the simple payback period may appear favorable, the longer discounted payback period reflects the financial prudence applied to account for the opportunity cost of invested capital and associated risks. These metrics demonstrate that while the project shows promise of recovering its capital costs, a more conservative financial analysis suggests a longer recovery period. The choice to prioritize sustainability and reduce carbon emissions, along with economic considerations, makes the project a compelling option for a responsible and sustainable energy transition.

4.2.5. Benefit-Cost Ratio

BCR for the green hydrogen production project utilizing the PEMEC plant with RESs is calculated to be 1.6:1. The BCR of 1.6:1 indicates that, for every unit of cost invested in the project, there is an associated benefit of 1.6 units. In financial terms, this signifies a positive return on investment, implying that the project generates a surplus of benefits over and above the incurred costs.

The BCR of 1.6:1 supports the economic viability and attractiveness of the green hydrogen production project. It suggests that the benefits derived from the project, including reduced carbon emissions, sustainable energy generation, and potential economic gains, outweigh the costs involved in implementing and operating the system. This metric is a strong indicator of the project's positive impact and potential for long-term financial sustainability.

Table 4.2: Financial Results

Parameter	**Value**
LCOH	USD 5.16 per kg H_2
IRR	0.4 %
NPV	USD 1,384,052,520
SPP	4.422 years
DPP	6.565 years
BCR	1.6:1

4.3. Environmental Analysis

The environmental impact analysis of green hydrogen production is a critical component of assessing the sustainability of this emerging technology. This analysis encompasses a comprehensive evaluation of the project's effects on the environment, including its potential to reduce carbon emissions compared to traditional hydrogen production methods, water consumption, and land use.

4.3.1. CO_2 Emissions Reduction

Green hydrogen production, using RESs, primarily solar PV and wind, yields a pronounced reduction in carbon emissions compared to conventional hydrogen production approaches reliant on fossil fuels, such as SMR and coal gasification. To provide a contextual perspective, a comparison of the CO_2 emissions stemming from green hydrogen production with those associated with natural gas, a commonly employed fossil fuel, is pertinent. When natural gas is employed for hydrogen production through SMR, it results in emissions ranging from approximately 12 to 14 kg CO_2-eq/kg H_2 produced. Given the annual demand of over 200,000 tons of hydrogen for the base case ammonia-based urea fertilizer plant, natural gas-based hydrogen production would contribute to carbon emissions exceeding 2.4 million metric tons annually. Additionally, considering coal, another prevalent fossil fuel employed in electricity generation and diverse industrial processes, coal combustion emits significantly higher levels of CO_2 compared to natural gas. Coal-fired power plants, on average, emit around 2.2 kg CO_2/kWh of electricity generated. This corresponds to approximately 22 kg CO_2/kg H_2 when coal is used for electricity generation, subsequently leading to hydrogen production. With the identical annual hydrogen demand, coal-based hydrogen production would result in carbon emissions surpassing 4.4 million metric tons annually. This comparative analysis underscores the substantive environmental advantage offered by green hydrogen production through the PEMEC plant with RESs, signifying a noteworthy reduction in annual carbon emissions when contrasted with emissions from natural gas and coal-based hydrogen production methods, which contribute 2.4 million and 4.4 million metric tons of CO_2, respectively.

4.3.2. Annual Water Consumption

In discussions concerning environmental impact, it is crucial to consider water consumption, an aspect that is often underestimated. The analysis reveals a water consumption rate of 13 liters/kg H_2 produced, resulting in an overall consumption of 2730 million liters of water annually for the production of over 2 million tons of hydrogen. Additionally, it is noteworthy that during the commissioning phase of the PEMEC plant, an initial requirement of 4 million liters of water is necessary. This water usage during commissioning is a one-time occurrence and represents a relatively minor portion of the overall water consumption for the project's operational life.

To put these figures in perspective, it's essential to consider the efficiency of water usage in green hydrogen production compared to other industrial processes. While water consumption is typically associated with green hydrogen, both grey and blue hydrogen production processes consume a significant amount of water, sometimes surpassing that of electrolysis [27]. For instance, in electrolysis, pure water consumption ranges from 10 to 15 liters/kg H_2 output. However, when comparing embodied water based on a life cycle inventory, the water consumption for steam reforming can be around 24 liters/kg H_2. In the case of coal gasification, this figure could rise even higher, to approximately 38 liters/kg H_2 [95]. The water requirement for hydrogen production could pose challenges in certain regions worldwide. For instance, regions with abundant solar potential, such as deserts, often grapple with water scarcity, and the establishment of desalination plants would necessitate significant additional energy inputs and costs. This challenge may be exacerbated by climate change, potentially acting as a barrier to hydrogen production in these regions.

4.3.3. Land Requirements

To produce 2 million tons of hydrogen annually, the project would necessitate approximately 59.9 acres of land. Land use considerations for PEMEC plant are integral to assessing the environmental impact and feasibility of green hydrogen production. PEMEC is a promising technology for generating hydrogen from renewable sources, primarily due to their scalability and efficiency. PEMEC are known for their relatively small physical footprint compared to alternative hydrogen production methods, such as SMR or AEC. This compact design is advantageous, especially in urban or densely populated areas, where available land may be limited. The land efficiency of PEMEC is a key factor contributing to their suitability for distributed and on-site hydrogen production.

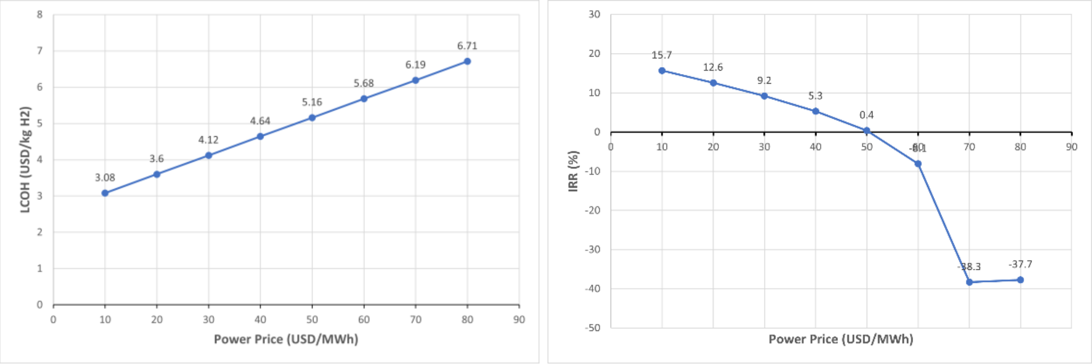
Green hydrogen production holds promise as a key contributor to decarbonization efforts across various sectors, particularly in transportation and industry. By significantly reducing GHG emissions, minimizing water consumption, and mitigating other environmental impacts, green hydrogen production represents a pivotal step towards a more sustainable and environmentally responsible energy future. Understanding and quantifying these environmental benefits are essential for informed decision-making, policy development, and the advancement of sustainable energy solutions.

4.4. Parametric Analysis

In the analysis of parametric results, it is evident that the economic feasibility of the proposed case, as indicated by the economic analysis conducted for the reference scenario, does not account for the significant influence exerted by various critical parameters. These parameters, including the Capacity Factor for renewable plants, Power Price, the WACC, Specific Energy Consumption, and the H_2 sell price, are highly susceptible to variations in the operating scenario. Consequently, a range of variations, as outlined in Table 4, is considered for these key parameters, allowing for the derivation of more general conclusions regarding the feasibility of the plants.

4.4.1. Power Price

The parametric analysis involving power prices ranging from USD 10/MWh to USD 80/MWh revealed significant impacts on project economics. LCOH varied from USD 3.08/kg H_2 to USD 6.71/kg H_2, while IRR ranged from 15.7% to -37.7%. These results emphasize the crucial role of power prices in determining the project's financial viability. Lower power prices contribute to reduced LCOH and improved IRR, highlighting the potential benefits of securing cost-effective electricity for green hydrogen production.

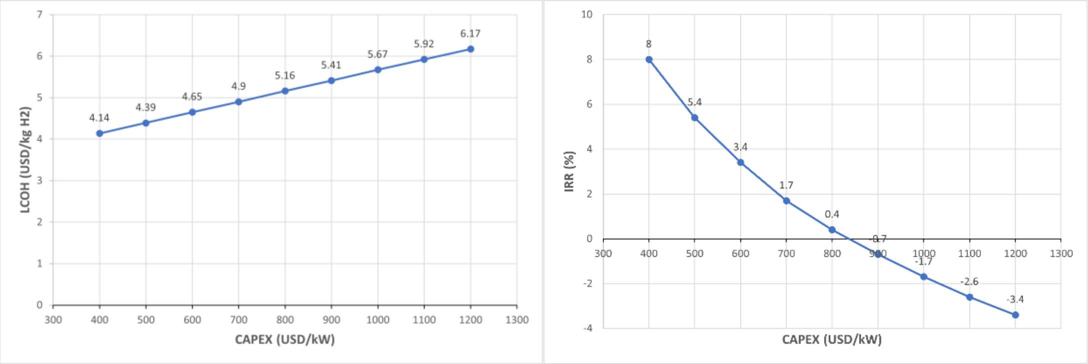


(a) (b)

Figure 4.2: (a) Power Price vs LCOH, (b) Power Price vs IRR

4.4.2. CAPEX

The parametric analysis considering variations in CAPEX, spanning USD 400/kW to USD 1200/kW, showcased the influence of CAPEX on project metrics. LCOH ranged from USD 4.14/kg H_2 to USD 6.17/kg H_2, while IRR fluctuated between 8% and -3.4%. This analysis underscores the importance of managing and optimizing capital costs, as higher CAPEX values can lead to less favorable LCOH and IRR outcomes.

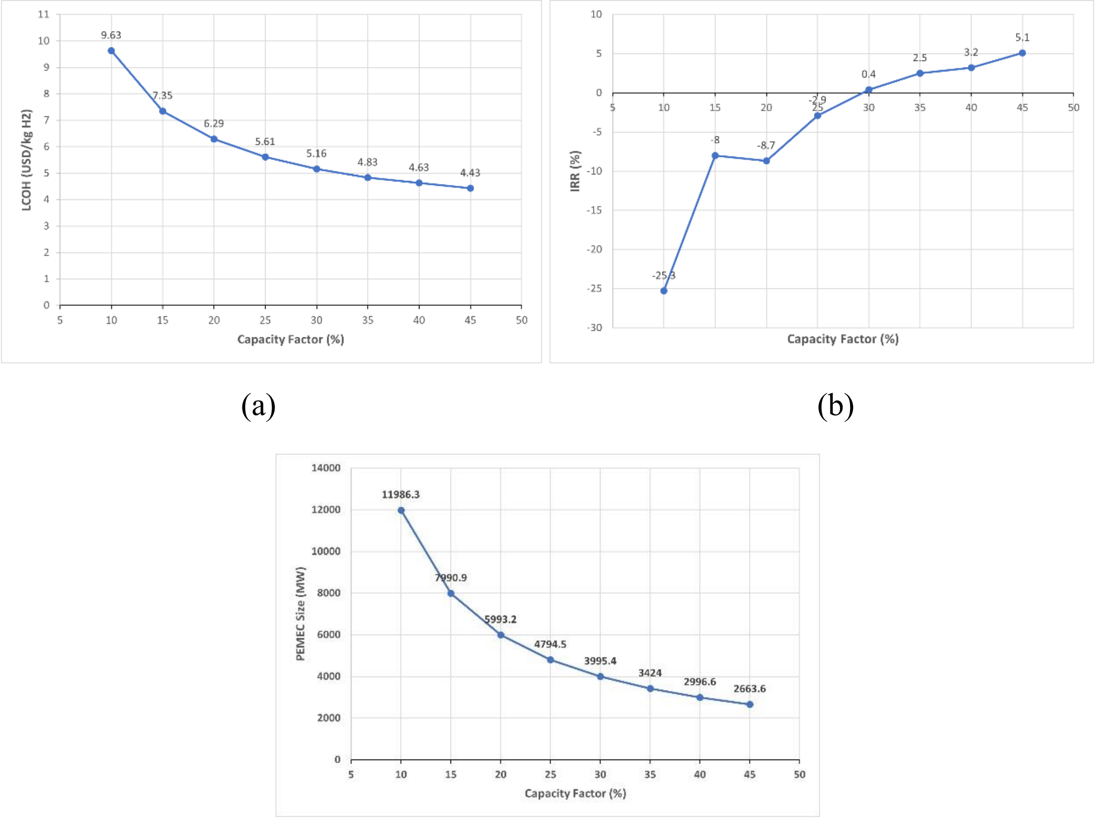


(a) (b)

Figure 4.3: (a) CAPEX vs LCOH (b) CAPEX vs IRR

4.4.3. Capacity Factor

In the parametric analysis spanning a range of capacity factors from 10% to 45%, notable fluctuations in key project metrics were observed. LCOH demonstrated substantial variability, ranging from USD 9.63/kg H_2 to USD 4.43/kg H_2. The IRR exhibited an even wider spectrum, fluctuating between -25.3% and 5.1%. The plant size, representing the installed capacity, ranged from 11,986.3 MW to 2,663.6 MW. These findings underscore the parametric of project economics to variations in the capacity factor, with higher capacity factors leading to lower LCOH and more favorable IRR values. Ensuring a reliable and high capacity factor is essential for achieving economically viable green hydrogen production.



(a) (b)

(c)

Figure 4.4: (a) CF vs LCOH (b) CF vs IRR (c) CF vs PEMEC Size

4.4.4. WACC

Exploring the impact of changes in Weighted Average Cost of Capital (WACC) from 2.5% to 20%, the IRR exhibited a range of 4.2% to -6.84%. This parametric analysis underscores the financial significance of the cost of capital. A lower WACC typically results in a more favorable IRR, highlighting the importance of securing financing at lower costs to enhance project profitability.

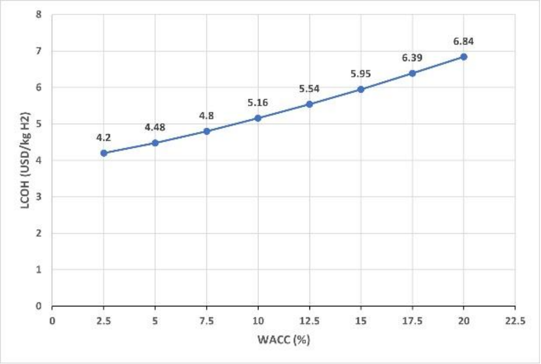


Figure 4.5: WACC vs LCOH

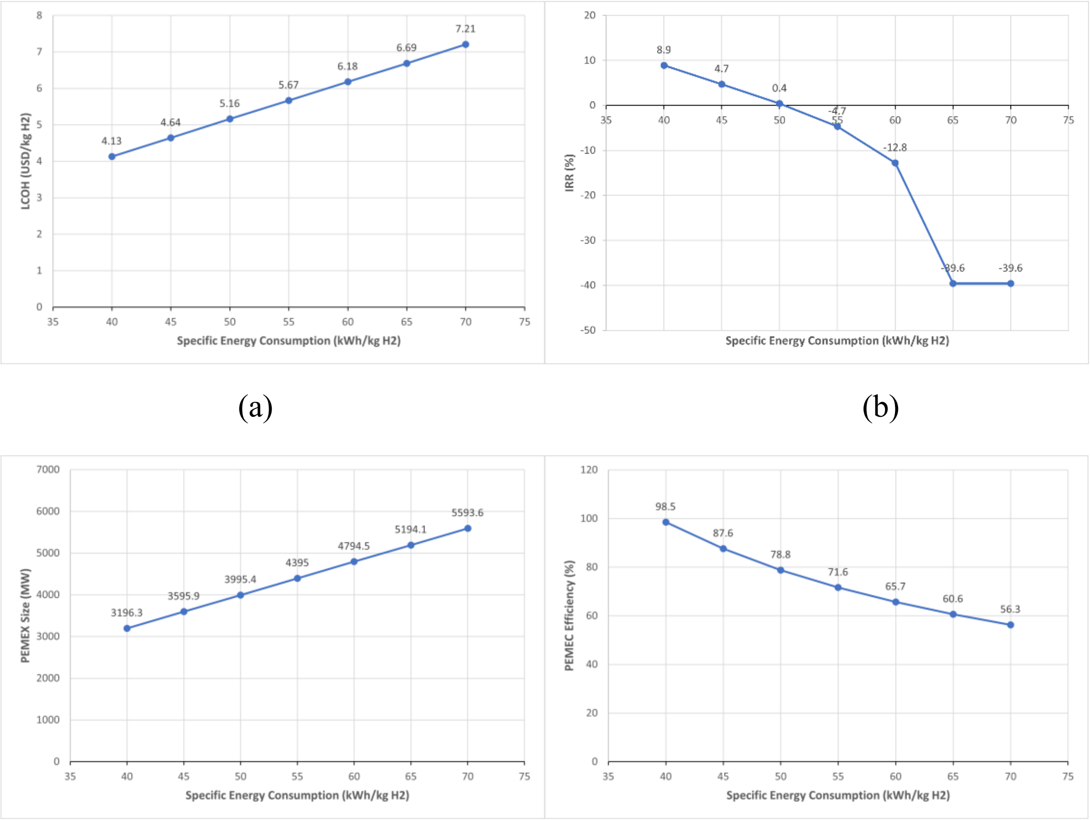
4.4.5. H_2 Sell Price

The parametric analysis concerning hydrogen selling prices in the range of USD 2/kg H2 to USD 6/kg H_2 revealed substantial variations in IRR, ranging from -39.6% to 15.3%. This analysis demonstrates the project's parametric to market conditions and underscores the challenge of ensuring a competitive hydrogen selling price to achieve positive financial outcomes.

Figure 4.6: Hydrogen Selling price vs IRR

4.4.6. Specific Energy Consumption

The analysis encompassing specific energy consumption variations from 40 kWh/kg H2 to 70 kWh/kg H2 led to significant fluctuations in LCOH, spanning USD 4.13/kg H_2 to USD 7.21/kg H_2, IRR, ranging from 8.9% to -39.6%, plant size spans from 3,196.3 MW to 5,593.6 MW, and electrolyzer efficiency ranges from 98.5% to 56.3%. These findings highlight the importance of efficient energy utilization in green hydrogen production, as lower consumption positively impacts both LCOH and IRR. Additionally, changes in specific energy consumption had an impact on plant size and electrolyzer efficiency, demonstrating the interconnectedness of various project aspects.



(a) (b)

(c) (d)

Figure 4.7: (a) SEC vs LCOH (b) SEC vs IRR (c) SEC vs PEMEC Size (d) SEC vs Electrolyzer Efficiency

Lastly, the sensitivity analysis performed to assess the impact on the LCOH provides valuable insights into the project's economic resilience and sensitivity to changes in critical factors. Figure 17 illustrates the impact of each parameter, considering a +/- 50% range variation, while the associated percentage variations in LCOH are reported. Let's delve into the comprehensive discussion of these sensitivity analysis results. Notably, the Capacity Factor exhibits a moderate impact, with LCOH varying from +14.15% to -42.44%, emphasizing the importance of consistent renewable energy generation. Power price fluctuations have a substantial effect, leading to a LCOH range of -25.00% to +25.19%, highlighting the project's sensitivity to electricity costs. CAPEX and SEC show significant variations, with LCOH ranging from -19.57% to +19.77% and -49.61% to +49.81%, respectively, underscoring the influence of equipment costs and energy efficiency. Lastly, WACC demonstrates a relatively modest impact, with LCOH varying from -15.31% to +13.18%, indicating that financing costs have a less pronounced effect on LCOH.

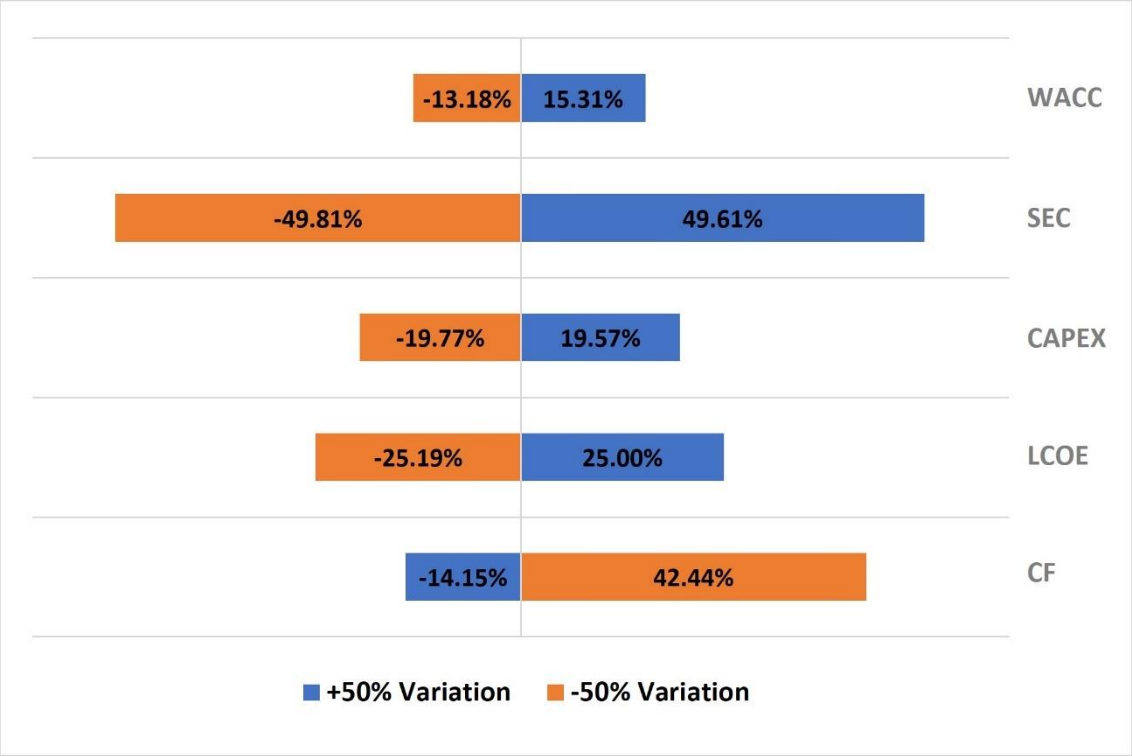


Figure 4.8: Sensitivity Analysis for LCOH

The parametric analyses provide valuable insights into the project's response to variations in critical parameters. Among these, the Capacity Factor significantly affects LCOH, reflecting the project's reliance on RESs. Conversely, hydrogen selling prices have the most substantial influence on IRR, emphasizing their impact on project profitability. Notably, WACC does not significantly affect IRR, as these variables are independent, but it does influence NPV. These findings underscore the importance of carefully managing and optimizing these key parameters to ensure the economic and environmental sustainability of green hydrogen production.

Summary

In this chapter, the comprehensive results and discussions surrounding the techno-economic and environmental analysis of green hydrogen production in Pakistan are presented. The study compares traditional hydrogen production methods, specifically SMR, with a proposed green hydrogen production scenario powered by RESs. The analysis focuses on a representative ammonia-based urea fertilizer plant in Pakistan, aiming to produce 2 million tons of green hydrogen annually. The technical analysis highlights the significant capacity requirements of the proposed green hydrogen plant due to the intermittent nature of RESs, as well as its high efficiency. The financial analysis indicates a competitive LCOH, though with a modest IRR due to economic realities in Pakistan. Nevertheless, the positive NPV and BCR make a strong case for the project. The environmental analysis emphasizes the substantial reduction in carbon emissions, reduced water consumption, and minimal land requirements associated with green hydrogen production. Finally, the parametric analysis reveals the project's vulnerability to variations in key parameters, such as power prices, capacity factor, specific energy consumption, CAPEX, WACC, and hydrogen selling prices, underscoring the importance of carefully managing these variables for the project's economic and environmental sustainability.

Chapter 05: Conclusion and Policy Recommendations

5.1. Conclusion

In conclusion, the comprehensive 3E analysis of green hydrogen production in Pakistan has revealed critical insights into the feasibility, economic viability, and environmental benefits of transitioning towards a sustainable hydrogen economy. The study began by comparing traditional hydrogen production methods, such as SMR, with a proposed green hydrogen production scenario powered by RESs. The findings underscore the challenges and opportunities associated with green hydrogen production in the context of a representative ammonia-based urea fertilizer plant in Pakistan.

From a technical perspective, the study highlighted the need for a substantial capacity of 3,995.4 MW of PEMEC systems, operating at a rate of 50 kWh/kg H_2 and 30% capacity factor. The overall efficiency of the PEMEC plant for green hydrogen production was determined to be 78.8% under these conditions. These findings underscore the essential requirement for meticulous planning and significant investment in energy storage and grid infrastructure to ensure a reliable and continuous supply of green hydrogen.

From an economic perspective, the research revealed a competitive LCOH of USD 5.16 per kg H_2, accounting for various factors related to the green hydrogen production system. The project exhibited an IRR of 0.4%, signifying the project's profitability. Additionally, the study showed a positive NPV of approximately USD 1,384,052,520 and a relatively short Simple Payback Period of 4.422 years and Discounted Payback Period of 6.565 years, indicating the potential for financial gains. While the IRR was modest, the competitive LCOH, positive NPV, and BCR further validate the economic viability of the project, despite the challenges posed by the economic realities in Pakistan.

The environmental analysis provided a compelling argument for green hydrogen production, showcasing a significant reduction in carbon emissions, reduced water consumption, and minimal land requirements compared to traditional hydrogen production methods. The parametric analysis underscored the project's vulnerability to variations in key parameters, emphasizing the importance of carefully managing these variables for the project's economic and environmental sustainability. Notably, the Capacity Factor significantly affected LCOH, reflecting the project's reliance on RESs. Hydrogen selling prices had the most substantial influence on IRR, highlighting their impact on project profitability. While the WACC did not significantly affect IRR, it influenced NPV, making it crucial to optimize these financial parameters.

The research underscores the critical benefits of transitioning to green hydrogen production in Pakistan. As an agricultural country, Pakistan's economy heavily relies on the fertilizer industry. However, the depletion of natural gas resources poses a long-term challenge to the sector. Green hydrogen production, powered by abundant renewable energy resources, offers a sustainable and environmentally friendly alternative. It not only ensures the continued production of vital resources like urea but also significantly reduces carbon emissions. This transition is not just a technological advancement; it is a strategic move towards a sustainable and prosperous future for Pakistan, ensuring the security of its energy supply and the well-being of its economy.

Despite the promising potential of green hydrogen, numerous challenges must be addressed to ensure its successful adoption in Pakistan. The high cost of renewable electricity, especially for electrolysis, remains a significant barrier to investment in green hydrogen production. The absence of PPA further compounds this challenge, as investors require a predictable revenue stream. Additionally, high interest rates, policy constraints, inflation, and tax rates pose economic barriers to green hydrogen projects. The low natural gas prices for ammonia production, which are attractive to fertilizer companies in Pakistan, hinder the competitiveness of green hydrogen. These challenges, if unaddressed, could delay the transition to green hydrogen and its positive impact on the environment and the economy.

5.2. Policy Recommendations

- **National Hydrogen Policy:** Given the absence of a clear policy framework for green hydrogen production in Pakistan, it is recommended that the government formulate a National Hydrogen Policy. This policy should outline a roadmap for the development of green hydrogen, including incentives for investors, regulatory support, and the establishment of PPAs to ensure a predictable revenue stream for green hydrogen producers. Such a policy would provide the necessary confidence to attract both domestic and foreign investment in the green hydrogen sector.
- **Tax Incentives and Financial Support:** To stimulate investment, the government should offer tax incentives and financial support to green hydrogen producers. This can include tax breaks, low-interest loans, and grants for research and development in hydrogen production technologies. Additionally, measures to control inflation and reduce the cost of capital would attract more investors to the sector.
- **Investment in Electrolyzer Technology:** To address the cost challenges associated with electrolyzer technology, the government should consider providing incentives or subsidies for the development and manufacturing of electrolyzer within Pakistan. This could significantly reduce the initial capital investment required for green hydrogen production and make it more competitive with grey/blue hydrogen.
- **By-Product Utilization:** Recognizing the by-product of water electrolysis, oxygen, as a valuable resource, Pakistan should encourage its collection and commercial utilization in industrial applications. Oxygen can be sold to various industries, such as healthcare, metallurgy, and wastewater treatment, thereby diversifying the revenue streams associated with green hydrogen production. This practice not only contributes to the circular economy but also helps offset the LCOH, making green hydrogen more economically competitive. Policymakers should establish guidelines for the safe and efficient collection, storage, and distribution of oxygen by-products, fostering collaboration between the green hydrogen sector and other industries.
- **Hydrogen Export and Trading:** Pakistan should explore opportunities for hydrogen export to countries where the demand for clean hydrogen is high. The government should facilitate the development of international partnerships and trade agreements to promote the export of green hydrogen. This initiative can not only

boost Pakistan's economy through hydrogen sales but also strengthen diplomatic ties and position the nation as a key player in the global clean energy market.

- **Transition to Renewable Energy:** Pakistan has abundant renewable energy resources. It is recommended that the government continue to invest in expanding its renewable energy capacity to ensure a stable and cost-effective supply of electricity for green hydrogen production. This transition will not only benefit the green hydrogen sector but also contribute to the overall energy security and sustainability of the nation.
- **Net Zero Transition and Carbon Markets:** To achieve a sustainable and green future, Pakistan should commit to a net-zero emissions target. The creation of a carbon market or a cap-and-trade system would incentivize industries to reduce their emissions and provide a financial impetus for cleaner technologies. Encouraging the integration of green hydrogen into industries and reducing reliance on carbon-intensive processes is a key aspect of this strategy.
- **Promotion of Green Hydrogen in Ammonia Production:** To encourage the utilization of green hydrogen in ammonia production, the government should explore options for subsidizing or incentivizing green ammonia production, as it plays a pivotal role in the agriculture sector. A shift towards green ammonia would not only reduce carbon emissions but also ensure the sustainability of the agricultural industry.
- **Industrial Decarbonization:** Encouraging the industrial sector, particularly the fertilizer industry, to transition to green hydrogen can be a win-win strategy. Offering subsidies for the adoption of green hydrogen in industrial processes can significantly reduce carbon emissions while fostering economic growth.
- **Green Economy Development:** Transitioning to green hydrogen aligns with global efforts to build green economies. Pakistan should work towards developing a green economy that not only reduces carbon emissions but also creates job opportunities and promotes sustainable development.

In conclusion, Pakistan stands at a crossroads in its pursuit of sustainable development. The implementation of the policy recommendations outlined above is instrumental in overcoming the challenges and creating an enabling environment for the growth of the green hydrogen sector in Pakistan, benefiting both the industry and the environment.

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