Social, Technical and Policy Barriers in the Green Hydrogen Implementation: A Case Study of Pakistan

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THESIS ACCEPTANCE CERTIFICATE

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DEDICATION

Dedicated to my exceptional parents, adored siblings and caring friends whose tremendous support and cooperation led me to this wonderful achievement

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Due praises are given to Allah Almighty, the Creator, and the Sustainer, without whose instruction not a single minute pass. He who has given us forte and blessed us with plenteousness without any measure. There are no words which can do justice to Him. I am empowered to Read and Write only by Him, who has bestowed upon me the knowledge I carry forward. I would first like to acknowledge EME College NUST that enabled me to conduct the research. I would like to extend much appreciation and gratitude to my advisor Dr. Shahbaz Abbas whose countless inspiration and guidance made it possible to complete my research work. In addition, Dr. Yasir and Dr. Sundus in the capacity of committee members; gave me guidance and feedback throughout the thesis process. I sincerely express my solemn gratitude with earnest sense of reverence to my parents for their encouragement, heartfelt prayers and kind wishes for successful completion of my studies along with this research work. Specially, I want to thank my siblings and caring friends from all my heart for always supporting and motivating me at every point of my research journey.

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Abstract

The transition to renewable energy systems demands innovative storage solutions to address social, technological, and policy challenges, as conventional storage methods drive emissions, compromising climate stability and energy security, making green hydrogen storage a pivotal alternative for a cleaner, resilient future. This research explores critical challenges hindering the efficiency and feasibility of green hydrogen storage systems through a comprehensive multi-method approach. Key challenges identified through comprehensive literature analysis, include economic recession, regional heterogeneity, cross-investor differences, political interference, digitalization and technological integration, and occupational health and safety. An agent-based model (ABM) is developed to identify the actors, agents and the decision makers who are responsible for the conducive implementation of green hydrogen storage system. After the simulation of ABM in NetLogo, an empirical validation is performed through 17 semi-structured interviews from the experts working in the manufacturing industry. The Analytical Hierarchy Process (AHP) was employed to quantify results, ensuring robustness through consistency ratio checks. Sensitivity analysis, applied with 5% adjustments to the pairwise comparison matrix, reinforced the reliability of findings. The comparative analysis revealed a weak correlation (0.399) between NetLogo values and AHP weights that are further analyzed with hybrid validation indices. The outcomes emphasize actionable insights for addressing systemic social, technological and policy challenges in the adoption of green hydrogen storage system. This study contributes to the discourse on renewable energy systems by providing a structured framework to assess and mitigate the multifaceted challenges in green hydrogen integration, particularly in the manufacturing sector.

Keywords: Green hydrogen storage system, Agent-based modelling, Social challenges, Technological challenges, Policy challenges, Hybrid Validation Matrix, Sensitivity analysis.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

ABM: Agent-Based Modeling

AHP: Analytic Hierarchy Process

AI: Artificial Intelligence SD: System Dynamics

ARL: Attock Refinery Limited

BP: British Petroleum

CBAM: Carbon Border Adjustment Mechanism

CCS: Carbon Capture and Storage

CI: Consistency Index

CO_2: Carbon dioxide

CR: Consistency Ratio

CSR: Corporate Social Responsibility

DES: Discrete Event Simulation

EEG: Renewable Energy Sources Act (Erneuerbare-Energien-Gesetz)

FAO: Food and Agriculture Organization

FCEV: Fuel Cell Electric Vehicle

FH2R: Fukushima Hydrogen Energy Research Field

GHG: Greenhouse Gas

GW: Gigawatt

H2: Hydrogen

HESC: Hydrogen Energy Supply Chain

HVI: Hybrid Validation Index

IEA: International Energy Agency

IoT: Internet of Things

KWh: Kilowatt-hour

MCDM: Multiple-Criteria Decision Analysis

METI: Ministry of Economy, Trade and Industry (Japan)

MW: Megawatt

NEPRA: National Electric Power Regulatory Authority (Pakistan)

OGDCL: Oil & Gas Development Company Limited

OHS: Occupational Health and Safety

RI: Random Index

SAIDI: System Average Interruption Duration Index

SAIFI: System Average Interruption Frequency Index

SDGs: Sustainable Development Goals

SDPI: Sustainable Development Policy Institute

SMR: Steam Methane Reforming

SMR: Steam Methane Reforming

T&D: Transmission and Distribution

TOPSIS: Technique for Order of Preference by Similarity to Ideal Solution

UNFCCC: United Nations Framework Convention on Climate Change

OECD: Organization for Economic Co-operation and Development

Chapter 1: Introduction

This chapter provides a comprehensive introduction to green hydrogen storage, emphasizing its role as a sustainable energy carrier for global decarbonization efforts. The chapter begins by categorizing hydrogen types and highlighting the environmental advantages of green hydrogen produced through renewable sources such as solar, wind, hydropower, biomass, and geothermal energy. Various hydrogen production methods, including electrolysis, thermochemical water splitting, and biomass gasification, are discussed. A key focus is placed on green hydrogen storage technologies, with a comparative analysis of their technical efficiency, scalability, carbon emissions and applicability across sectors. The chapter also explores Pakistan's vulnerability to climate change, emphasizing the potential of green hydrogen storage to support energy security, industrial sustainability, and decarbonization goals. The research rationale, objectives, and knowledge gaps identified in the chapter establish a foundation for the literature review in the following chapter, which will critically analyze storage technologies and global advancements in the field, along with challenges in green hydrogen storage implementation.

Green hydrogen, also known as renewable hydrogen, is a clean and sustainable form of hydrogen produced using renewable energy sources such as wind, solar, or hydropower to electrolyze water. This process splits water molecules into hydrogen and oxygen, with the hydrogen being captured for use as a clean energy carrier. Unlike conventional hydrogen production methods, which often rely on fossil fuels and emit greenhouse gases, green hydrogen production generates net-zero carbon emissions, making it an environmentally friendly alternative. Net-zero refers to achieving a balance where the total CO_2 emissions from energy and industrial processes are reduced to zero, accounting for carbon capture and storage (Rogelj et al., 2015).

Hydrogen can be produced through three main methods: grey, blue, and green. Grey hydrogen is extracted from fossil fuels like coal, oil, or natural gas, resulting in significant carbon dioxide emissions. Blue hydrogen also uses fossil fuels but incorporates carbon capture and storage technologies to mitigate emissions by capturing and storing the emitted CO_2. However, both grey and blue hydrogen are fundamentally reliant on fossil energy sources, making them less sustainable long-term solutions. In contrast, green hydrogen is produced from renewable energy sources such as solar and wind, completely eliminating CO_2 emissions during both production and utilization, thereby aligning with decarbonization goals (Abdulla et al., 2021; Saha et al., 2024).

The carbon capture and storage (CCS) technologies used in blue hydrogen present additional challenges, particularly regarding the transportation of the captured CO_2 through pipelines. Pipeline networks are considered the highest-risk aspect of CCS infrastructure, necessitating extensive safety measures and regulatory oversight. While CO_2 and natural gas pipelines share similar construction and installation practices, their risk profiles differ significantly due to the unique properties of the gases. CO_2 is non-flammable but toxic and denser than air, whereas natural gas is lighter than air and explosive. Incident-based models for CO_2 pipelines have often overestimated the risks by 2-3 orders of magnitude compared to natural gas pipelines (Duncan & Wang, 2014). Furthermore, over 80% of CCS projects initiated in the past three decades have failed, further highlighting the limitations of blue hydrogen as a sustainable solution (Pingkuo & Junqing, 2024). In contrast, green hydrogen eliminates these risks entirely by avoiding the need for CO_2 capture and transportation infrastructure, as it does not rely on fossil fuels. This makes green hydrogen a more sustainable, efficient, and safer alternative, reinforcing its role as the focal point in the transition toward a low-carbon energy future. As the world continues to address the pressing challenge of mitigating climate change, the strategic deployment of green hydrogen, supported by a comprehensive understanding of its production, transportation, and integration within energy systems, will be crucial in driving the shift toward a more sustainable and resilient energy landscape.

One of the key advantages of green hydrogen is its ability to integrate seamlessly with renewable energy systems. Green hydrogen can serve as an energy storage medium, capturing excess electricity generated by renewable sources such as wind and solar during periods of low demand. This storage capability is particularly useful in Pakistan's rural areas, where local energy systems could be supported by green hydrogen to provide consistent power. By utilizing solar or wind energy to produce hydrogen, rural communities can store this energy for periods when renewable generation is insufficient, thereby enhancing energy access and reliability. This approach addresses the persistent challenges of energy shortages and limited grid infrastructure in remote regions, ultimately promoting sustainable development and resilience. Furthermore, this stored hydrogen can be converted back into electricity when demand peaks, addressing the intermittency issues associated with renewable energy generation and contributing to a more stable and resilient energy system.

Green hydrogen storage presents significant potential for decarbonizing sectors such as transportation, industry, and energy storage due to its high energy density (120 MJ/kg) and long-term storage capabilities without degradation, making it ideal for seasonal storage and energy-intensive processes requiring extreme heat (Jayaprabakar et al., 2024). It offers a zero-carbon, on-demand fuel supply, positioning it as a sustainable alternative to fossil fuels like natural gas and coke. The manufacturing sector, responsible for 30% of total energy use and 25% of greenhouse gas (GHG) emissions in the United States as suggested by Metwally et al. (2024), remains a major contributor to global emissions, with conventional storage methods relying on carbon-intensive extraction and processing that heighten emissions and operational inefficiencies (Aouad et al., 2024; Y. Liu & Rui, 2022). Without effective intervention, inefficient storage alone could account for 1.7% of global carbon emissions by 2030 (Zuck & Tsafrir, 2023). Technological advancements, including underground hydrogen storage and integrated storage systems, have demonstrated improved energy flexibility, resilience, and resource efficiency (Bhardwaj, 2024a; Maka & Mehmood, 2024).

Existing studies on green hydrogen storage implementation in developing countries have primarily focused on challenges such as high investment costs, financing limitations, weak institutional frameworks, water scarcity, and the imbalance between local consumption and export demands, all of which could hinder development (Akomolehin et al., 2024; Komorowski & Grzywacz, 2023). Further research has addressed technical and economic evaluations of storage methods, emphasizing infrastructure adaptation, efficiency optimization, and the need for new transport and distribution systems to meet increasing energy demands and reduce emissions (Fan, 2024a; Kourougianni et al., 2024). Risco-Bravo et al. (2024) and Vallejos-Romero et al. (2022) have assessed risks, socio-environmental impacts, and public perception, for optimizing Power-to-Hydrogen-to-Power (P2H2P) systems whereas Rasul et al. (2022) and Ma et al. (2024)emphasized the critical role of government support and need for cost reduction through economies of scale. While these studies have effectively explored technological, social, and policy challenges, they focus mainly on surface-level issues such as supply chain limitations and infrastructure costs (Ikumapayi et al., 2024; Spatolisano & Pellegrini, 2024). Manufacturing sector in developing countries is vulnerable to dynamic complexities which needs to be critically analyzed. However, existing research has not explored these economic, technological, and policy challenges in resource constrained settings (Mohamed & Abdulle, 2024; V, 2024). Agent-Based Modeling (ABM) has been widely applied in the energy sector, primarily focusing on local energy storage mechanisms, interactions among energy communities, battery-electric vehicles, and renewable energy sources to enhance self-sufficiency (Laugs et al., 2024; Wang & Blondeau, 2024). Ding et al. (2024) and Preziuso & Odonkor (2024) have used ABM to explore technology adoption patterns in commercial and residential buildings, while Saqib (2024) and Safarzyńska & van den Bergh (2022) have applied ABM to assess climate-energy policies and emissions reduction strategies. This study addresses this gap by applying a hybrid ABM-AHP framework to identify and prioritize the critical challenges hindering green hydrogen storage adoption, providing a novel contribution to sustainable energy research in developing economies.

Green hydrogen storage is particularly important for Pakistan's energy transition, offering a sustainable path to decarbonize the industrial and energy sectors. Pakistan has considerable potential for renewable energy production, supported by its rich solar, wind, and hydropower resources. Solar energy is the most accessible and affordable option, with an installed capacity of 2 GW. Wind energy is also growing in popularity, contributing 1 GW national electricity grid. However, hydropower is the least developed, with only 100 MW of installed capacity, indicating room for further development (Awais & Wajid, 2024). Table 1 provides renewable energy potential in Pakistan, emphasizing the vast opportunities for sustainable energy development.

Table 1: Potential of Renewable Energy in Pakistan (Adapted from Habib et al., 2021)

Source	Potential
Wind Energy	360,000 MW
Solar Energy	2,900,000 MW
Hydro-power Energy	60,000 MW

Source: Habib, S., Iqbal, K. M. J., Amir, S., Naseer, H. M., Akhtar, N., Rehman, W. U., & Khan, M. I. (2021). Renewable Energy Potential in Pakistan and Challenges in its Development for Overcoming Power Crises | The journal of contemporary issues in business and government. https://cibgp.com/au/index.php/1323-6903/article/view/1547

Pakistan faces unique challenges in transitioning to sustainable energy due to its substantial reliance on imported fossil fuels, which makes the energy sector highly vulnerable to international price fluctuations and economic instability. In addition to these challenges, Pakistan's limited financial resources and lack of infrastructure further complicate the transition, highlighting the need for targeted policies and investments in renewable technologies. In 2022, global oil prices surged by approximately 70%, causing significant economic strain on Pakistan (World Development Report, 2022). Such fluctuations not only increase production costs for industries but also undermine energy reliability, stalling economic growth and development.

Moreover, Pakistan is highly susceptible to climate change impacts, including rising temperatures, frequent flooding, and extreme weather events. The adoption of sustainable energy solutions, such as green hydrogen, is crucial for both environmental sustainability and socio-economic resilience.

1.1 Types of Hydrogen

Hydrogen can be produced through a variety of methods, each distinguished by its energy source and environmental impact. These production methods are categorized by different colors: green, grey, brown, blue, yellow, pink, turquoise, and white hydrogen. The key distinction lies in the amount of carbon emissions produced and the energy requirements involved.

Grey hydrogen is produced using natural gas through steam methane reforming. This process is cost-effective but generates significant carbon emissions, approximately 10 tons of CO_2 per ton of hydrogen produced, making it an unsustainable option. Grey hydrogen is mass-produced to meet 96% of the global hydrogen demand (Osselin et al., 2022). Similarly, **brown hydrogen** is produced from coal through gasification and is also cost-effective but carbon-intensive, contributing heavily to greenhouse gas emissions.

Blue hydrogen offers an improvement by incorporating CCS technology to reduce emissions. Though it is more environmentally friendly compared to grey or brown hydrogen, it comes at a higher cost due to the additional capture and storage processes.

Yellow hydrogen is produced through water electrolysis powered by renewable energy, such as wind or solar, making it a carbon-free option. However, its production is energy-intensive and costly. On the other hand, **pink hydrogen** is produced using grid electricity for electrolysis, with its carbon footprint varying based on the energy mix of the grid.

Green hydrogen is a type of hydrogen produced through electrolysis of water using electricity generated from 100% renewable energy sources, such as wind, solar, or hydroelectric power. This method ensures that no carbon emissions are released during the production process, making it a truly carbon-free and environmentally sustainable form of hydrogen. Table 2 shows different types of hydrogen with their description and characteristics.

Table 2: Types of Hydrogen (Adapted from Davey, 2024)

Source	Description	Characteristics
Grey	Produced from natural gas using steam methane reforming	Lowest cost but emits ~10 tonnes of CO_2 per tonne of H2
Brown	Produced from coal using gasification	Low cost but not carbon-free
Blue	Produced from any fossil fuel with CCS	Carbon-free but higher cost

Yellow	Produced through water electrolysis using renewable-based electricity	High cost, carbon-free
Pink	Produced through water electrolysis using grid electricity	Varies depending on grid's carbon intensity
Turquoise	Produced through methane splitting (pyrolysis)	High cost, carbon-free
White	Produced as a by-product of industrial processes or in natural form	High cost, availability issues
Green	Produced through water electrolysis powered entirely by renewable energy	Zero carbon emissions, high cost, sustainable, ideal for decarbonization

Source: Davey, R. (2024). The Different Types of Hydrogen: An Overview. https://www.azocleantech.com/article.aspx?ArticleID=1894

1.2 Types of Renewable Energy Sources for Producing Green Hydrogen

Green hydrogen production relies on renewable energy sources that drive water electrolysis, splitting water into hydrogen and oxygen. The following renewable sources are essential for green hydrogen production:

1.2.1 Solar Energy

Solar energy is one of the predominant renewable sources for green hydrogen production. By capturing sunlight and converting it into electricity through photovoltaic panels, solar power serves as the driving force for water electrolysis, splitting water into hydrogen and oxygen. The global installed capacity for solar energy exceeded 1,150 GW in 2022, highlighting the rapid adoption of solar technologies worldwide (World Energy Outlook - IEA, 2022). For countries like Pakistan, with significant solar irradiance, solar energy provides a viable and scalable solution for green hydrogen production. A more sustainable approach involves generating hydrogen through water electrolysis powered by renewable energy sources, including wind, hydroelectric, or solar power (Aissani et al., 2024) .

1.2.2 Wind Energy

Wind power is another crucial renewable source for the production of green hydrogen. Wind turbines generate electricity, which can be used in the electrolysis process to produce hydrogen. According to the Global Wind Energy Council (2022), the global wind power capacity reached approximately 907 GW in 2022. Countries such as Denmark and Germany have already successfully integrated wind energy into their green hydrogen production frameworks, showcasing the potential of large-scale wind-to-hydrogen projects. With its favorable coastal and mountainous geography, Pakistan has significant untapped potential for wind energy development, making wind a promising option for renewable hydrogen production.

1.2.3 Hydropower

Hydropower is a stable and reliable renewable energy source that can be utilized for producing green hydrogen. The integration of hydropower with other renewable sources can create a robust energy framework that supports the transition to a hydrogen economy (Yilmaz, 2024). The electricity generated by hydropower plants is applied in the electrolysis process. As of 2022, global hydropower installed capacity was approximately 1,360 GW (Hydropower Status Report, 2022). Pakistan's vast river systems also present considerable hydropower resources, which could be leveraged to enhance green hydrogen production, contributing to both energy security and sustainable development (Hosseini & Wahid, 2016; Pantskhava & Jishkariani, 2024a).

1.2.4 Biomass Energy

Biomass energy is generated by burning organic materials such as agricultural waste or wood. The resulting electricity can be used in the electrolysis process for green hydrogen production. According to the Worldbioenergy Association (2022) report, the global biomass power capacity reached approximately 150 GW in 2022. Biomass is especially relevant in rural areas of Pakistan, where agricultural residues are abundant and can be harnessed to produce clean energy, supporting localized hydrogen generation and reducing rural energy poverty. Pakistan produces over 108 million tons of crop residues annually, generating 21,390 GWh of electricity (Fatima & Zeeshan, 2024; Wakeel et al., 2023). Technologies such as dark fermentation and photo fermentation are viable methods for bio hydrogen production, which can be integrated into rural energy systems (Fawad Saleem Satti et al., 2024). Hydrogen can be produced using renewable resources, such as biomass, though this process does result in some carbon dioxide emissions (Chmielniak et al., 2024).

1.2.5 Geothermal Energy

Geothermal energy, while less commonly employed, is also a viable renewable energy source for green hydrogen production. Geothermal heat is converted into electricity, which is subsequently used in the electrolysis of water (Chidire et al., 2023). Pakistan has significant geothermal potential, particularly in the Sindh province, where hot springs like Naing Shareef and Gaji Shah exhibit pool water temperatures of 43 °C and 45 °C, indicating promising geothermal energy resources yet to be fully utilized (Jamali et al., 2024).Geothermal energy could serve as a complementary renewable source in regions of Pakistan with geothermal activity, adding diversification to hydrogen production portfolios (Dincer & Ishaq, 2022; Gondal et al., 2017).

1.3 Hydrogen Production Methods

Hydrogen is a versatile energy carrier, and its storage plays a crucial role in managing energy supply and demand:

1.3.1 Steam Methane Reforming (SMR)

This is the most common method used for producing grey and blue hydrogen. It involves reacting methane with steam to produce hydrogen and carbon dioxide. In the case of blue hydrogen, carbon capture and storage technologies are used to prevent carbon emissions. Figure 1 shows schematic of traditional methane reforming unit used for hydrogen production.

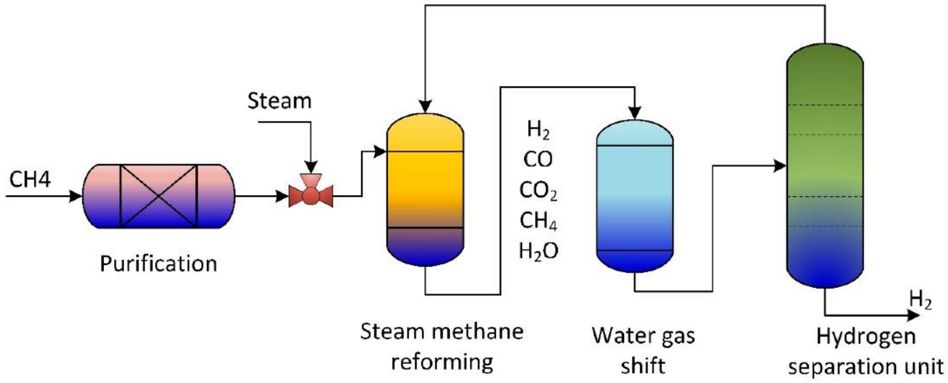

Figure 1: Schematic of traditional methane reforming unit for hydrogen production

(Adapted from Cecilia et al., 2022)

Source: Cecilia, A., Tost, R. M., & Ghasem, N. (2022). A Review of the CFD Modeling of Hydrogen Production in Catalytic Steam Reforming Reactors. International Journal of Molecular Sciences 2022, Vol. 23, Page 16064, 23(24), 16064. https://doi.org/10.3390/IJMS232416064

1.3.2 Electrolysis of Water

Green hydrogen is produced through electrolysis, where electricity is used to split water into hydrogen and oxygen. If the electricity comes from renewable sources, the entire process is carbon-neutral. The efficiency of electrolysis varies, but typically, it requires around 50-55 kWh of electricity to produce 1 kg of hydrogen, which contains about 33.3 kWh of energy (World Energy Outlook - IEA, 2021). Despite the energy losses, green hydrogen remains a key component of decarbonization efforts due to its clean production process. Figure 2 shows electrolysis process done for hydrogen production.

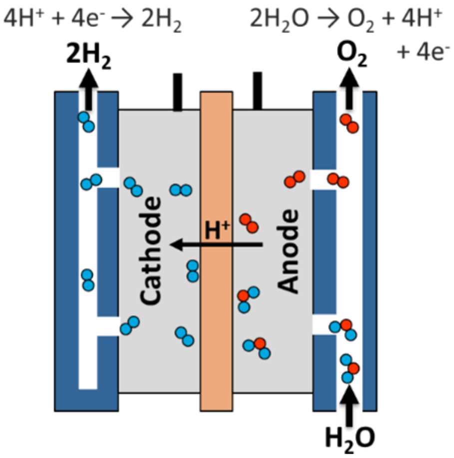

Figure 2: Hydrogen production through electrolysis

Source: Hydrogen Production: Electrolysis | Department of Energy. Retrieved from https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis

1.3.3 Thermochemical Water Splitting

This involves using high temperatures (often provided by concentrated solar power) to split water into hydrogen and oxygen. Although still under research and development, this technique holds potential for producing hydrogen in an energy-efficient manner. Figure 3 shows prediction of hydrogen through thermochemical water splitting.

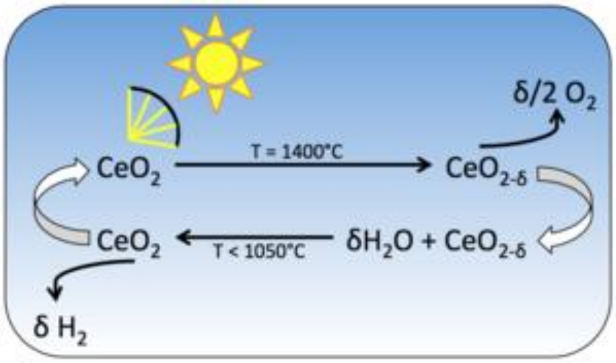

Figure 3: Production of Green Hydrogen through Thermochemical Splitting

(Adapted from Asundi, 2015)

Source: Asundi, A. (2015). Thermochemical Water Splitting by Ceria. http://large.stanford.edu/courses/2015/ph240/asundi1/

1.3.4 Biomass Gasification

Biomass can be converted into hydrogen through gasification, a process that involves heating organic materials in the presence of limited oxygen to produce a mixture of hydrogen, carbon monoxide, and other gases. This method is considered renewable when sustainably managed biomass is used. Figure 4 shows Biomass Gasification unit used for hydrogen production.

Figure 4: Biomass Gasification

Source: Yuzhu, C., Abeysinghe, D. J., Jiawen, C., Boxi, G., & Qiang, D. G. (2024). Biomass Gasification | Chi-Hwa Wang Research Group. https://blog.nus.edu.sg/chbewch/gasification-technology/gasification-technology/biomass-gasification/

1.4 Green Hydrogen Storage Applications

Hydrogen storage plays a vital role across various sectors. It can be scaled easily for massive applications, such as grid-scale energy reserves and seasonal storage, without geographic constraints like pumped hydro or thermal energy systems. Unlike batteries, which are limited by short storage durations, hydrogen can address industrial decarbonization (e.g., steel production), long-term energy storage, and heavy transport. Hydrogen's zero-carbon emissions at the point of use make it the cleanest storage option. Competing technologies like batteries involve mining rare-earth elements, resulting in habitat destruction and emissions during material extraction and processing. Table 3 shows a comparative analysis of different storage technologies.

Table 3: Comparative Analysis of Different Storage Technologies

Technology	Energy Density	Efficiency	Scalability	Applications	Carbon Emissions	Challenges
Green Hydrogen	Very High (120 MJ/kg)	30–40%	Highly scalable for long-term storage	Industry, transport, seasonal storage	Low emissions when produced via renewables; zero-carbon output at point of use (Criollo et al., 2024a).	Lower efficiency. Infrastructure costs for production, transport, and storage.
Solid-State Batteries	High	> 90%	Limited to small-medium scale	Consumer electronics, EVs	Moderate impact due to rare-earth mining; less toxic than lithium-ion (Machín et al., 2024).	Early-stage technology with high costs.
Flow Batteries	Medium	~75%	Modular scaling	Renewable energy integration	Low emissions; non-toxic vanadium often used. Minimal environmental degradation (Yadav et al., 2024).	Low energy density. High initial costs.
Thermal Energy Storage	Application-specific	~70–90%	Application-specific	Industrial processes, solar plants	Low emissions if paired with renewable heat sources; negligible pollution	Highly context-dependent; not universally applicable.

					(Wickramasinghe & Zhang, 2022).	
Flywheels	Low	~90%	Small-scale	Frequency stabilization, grid services	Negligible emissions during operation but considerable during manufacturing stage; mostly recyclable components (Cellura et al., 2022).	Low energy density. Limited long-term use.

1.4.1 Electricity Generation

Hydrogen can be utilized in fuel cells to generate electricity, whereby a hydrogen fuel cell combines hydrogen and oxygen to produce electricity, water, and heat (Onalaja et al., 2024). This process is highly efficient, with an energy conversion efficiency of around 60% (Bektaş & Arpa, 2024). Such fuel cells have practical applications in stationary power generation, backup power supplies, and grid balancing, providing reliable energy during outages (Abdin, 2024; Trachte & Fumey, 2024). Large-scale hydrogen fuel cell installations in South Korea are now providing stable power, demonstrating the viability of hydrogen as a reliable electricity source (KEA - Korea Energy Agency, 2022; Shin, 2022).

1.4.2 Transportation

Hydrogen is increasingly being employed as a fuel for vehicles, particularly in fuel cell electric vehicles (FCEVs)(C. Li & Wu, 2024). These vehicles offer zero emissions, with water vapor as the only byproduct, making them an environmentally friendly alternative to conventional fossil fuel-based transportation. Prominent examples include the Toyota Mirai and Hyundai Nexo, which are leading the market in hydrogen-powered vehicles (Fan, 2024b; Hydrogen Council, 2022 ; Li & Wu, 2024). The infrastructure for hydrogen refueling is growing globally, enhancing the feasibility of hydrogen as a mainstream transportation fuel.

1.4.3 Industrial Applications

Manufacturing companies are utilizing green hydrogen as an energy storage medium, converting surplus renewable energy into hydrogen for later use. Hydrogen is extensively used in industrial processes such as ammonia production, steelmaking, and refining (Hassan et al., 2024). This production of electricity has shown costs ranging from 43 to 79 ct/kWh (Kalchschmid et al., 2023). In Italy, green hydrogen is injected into the natural gas transmission network, enhancing storage capabilities and reducing CO_2 emissions by 32.348 tonnes annually (Arpino et al., 2023). Such applications highlight the potential of green hydrogen to replace fossil fuels and support industries in meeting stringent emission reduction targets.

1.4.4 Green Hydrogen Storage as a Sustainable Energy Solution

Green hydrogen is a clean and versatile energy carrier that plays a crucial role in achieving sustainability, particularly for industrial applications. In the context of Pakistan, sustainability is not only an environmental objective but also an economic necessity. Challenges such as energy insecurity, high dependence on imported fossil fuels, and the adverse impacts of climate change highlighting the need for green hydrogen storage as a viable solution (Tunio, 2024).

The shift towards sustainable energy solutions, such as green hydrogen storage, is driven by the need to address climate change and environmental degradation associated with conventional energy storage (Criollo et al., 2024b). Recent advances in electrolysis systems have achieved higher efficiency rates while reducing production costs, making green hydrogen increasingly viable for industrial applications (Fan, 2024c). Storage technology improvements include enhanced materials such as nanomaterials and solid-state electrolytes and containment designs that offer better energy density and safety features (Chandrakala et al., 2024; Osman et al., 2024). These combined developments are particularly significant in the manufacturing sector, where improved electrolysis efficiency and storage solutions directly impact the economic feasibility of green hydrogen adoption (Kim et al., 2024; Razmi et al., 2023).

1.6 Climate Change Context in Pakistan

1.6.1 Vulnerability to Climate Change

Climate change has severely affected the world, with South Asia being especially vulnerable due to limited public awareness and adaptation efforts. Pakistan, as a key South Asian country, has experienced significant impacts, including rising temperatures, droughts, pest outbreaks, health issues, and changes in seasons and lifestyles, with these challenges expected to continue(Peter et al., 2024). Pakistan ranks 23rd in the Inform Risk Index and 8th in global vulnerability to climate change (Idris, 2024; Sherin, 2023). The country has been facing severe and frequent climate-induced events that have devastating impacts on its population and economy. Rising temperatures, unpredictable rainfall patterns, and increasingly intense weather events underscore the urgency for robust mitigation and adaptation strategies. Studies conducted on Pakistan highlighted that climate change has the potential to significantly harm the country, with substantial environmental, economic, and social impacts (Makki et al., 2024; Shahbaz et al., 2024).

1.6.2 Economic Impacts of Climate Change

The destruction caused by climate-induced events has led to increased food insecurity and economic instability, as agriculture remains a major source of income for much of Pakistan's population. The Food and Agriculture Organization (FAO) reported significant losses in the agricultural sector, further exacerbating food insecurity across the country (FAO,2022). Additionally, infrastructure damage, including the destruction of over 2 million houses and 13,000 kilometers of roads, has severely hindered mobility and economic activities. According to the World Bank, recovery from the damage to infrastructure will take years, placing significant strain on economic development (World Development Report,2022). The vulnerability of the agricultural sector is a major global concern, as changes in weather patterns threaten the stability of production and food supplies. This challenge impacts global feeding patterns, particularly in countries where agriculture is a key part of their economy and overall productivity (Lakshmi et al., 2024). Due to widespread impact of climate change on economic growth, this has become a major concern for both local and international environmental policymakers. The 2022 floods were among the most severe in Pakistan's history, affecting over 33 million people and resulting in damages and economic losses exceeding $30 billion. The floods destroyed homes, displaced millions, and severely affected agricultural productivity, damaging an estimated 1.5 million hectares of crops, including rice, cotton, and wheat (National Disaster Management Authority Report, 2022).

1.6.3 Need for Climate Adaptation and Mitigation Strategies

An examination of historical climate data reveals the undeniable reality that climate change is an ongoing process in Pakistan. The rate and nature of these changes are expected to fluctuate over time and across different geographical regions, leading to profound effects on various aspects of society, including the environment, economy, and social dynamics (Hakovirta, 2023). The extreme events that Pakistan faces highlight the urgent need for robust climate adaptation and mitigation strategies. Green hydrogen storage is one such solution that offers significant potential for mitigating greenhouse gas emissions, ensuring a stable energy supply, and fostering economic resilience against climate-induced disruptions (Han et al., 2021).

1.7 Advantages of Green Hydrogen Storage Adoption

1.7.1 Decarbonization and Climate Targets

The primary motivation for adopting green hydrogen storage lies in its potential to achieve decarbonization and contribute to sustainable development. According to the International Energy Agency (IEA), hydrogen could contribute up to 20% of the world's CO_2 reduction needs by 2050 if implemented at scale (World Energy Outlook - IEA, 2021). The industrial sector, particularly in countries like Pakistan, is a significant contributor to greenhouse gas emissions. Transitioning to green hydrogen storage offers a viable pathway to significantly reduce the carbon footprint of these industries, thereby supporting the achievement of global climate targets and meeting international climate commitments.

1.7.2 Socio-Economic Development Objectives

The adoption of green hydrogen storage also aligns with Pakistan’s socio-economic development objectives. Research indicates that investment in green hydrogen infrastructure could create over 700,000 jobs globally by 2030, with significant potential for job creation in developing countries like Pakistan (IRENA, 2021; Pantskhava & Jishkariani, 2024b). Investment in green hydrogen storage technology has the potential to stimulate economic growth, create new job opportunities, and promote technological innovation (Bhardwaj, 2024b). By developing local capabilities in hydrogen production, installation, and maintenance, Pakistan can foster employment opportunities and skill development in emerging green technologies, thereby contributing to broader economic development.

1.7.3 Addressing Energy Access in Rural Areas

Pakistan's electricity sector suffers from outdated infrastructure and inadequate transmission and distribution systems, leading to frequent outages (H. Ahmad & Jamil, 2024). Approximately 45 million people in Pakistan lack access to the electricity grid, indicating a significant portion of the population does not have reliable electricity. Despite an increase in installed capacity to over 40,000 MW, the country still faces a power shortfall of 6,000 to 6,500 MW, indicating inefficiencies in the system (Chughtai et al., 2023). This situation contributes to the country's ranking of 110th among 135 countries for electricity provision (Aized et al., 2021). Through localized production using small-scale renewable energy installations, such as solar or wind power, green hydrogen storage can serve as a clean and versatile energy solution for electricity generation, as well as a fuel for cooking and heating (M. Ali et al., 2023; Chirosca et al., 2024; J. Zhang & Li, 2024). This approach can help bridge the energy access gap in rural areas, reduce dependence on traditional biomass, and enhance the quality of life for these communities by providing a sustainable and reliable energy source.

1.7.4 Enhancing Energy Security in Pakistan through Green Hydrogen Storage

Green hydrogen storage represents a pathway to enhancing energy security in Pakistan by offering a domestically produced clean energy option that reduces dependence on imported fuels and mitigates climate impacts (Sharma et al., 2024). Additionally, green hydrogen storage can help diversify Pakistan's energy mix and improve resilience to global energy market fluctuations

(Oluwadayomi Akinsooto et al., 2024). This diversification is crucial, given Pakistan's vulnerability to both climate change and energy price volatility. By integrating green hydrogen storage into its energy portfolio, Pakistan can move towards a more sustainable and secure energy future, addressing both environmental and economic challenges.

Green hydrogen storage provides an opportunity for Pakistan to enhance its energy security. Pakistan's reliance on imported fossil fuels constitutes nearly 28% of its energy consumption, making it highly vulnerable to global energy price fluctuations (Triantoro et al., 2023; Ul Arafeen et al., 2018). This reliance incurs substantial economic costs, with over $3.7 billion spent annually on imports (Asghar et al., 2023). By diversifying energy sources and utilizing indigenous resources, like Thar coal, and syngas production, the country may reduce reliance on imported fossil fuels and enhance energy stability (Kanwal et al., 2022). The implementation of green hydrogen storage using domestic renewable energy resources, such as solar and wind, can further strengthen Pakistan's energy independence and reduce vulnerability to price volatility in international energy markets (Khatri et al., 2022).

1.8 Research Rationale

The significance of the energy sector in driving economic growth and ensuring sustainable development cannot be overstated. However, the transition towards green energy storage solutions, such as hydrogen, is fraught with numerous challenges, including economic, political, and technological uncertainties. Despite the increasing focus on green energy storage systems, the decision-making processes required to overcome these challenges remain poorly understood, especially in the context of integrating expert opinions with model-based simulations. This gap in knowledge limits the ability of energy stakeholders to effectively prioritize critical variables and mitigate risks.

Existing research primarily addresses the technical and economic aspects of green hydrogen storage adoption but often overlooks the interplay between stakeholder perspectives and simulation-based thresholds. For instance, expert opinions obtained through methods like the Analytic Hierarchy Process (AHP) provide valuable qualitative insights, but they lack the quantitative rigor needed for precise threshold determination. Conversely, simulation models such as Agent-Based Modeling (ABM) generate quantitative thresholds but fail to incorporate the nuanced priorities of human experts. This disconnect between qualitative judgments and quantitative analyses poses a significant challenge to effective decision-making in the energy sector. This study seeks to bridge the gap by integrating AHP and ABM methodologies to develop a hybrid decision-making framework. By conducting simulations using NetLogo and validating the results through expert interviews and AHP, the research aims to uncover the alignment (or misalignment) between simulated thresholds and expert-determined weights. Additionally, sensitivity analyses and gap analyses will be conducted to refine the prioritization of variables and identify key inconsistencies. The findings will be further validated through the development of a Hybrid Validation Index (HVI), providing a robust mechanism for comparing the outputs of the two approaches.

The rationale for this research lies in its potential to enhance decision-making processes in the energy sector. By combining quantitative simulations with expert insights, the study will provide energy stakeholders with actionable frameworks for prioritizing variables such as economic recessions, political interference, and technological challenges. These insights will not only aid in the adoption of green hydrogen storage technologies but also contribute to a broader understanding of hybrid validation approaches in complex decision-making environments. Ultimately, this research aims to align technical innovations with stakeholder priorities, paving the way for more resilient and sustainable energy systems.

1.9 Research Objectives

The primary objective of this study is to identify and analyze the significant challenges associated with green hydrogen storage. By conducting a comprehensive literature review and expert consultations, the study aims to highlight critical variables that impact the scalability, efficiency, and safety of green hydrogen storage technologies. This identification process will contribute to a deeper understanding of challenges hindering the advancement of green hydrogen infrastructure.

A core objective of the research is to design and implement an ABM that simulates the identified challenges in green hydrogen storage. The ABM will model the interactions between key variables, providing insights into how different factors influence system behavior under various scenarios. This simulation-based approach will support the validation of theoretical findings and assist in visualizing the impact of complex dynamics on green hydrogen systems.

The study further aims to gather and analyze expert opinions and stakeholder insights from Pakistan's energy sector through semi-structured interviews. This objective focuses on capturing industry-specific challenges and validating model assumptions with real-world perspectives. The inclusion of expert feedback will ensure the model's relevance and practical applicability in the context of Pakistan's energy transition towards sustainable hydrogen solutions.

1.10 Research Questions

This study addresses the following key research questions:

1. What are the major challenges to green hydrogen storage implementation in Pakistan's manufacturing sector?
2. How can ABM be utilized to model challenges arising from the actions of government agents and technology developers in implementing green hydrogen storage in Pakistan?
3. What are the opinions of hydrogen experts in Pakistan about the identified challenges in ABM model?

1.11 Research Gap

Despite the increasing focus on green hydrogen and its potential for sustainable energy solutions globally, there is limited research specific to Pakistan on the socio-technical and policy challenges that impede the adoption of green hydrogen storage in the manufacturing sector. While technological infrastructure, social awareness, and acceptance have been studied, Pakistan presents unique challenges that go beyond the commonly explored variables. Challenges such as regional heterogeneity, cross-investor differences, political interference, economic recession, digitalization and technological integration, and occupational health and safety (OHS) require in-depth analysis in the Pakistani context. Pakistan's issues are distinct due to the country's naturally diverse education levels, political landscape, resource distribution, and regional opportunities. Countering these challenges is crucial, as understanding the impact of each challenge is necessary for framing effective policy solutions. Unlike other regions, Pakistani stakeholders prioritize economic survival over climate change, which adds another layer of complexity. Therefore, developing policies that incorporate and address all these potential challenges is essential. This study uniquely utilizes Agent-Based Modeling (ABM) to analyze the socio-technical and policy challenges, offering insights that were previously unattainable. ABM enables a more nuanced exploration of interactions among diverse stakeholders, providing a detailed understanding of how individual behaviors and systemic dynamics influence the adoption of green hydrogen. By simulating different policy scenarios, the study aims to identify the most effective strategies for promoting green hydrogen adoption, making a significant contribution to both academic literature and practical policymaking.

In summary, this chapter has established the foundation for the study by providing a comprehensive exploration of green hydrogen storage technologies, production methods, and renewable energy sources, alongside the climate and energy security challenges faced by Pakistan. The discussion has highlighted the potential of green hydrogen storage in supporting decarbonization, industrial sustainability, and long-term energy resilience. Additionally, the research rationale and existing knowledge gaps have been identified, underscoring the need for further investigation into optimal storage applications and policy frameworks. The next chapter will critically review the existing literature on green hydrogen storage technologies and their practical implementations, offering a theoretical basis to support the research objectives and methodological framework of this study

Chapter 2: Literature Review

This research is grounded in a comprehensive review of academic literature to explore the challenges and variables influencing the development and adoption of green hydrogen technologies. A systematic approach was employed to collect, analyze, and synthesize relevant literature, ensuring a strong theoretical foundation for the study. The search process began with the identification of specific keywords related to the topic. Key terms included: "green hydrogen supply chain challenges," "agent-based modeling in renewable energy systems," "challenges to green hydrogen adoption," "Analytic Hierarchy Process (AHP) in energy decision-making," "validation techniques for hybrid energy models," and "sensitivity analysis in energy modeling." These keywords were combined with Boolean operators (AND, OR, NOT) to improve search precision and capture a broad range of perspectives. The literature search was conducted using prominent academic databases and search engines, including Scopus, Web of Science, Google Scholar, ScienceDirect, and institutional resources available through Cardiff Metropolitan University's MetSearch and MetLibrary systems. The selection criteria focused on peer-reviewed publications from the last decade to ensure the research incorporates contemporary advancements. Additionally, seminal works in renewable energy systems and green hydrogen storage technology were reviewed to provide historical and theoretical context. The screening process involved evaluating abstracts, methodologies, and findings for relevance to the study’s objectives.

Priority was given to studies that addressed the integration of green hydrogen into energy systems, the use of ABM for simulating energy supply chains, and the application of multi-criteria decision-making tools such as AHP. The review also included literature on validation frameworks, particularly those blending quantitative and qualitative approaches for evaluating model outputs. To ensure a comprehensive understanding of the topic, additional keywords were refined to align with the core focus of the research. These included terms such as "social acceptance of hydrogen energy technologies," "technological challenges to hydrogen storage," "policy frameworks for green hydrogen adoption," "agent-based modeling for energy storage technologies," and "optimization of hydrogen supply chains through ABM." This broader set of keywords captured the multidimensional challenges—social, technological, and policy-related—of green hydrogen storage systems and their modeling through ABM. Such an approach allowed the review to encompass diverse perspectives and methodologies, establishing a robust basis for subsequent analysis and discussion.

2.1 Sustainability and Its Significance

2.1.1 What is Sustainability?

Sustainability refers to the ability to meet present needs without compromising the ability of future generations to meet their own needs. It involves balancing economic growth, environmental protection, and social equity. The concept of sustainability has evolved from a localized, technical focus to a broader, value-driven global issue, encompassing diverse interpretations and definitions. Today, most sustainability frameworks include environmental, social, and economic dimensions, but different stakeholders emphasize these aspects differently based on their perspectives and goals (Jackson & Holm, 2024).

2.1.2 Role of the Manufacturing Sector in Sustainability

Manufacturing is a process that uses available resources, such as machines, manpower, materials, and money, to produce market-ready products (Davim, 2024). While manufacturing typically refers to the creation of products, Zhang et al. (2024) suggests using the term more broadly to encompass all forms of physical production, including processing industries and energy generation. Hence, the term "manufacturing" represents entire value chain of physical production, ranging from ideation and design to final fabrication.

The manufacturing sector, as one of the largest contributors to greenhouse gas emissions, plays a critical role in achieving sustainability. Sustainable manufacturing focuses on reducing the ecological impact of production processes by evaluating and improving its practices. It involves enhancing manufacturing systems and processes while maintaining both performance and environmental sustainability. A system cannot be considered sustainable if it depletes natural resources, generates waste, or harms the environment. In fact, a sustainable system is one that operates in a closed loop, where what is extracted is effectively returned or reused by the system. Therefore, sustainability and manufacturing can coexist by prioritizing environmental balance alongside economic growth (Pu et al., 2024). Green manufacturing can be defined as the design, development, and implementation of processes that minimize or eliminate the use and generation of substances harmful to human health and the environment. Similarly, green marketing and green supply chains focus on promoting and managing products and services in ways that prioritize environmental sustainability and reduce ecological impact (Abel & Kenechukwu, 2024; Fagan, 2024). Toyota's implementation of lean manufacturing practices, combined with renewable energy sources, has led to significant reductions in emissions and energy consumption in its production facilities (Toyota USA Newsroom, 2021; Wiese et al., 2015). By optimizing energy use and incorporating solar power into its production lines, Toyota has successfully minimized its environmental footprint while maintaining high productivity levels.

In 2018, the manufacturing sector was the largest contributor to energy system emissions. The sector is a major contributor to poor environmental performance due to high emissions *of* NOx, CO_2, and SO_2 from metal, chemical, and cement production (Ramli & Munisamy, 2015). Pakistan's manufacturing sector plays a substantial role in the country's environmental challenges, with data indicating that it generates approximately half of the nation's total pollution (S. N. Shah et al., 2022). This significant environmental impact stems from various industrial activities across different manufacturing subsectors. The sector's environmental footprint is particularly evident in key industries. The textile industry, cement production, and leather tanning operations pose serious environmental concerns through their discharge of untreated effluents into natural water bodies. This practice leads to widespread water contamination, affecting both aquatic ecosystems and communities that depend on these water sources (Baig et al., 2022).

Energy consumption patterns in manufacturing activities directly contribute to increased carbon emissions. The relationship between industrial energy use and carbon emissions is particularly concerning given the sector's reliance on fossil fuels and often inefficient energy utilization practices. This creates a cycle where manufacturing growth, while economically beneficial, leads to heightened environmental degradation through increased carbon emissions (Tanveer et al., 2021).

In addition to environmental concerns imposed by industry, reliance on imported fossil fuels makes Pakistan highly vulnerable to international price fluctuations, which directly affect manufacturing costs and energy access (Fazal et al., 2022). Rising fuel prices can lead to increased costs for raw materials and production, especially in energy-intensive industries such as cement and steel manufacturing (Sikandar & Chaudary, 2023). These price fluctuations can also result in energy shortages, affecting productivity and disrupting supply chains. Economic instability due to fluctuating energy costs discourages long-term planning and investment in cleaner technologies like green hydrogen, as businesses become hesitant to allocate resources amid uncertainty (N. Ali, Karl Butzbach, et al., 2024).

Sustainable manufacturing aims to reduce the ecological impact of production processes by evaluating and improving practices (Awasthi et al., 2020). The US department of Commerce defines sustainable manufacturing as processes that minimize negative environmental impacts, conserve resources and ensure safety for employees, communities, and consumers (Gbededo et al., 2018; Peter et al., 2024). Sustainable manufacturing can hence be concluded as adoption of practices focusing on minimizing negative environmental impacts, conserving energy and natural resources, and ensuring safe working environments.

2.1.3 Diverse Academic Perspectives on Sustainability

The diversity of sustainability perspectives is evident in academia, where different disciplines employ unique methods to define and approach sustainability (Singha & Singha, 2024). While environmental sustainability focuses on reducing the depletion of natural resources and minimizing ecological damage, social sustainability emphasizes the importance of equity, well-being, trust, accessibility, community development, and improving quality of life (de Fine Licht & Folland, 2024; Rajendran et al., 2024). Economic sustainability, on the other hand, involves ensuring long-term economic viability without compromising environmental and social aspects (Shayed et al., 2024).

2.1.4 Socio-Technical Megatrends

The socio-technical megatrends contributing to climate change are primarily driven by rising greenhouse gas emissions from multiple sectors, including energy, industry, and land-use changes. Industrial activities have seen a marked rise in emissions, driven by strong demand for materials and energy services, especially in Eastern and Southern Asia (Lima Abreu et al., 2024). Land use changes account for approximately 44% of emissions, with deforestation and agricultural expansion being major contributors (Lamb et al., 2021). Soil management practices can either exacerbate or mitigate these emissions Application of organic matter such as compost and biochar can reduce N_2O emissions by 25% and 33%, respectively, particularly when not combined with mineral nitrogen fertilizer. Whereas, co-application with mineral fertilizers can increase N_2O emissions by 14% (Valkama et al., 2024). Developed countries have seen a reduction in emissions, while low to medium-income countries have experienced a 130% increase since 1990, highlighting the need for region-specific policies (Oreggioni et al., 2021). Table 4 provides a snapshot of key global economic, demographic, and energy trends today and forecasts where these metrics might be in 50 years. It highlights the substantial growth anticipated in population, urbanization, global GDP, and energy consumption, with significant implications for policy and financial planning.

2.2 Social, Technological, and Policy Challenges

The transition to green hydrogen storage in Pakistan's manufacturing industry faces significant challenges, categorized into social, technological, and policy challenges. Social, technological, and policy challenges has direct impact on the feasibility and scalability of green hydrogen storage technologies, particularly in developing countries (Abidemi Obatoyinbo Ajayi et al., 2024; Adebola Folorunso et al., 2024). The emphasis on these specific dimensions stems from their interconnected nature and cumulative impact on project success (Alragabah & Ahmed, 2024). Together, these factors were prioritized as they capture both structural challenges and implementation risks that can obstruct successful green hydrogen storage adoption in manufacturing industry (Haris & Yang, 2023a). Addressing these challenges is essential for ensuring the successful implementation of green hydrogen storage in Pakistan's manufacturing sector.

2.2.1 Social Challenges

Social challenges arise from societal factors such as public perception, community engagement, regional disparities, and workplace safety (Denham, 2020; Kipāne & Vilks, 2023). These challenges influence how well innovative storage technologies are accepted and implemented within communities or regions. Social sustainability involves focusing on aspects such as equity, ethics, health, gender balance, and empowerment, all within a broader sustainability framework (Leal Filho et al., 2022) .

2.2.1.1 Regional Heterogeneity

Regional heterogeneity encompasses the diverse socio-economic conditions, development levels, and resource availability across various regions, significantly influencing the adoption of green hydrogen storage technologies (Baizholova & Nuralina, 2024; Duc et al., 2024). In Pakistan, regions with higher economic activity and better infrastructure are more likely to adopt innovative technologies, whereas rural and underdeveloped areas often face significant challenges related to energy access, economic viability, and infrastructural limitations (N. Ali, Butzbach, et al., 2024; Jawwad Riaz, 2024). These disparities critically shape where and how green hydrogen projects can be sustainably implemented.

The importance of understanding regional disparities is highlighted by Beenstock & Felsenstein (2008), who emphasize the need to consider socio-demographic differences and variations in living costs across regions when analyzing adoption patterns. Identifying these differences is crucial for uncovering potential obstacles and opportunities in green hydrogen implementation. Mili & Martínez-Vega (2019) further argue for the necessity of tailored sustainability indicators that consider diverse regional conditions and priorities, thereby addressing inequalities in sustainability research and ensuring context-specific development approaches.

Q. Liu et al. (2024) discuss how geographical variations, development disparities, and diverse natural environments complicate the adoption of green hydrogen storage, necessitating localized approaches that effectively address unique regional challenges. Similarly, Brelsford et al. (2017) note that disparities in income, access to services, and socio-economic conditions across regions contribute to differing levels of inequality and variations in sustainable development outcomes, particularly in urban areas. These complexities necessitate a deeper understanding of regional contexts to devise effective strategies for hydrogen storage implementation.

Despite these challenges, regional heterogeneity also presents unique opportunities (Morton & Cook, 2022). Bolz et al. (2024) argue that although challenges to hydrogen transition are often discussed at the federal level, regional actors have significant opportunities to drive this transition by leveraging local decision-making processes and capitalizing on regional strengths. L. Li et al. (2022) demonstrate that regional integration policies can dynamically influence green innovation, though the effects may vary based on factors such as city size, location, and pollution levels.

Understanding these dynamics is crucial for identifying the pathways through which regional efforts can advance the adoption of green hydrogen.

De Laurentis & Pearson (2021) provide an analysis of how regional actors interact with energy systems, resource flows, and infrastructures to achieve their sustainability goals. Their study emphasizes the importance of resource availability and infrastructure renewal as key factors in the successful adoption of green hydrogen technologies. Roussafi (2021) introduces the concept of the "renewables pull" effect, suggesting that differences in renewable energy conditions across regions can influence business location decisions, potentially leading to industrial shifts based on renewable resource availability.

These factors collectively demonstrate that while regional disparities pose substantial challenges to the implementation of green hydrogen storage, they also create opportunities for targeted interventions and localized solutions that leverage unique regional strengths. Effectively addressing these disparities requires tailored strategies that align green hydrogen projects with the specific socio-economic and infrastructural conditions of each region, transforming potential obstacles into opportunities for sustainable innovation and growth (Cheilas et al., 2024).

2.2.1.2 Occupational Health and Safety

Occupational Health and Safety (OHS) are the systems of technical, operational, and organizational elements that reduce the possibility of vulnerability of various hazards, or accidents, or limit their intensity in the manufacturing industry. These can be physical, non-physical, or human actions based on specific procedures (Qiao et al., 2022). The effectiveness of these measures is influenced by their design, implementation, and ongoing assessment, which is crucial for ensuring their reliability and performance in emergency situations (Barkhatov et al., 2022). Green hydrogen gases highly susceptible to ignition from even the smallest spark, and hydrogen production facilities often have hydrogen gas present in the atmosphere which creates a high probability of ignition scenarios (Davies et al., 2024; Suwa, 2024).Additionally, hydrogen exhibits the highest self-diffusion rates compared to larger molecules like methane and nitrogen, particularly in Nano pores (Chang et al., 2024). Green hydrogen facilities should meet all the conditions for potential explosions, especially in storage and gas pressure areas, making effective preventive measures crucial to mitigate these risks (Alfasfos et al., 2024; Gordienko & Shebeko, 2022). Managing hydrogen process safety throughout the lifecycle of a project—from commissioning to operation—poses unique challenges, requiring adherence to safety standards that meet or exceed those expected by asset owners, regulators, and the surrounding community (Raghavendra Rao et al., 2024). The concept of risk encompasses both the frequency or probability of a harmful event occurring and the consequences of that event (Accastello et al., 2022; Sven Ove Hansson, Risk - PhilPapers, 2008). The integrated approach proposed by Soltanzadeh et al. (2024) emphasizes the need to analyze safety and security risks concurrently, identifying four dimensions: occurrence probability, severity, vulnerability, and securing. A preventive approach to OHS, rather than a reactive one, is crucial to effectively manage safety risks (Akerstrom et al., 2024) .

By fostering a culture of safety and emphasizing preventive measures, organizations can enhance their operational resilience and contribute to the broader goal of sustainable industrial practices (Tayab et al., 2024).However, while companies tend to emphasize their overall management approach to OHS, they often fall short in providing comprehensive quantitative and qualitative information beyond the conventional metrics of occupational injury rates (Berthet et al., 2024). Additionally, OHS training programs are inadequately analyzed in quantitative terms, making them the least reported indicator in sample reports (El Kholti et al., 2024). This suggests that however significant progress has been made in adopting OHS policies and practices, there are still gaps in comprehensive reporting and implementation.

2.2.2 Technological Challenges

Chester & Allenby (2020) demonstrates technological challenges as the integration of innovative storage technologies into physical infrastructure, operational complexities arising from new capabilities and vulnerabilities, and the need for infrastructure managers to adapt to rapidly changing systems governed by software and artificial intelligence.

2.2.2.1 Economic Recession

Economic recession is characterized by a significant decline in economic activity, impacting key macroeconomic indicators such as GDP, employment, investment spending, household income, and industrial production (Christiano, 2017; Verma & Dutta, 2013). These declines typically persist for several months whereas green hydrogen storage technology often require substantial upfront investment and time to develop, making them less attractive during economic uncertainty (Kumar et al., 2023).The cyclical nature of recessions disrupts long-term planning, affecting industries' ability to invest in innovative solutions like green hydrogen storage (Ibrahim, Lanhui, & Habibi, 2018).

Mazurek & Mielcová (2013) suggested that during prolonged economic downturns, industries deprioritize investments in costly emerging technologies. Peimani (2022) also confirmed that during economic downturns, investments in renewable energy and green hydrogen technologies are impacted, as industries prioritize immediate financial stability over uncertain, long-term projects. The establishment of green hydrogen infrastructure requires substantial investment in storage technologies such as compressed hydrogen, cryogenic liquid hydrogen, and solid material storage (Xie et al., 2024). Limited access to capital exacerbates the challenge, as investors are often hesitant to fund projects with uncertain returns and high initial costs (N. Ma et al., 2024).

Economic recessions lead to a shift in public perception, where immediate economic survival takes precedence over environmental issues which can be seen in Pakistan’s perspective as well (Waheed et al., 2022). Studies, such as those conducted, indicate a decline in public belief in climate change, presenting additional challenges for garnering support for green hydrogen storage projects.

2.2.2.2 Digitalization and Technological Integration

Digitalization includes digital platforms that enhance collaboration and efficiency, enabling enterprises to optimize productivity and improve coordination across value chains (Kovtunenko & Lozan, 2024; Peiró et al., 2024). These tools facilitate real-time communication and decision-making, contributing to innovative development and competitive advantages in a dynamic economic environment (Rajan et al., 2024).

The lack of technological integration in manufacturing limits the ability to foster open innovation and effectively utilize resources (Hakaki et al., 2021). Lack of technological integration in manufacturing can hinder open innovation practices, limiting access to external knowledge and skills, which are crucial for resource utilization and accelerating product innovation in the Industry 4.0 context (Gradillas & Thomas, 2025; Mubarak et al., 2024).The absence of technologies such as artificial intelligence (AI) and big data impedes continuous improvement, reducing competitiveness and stalling progress in manufacturing (Masod & Zakaria, 2024).

Limited availability of smart technologies, including wireless communication and energy storage, hampers the deployment of smart grids and the integration of renewable energy resources in the developing countries (M. A. Raza et al., 2022). IoT sensors are crucial for real-time monitoring of hydrogen production and storage, ensuring operational safety by detecting leaks and anomalies (H. J. Hwang & Hwang, 2024). The lack of AI-driven analytics and predictive maintenance capabilities makes optimizing hydrogen production processes challenging, increasing downtimes and reducing the feasibility of green hydrogen storage projects (Peng et al., 2023). Without predictive maintenance, the likelihood of system failures is higher, compromising the safety of hydrogen facilities (Buttner et al., 2024). The integration of reliability data, such as that from the Hydrogen Component Reliability Database (HyCReD), supports risk reduction and failure rate analysis in hydrogen facilities (Gusev et al., 2024). Digital tools like Big Data, AI, IoT, and Distributed Ledgers are essential for efficiently balancing supply and demand, enhancing grid capacity, and integrating renewable Distributed Energy Resources (DERs) (Catalina Spataru et al., 2024). Their absence significantly hampers the transition to a sustainable energy system (Komala et al., 2024).

2.2.3 Policy Challenges

Policy challenges due to religion-based politics, inefficiencies, corruption, and interventionism hinder investment and economic potential, particularly in rural areas and among the poor (Ray-Chaudhuri, 2013). Stable political environments foster robust economic policies, while instability can lead to downturns (He & Tang, 2024). Regulatory unpredictability often deters investment, as entrepreneurs fear sudden policy changes that could adversely affect their businesses (Brunetti et al., 1997; Zhou et al., 2024).

2.2.3.1 Cross-Investor Differences

Different investor groups exhibit distinct motivations, influenced by factors such as risk tolerance and ethical considerations (Signori, 2020). Eckert et al. (2024) highlight that differences in behavior and motives among investors influence investment decisions, potentially affecting renewable energy project funding. According to Bhardwaj (2024b), cross-investor differences can influence investment flows and the adoption of storage technologies, affecting the scale and nature of investments in renewable energy projects. Differences in investor confidence regarding the technological maturity of hydrogen storage solutions can lead to varied investment levels (Palmer et al., 2024).

Sustainability-oriented investors are more inclined to prioritize non-financial returns, such as environmental impact, which affects their investment amounts and the number of campaigns they support (Hermesmann et al., 2023; Hornuf et al., 2022) . Wins & Zwergel (2014) emphasize that investor motives and attitudes are crucial determinants of investment decisions. In emerging markets, investor behavior can vary significantly, leading to differences in risk-sharing and contributing to additional risk premiums (Jung et al., 2009). Linnerud & Holden (2015) observed that concerns about capacity challenges varied based on investor experience, with experienced investors expressing greater concern regarding abrupt policy changes compared to local landowners with limited energy sector experience. Kilinc-Ata & Dolmatov (2023) provide insights into how various factors influence renewable energy investments across OECD and BRICS countries. Tale & Rege (2024) emphasize that investors' beliefs about the technical viability of technologies often outweigh policy effectiveness, particularly for those with short investment horizons who are vulnerable to external pressures. Understanding these diverse investor dynamics is essential for developing tailored investment strategies that attract both local and foreign investors to green hydrogen storage initiatives.

2.2.3.2 Political Interference

Political interference is a significant challenge to the adoption of green hydrogen storage technologies (Oluwadayomi Akinsooto et al., 2024). Political interference in the administration leads to poor performance, inefficiencies, and corruption, ultimately hindering effective resource allocation in renewable energy initiatives (Mngomezulu, 2020). Masoud (2023) also suggested that this interference negatively influences procurement performance, particularly in contract awards and legal framework implementation, leading to inefficiencies. Critics such as Romm (1993) have highlighted how politicians, special interest groups, and lobbyists use political arguments to justify continued investments in fossil fuels and nuclear power under the guise of "clean" energy. This mislabeling is often used to support long-term research and development in fossil fuel and nuclear technologies, promoting them as environmentally friendly alternatives (Monyei & Jenkins, 2018; Sperling & Cannon, 2004).

In Pakistan, political factors have been identified as major obstacles that weaken the capability of project organizations to effectively implement renewable energy initiatives (Haris & Yang, 2023b). Political environment in Pakistan is characterized by fragmentation and elite capture, which hampers effective governance and resource allocation (Mirza & Munir, 2023). Public resources are often allocated based on political allegiance rather than need, leading to disparities across regions (Ahmed, 2023).

Oluwadayomi Akinsooto et al. (2024) highlights that political interference can hinder the development of hydrogen technologies by creating uncertainty, which discourages investment. Political uncertainty, such as government official turnover, leads firms to reduce environmental investment (Niu & Zhou, 2023). A clear and realistic strategy is essential to minimize investment risks and promote green hydrogen storage implementation (Ajanovic et al., 2024; Das, 2023).

After conducting a comprehensive literature review on energy transition challenges in developing countries, six critical variables were identified: **economic recession, regional heterogeneity, cross-investor differences, political interference, digitalization and technological integration, and occupational health and safety (OHS)**. These variables emerged as recurring challenges highlighting their significance in shaping the resilience and sustainability of energy storage systems in developing economies. Each of these play a crucial role in shaping its efficiency and scalability, particularly in the context of a developing country like Pakistan. Understanding how these variables interact provides insights into the complex social, technical, and policy challenges that must be addressed to support green hydrogen adoption in the manufacturing sector.

2.3 Global Energy Trends and Pakistan's Energy Landscape

Global energy trends reveal significant disparities in energy consumption and emissions across regions and countries. As of 2017, countries like Saudi Arabia, Venezuela, and Canada hold the largest oil reserves, while Saudi Arabia, Russia, and the United States are the top producers and consumers of oil globally (Johnston, 2014). Saudi Arabia is a leading oil producer, leveraging its vast reserves to maintain a pivotal role in global markets. United States surpassed both Saudi Arabia and Russia in oil production by 2018, largely due to the shale revolution, which has reshaped global supply dynamics (Zolina et al., 2019). Similar trends are observed in natural gas, where Russia holds the largest natural gas reserves, followed by Iran and Qatar. In terms of production, the United States and Russia are the dominant players, with the U.S. producing 728 billion m^3 and Russia 579 billion m^3 in 2014 (Breeze, 2016; "Natural Gas Production," 2022). On the other hand, coal reserves are heavily concentrated in the U.S., Russia, and China, with China playing a pivotal role in global energy dynamics as both the largest producer and consumer. In 2018, China accounted for 45.4% of global coal production while also being the leading importer, primarily due to its reliance on coal for electricity generation, which makes up 68% of its energy mix ("China," 2023; Yang et al., 2020). Similarly, the U.S. and Russia hold significant coal reserves, supporting their domestic energy needs and export activities (X. Liu & Song, 2024; L. P. Thomas, 2013).These disparities highlight entrenched dependencies on fossil fuels, presenting significant hurdles for the transition to cleaner energy systems.

Pakistan's hydrocarbon reservoirs, comprising oil, gas, and coal, present a complex landscape of production levels and potential. The country has significant reserves, yet faces challenges in optimizing production. Pakistan has crude oil reserves of 27 billion barrels (22.6 million barrels produced), natural gas reserves of 8 trillion cubic meters (93 million cubic meters produced), and coal reserves of 185 billion tons (4.6 million tons produced) (Rasool et al., 2022). Natural gas is expected to peak in 2024 at 32.70 million toe, and coal production is anticipated to peak in 2080 at 134.06 million toe (Ur Rehman et al., 2017). Gypsum production is forecasted to increase by 45%, and oil production is projected to increase eightfold (Saadat et al., 2021).

2.3.1 Energy Use Inequality

Energy access and consumption patterns reveal significant global and domestic inequalities. Current data shows stark disparities between developed and developing nations, with US and Europe exhibiting much higher per capita energy consumption compared to Pakistan, India, and Bangladesh, emphasizing the need for renewable energy focus (A. Khan et al., 2024). China, while having a high energy consumption structure, particularly in clean energy utilization, still faces challenges in achieving carbon reduction goals, indicating disparities in energy consumption patterns compared to developed nations like the United States (H. Li et al., 2022). The factors driving energy consumption also exhibit distinct patterns between developed and developing economies. In developing nations, the primary determinants center around fundamental economic indicators such as GDP growth and capital investment levels, along with seasonal factors like winter temperatures that affect energy demand. In contrast, developed nations show a different set of influencing factors, where energy consumption patterns are more closely tied to international trade dynamics, institutional factors such as corruption levels, and technological advancement through innovation (Dokas et al., 2022).

Research consistently demonstrates a strong positive correlation between the Human Development Index (HDI) and energy consumption levels, highlighting energy's crucial role in societal development and economic advancement (Pham et al., 2024). HDI in Moldova, Europe indicates that a one-percentage-point increase in renewable energy leads to approximately a 1.6% increase in HDI, emphasizing energy's critical role in human development (Dokas et al., 2022). Nations with higher energy consumption generally exhibit improved living standards, better healthcare outcomes, and stronger economic indicators. However, this relationship also underscores the challenges faced by countries with limited energy access (Bonhomme & Treiner, 2024).

Pakistan's energy landscape reflects these broader challenges. As of 2020, only 49.3% of Pakistanis relied on clean fuels for cooking, with only 26% of rural areas having access, indicating significant portion of the population, estimated at 110 million people, lacks access to cooking fuels (M. S. Khan & Khan, 2023). Multidimensional Energy Poverty Index reveals that 32% of households in Punjab experience energy poverty, with significant disparities across divisions (Gill et al., 2022). These statistics highlight the fundamental challenges Pakistan faces in its green energy transition efforts, particularly when considering the complex interplay of economic constraints, political dynamics, and infrastructure limitations (Zafar & Raja, 2022). The country's energy transition challenges are further complicated by existing infrastructure gaps, regional development disparities, and resource allocation issues. These factors create additional obstacles in implementing comprehensive energy solutions, particularly in rural and economically disadvantaged areas (Riaz & Perdhana, 2024). Understanding these disparities is crucial for developing effective policies that can address both energy access and environmental sustainability goals simultaneously.

2.3.2 Emissions Inequality

Emissions inequality is another pressing concern. The majority of these emissions originate from wealthier nations, exacerbating global inequality in both energy access and emissions. The world's wealthiest 1% contribute more than twice the carbon emissions of the poorest half of the global population (Bhattacharya, 2022). This imbalance complicates global efforts toward emission reductions and highlights the disproportionate burden on developing countries, where energy poverty coexists with the need to reduce carbon emissions (Skare et al., 2024). The emissions inequality raises important questions about climate justice and fair transition pathways. Developing nations argue that their path to economic development should not be constrained by emissions restrictions, given that developed countries achieved their current economic status without such limitations (Chancel, 2022; Rauner et al., 2024). This perspective emphasizes the need for substantial financial and technological support from developed nations to enable sustainable development pathways in emerging economies.

The situation in Pakistan exemplifies these challenges. As the country strives to improve living standards and industrial capacity, it must balance increasing energy demand with environmental responsibilities. This balance becomes particularly critical when considering that many Pakistanis still lack access to reliable energy sources, making the transition to cleaner alternatives more challenging without compromising development goals (Muhammad et al., 2024). Demand-side management (DSM) can help Pakistan balance increasing energy demand with environmental responsibilities by potentially saving 10.0%–15.0% of primary energy (Chughtai et al., 2024).

2.3.3 Challenges in Pakistan's Energy Transition

Pakistan's energy transition confronts significant challenges rooted in its existing infrastructure and heavy reliance on fossil fuels. The transmission and distribution network suffers from substantial T&D losses, which burden the system's operational and financial performance (Abdullah et al., 2024). These losses stem from aging infrastructure, technical inefficiencies, and persistent gaps in revenue collection through bill recovery. System reliability metrics highlight critical operational challenges (Ajenikoko et al., 2022). The System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI) demonstrate concerning levels of power outages across the network (Aslami et al., 2024). These interruptions significantly impact industrial productivity and create uncertainty for potential renewable energy investors who require stable grid infrastructure.

The integration of renewable energy sources, particularly solar and wind power, presents additional complexities. The variable nature of these energy sources demands sophisticated grid management capabilities that the current infrastructure lacks. This technical limitation, combined with logistical challenges in establishing renewable projects in resource-rich but infrastructure-poor regions, complicates the transition to sustainable energy solutions (Greig, 2023).

The path forward requires comprehensive infrastructure modernization and policy reforms. This includes upgrading transmission networks, implementing advanced grid technologies, and developing supportive policy frameworks to attract renewable energy investment (Janjua et al., 2023). Success in this transition depends on addressing these challenges while maintaining system reliability and financial sustainability.

2.4 Comparative Analysis of Green Hydrogen Adoption: Pakistan vs. International Context

The adoption of green hydrogen storage in Pakistan contrasts significantly with international trends due to differences in economic capacity, policy frameworks, and technological readiness. While developed countries like Germany and Japan have made substantial progress in integrating green hydrogen into their energy systems through strong government support, targeted financial incentives, and advanced infrastructure (Waheed et al., 2022). Pakistan faces considerable challenges such as economic recession, political interference, and limited technological integration. The lack of consistent policies and investment incentives further exacerbates these challenges (Oryani et al., 2021)

In terms of digitalization, developed countries have leveraged advanced digital technologies, including IoT and AI, to enhance the efficiency and safety of hydrogen storage systems (De Felice & Petrillo, 2021; Wu et al., 2022). In contrast, Pakistan is still in the early stages of digital adoption, with significant gaps in infrastructure and digital literacy hindering progress (M. A. Raza et al., 2022). Additionally, political stability and transparency are crucial factors that have enabled countries like Denmark and the Netherlands to attract substantial investments in renewable energy projects, whereas Pakistan struggles with political interference and regulatory inconsistencies (W. Li & Zhang, 2010; Rogger & Oliver, 2018).

Countries like Denmark, Japan, and Germany have demonstrated the potential benefits and challenges of transitioning to sustainable energy in the manufacturing sector. Denmark has integrated wind energy, which now accounts for nearly half of the nation's electricity production (The Danish Energi Agency | Energistyrelsen, 2022). Japan has invested heavily in hydrogen technology, combining public and private sector efforts as part of its energy diversification strategy (METI Ministry of Economy, Trade and Industry, 2021). Germany have successfully begun integrating green hydrogen into their energy systems, particularly in heavy industries such as steel and cement production, demonstrating its potential to decarbonize high-emission sectors. This example highlights how a systematic approach to green hydrogen adoption can facilitate significant emissions reductions in challenging industrial sectors, providing a template for similar initiatives in developing countries like Pakistan. Germany’s Renewable Energy Sources Act (EEG) and the National Hydrogen Strategy have been instrumental in this integration (Federal Gazette, 2021; Federal Ministry for Economic Affairs and Climate Action, 2022). These initiatives have contributed to substantial emission reductions, with Germany reporting a decrease in carbon emissions of approximately 35% from 1990 levels, partly due to renewable energy adoption, including green hydrogen (BMUV: Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection, 2022). These cases illustrate that targeted government policies, financial incentives, and long-term planning are key to overcoming challenges and achieving successful energy transitions. North Africa is witnessing remarkable progress across several nations, each carving a distinct path toward development and sustainability. Morocco stands out for its groundbreaking achievements in renewable energy, setting a benchmark for the region through large-scale projects such as the Noor Ouarzazate Solar Complex. Algeria is exploring significant opportunities for economic diversification, leveraging its natural resources and strategic position to reduce reliance on hydrocarbons. Tunisia remains steadfast in its commitment to sustainability, emphasizing green initiatives and progressive environmental policies. Egypt continues to assert itself as a leader in the region, driving forward ambitious infrastructure projects and renewable energy investments while fostering collaboration across Africa and the Middle East. Meanwhile, Mauritania is emerging as a key player, capitalizing on its untapped potential and strategic initiatives to strengthen its role in the regional and global energy landscape (Bayssi et al., 2024). To strengthen the applicability of these lessons to Pakistan, it is essential to consider how these approaches can be adapted to the country's unique socio-economic context, ensuring that similar successes can be achieved despite regional differences.

Addressing these disparities requires Pakistan to learn from successful international strategies, such as creating stable policy environments, offering targeted financial incentives, and promoting digital integration to overcome technological challenges. By adapting these practices, Pakistan can create a more favorable environment for the adoption and scaling of green hydrogen storage technologies.

Chapter 3: Methodology

To ensure a comprehensive analysis of energy transition challenges, this study incorporates Pakistan as a case study, reflecting the unique challenges within a developing country context. Pakistan's energy landscape was evaluated based on key variables identified through literature review and expert interviews focusing on storage limitations that exacerbate economic instability, energy dependency, climate vulnerability, and underutilization of renewable capacity. The selection of Pakistan was justified due to its significant reliance on imported fossil fuels, economic constraints, and inadequate infrastructure, all of which influence its sustainable energy trajectory. Recent economic reports and climate vulnerability assessments were included to analyze the impact of global energy trends. Climate vulnerability was incorporated using global risk indices, where Pakistan ranked 23rd in the Inform Risk Index and 8th in global climate vulnerability (Aleha et al., 2024; Idris, 2024).

The study is grounded in pragmatism, which emphasizes practical solutions by selecting methods that best address the research problem. Pragmatism avoids rigid adherence to a single philosophical stance and focuses instead on actionable outcomes (Bergman, 2012; Tashakkori & Teddlie, 2010). The methodological framework for this study was structured into three interconnected phases to ensure a comprehensive analysis of the energy transition challenges in Pakistan as shown in Figure 5.

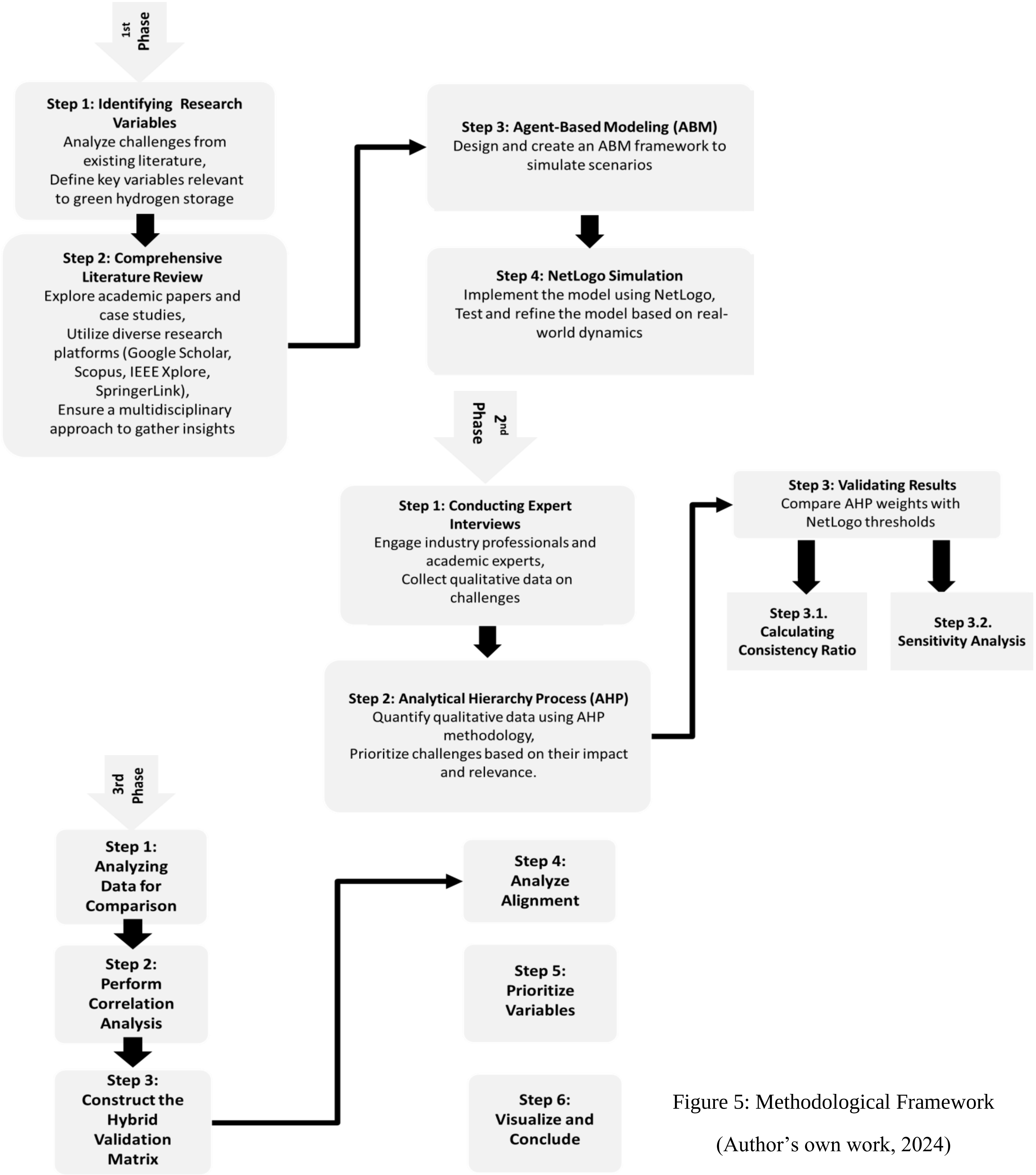

Figure 5: Methodological Framework

(Author’s own work, 2024)

The research adopted a mixed-methods approach, integrating qualitative and quantitative methods to explore the challenges associated with green hydrogen storage comprehensively. The research strategy combined multiple methods to achieve a holistic understanding of the problem. ABM provided quantitative insights by simulating real-world scenarios and generating threshold values for critical variables in green hydrogen storage, while AHP allowed for the prioritization of challenges based on expert opinions. By incorporating these methods, the study leveraged the strengths of both qualitative and quantitative approaches to create a robust framework for decision-making in the green hydrogen storage sector. Hybrid Validation Matrix (HVM) is constructed for findings of ABM and AHP. ABM is a computational approach that simulates interactions of autonomous agents within a virtual network, allowing for the exploration of individual dynamics and global system characteristics (Rand, 2024). On the other hand, AHP, is a multi-criteria decision-making method that involves pairwise comparisons to evaluate alternatives based on various criteria, facilitating structured decision-making in complex scenarios (Rodrigues de Oliveira & Duarte, 2024).

The study's approach to theory development is primarily inductive, beginning with an extensive review of existing literature to identify key decision variables influencing green hydrogen storage. Inductive reasoning is characterized by the development of theory based on observed patterns, which aligns with the study’s goal of identifying variables through literature and stakeholder dynamics (Sukma & Saragih, 2017). However, elements of deductive reasoning emerged in the validation phase, where hypotheses about variable relationships were tested using expert input, creating a mixed approach to theory development.

Pragmatism approach allowed for flexibility, enabling the integration of secondary data analysis through literature review and primary data collection through expert interviews, ensuring a balanced exploration of the research problem. The data collection was divided into two distinct phases.

- In the first phase, secondary data from existing literature formed the foundation for the development of the ABM framework. This phase utilized academic journals, case studies, and technical reports to model the dynamic behaviors of stakeholders within the green hydrogen storage ecosystem. Secondary data analysis is a key tool for model development, particularly when exploring under-researched areas (Johnston, 2014).

- In the second phase, primary data was collected through semi-structured interviews with experts from academia, industry, and the energy sector. These interviews served to refine the variables identified earlier, quantify their importance using AHP, and validate the simulation results.

The research strategy was shaped by a **cross-sectional design**, which focuses on analyzing data at a single point in time to understand relationships among variables (Flick, 2022). This approach was particularly relevant to this study, given the dynamic but temporally constrained context of green hydrogen storage adoption challenges in Pakistan. By capturing variables and their interdependencies at a specific time, the study was able to simulate realistic scenarios and derive actionable insights.

3.1 Phase 1: Development of Agent-Based Model for Green Hydrogen Storage

3.1.1 Agent Based Modelling (ABM)

The first phase of this research focused on employing ABM to explore the dynamics of green hydrogen storage adoption. ABM is a computational model that simulate interactions of multiple heterogeneous agents to derive complex aggregate phenomena (Rodríguez-Arias et al., 2023; Savin, 2023). It promotes sustainability by analyzing socio-technical interactions, integrating sustainable practices, and formulating effective policies to enhance financial and environmental outcomes (Larrea-Gallegos et al., 2024).

ABM was chosen because of its ability to simulate the complex, non-linear interactions among diverse stakeholders and external factors in socio-technical systems (Kaniyamattam, 2022). This approach is particularly effective in modeling the interactions of heterogeneous agents, including government bodies, technology developers, manufacturing industries, and storage equipment providers, each with unique decision-making processes. Unlike traditional models, ABM captures emergent phenomena, which arise from micro-level behaviors and interactions to produce macro-level outcomes such as investment decisions and facility development (Railsback & Grimm, 2019). It can also evaluate multiple business models for hydrogen production which can reduce production costs by approximately 5.6% allowing, for the exploration of flexible operational strategies that adapt to market conditions, potentially maintaining competitive hydrogen prices (Christensen et al., 2024). This ability makes ABM a preferred choice for addressing the multifaceted challenges of green hydrogen storage.

While ABM was ultimately chosen for this study, other modeling techniques were considered but deemed less suitable for the research objective. System Dynamics (SD) models are well-suited for analyzing feedback loops and aggregate-level behavior over time (Mousavi et al., 2023). However, SD models primarily operate at a macro-level and lack the ability to represent heterogeneous agents or their unique decision-making processes. This limitation made SD unsuitable for this study, which required modeling individual stakeholders' interactions and adaptive behaviors (Eden & Ackermann, 2021; Tiller et al., 2021). Discrete-Event Simulation (DES) is effective for modeling sequential and process-oriented systems, such as manufacturing workflows or logistical operations (Robinson, 2014). While it could potentially capture operational aspects of green hydrogen storage, DES is not designed to simulate emergent phenomena or the dynamic interactions between agents, which are central to this research (Moncion et al., 2010). DES typically operates within a static framework, making it challenging to adapt to changing (Jia et al., 2019).Optimization Models focus on finding the optimal solution for predefined objectives, such as minimizing costs or maximizing resource efficiency (Janssen & Ostrom, 2006). However, optimization models are inherently static and deterministic, lacking the flexibility to capture the adaptive, iterative decision-making processes of stakeholders (Weckenborg et al., 2024; Yu & Solvang, 2020).

ABM was preferred over these techniques because it could simulate the heterogeneity of agents, their adaptive behaviors, and the emergent system-level outcomes that arise from their interactions. This capability was critical for understanding the socio-technical challenges of green hydrogen storage adoption

To begin this phase, secondary data from academic literature was comprehensively analyzed to identify key decision variables relevant to green hydrogen storage. These variables included regional heterogeneity, political interference, economic recession, cross-investor differences, lack of digitalization and technological integration, and occupational health and safety concerns. By studying the interplay between these variables, the ABM framework was designed to model the interactions among actors, market agents, and external uncertainties, providing a dynamic representation of the system. The overview of our ABM is depicted in Figure 6, which categorizes variables into four interconnected domains:

- **Actors**: The government and technology developers, who shape policies and provide technological solutions.
- **Decisions:** Decisions are the identified challenges from literature that needs to be evaluated.
- **External Factors and Uncertainties**: These include supply chain disruptions, financial market volatility, and political instability, which exert significant influence on decision-making processes.
- **Criteria and Goals**: Challenges are evaluated based on their magnitude, long-term implications, and alignment with research objectives, with the ultimate goals being renewable energy integration, carbon neutrality, and technology resistance mitigation.

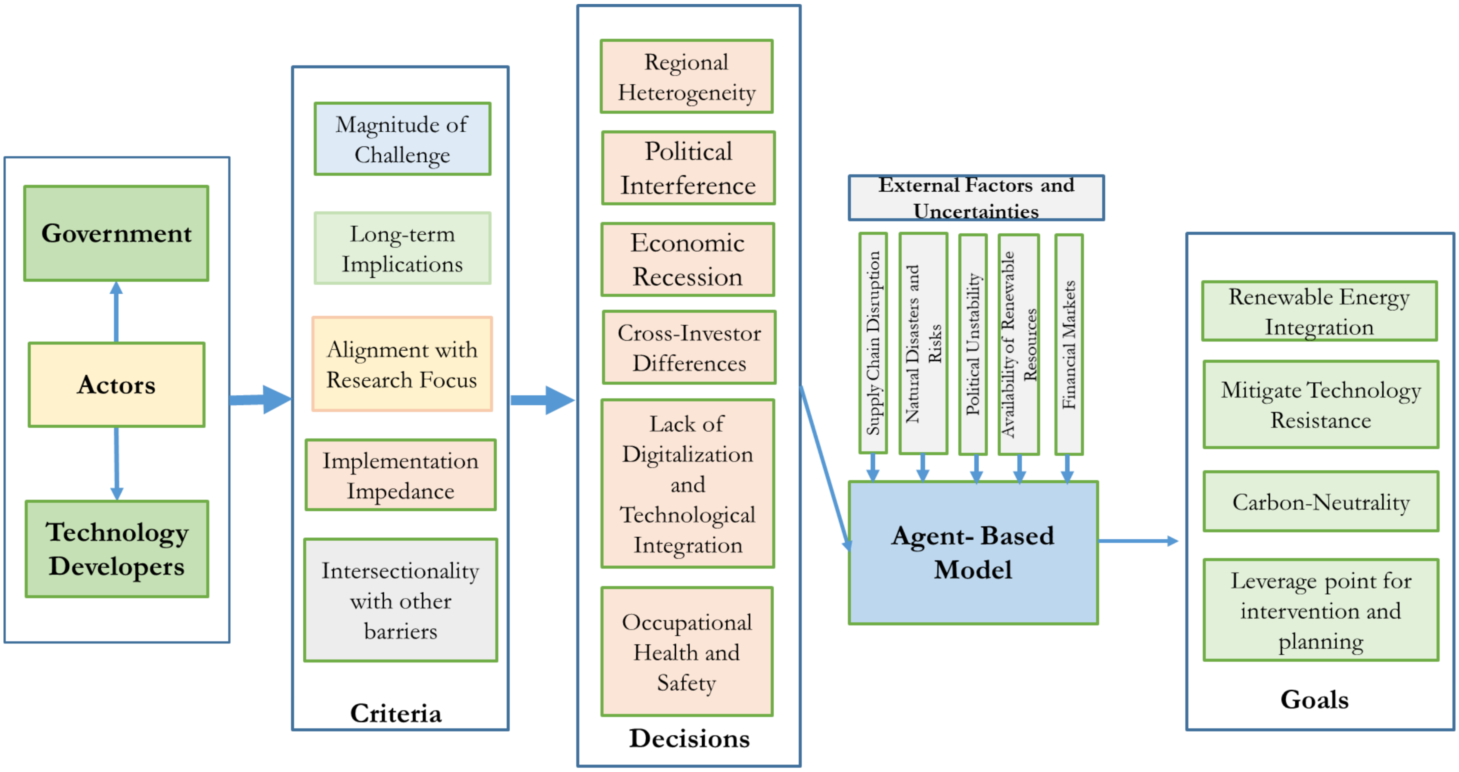

Figure 6: Agent based Model Overview (Author's Own Work,2024)

3.1.2 NetLogo Simulation

NetLogo is specifically designed for agent-based simulations and is widely used in academic research for studying socio-technical systems (Wilensky, 1999). Other platforms, such as AnyLogic, Repast, and GAMA, were also considered for implementing the ABM. However, these platforms have limitations that made them less suitable for this study. While AnyLogic is a powerful tool capable of integrating multiple modeling paradigms (e.g., ABM, DES, and SD), it requires a steep learning curve and advanced programming skills, which were not necessary for this study's objectives (Borshchev & Grigoryev, 2013). Repast is another popular ABM platform but is primarily designed for Java-based programming, making it less accessible for researchers without advanced coding expertise (Barnes & Chu, 2010; Li-qun, 2011). GAMA offers advanced visualization and computational capabilities but is resource-intensive and requires significant customization, which was beyond the scope of this study (Grignard et al., 2013). NetLogo was selected because it offered the best balance of functionality, ease of use, and visualization capabilities, aligning with the study’s objectives and available resources

NetLogo was selected as the implementation platform for the ABM due to its accessibility, versatility, and ability to model complex systems with minimal computational overhead. Its advantages include:

- **Ease of Use**: NetLogo provides an intuitive interface and a simplified programming language, making it easier to model and visualize complex systems without extensive programming expertise (Menárguez et al., 2018).

- **Visualization Capabilities**: The platform offers built-in visualization tools, enabling real-time observation of agent interactions and emergent behaviors, which are critical for understanding dynamic systems (Fernandez, 2020).

- **Community Support**: NetLogo has an extensive library of pre-built models and a strong user community, which facilitates learning and sharing of best (Cheng et al., 2023).

- **Integration with Analytical Tools:** Supports seamless integration with platforms like R and Python, enabling advanced data analysis, simulation experiments, and visualization of outputs (Salecker et al., 2019; Thiele & Grimm, 2010).

- **Customizable and Scalable:** Facilitates the modeling of both simple and complex systems with customizable agent interactions, while remaining computationally efficient for large-scale simulations (Selje et al., 2024).

3.2 Phase 2: Expert Validation and Prioritization Using AHP

The second phase of this research involved collecting primary data through semi-structured interviews with domain experts and applying the Analytical Hierarchy Process (AHP) to refine and prioritize the decision variables identified in Phase 1. This phase integrated qualitative insights from experts with a quantitative decision-making framework, ensuring a robust evaluation of the challenges associated with green hydrogen storage. A critical component of this phase included validating the AHP results using sensitivity analysis and consistency ratio checks to ensure reliability and robustness.

3.2.1 Collection of Primary Data

The semi-structured interviews served as a foundational step in validating and enriching the decision variables identified during the literature review and ABM simulation. These interviews were designed to capture diverse expert perspectives on the challenges and challenges to green hydrogen storage adoption.

Experts were selected using purposive sampling to ensure representation from academia, industry, and the energy sector. A total of 17 experts participated, including professionals from organizations such as Oil and Gas Development Company Limited, Attock Refinery Limited, and Sustainable Development Policy Institute. A semi-structured approach allowed for open-ended responses while maintaining consistency across interviews. Questions centered on the relevance, impact, and interdependencies of decision variables, including political interference, regional heterogeneity, economic recession, cross-investor differences, occupational health and safety and lack of digitalization and technological integration. The experts confirmed the criticality of the identified decision variables and emphasized additional nuances, such as the importance of workforce training and public-private partnerships in overcoming challenges. These insights were crucial for informing the AHP process.

3.2.2 Applying Analytical Hierarchy Process (AHP)

AHP was applied to systematically prioritize the decision variables based on the insights gathered from the interviews. AHP was chosen for its ability to structure complex, multi-criteria decision problems into a hierarchy, transforming qualitative judgments into numerical weights (T. L. Saaty, 1980). This method is particularly suitable for socio-technical challenges, where variables are interdependent, and stakeholder preferences vary significantly.

AHP was preferred over alternative techniques due to its ability to handle complex decision-making with interdependent criteria. TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) was considered but deemed less suitable as it assumes independence between criteria, which does not align with the interconnected nature of decision variables in this study (K. Y. Hwang & C.L., 1995).WSM (Weighted Sum Model) was rejected because of its reliance on linear assumptions, which fail to capture the non-linear interactions in this context (Triantaphyllou, 2000). ELECTRE was not chosen as its reliance on threshold parameters introduced subjectivity, reducing transparency (Govindan & Jepsen, 2016). ANP (Analytic Network Process), while capable of modeling interdependencies, was not selected due to its computational complexity and qresource-intensive implementation (T. L. Saaty & Vargas, 2013). AHP was ultimately chosen for its rigorous validation methods (e.g., Consistency Ratio), quantification of qualitative judgments, and ability to integrate expert insights systematically.

Microsoft Excel (MS Excel) is used to solve AHP. MS Excel is commonly used for solving the AHP due to its ease of access and capability to manage complex calculations effectively (Padilla-Garrido et al., 2014). It allows users to input pairwise comparisons directly and compute the weights for each criterion based on their relative importance (Esen, 2023). Excel can also be utilized to verify the consistency of judgments, ensuring the decision-making process remains systematic and reliable.

The AHP process was conducted in the following steps:

1. **Pairwise Comparison Matrix Construction**: Experts compared decision variables pairwise based on their relative importance using a scale from 1 (equal importance) to 9 (extremely more important).

2. **Priority Weight Calculation**: The relative importance of each variable was calculated, resulting in a ranked list of priorities.
3. **Visual Representation of Results:** The results obtained were represented using graphs and charts for better visualization and understanding of results.

3.3 Validation of AHP Results

To ensure the robustness of the AHP results, two validation techniques were employed. The consistency ratio checks and sensitivity analysis provided a strong validation of the reliability and robustness of the models used in this study.

3.3.1 Consistency Ratio Check

The CR ensured that the expert judgments used to construct the pairwise comparison matrix were logical and reliable. A CR value below 0.1 confirmed the consistency of the judgments, enhancing confidence in the results. The Consistency Ratio (CR) is computed by dividing the CI by the Random Index (RI) as shown in equation 1;

$$CR = \frac{CI}{RI} \tag{1}$$

Where Consistency Index (CI) is calculated using equation 2:

$$\boldsymbol{CI = \frac{\lambda max - n}{n - 1}} \tag{2}$$

The **Random Index (RI)** values are predefined and depend on the size of the matrix **n**. Table 4 shows RI values for common matrix sizes.

Table 4: Random Index (RI) values for matrices of various sizes (Adapted from Saaty, 1987).

n (Matrix Size)	**RI Value**
1	0.00
2	0.00
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49

Source: Saaty, R. W. (1987). The analytic hierarchy process—what it is and how it is used. Mathematical Modelling, 9(3–5), 161–176. https://doi.org/10.1016/0270-0255(87)90473-8

This final CR is well below the common threshold of 0.1 to 0.2 typically used to indicate acceptable consistency in AHP calculations (Sedghiyan et al., 2021). Low CR value strengthens the validity of the findings, ensuring robust identification of the challenges.

3.3.2 Sensitivity Analysis

The sensitivity of the priority weights was tested by adjusting the original pairwise comparison matrix. 5% Decrease (Factor 0.95) simulated the impact of underestimating the importance of variables.5% Increase (Factor 1.05) simulated the impact of overestimating the importance of variables. The analysis revealed proportional changes in priority weights, with no drastic deviations, demonstrating the robustness and stability of the AHP results.

The AHP analysis provided a structured prioritization of decision variables, integrating the qualitative insights from interviews with the quantitative rigor of pairwise comparisons. High-priority challenges, such as political interference and regional heterogeneity, were identified as critical challenges requiring immediate attention. The validation through consistency ratio and sensitivity analysis reinforced the reliability of the results. These findings served as a foundation for Phase 3, where the results were integrated into the Hybrid Validation Matrix for comprehensive evaluation.

3.3 Phase 3: Construction of the Hybrid Validation Matrix

The third phase of this research involved combining insights from the NetLogo simulation thresholds (developed in Phase 1) and the AHP weights (derived in Phase 2) to construct a comprehensive Hybrid Validation Matrix. This matrix was developed to compare and validate the outputs from both methods and to provide a more nuanced understanding of the prioritization of challenges associated with green hydrogen storage.

3.3.1 Why a Hybrid Validation Approach?

The hybrid approach was necessary to bridge the gap between the two methodologies—ABM (simulation-based insights) and AHP (expert-driven prioritization). While both methods offered valuable perspectives, their results needed to be integrated and compared to identify consistencies, discrepancies, and areas requiring further investigation. This hybrid validation process ensured a more robust and holistic evaluation of the decision variables by leveraging the strengths of both methodologies.

1. **NetLogo Thresholds**: These represent the threshold values for each decision variable, as identified through agent-based modeling in Phase 1. These values highlight the points at which each variable significantly impacts the system’s dynamics.

2. **AHP Weights**: These are the priority rankings assigned to the same decision variables based on expert judgments in Phase 2. These weights provide a structured, stakeholder-driven perspective on the relative importance of each variable.

3.3.2 Construction of the Hybrid Validation Matrix

Threshold values from the NetLogo simulation were normalized to ensure comparability with AHP weights. The re-normalization process scaled these thresholds to a range between 0 and 1, consistent with the AHP weight scale. The priority weights calculated from the pairwise comparison matrix in Phase 2 were directly used. The gap between NetLogo thresholds and AHP weights for each variable was calculated using formula in equation 3;

$$\text{Gap }(\text{Netlogo} - \text{AHP}) = \text{Normalized Netlogo Threshold} - \text{AHP Weight} \qquad (3)$$

This gap represents the difference between the two methodologies' perspectives on each variable's relative importance. Both NetLogo and AHP results were ranked independently and alignment (or misalignment) between the rankings was determined and recorded.

3.3.3 Hybrid Validation Index Calculation

The Hybrid Validation Index (HVI) was calculated as a weighted combination of NetLogo thresholds and AHP weights as shown in equation 4. This index served as an integrative measure of each variable's overall importance.

$$Hybrid\ Validation\ Index = a.\ Normalized\ NetLogo\ Threshold + (1 - a).\ AHP\ Weight \qquad (4)$$

Here, α is a weighting factor assigned based on the relative confidence in each methodology. In this study, equal weights ($\alpha = 0.5$) were assigned to both methods (Y. Ma et al., 2023).

In hybrid validation frameworks, equal weights are often applied when combining two independent methods, particularly when they are perceived to offer equally important yet distinct perspectives (Vaidya & Kumar, 2006). Using equal weights as a baseline in multi-criteria decision-making (MCDM) applications unless strong evidence or justification exists for unequal weighting. Literature also supports the use of equal weighting in cases where no empirical justifications for unequal weights exist. Ho (2008) and Halog & Manik (2011) argue that equal weights provide a logical starting point in such scenarios, ensuring that both qualitative (AHP) and quantitative (NetLogo) methods are treated fairly. Furthermore, equal weighting is appropriate when both methods contribute equally to the study's research objectives (Caprioli et al., 2023). By assigning equal weights, this study avoided potential biases and emphasized the importance of integrating both stakeholder-driven insights and simulation-based thresholds.

When integrating subjective expert opinions with simulation-based or empirical findings, equal weighting ($\alpha = 0.5$) ensures that both methods are treated fairly, reflecting an unbiased integration of perspectives. This approach is commonly used in hybrid decision-making models when combining qualitative and quantitative data (e.g., AHP, simulation results, or data-driven analytics). For instance, studies in fields such as energy planning and environmental management frequently adopt $\alpha = 0.5$ to achieve a balanced comparison between expert-based and system-based methods (Čeponis, 2021).

3.3.4 Visual Presentation of Results

The Hybrid Validation Matrix was visually analyzed to identify patterns, gaps, and trends:

- **Bar Graphs**: These were used to compare NetLogo thresholds, AHP weights, and the Hybrid Validation Index for each variable, highlighting areas of alignment or divergence.
- **Scatter Plots**: Correlations between NetLogo thresholds and AHP weights were visualized to quantify the degree of agreement between the two methods.

3.3.5 Impact of the Hybrid Validation Matrix

Hybrid Validation Matrix served as an essential analytical tool in understanding green hydrogen storage challenges by combining multiple data perspectives (Khan, 2024). The integration of simulation thresholds with expert-assigned weights created a comprehensive framework for evaluating key variables (Sadeghzadeh & Keivan, 2015). This methodological approach ensured the analysis captured both quantitative modeling results and qualitative expert knowledge, providing a robust foundation for understanding implementation challenges.

The matrix's strength lay in its ability to unite theoretical and practical insights, creating a balanced assessment of each variable's significance (De Tré et al., 2017). This dual perspective proved valuable in developing a more complete understanding of the challenges facing green hydrogen storage implementation in Pakistan's manufacturing sector.

Chapter 4: Data Analysis and Results

The data analysis was based on the comprehensive review of existing literature by the researcher, and it was further supported by the interview results and by using the ABM approach. The in-depth analysis of the literature provided compelling insights into understanding the role of economic recession, political interference, regional heterogeneity, cross-investor differences, OHS in impacting the energy sector.

The research methodology included a triangulation approach, combining qualitative and quantitative methods, to ensure the accuracy and validity of the findings (P. Zhou et al., 2006). This triangulation approach integrated three key dimensions: methodological triangulation (e.g., using ABM simulations alongside expert interviews), data triangulation (e.g., combining insights from literature reviews, interviews, and simulation outputs), and theoretical triangulation (e.g., drawing on adaptive management and system dynamics theories). This ensured a robust validation of the findings by examining the research problem from multiple angles and reducing potential biases. The results of the data analysis revealed critical thresholds and correlations among the identified challenges, demonstrating their interdependence and collective impact on the energy sector. Therefore, the Agent-Based Modeling approach can be an effective tool for understanding the dynamics of these challenges by simulating their interactions and impacts in a holistic manner. The findings suggest that addressing the identified variables requires integrated strategies to ensure operational resilience and sustainability. Furthermore, the analysis showed that the ABM approach provides valuable insights into the interdependencies and feedback loops within the system, allowing for a better understanding of how changes in one challenge can amplify or mitigate others and ultimately affect overall system performance (Khan et al., 2023). By employing an ABM approach, this study not only provides valuable insights into these interactions within a complex system but also highlights the importance of collaborative strategies and technological advancements to address challenges effectively.

Additionally, the findings demonstrate the effectiveness of the ABM approach in analyzing and addressing systemic challenges in the energy sector. The dynamic nature of these challenges necessitates ongoing adjustments and refinements to strategies, as highlighted by the Adaptive Management Framework (Hull, 2022). The ABM approach provides a valuable tool for understanding and addressing these challenges (Lewis et al., 2023). It allows for the characterization and representation of complex feedback interactions, nonlinearity, delays, and causality within the system. By adopting an ABM approach, researchers and practitioners can capture the dynamic nature of these challenges, including feedback loops and causal relationships, enabling a deeper understanding of the underlying dynamics and complex interconnections at play. In conclusion, the ABM approach is a valuable tool for analyzing and addressing systemic challenges in the energy sector (Vuthi et al., 2022).

Phase 1: Agent Based Model(ABM)

High level framework of ABM interactions is shown in Figure 7. In this model, the primary actors are the **government** and **technology developers**, while the **market agents** are represented by the manufacturing and storage equipment industries. The available facilities encompass green hydrogen production plants, which play a pivotal role in the system. The interactions among these entities are depicted using arrows, illustrating the dynamic relationships within the model. These interactions revolve around key decision variables that influence the overall system dynamics. The **government**, as a central actor, introduces political interference, which affects both the storage equipment and manufacturing industries. This influence is bidirectional, reflecting the potential for varying outcomes. Additionally, the manufacturing and storage equipment industries are influenced by two critical variables: economic recession and regional heterogeneity, which shape investment decisions. These decisions, in turn, contribute to cross-investor differences and further regional disparities in decision-making. These interdependent factors collectively influence the establishment and operation of green hydrogen production facilities, highlighting the complexity of the decision-making ecosystem. The technology developers also play a significant role in the model. Their dual function involves contributing directly to the setup of green hydrogen facilities while simultaneously being associated with two additional variables: occupational health and safety and the lack of digitalization and technological integration. These variables, shaped by the actions of technology developers, further impact the development and functionality of the facilities. Together, this interconnected network of actors, market agents, decision variables, and facilities underscores the complexity of the system, emphasizing the intricate interdependencies that must be addressed to achieve effective green hydrogen storage implementation. This figure represents interactions going inside Agent Based Model between different actors and market agents impacting investment decisions for plant (represented by facility in our model) set up.

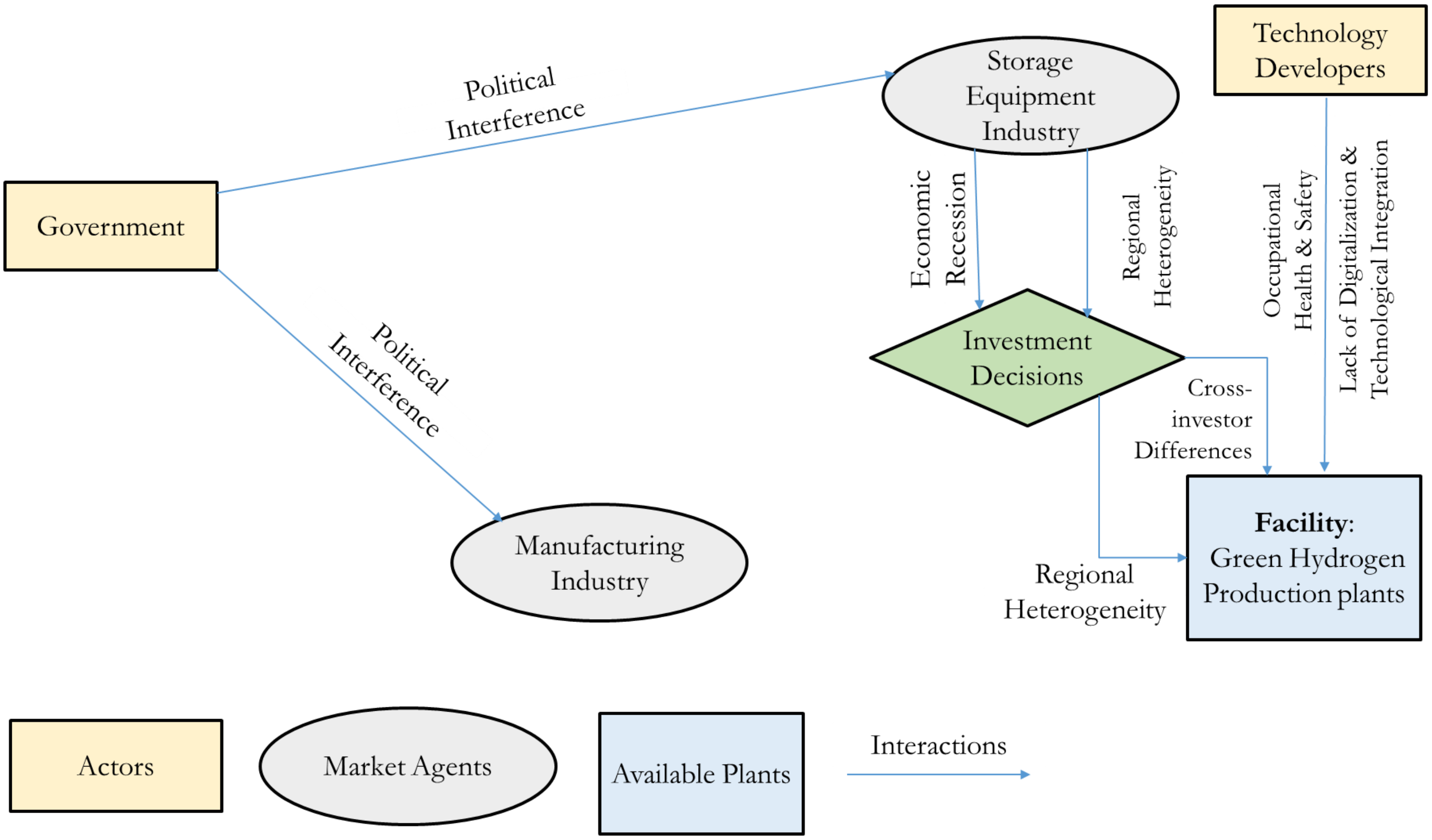

Figure 7: Agent Based Model Interactions (Author's own work, 2024)

4.1 NetLogo Simulations

ABM built in Fig 2 was used as input in NetLogo and was simulated in a virtual environment. NetLogo simulation output offers critical insights into the challenges associated with green hydrogen storage implementation. These simulations exhibit three primary patterns providing a comprehensive framework for analyzing ABM. NetLogo simulations exhibit three primary patterns providing a comprehensive framework for analyzing ABM.

Cyclic Trends: Regular patterns or fluctuations that repeat over time without a fixed period (Chatterjee et al. ,2023).

Dynamic Trends: Continuous, non-repeating changes due to system interactions or external influences (Ovaskainen et al.,2020).

Stochastic Trends: Patterns influenced by randomness or probabilistic factors, inherently unpredictable (Chen et al. ,2023).

4.1.1 Economic Recession

The role of economic recession in influencing energy sector operations can be seen in Figure 8. The graph demonstrates the normalized threshold (0-1) over a simulation time of 1,000 seconds which implies 1000 iterations. The peaks and troughs represent the fluctuations in financial stability during the simulation period.

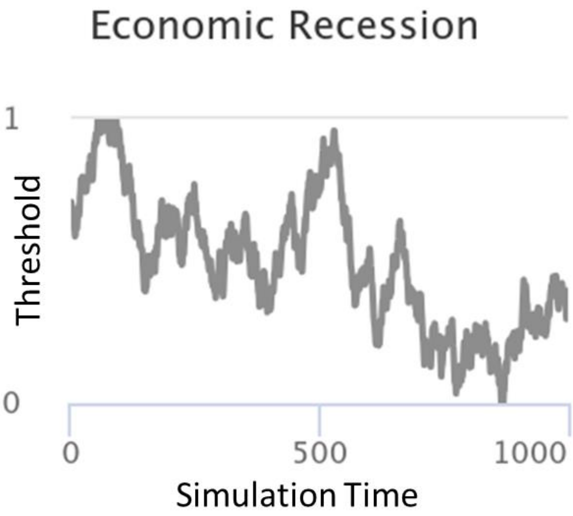

Figure 8: Economic Recession Trend obtained from
NetLogo Simulations (Author’s own work, 2024)

The graph of economic recession depicts a **cyclic pattern** characterized by periodic fluctuations between peaks and troughs, which represent alternating phases of economic recovery and downturns. These trends reflect the inherent instability of financial systems, as seen in real-world economies. The **dynamic behavior** in the graph, represented by variations in the amplitude of the cycles, reflects the impact of external factors such as policy changes, market conditions, and technological advancements. The **stochastic trend**, visible in the irregular fluctuations, illustrates the unpredictable and complex nature of economic recessions. Overall, this simulation highlights the interconnected challenges posed by economic recessions, emphasizing the importance of adaptive financial models, robust policy interventions, and resilient technological strategies. The stochastic nature of the observed trends aligns with economic literature that emphasizes the complex and unpredictable nature of recessions. This irregularity suggests that even small changes in the initial conditions or behaviors of agents can produce amplified and unforeseen outcomes within the system. Such behavior underscores the non-linear dynamics inherent in economic systems.

From an ABM perspective, the graph validates the model's ability to simulate emergent dynamics and replicate realistic economic conditions. The alternating periods of economic recovery and downturns highlight the critical moments when financial stability either fosters system efficiency or disrupts it significantly. This supports the relevance of the ABM approach in capturing interdependencies and feedback loops within the energy sector's operations.

The threshold value for economic recession in NetLogo is 0.1945. This value represents the **critical point** at which economic recession begins to have a substantial impact on the system's dynamics. Below this threshold, the effects of economic recession on decision-making (e.g., investments in green hydrogen storage) may be minimal or manageable. However, once the value exceeds 0.1945, the system likely experiences significant disruptions, such as reduced investments, increased operational risks, or slowed progress toward storage facility implementation.

4.1.2 Regional Heterogeneity

The **cyclic pattern** observed in Figure 9 highlights initial stability, followed by a sharp rise and subsequent plateau, indicating recurring disparities in regional adaptability and resource allocation. The **dynamic behavior** is evident in the sharp rise, representing systemic shifts driven by uneven infrastructure development or policy interventions. The **stochastic trend**, characterized by early erratic fluctuations, points to the unpredictable attempts at regional standardization. The later plateau demonstrates persistent disparities, driven by complex regional challenges such as uneven energy access, technological gaps, or socio-political factors. Addressing these trends requires tailored regional policies, equitable resource allocation, and collaborative frameworks to reduce disparities and enable balanced progress in green hydrogen adoption.

The graph of regional heterogeneity begins with relatively low fluctuations, indicating initial regional stability. However, after the midpoint of the simulation, a sharp and sustained rise is observed, followed by a plateau at high values. This trend suggests increasing disparities in regional adaptability or resource allocation as the system evolves. The plateau phase highlights persistent heterogeneity, indicating that attempts to standardize regional performance were either insufficient or ineffectively implemented. The sharp rise in the later phases of the simulation likely reflects external interventions or changing conditions that disproportionately benefited or disadvantaged certain regions. Such interventions could include uneven infrastructure development, policy adaptations, or resource distribution. This dynamic behavior points to the critical role of tailored regional strategies in addressing localized challenges and ensuring overall system balance. The earlier stochastic fluctuations represent initial attempts to align regional performance, as variations in alignment caused unpredictable results. However, the stability at higher values indicates entrenched disparities that are difficult to mitigate without targeted efforts. The normalized threshold value of **0.1223** derived from the NetLogo simulation highlights the critical point at which regional disparities become significant, necessitating immediate intervention.

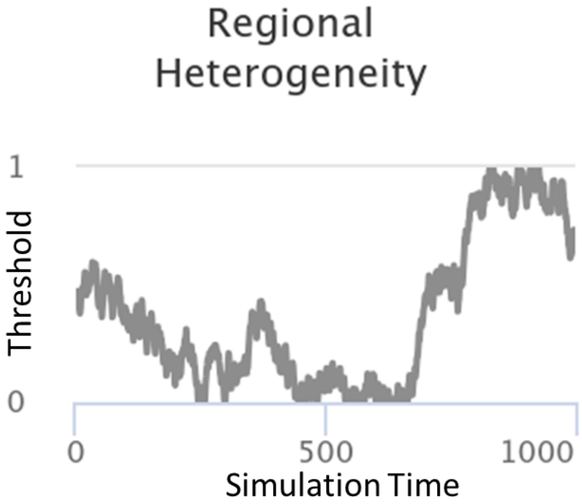

Figure 9: Regional Heterogeneity obtained from NetLogo Simulations (Author's own work. 2024)

These findings emphasize the importance of customized approaches to infrastructure investment and policy implementation. Strategies that prioritize equitable resource distribution and address regional-specific needs can play a pivotal role in reducing heterogeneity and improving system-wide efficiency.

4.1.3 Political Interference

The graph in Figure 10 represents political interference where a pattern of steep peaks and valleys is followed by a gradual stabilization over time. This **cyclic behavior** highlights alternating phases of intense political intervention and periods of relative calm. The peaks indicate moments of heightened interference, likely due to sudden policy shifts or conflicts between stakeholders, while the valleys represent instances of reduced political disruptions. The **dynamic behavior** observed in the graph is particularly notable. Following the initial peak, the downward trend suggests a possible alignment in political priorities or the stabilization of governance structures. Such periods of reduced interference often correspond to collaborative policymaking or external pressures encouraging consistency in regulations. However, the resurgence of instability toward the end of the simulation signals underlying vulnerabilities in governance systems, potentially caused by new policy disagreements or external geopolitical factors. The **stochastic nature** of the trends aligns with literature on governance challenges, which often describe political dynamics as unpredictable and influenced by a multitude of external and internal factors. This unpredictability reinforces the need for robust governance frameworks that can adapt to changing political landscapes while minimizing disruptions to critical energy sector projects.

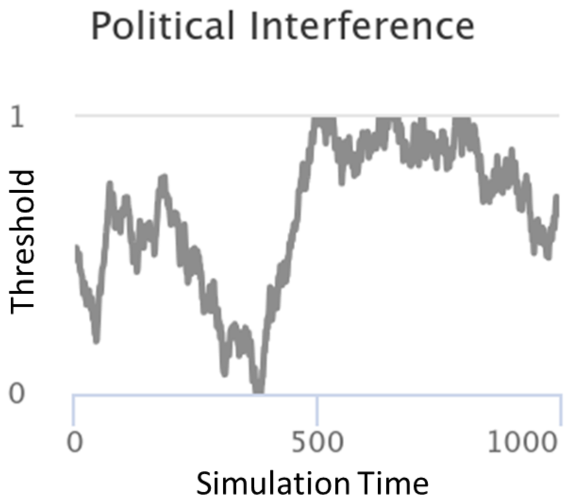

Figure 10: Political Interference Trend obtained from NetLogo Simulations (Author’s own work, 2024)

The findings underscore the importance of fostering strong stakeholder alignment and governance mechanisms to mitigate the impacts of political interference. The normalized threshold value of **0.1388** from the NetLogo simulation highlights a critical point where political stability begins to have a noticeable impact on reducing disruptions within the system. Enhanced collaboration between government bodies and private entities can help establish consistent regulatory environments, reducing the frequency and intensity of disruptions. The simulation results emphasize the value of integrating adaptive governance strategies to sustain momentum in energy sector operations.

4.1.4 Lack of Digitalization

The graph in Figure 11 represents the lack of digitalization. This graph exhibits periodic fluctuations, characterized by rising and falling trends over the simulation period. This **cyclic pattern** reflects varying levels of digital readiness and intervention, highlighting the reflects uneven progress in digital transformation initiatives within the system. The **dynamic behavior** reflects oscillatory nature of the graph suggests that external factors, such as policy updates, technological advancements, and resource allocation, drive these variations. The sharp declines indicate successful periods of digital adoption and integration, while the subsequent rises suggest challenges in sustaining these efforts due to systemic challenges or resource constraints. The **stochastic trends** observed align with literature on the uneven pace of digital adoption, particularly in developing economies, where technological progress is often hindered by infrastructure limitations, skill gaps, and policy inconsistencies. The irregular fluctuations underscore the complex and non-linear nature of digital transformation; as minor disruptions can lead to significant setbacks in achieving sustained progress.

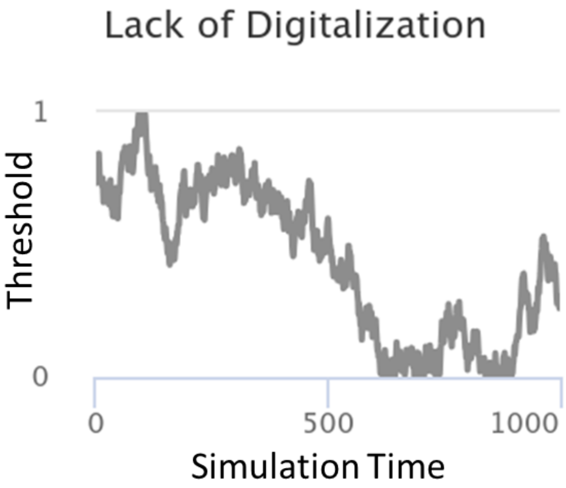

Figure 11: Lack of Digitalization and Technological Integration Trend obtained from NetLogo Simulations (Author's own work, 2024)

The normalized threshold value of **0.0947** from the NetLogo simulation highlights the critical point at which digital integration begins to significantly improve system performance. This finding emphasizes the importance of targeted investments in infrastructure, workforce development, and policy frameworks to accelerate digitalization and ensure long-term benefits for the energy sector.

4.1.5 Cross-Investor Differences

The graph (Figure 12) illustrating cross-investor differences shows an initial plateau, followed by a sharp decline, and subsequent fluctuations over time. This **cyclic pattern** reflects the gradual convergence of investor priorities as collaborative frameworks and shared goals emerge within the system. The **dynamic behavior** of the graph indicates that the shifts in trends are influenced by factors such as policy alignment, market standardization, and external interventions. The sharp decline suggests significant progress in aligning investor interests, likely driven by collaborative decision-making processes or external regulatory pressures. However, the subsequent fluctuations highlight ongoing challenges in maintaining this alignment due to varying priorities and external economic conditions. The **stochastic nature** of the decline is consistent with literature on investor dynamics, which describes the complex interplay between individual and collective interests. As markets mature and shared goals become more prominent, misalignments reduce, resulting in greater operational stability. However, the persistence of fluctuations underscores the need for continued efforts to address emerging conflicts and ensure sustained alignment.

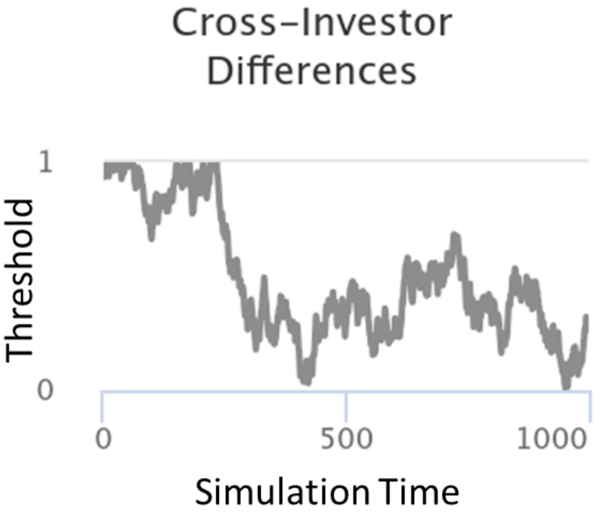

Figure 12: Cross-Investor Differences Trend obtained from NetLogo Simulations (Author’s own work, 2024)

The normalized threshold value of **0.2597** derived from the NetLogo simulation emphasizes the critical point where investor alignment begins to have a significant impact on resource allocation and operational efficiency. This highlights the importance of establishing long-term collaborative strategies, fostering transparency, and promoting trust among investors to mitigate conflicts and enhance system performance.

4.1.6 Occupational Health and Safety (OHS)

The graph of Occupational Health and Safety (OHS) as shown in Figure 13 depicts recurring peaks and troughs. This reflects periodic cycles of heightened concern followed by temporary improvements in safety standards. These **cyclic nature** indicates the ongoing struggle to maintain consistent OHS compliance within the rapidly evolving context of green hydrogen projects. The variations in amplitude, as seen in the **dynamic behavior** of the graph, suggest that industry growth, enforcement of safety regulations, and the emergence of new operational risks significantly influence the trends. Sharp peaks in the graph correspond to moments of increased focus on safety, likely triggered by external audits or incidents, while the subsequent declines may reflect challenges in sustaining a robust safety culture. The **stochastic trends** observed align with the findings in OHS literature, which highlight the difficulties in embedding sustainable safety practices in emerging industries. These irregular fluctuations underscore the complex, non-linear nature of achieving long-term OHS improvements, particularly in industries characterized by rapid technological advancements and diverse workforce dynamics.

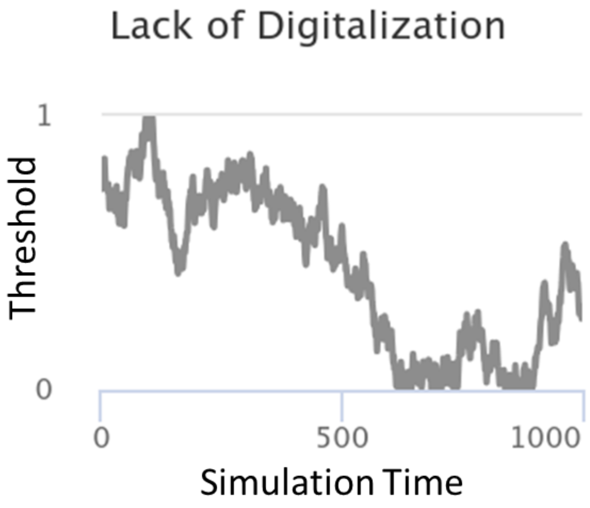

Figure 13: Occupational Health and Safety Trend obtained from NetLogo Simulations (Author’s own work,2024)

The normalized threshold value of **0.1905** derived from the NetLogo simulation highlights a critical point where safety interventions begin to yield significant improvements in compliance and risk mitigation. This underscores the importance of proactive measures, such as continuous training, investment in advanced safety technologies, and stringent regulatory enforcement, to address the inherent risks associated with green hydrogen projects.

The analysis emphasizes the need for a systemic approach to safety management, prioritizing not only compliance but also the development of a resilient safety culture capable of adapting to evolving risks. Enhanced collaboration between stakeholders, including regulators, industry leaders, and workers, will be crucial in sustaining long-term OHS improvements.

4.1.7 Combined Decision Variables

Variables demonstrates overlapping peaks and significant interconnections among the variables. The fluctuating trends highlight the mutual influence of variables as external shocks, such as policy shifts or market disruptions, amplify their interactions. This interconnectedness is a key characteristic of complex systems, where the behavior of one variable significantly impacts the others. Late-stage stabilization is evident in the reduced variability toward the end of the simulation. This pattern suggests that as challenges are addressed and stakeholder priorities converge, the system begins to approach equilibrium. Such stabilization reflects the effectiveness of adaptive strategies and collaborative frameworks in mitigating variability and fostering system resilience. The trends observed align with real-world dynamics of sustainable energy projects. The initial variability corresponds to challenges such as misaligned goals, resource constraints, and regulatory inconsistencies. However, as policies evolve and collaborative governance takes precedence, these challenges are gradually mitigated, resulting in improved synchronization among decision variables. This analysis emphasizes the importance of adaptive policies, strategic planning, and stakeholder collaboration to address the inherent complexities of interconnected systems. By fostering alignment and addressing challenges early, organizations can ensure smoother operations and sustainable outcomes in energy sector projects.

Table 5 provides a detailed analysis of the trends observed in NetLogo graphs for each decision variable. It also includes an interpretation of the implications posed by each trend.

Table 5: NetLogo Simulations Showing Variables' Fluctuation Trends

(Author's own work, 2024)

Variable	Trend	Interpretation
Economic Recession	Prolonged period of elevated values (high spike) followed by gradual decline	Significant and sustained influence for a substantial period before showing indications of weakening
Political Interference	Significant oscillations, steep upward movements	Irregular but intense influence not sustained over time
Cross-Investor Differences	Initial peak followed by an early and sustained decrease.	Initial high impact, followed by early decline and eventual stabilization with minor fluctuations
Regional Heterogeneity	Slightly elevated start, a drop in the middle, and a pronounced peak toward the end	Initially reflects significant disparities, which decrease mid-way but a sharp rise at the end
Lack of Digitalization	Sharp initial intensity, followed by a steady decline over time, and a minor resurgence towards the end	Starts with high challenges, gradually decreases with adoption, but resurges slightly.
Occupational Health and Safety	Initial peak, followed by a significant drop, and then another sharp rise	Starts strong, declines due to resource gaps, and resurges with renewed focus driven by regulatory actions.

4.2 Analytical Hierarchy Process (AHP)

In 2nd phase, the Analytical Hierarchy Process (AHP) was employed to evaluate and prioritize the identified variables based on their significance. To gather qualitative insights for this study, approximately 17 semi-structured interviews were conducted with experts and stakeholders directly or indirectly associated with the energy sector. The participants were selected using purposive sampling, a method that ensured the inclusion of individuals with relevant expertise and experience in the domain of green hydrogen and energy systems. This approach was particularly effective in capturing diverse perspectives and in-depth knowledge about the challenges and opportunities in the sector.

4.2.1 Population Estimation

The research population was strategically selected to ensure high-quality insights into green hydrogen storage implementation in Pakistan's manufacturing sector. Participants were required to be actively employed in Pakistan's energy sector, possess an exposure to hydrogen production and storage industries, and have a minimum of five years of relevant experience. This selection approach ensured that participants could provide informed perspectives grounded in both practical knowledge and historical understanding of industry developments. Their current employment in the energy sector, combined with specific hydrogen industry expertise and substantial experience, enabled them to offer comprehensive insights into the technical, operational, and implementation aspects of green hydrogen storage systems within the Pakistani context.

Modified Delphi with Sectoral Analysis was employed to estimate the population size of professionals involved in hydrogen storage. This involves evaluating the maximum population that can be supported in a given area, considering local resources and ecological balance (Harutyunyan, 2024). This structured communication technique gathers expert opinions to reach a consensus on population estimates, particularly useful in contexts with limited data, aligning with methodologies described in recent studies (Xu et al., 2022). The sources collectively justify the roundabout figure of 200–500 professionals, based on the active yet nascent state of hydrogen-related research and policy in Pakistan.

4.2.1.1 Delphi Method

The Delphi method is a structured communication technique that gathers expert opinions through multiple rounds of questionnaires, allowing for anonymous feedback and consensus-building to estimate population size and demographics effectively in crisis situations (Franc et al., 2023; Kondos et al., 2023). The Delphi method results were calculated on base of following assumptions as done by Sablatzky (2022) and Nasa et al. (2021):

- Expert Panel Selection assumes the selected panel accurately represents the diversity of academia, industry, and energy sector expertise in Pakistan.

- Conducted interviews with experts to gather insights on the number of professionals in the green hydrogen sector.
- Consensus-Based Estimate from multiple survey rounds converged on an estimated 300 experts.

This method estimated a population of around 300 experts of green hydrogen sector in Pakistan.

4.2.1.2 Sector Analysis Method

The sector analysis method for calculating population size involves a systematic approach that utilizes spatial data and statistical techniques to enhance accuracy. This method is particularly effective in urban planning and resource allocation, as it allows for a detailed understanding of population distribution across various sectors (Dai et al., 2024; Kosyakov & Sadykov, 2019). Sector Analysis method results were calculated on base of following assumptions as done by Yusuf et al. (2014):

- Academic Publications: ResearchGate studies on green hydrogen potential in Pakistan.
- Patents: Limited patent data reflecting an emerging field.
- Industry Reports: SDPI publications and details from Oracle Power and China Power projects.

This method estimated a population of around 400 experts of green hydrogen sector in Pakistan.

4.2.1.3 Overlap Calculation for Assumptions

The assumption of a **50% overlap** between Delphi and Sectoral estimates is based on the need to balance the potential duplication of experts across both methods while ensuring representation from both datasets.

Delphi Estimate (D): 300 experts

Sectoral Estimate (S): 400 experts

Overlap Percentage is assumed to be 50% of Delphi experts. Overlap is calculated by using equation 5;

$$Overlap\ (O) = 0.5 \times Delphi\ Estimate \tag{5}$$

$$Overlap\ (O) = 0.5 \times 300 = 150\ experts \tag{6}$$

150 experts were common in both methods' estimation results as calculated in equation 6.

Equation 7 is used to calculate total number of experts after calculation of overlap between two methodologies;

$$Total\ Experts = Delphi\ Estimate\ +\ Sectoral\ Estimate - Overlap \tag{7}$$

$$Total\ Experts\ (without\ weightage)\ = 300 + 400 - 150 = 550 \tag{8}$$

Total experts after removing overlap of findings and without assigning any weightage came out to be 550 (equation 8).

4.2.1.4 Weightage for Reliability

Both Delphi and Sectoral Analysis are assigned equal reliability (50%) as shown in equation 8, 9 and 10. Both methods have distinct strengths and limitations. By assigning equal reliability, the study avoids favoring one method over the other, ensuring that both contribute equally to the final population estimate. Delphi relies on iterative expert consensus, often reducing biases, while Sectoral estimates typically reflect broader stakeholder perspectives. Assigning 50% reliability allows both methodologies to complement each other.

Weighted Delphi

$$= 0.5 \times Delphi\ Estimate = 0.5 \times 300 = 150 \tag{8}$$

Weighted Sectoral

$$= 0.5 \times Sectoral\ Estimate = 0.5 \times 400 = 200 \tag{9}$$

Weighted Overlap

$$= 0.5 \times Overlap = 0.5 \times 150 = 75 \tag{10}$$

Final Adjusted Estimate

$$\begin{gathered} = Weighted\ Delphi\ \ +\ Weighted\ Sectoral - Weighted\ Overlap \\ = 150 + 200 - 75 = \ 275 \end{gathered} \tag{11}$$

Total experts (with weightage) = 275 experts (Equation 11)

4.2.1.5 Final Population Weightage

- **Without Weightage:** 550 experts
- **With Weightage:** 275 experts

This calculation ensures a systematic approach to estimating the expert population, accounting for overlap and reliability of methods.

4.2.2 Sample Size Calculation

Following metrics are used to calculate the required sample size using the standard sample size formula shown in equation 12, ensuring the selected sample accurately represents the population under study. The formula applied is:

$$n_o = \frac{Z^2\ \times P\ \times (1 - P)}{E^2} \tag{12}$$

Where $n_o =$ Required sample size

$P =$ Population proportion

$Z =$ Z − value (confidence level)

$E =$ Margin of Error

Confidence Level: 90-95% (lower confidence for exploratory design)

Margin of Error: ± 15% (reflects exploratory and emergent nature)

Population Proportion: 10%–20% (small due to niche expertise)

Sample size of 15 experts can be scientifically justified, especially for qualitative research focusing on emerging technologies which is aligned with literature also (Damanbagh & Alizadeh, 2024; Vuthi et al., 2022)

4.2.3 Primary Data Collection: Selection Criteria

The interviewees represented a mix of professionals from Oil and Gas Development Company Limited (OGDCL), Sustainable Development Policy Institute (SDPI), and Attock Refinery Limited (ARL), as well as experts from academia specializing in energy systems and policy research. The purposive selection ensured that participants were knowledgeable about key areas research areas, had exposure to R&D and energy sector and had a considerable work experience of at least 5 years in relevant field as done by Cioccolanti et al. (2021) and B. Thomas et al. (2022). Table 6 outlines the criteria for participant selection, including their work experience, role, and position within the company.

Code	**Organization**	**Position**	**Role**	**Years of Experience**
S1.	**SDPI**	Senior Research Associate	Lead Energy Unit	6+
S2.	**SDPI**	Senior Research Associate	Business Development Unit	6+
S3.	**SDPI**	Associate Research Fellow	Head of Ecological Sustainability and Circular Economy	5+
A4.	**ARL**	Assistant Manager	Technical Services	15
A5.	**ARL**	Deputy Manager	Technical Services	19
A6.	**ARL**	Manager	Technical Services	30
A7.	**ARL**	Senior Engineer	Hydrogen Unit	10
O8.	**OGDCL**	Manager HSEQ	Enterprise Risk Management	26+
O9.	**OGDCL**	Senior Officer	HSEQ Department	16
O10.	**OGDCL**	Senior Officer	Product Data Management	14
O11.	**OGDCL**	Manager	Business Development	25
O12.	**OGDCL**	Senior Engineer	Joint Venture and Business Development	15+
O13.	**OGDCL**	Chief Engineer	Process and Plants Department	22
O14.	**OGDCL**	Deputy Chief Engineer	HSEQ Department	15

O15.	**OGDCL**	General Manager	HSEQ Department	25
N16.	**NUST**	Assistant Professor	USPCAS-E	5+
N17.	**NUST**	Assistant Professor	In charge of Sustainable Energy Analytics Lab	13

Table 6: Primary Data Collection Criteria (Author's own work,2024)

The semi-structured interview format allowed for a balance between open-ended questions and guided discussions, enabling the participants to share their insights freely while ensuring the data remained relevant to the research objectives. The collected data were subsequently analyzed to identify recurring themes, trends, and challenges, forming a critical component of the study's findings and validation process. The results were processed using a structured methodology.

4.2.4 Pairwise Comparison Matrix

A pairwise comparison matrix was developed for all variables identified during the literature review and expert interviews. Each variable was compared with others based on its relative importance, and the values were assigned using the Saaty scale (1–9) (Movafaghpour, 2019). The identified variables of economic recession, political interference, cross-investor differences, regional heterogeneity, Occupational health and safety and digitalization and technological integration were compared with one another. The matrix is a square matrix ($n \times n$), where n is the number of variables. In this case there are 6 variables so the matrix will be 6×6 matrix. The comparison scale used is as follows:

1: Equal importance.

3: Moderate importance.

5: Strong importance

7: Very strong importance.

9: Extreme importance.

Reciprocal values $(1/aij)$ are used for inverse comparisons. If $a12 = 3$, then $a21 = 1/3$.Diagonal elements (aii) are always 1 because a variable is equally important to itself.

Reciprocal property is defined by equation 13;

$$aij = \frac{1}{aij} \tag{13}$$

Table 7 shows pairwise comparison matrix calculated for AHP.

Table 7: Pairwise Comparison Matrix (Author's own work, 2024)

Variables	Economic Recession	Political Interference	Cross Investor Differences	OHS	Regional Heterogeneity	Lack of Digitalization
Economic Recession	1	1.314285714	2	4	8	13.33333333
Political Interference	0.760869565	1	1.75	3.5	7	11.66666667
Cross Investor Differences	0.5	0.571428571	1	2.4	4	6.666666667
OHS	0.25	0.285714286	0.416666667	1	2	3.333333333
Regional Heterogeneity	0.125	0.142857143	0.25	0.5	1	2.166666667
Lack of Digitalization	0.075	0.085714286	0.15	0.3	0.461538462	1

The normalized matrix ensures all comparisons are standardized. Each column is divided by its sum, so the total of each column equals 1. The total for each column is calculated using formula in equation 14;

$$Column\ Sum\ for\ Variable\ i = \sum_{j=1}^{n} aji \tag{14}$$

Each element is divided by the respective column sum shown in equation 15:

$$a^{'}ij = \frac{aij}{Column\ Sum\ for\ Variable\ j} \tag{15}$$

After entering the data gathered through semi structured interviews and doing the required computations, results shown in table 8 are obtained.

Table 8: Normalized Pairwise Comparison Matrix (Author's own work, 2024)

Variables	Economic Recession	Political Interference	Cross Investor Differences	OHS	Regional Heterogeneity	Lack of Digitalization
Economic Recession	0.368885325	0.386554622	0.359281437	0.341880342	0.356164384	0.349344978
Political Interference	0.280673617	0.294117647	0.314371257	0.299145299	0.311643836	0.305676856
Cross Investor Differences	0.184442662	0.168067227	0.179640719	0.205128205	0.178082192	0.174672489
OHS	0.092221331	0.084033613	0.074850299	0.085470085	0.089041096	0.087336245
Regional Heterogeneity	0.046110666	0.042016807	0.04491018	0.042735043	0.044520548	0.056768559
Lack of Digitalization	0.027666399	0.025210084	0.026946108	0.025641026	0.020547945	0.026200873

The priority vector gives the relative weight ($\mathcal{W}i$**)** of each variable. It is calculated as the row average of the normalized matrix.

$$\mathcal{W}i = \frac{\sum_{j=1}^{n} a^{'}ij}{n} \tag{16}$$

$\mathcal{W}i$ = priority weight for variable and $a'ij$ = normalized value.

Using equation 16, the relative weight for each variable is shown in table below. Ranks are assigned on the of relative weights in priority vector as shown in table 9.

Table 9: Priority Vector (Author's own work, 2024)

Variables	Priority Vector	Rank
Economic Recession	**0.360351848**	**1**
Political Interference	**0.300938085**	**2**
Cross Investor Differences	**0.181672249**	**3**
OHS	**0.085492112**	**4**
Regional Heterogeneity	**0.046176967**	**5**
Lack of Digitalization	**0.025368739**	**6**

Figure 14 illustrates the trends of the results obtained without normalization, whereas Figure 15 displays the trends and their corresponding values after normalization.

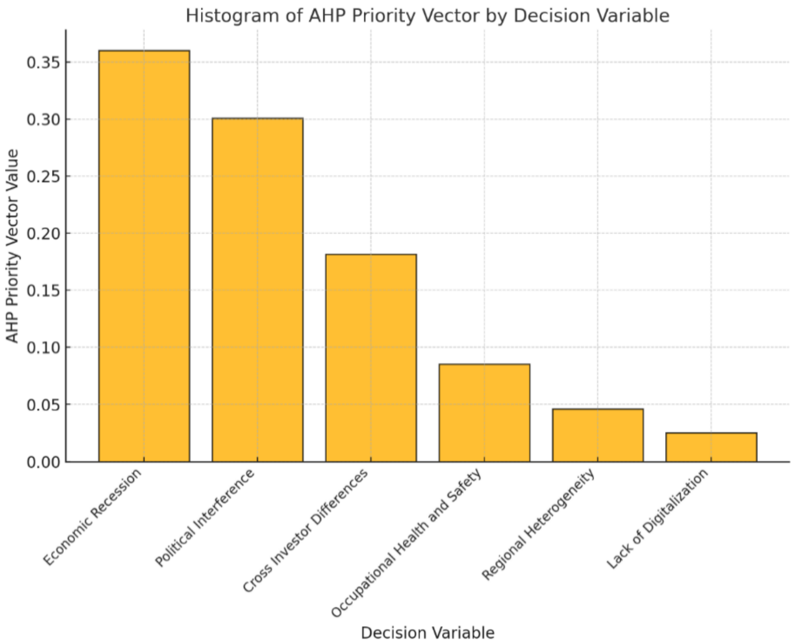

Figure 14: Histogram of AHP Priority Vector
(Author's own work, 2024)

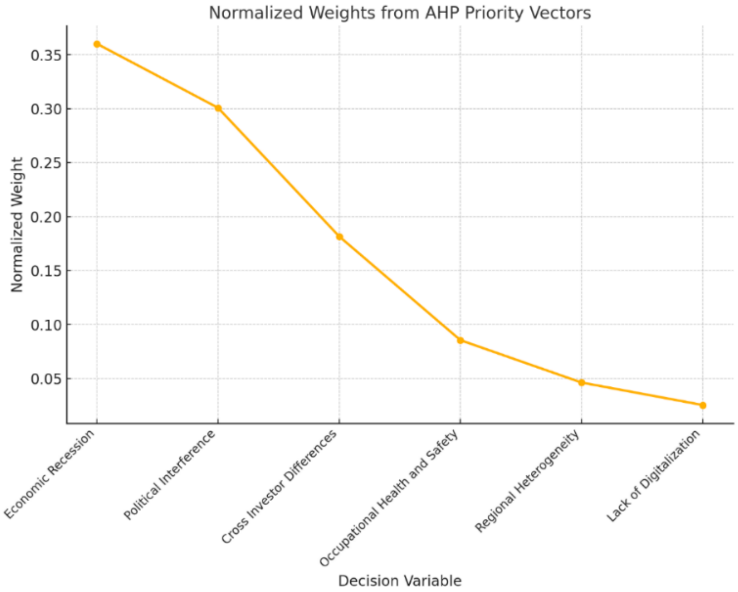

Figure 15: Normalized Weights from AHP Priority Vectors
(Author's own work, 2024)

4.3 Validation of Results

Validity tests are essential components of any rigorous research methodology, ensuring that the results derived from the analytical process are credible, reliable, and applicable. In this study, validity tests play a pivotal role in assessing the robustness and accuracy of the methods used, thereby enhancing the overall trustworthiness of the findings. Two key validity tests applied are the **Consistency Ratio (CR)** and **Sensitivity Analysis**, each serving complementary purposes in evaluating the research framework. Since expert evaluations often involve subjective assessments, there is a potential for inconsistency in the prioritization of variables. The CR evaluates the degree of consistency by comparing the calculated consistency index (CI) with a random index (RI), derived from a matrix of random judgments. Similarly, sensitivity analysis This analysis helps to identify the extent to which the findings are dependent on the initial inputs, highlighting the most critical factors and potential vulnerabilities. By incorporating sensitivity analysis, the research framework ensures that the conclusions are not only valid under current conditions but also resilient to minor changes, thus enhancing their practical applicability and generalizability. Together, the CR and sensitivity analysis provide a comprehensive evaluation of the research framework's validity. The CR ensures that the expert judgments are logically sound, while sensitivity analysis confirms the stability of the results against potential variations. These tests collectively strengthen the methodological rigor of the study, ensuring that the findings are not only accurate but also robust and reliable for practical decision-making.

By integrating these validity tests at the outset, this research establishes a foundation of methodological soundness, providing stakeholders with confidence in the robustness and applicability of the results

4.3.1 Calculating Consistency Ratio

The Consistency Ratio (CR) is a critical metric in the Analytic Hierarchy Process (AHP), utilized to evaluate the logical consistency of judgments made during the pairwise comparison of variables. The threshold for acceptable consistency, as proposed by Saaty, is $CR < 0.1$, indicating that the inconsistencies in the comparisons are within acceptable limits.

Consistency Index (CI) is calculated using equation 17;

$$CI = \frac{\lambda \max - n}{n - 1} \tag{17}$$

Where

λmax: Maximum eigenvalue of the matrix.

n: Number of variables.

The value of CI calculated using this formula is put in **Consistency Ratio(CR)** formula shown in equation 18;

$$CR = \frac{CI}{RI} \tag{18}$$

RI: Random Index based on n (RI =1.24 for n =6)

For calculating λmax , the pairwise matrix is multiplied by the priority vector, then divided by the corresponding weight. The results are averaged to find λmax . After entering the required data, results were calculated as shown in equation 19 and 20;

$$CI = \frac{6.01355 - 6}{5} = 0.00271 \tag{19}$$

$$CR = \frac{0.00271}{1.24} = 0.00219 \tag{20}$$

Since $CR < 0.1$, the judgments are consistent. This confirms that the judgments made during the expert evaluation process were logical and coherent, validating the reliability of the input data used in the analysis. This not only validates the consistency of expert judgments but also enhances the reliability of the overall analytical framework. This aligns with the objective of delivering methodologically sound and actionable insights, reinforcing the validity of the findings presented by the researcher.

4.3.2 Sensitivity Analysis

Sensitivity Analysis evaluates how sensitive the final priority rankings are to changes in input values (judgments). For AHP, this typically involves adjusting the pairwise comparisons or the weights and observing the impact on the consistency ratio and rankings. This evaluates the robustness of the results by examining how changes in input data influence the outcomes. It involves systematically varying key parameters, such as weights or priorities, to assess the stability and reliability of the derived results. In this study, a 5% adjustment to the pairwise comparison matrix is applied during sensitivity analysis to explore the impact of minor variations in expert judgments. Formulas used are shown in equation 21 and 22;

$$Decreased\ Weights\ (5\%\ Reduction): Decreased\ Weight\ = Original\ Weight\ \times 0.95 \quad (21)$$

$$Increased\ Weights\ (5\%\ Increase): Increased\ Weight = Original\ Weight\ \times 1.05 \quad (22)$$

These formulas are used to evaluate the robustness of the model by slightly adjusting the original priority weights. The multiplication factor (0.95 or 1.05) represents a 5% decrease or increase. For each criterion, multiply the original weight by 0.95 to get the decreased weight and by 1.05 to get the increased weight.

Table 10: Sensitivity Analysis (Decrease/ Increase by 5%) (Author's own work, 2024)

Criteria	**Original Weights**	**Decreased Weights (0.95)**	**Increased Weights (1.05)**
Economic Recession	**0.3604**	0.3424	0.3784
Political Interference	**0.3009**	0.2859	0.3159
Cross Investor Differences	**0.1817**	0.1726	0.1908
OHS	**0.0855**	0.0812	0.0898

Regional Heterogeneity	**0.0462**	0.0439	0.0485
Lack of Digitalization	**0.0254**	0.0241	0.0267

Adjusted weights shown in table 10, directly replace the original weights for comparison. Recalculation is needed to observe whether changes in weights impact the relative priority rankings of criteria. This helps assess the sensitivity and robustness of the overall model. Comparison is done using the recalculated weights for all criteria under adjusted scenarios (increased and decreased) to the original rankings.

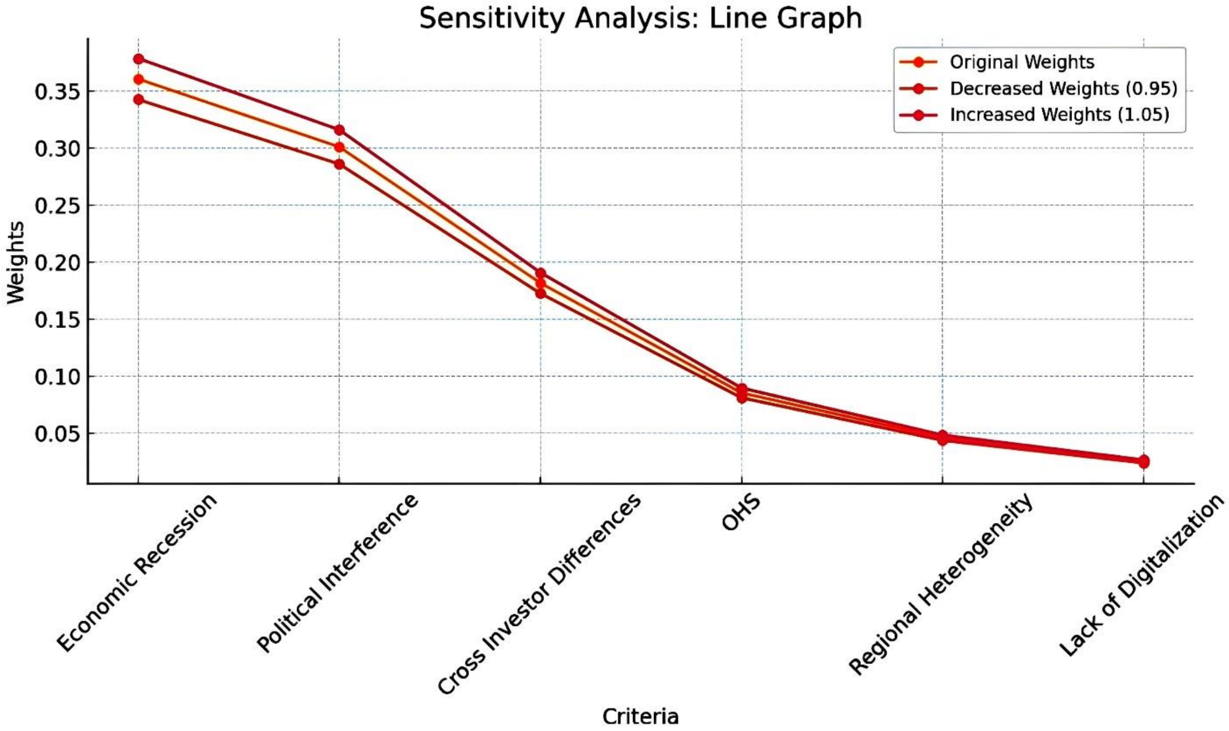

Figure 16 : Sensitivity Analysis (Author’s own work, 2024)

The small perturbations in input judgments (weights) did not result in significant changes to the rankings which can be seen in Figure 16, indicating that the model is consistent and robust. The higher-ranked variables (Economic Recession and Political Interference) show a larger spread, reflecting greater sensitivity to weight changes. However, as priority decreases, the gap progressively narrows, suggesting that these variables have a smaller influence on the overall model results when slightly adjusted. This analysis helps to identify the extent to which the findings are dependent on the initial inputs, highlighting the most critical factors and potential vulnerabilities. By incorporating sensitivity analysis, the research framework ensures that the conclusions are not only valid under current conditions but also resilient to minor changes, thus enhancing their practical applicability and generalizability.

4.4 Hybrid Validation Matrix

4.4.1 Gap Analysis

The gaps between NetLogo thresholds and AHP weights reveal differences in emphasis as shown in Figure 17. Negative gaps are those who get a negative value after finding difference (e.g., for Economic Recession; $0.1945 - 0.3604 = -0.1659$) as shown in table. Similarly, positive gaps are those who get a positive value after finding difference (e.g., for Lack of Digitalization; $0.0947 - 0.0254 = 0.0693$). The gap for each variable was calculated using equation 3. The gaps (NetLogo Threshold−AHP Weight) reveal differences in emphasis:

- **Positive Gaps**: Indicate that NetLogo assigns higher importance (e.g., Cross Investor Differences, OHS).
- **Negative Gaps**: Show that AHP experts emphasize these variables more (e.g., Economic Recession, Political Interference).

These gaps underline the importance of a hybrid approach to balance simulation and expert-driven insights.

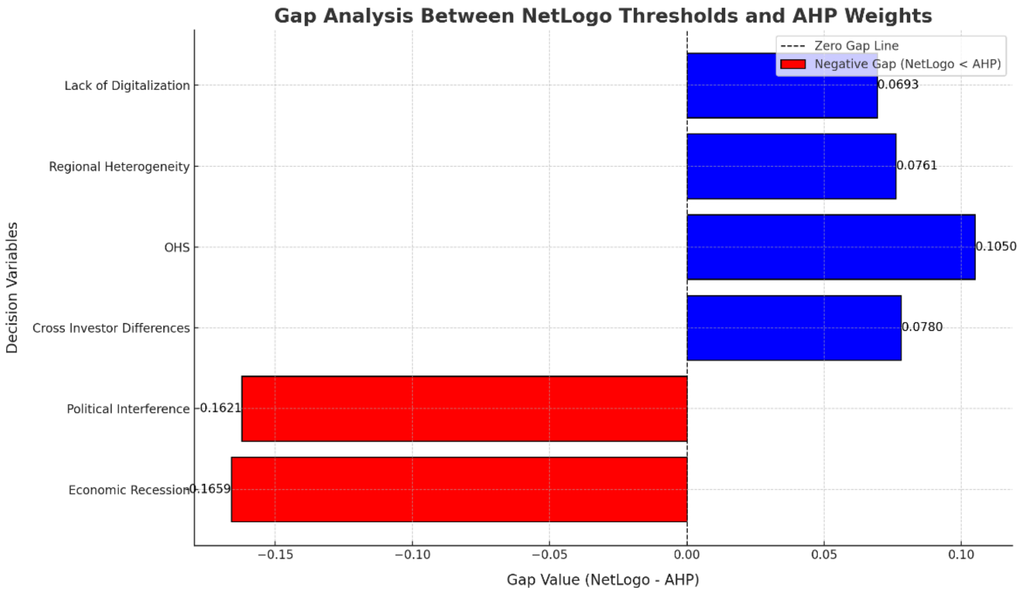

Figure 17: Gap Analysis (Author's own work, 2024)

4.4.2 Calculation Correlation between NetLogo thresholds and AHP weights

Correlation analysis plays a vital role in statistical methodology by providing a foundational framework for advanced analytical processes. As a statistical tool, it enables researchers to assess relationships between variables quantitatively, which is essential for accurate forecasting and informed decision-making in research contexts (Gleason et al., 2020). This analytical approach proves particularly valuable when researchers need to establish equivalency across different methodological approaches, as it provides a standardized way to compare and validate results from diverse studies.

The significance of correlation analysis extends beyond basic relationship assessment, as it serves as a critical tool for identifying underlying patterns and potential biases in research data (R. Shi & Conrad, 2009). This capability is especially important when researchers need to integrate data from multiple methodological sources. By establishing clear relationships between different data sets and methods, correlation analysis helps ensure that findings can be combined and compared meaningfully, reducing the risk of methodological inconsistencies affecting research outcomes (Y. Shi et al., 2023).

Equation 23 is used to calculate correlation;

$$\boldsymbol{\gamma} = \frac{\sum\left(\left(\left(\boldsymbol{x} - \boldsymbol{mean}(\boldsymbol{x})\right)\right).\left(\boldsymbol{y} - \boldsymbol{mean}(\boldsymbol{y})\right)\right)}{\sqrt{\sum\left(\boldsymbol{x} - \boldsymbol{mean}(\boldsymbol{x})\right)^{\mathbf{2}}.\sum\left(\boldsymbol{y} - \boldsymbol{mean}(\boldsymbol{y})\right)^{\mathbf{2}}}} \tag{23}$$

Where $\boldsymbol{x}$ = NetLogo Thresholds and $\boldsymbol{y}$ = AHP Weights

$$\boldsymbol{Correlation}\ (\boldsymbol{\gamma}) = \frac{\mathbf{0.01663}}{\mathbf{0.04166}} = \mathbf{0.3991} \tag{24}$$

Equation 24 shows that after calculations, correlation between findings of both methodologies came out to be 0.3991. This correlation value falls in the range of 0.3 to 0.5, indicating a weak positive relationship. This means that as NetLogo thresholds increase, there is a weak tendency for AHP weights to also increase. However, the relationship is not strong or consistent. The weak positive correlation suggests that the alignment between NetLogo thresholds (derived from simulations) and AHP weights (derived from expert judgments) is limited: NetLogo thresholds represent quantitative outcomes from an agent-based model (ABM) whereas AHP weights represent expert-based evaluations of variable importance. The weak relationship implies that the variables considered significant by experts do not perfectly align with the patterns observed in the simulation outcomes. This gap could highlight a discrepancy between model-based predictions and expert judgments, necessitating further investigation. Figure 18 graphically represents correlation between NetLogo and AHP results used data plots.

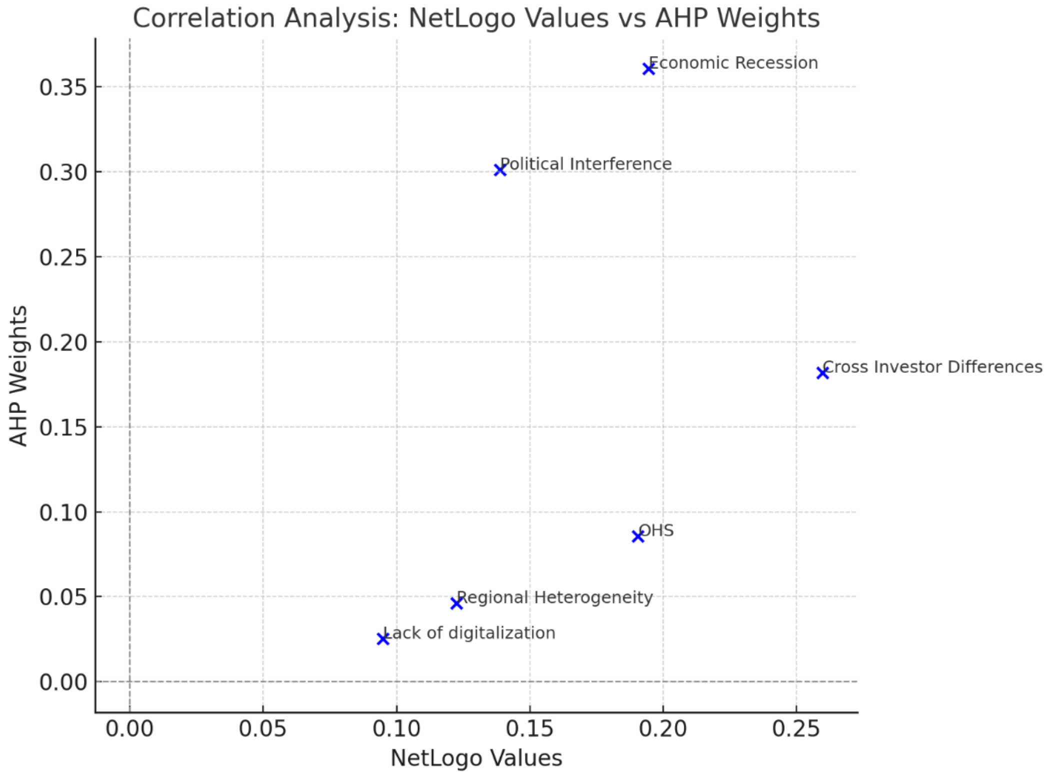

Figure 18: Correlation between NetLogo Thresholds and AHP Weights
(Author’s own work, 2024)

4.4.3 Integration of NetLogo and AHP Results

The Hybrid Validation Index (HVI) combines the insights from NetLogo thresholds (simulation-based) and AHP weights (expert-based) using the equation 25;

$$HVI = \frac{Netlogo\ threshold + AHP\ Weight}{2} \tag{25}$$

This equal-weighted approach ensures that both methodologies contribute equally to the hybrid results, minimizing bias from either simulation or expert judgments.

Table 11: Hybrid Validation Matrix (Author’s own work, 2024)

Decision Variables	**Normalized NetLogo Thresholds**	**Normalized AHP Weights**	**Gap (NetLogo - AHP)**	**AHP Rank**	**NetLogo Rank**	**Rank Alignment**	**Hybrid Validation Index**	**Priority Category**
Economic Recession	0.1945	0.3604	-0.1659	1	2	Not Aligned	0.27745	Very High
Political Interference	0.1388	0.3009	-0.1621	2	4	Not Aligned	0.21985	High
Cross Investor Differences	0.2597	0.1817	0.078	3	1	Not Aligned	0.2207	High
OHS	0.1905	0.0855	0.105	4	3	Not Aligned	0.138	Medium
Regional Heterogeneity	0.1223	0.0462	0.0761	5	5	Aligned	0.08425	Low
Lack of Digitalization	0.0947	0.0254	0.0693	6	6	Aligned	0.06005	Very Low

The Hybrid Validation Matrix successfully integrates simulation and expert perspectives, providing a comprehensive prioritization of decision variables. Misalignments in ranks highlight the importance of using multiple validation methods. Consistency for low-priority variables enhances confidence in results. The results from table 11 indicate that economic recession and political interference emerged as the most critical variables, both showing a very high and high priority category, respectively, despite rank misalignment between the AHP and NetLogo results. Cross-investor differences and OHS showed rank misalignment, highlighting the complexity of these variables across different validation methods. In contrast, regional heterogeneity and lack of digitalization were ranked with lower priority and showed alignment between the AHP and NetLogo ranks, suggesting lower influence on green hydrogen storage adoption in the manufacturing sector. Consistency for low-priority variables enhances confidence in results. The trends are shown in Fig: 19.

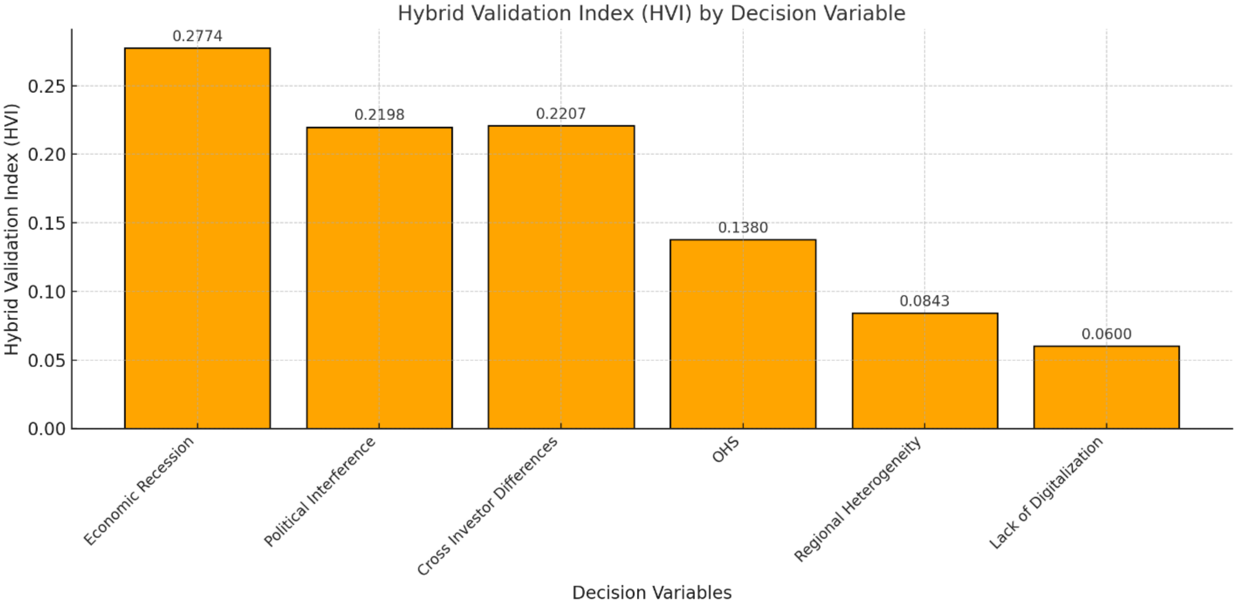

Figure 19: Hybrid Validation Index Histogram (Author's own work, 2024)

Chapter 5: Discussion, Limitation and Conclusions

The discussion chapter serves as a critical analysis and interpretation of the research findings in light of the objectives set forth in this study. It bridges the gap between the results obtained and their implications for the broader context of green hydrogen storage systems, focusing on the identified social, technological, and policy challenges. This chapter delves into the meaning and significance of the findings by comparing them with existing literature and theoretical frameworks. It evaluates how the results align with or diverge from established studies, providing insights into emerging trends, opportunities, and challenges in green hydrogen storage systems. Furthermore, the chapter integrates expert perspectives from the interviews conducted, shedding light on the practical implications of these challenges in real-world scenarios.

Special attention is given to the interplay between agent-based modeling results and the qualitative insights obtained through the AHP. The discussion highlights the impact of key variables on the adoption and scalability of green hydrogen storage systems while addressing potential limitations of the research and avenues for future exploration. This comprehensive analysis forms the foundation for proposing actionable recommendations to address the identified challenges and foster the development of sustainable hydrogen energy solutions.

This discussion integrates global examples from both developed and developing countries, analyzing how energy sector challenges manifest differently across contexts. It also provides a comparative analysis of how developed countries successfully addressed similar issues, providing actionable insights for countries like Pakistan. The data analysis was based on the comprehensive review of existing literature by the researcher.

5.1 Final Rank Analysis

Economic Recession emerged as the highest-priority variable (HVI: 0.27745). AHP ranked also ranked economic recession as the most critical variable (Rank 1), reflecting the expert consensus that economic instability disrupts investment, planning, and overall system stability. However, NetLogo simulations ranked it second, suggesting that its influence, while significant, depends on interactions with other variables. This reflects its foundational role in destabilizing financial flows, reducing investor confidence, and disrupting long-term planning (Abdullahi &

Abdullahi, 2024; Nieto-Chaupis, 2024). The cascading effects of economic instability amplify risks in other areas, such as political interference and investor alignment, creating a vicious cycle of uncertainty.

Political Interference, ranked High in priority (HVI: 0.21985), acts as both a direct obstacle and a catalyst for corruption, rent-seeking behavior, and governance instability (Eryanto et al., 2022). AHP also ranked it second, underlining its role in fostering policy instability, corruption, and governance issues that derail long-term projects. Experts argue that these factors erode institutional trust and create inefficiencies that compound over time (A. Aslam et al., 2023; Ogunode et al., 2024). However, NetLogo simulations ranked it fourth, suggesting that its immediate systemic impact might be less pronounced. In contexts like Pakistan, frequent shifts in political regimes lead to policy reversals, disrupted supply chains, and bureaucratic inefficiencies. Political rent-seeking, where key stakeholders leverage power for personal or partisan gain, diverts resources from productive uses.

Cross-Investor Differences is ranked as a high priority variable in Hybrid validation matrix and third by AHP, reflecting the systemic challenges arising from misaligned goals among stakeholders. NetLogo simulations, however, ranked this variable first, suggesting that in a dynamic system, investor misalignment creates the most immediate disruptions, directly affecting decision-making and resource allocation. In public-private partnerships or joint ventures, these differences often manifest in disputes over resource allocation, operational priorities, and profit-sharing, leading to project delays and inefficiencies (Musenero et al., 2021). In Pakistan’s energy sector, where multiple stakeholders with varying interests operate, such conflicts are common, further compounded by political and economic volatility as suggested by Liang et al. (2023) and Yasmeen et al. (2021).

OHS, ranked as a medium-priority variable (HVI: 0.138) and fourth in rank by AHP, is critical for ensuring workforce stability and operational continuity. While its systemic impact may appear less significant than economic or political factors, the neglect of OHS can lead to labor disruptions, increased accidents, and legal challenges, particularly in energy sectors as supported by literature (Gjorgjev & Byanov, 2022; Saraswaty, 2024). NetLogo ranked OHS slightly higher at third, suggesting that neglecting safety can cause immediate and visible disruptions, especially in laborintensive projects. In Pakistan, inadequate enforcement of safety standards poses significant risks, not only to workers but also to project timelines and budgets.

Regional Heterogeneity and Lack of Digitalization and technological integration, while categorized as low-priority variables in both the models, indirectly influence higher-priority challenges by creating inefficiencies across the system as backed by literature (Detemple & Wicht, 2024; Аралбаева, 2023) .Regional disparities in infrastructure and governance exacerbate coordination challenges, particularly in large-scale, multi-region projects. Similarly, the lack of digital infrastructure limits the ability to adopt innovative solutions and respond dynamically to emerging challenges.

The results of this study highlight the interdependent nature of challenges within the energy sector, emphasizing that no single variable operates in isolation which aligns with the literature (Laimon et al., 2022; Shahzad et al., 2023).

5.2 Social Challenges

5.2.1 Regional Heterogeneity

Regional heterogeneity plays a critical role in the success or failure of large-scale sustainability initiatives, including green hydrogen storage. The following discussion integrates key findings and examples from both developed and developing countries, along with real-world project outcomes, to illustrate how uneven regional conditions affect implementation.

Countries such as Germany and Norway have advanced green hydrogen hubs, benefiting from policy alignment, advanced infrastructure, and skilled labor (Larsgård, 2024). However, even within Europe, projects in Eastern regions often face delays due to limited infrastructure and policy inconsistencies. While green hydrogen development is prioritized in India, uneven energy access and resource constraints between urban and rural areas have slowed implementation (Panelli & Ali, 2024). These examples demonstrate how existing disparities—policy readiness, economic capacity, and infrastructure—directly influence the pace of green hydrogen adoption.

Fernández-González et al. (2022) highlight how heterogeneity in geological conditions caused unanticipated challenges in salt cavern integrity, delaying hydrogen storage projects and increasing costs. This showcases how natural regional variations create unique risks. Larsgård (2024) points out that a lack of harmonized policies across municipalities led to funding lapses and logistical inefficiencies in developing hydrogen hubs. In India and sub-Saharan Africa, limited renewable energy infrastructure, compounded by economic disparities, has led to delayed green hydrogen deployment, with resource-rich regions seeing progress while others stagnate (A. Raza et al., 2024).

Reducing the impact of regional disparities on green hydrogen projects requires a multifaceted approach that recognizes the unique challenges faced by different areas. One of the most pressing needs is **policy harmonization**. Without a unified framework, regions with stronger infrastructure and financial capabilities naturally advance faster, leaving less-developed areas behind. Another important strategy is implementing **targeted interventions**. Instead of spreading resources thinly, focusing on areas that lag behind can create a more balanced approach. Germany provides an excellent example of this, where targeted investment in underdeveloped areas has successfully reduced disparities. By prioritizing these regions, governments and organizations can ensure that the benefits of green hydrogen are accessible to all, rather than being confined to a few advanced areas. Lastly, **technological adaptations** are essential to overcome localized challenges. (Zoback & Smit (2023) argue that storage solutions must be tailored to specific regional conditions. For instance, regions with complex geology may benefit from shallow cavern storage instead of traditional methods. Such adaptations ensure that even areas with natural limitations can participate in the green hydrogen revolution. By addressing the unique needs of different regions, we can create a more inclusive and effective system.

5.2.2 Occupational Health and Safety (OHS): Workforce Vulnerabilities

OHS challenges (priority vector: 0.0855, HVI: 0.138) include weak safety regulations and limited automation, leading to frequent accidents and reduced workforce productivity.

The **Hub Power Plant** in Baluchistan reported multiple safety incidents due to outdated equipment and poor worker training (Yaqoob et al., 2024). Coal mines supplying power plants frequently experience fatal accidents, delaying projects and increasing costs (Pakistan Energy Outlook Report, 2022).The mining sector of South Africa improved safety by adopting ISO-certified standards and incentivizing investments in safety technology, reducing fatal accidents by 30% over five years (Van Heerden et al., 2015).

Norway's offshore energy sector uses automation and robotics to minimize human exposure to hazardous tasks, significantly reducing workplace accidents (Johansen et al., 2023).

Pakistan should enforce strict regulations by adopting global safety standards and penalize non-compliance. tax breaks should be provided for companies that adopt safety technologies and training programs. Deploy Automation by drones and robots for hazardous tasks, as demonstrated by Norway.

5.3 Technological Challenges

5.3.1 Economic Recession: A Catalyst for Delays and Underfunding

Economic recessions were identified as the most critical challenge, with a priority vector of 0.3604 and Hybrid Validation Index (HVI) of 0.27745. Recessions lead to reduced investments, cost overruns, and delays in energy projects.

Pakistan's **Neelum-Jhelum Hydropower Project** suffered from repeated delays, with its cost ballooning from PKR 15 billion to PKR 500 billion due to economic downturns, currency devaluation, and inadequate funding mechanisms (Pakistan Energy Outlook Report,2022). Similarly, the COVID-19 pandemic diverted public funds away from renewable projects, delaying wind and solar developments (Y. Li et al., 2023). In Indonesia, the pandemic led to a 9.6% decrease in capital costs for renewable energy, indicating a shift in focus from long-term sustainability to immediate crisis management (Al Hasibi & Bawan, 2023).

During the 2008 financial crisis, Germany sustained its renewable energy momentum by issuing green bonds and offering low-interest loans through the **KfW Development Bank** (Zavadskas & Turskis, 2011). These tools provided financial stability to solar and wind energy projects. The American Recovery and Reinvestment Act (2009) allocated $90 billion for clean energy projects during the recession, spurring investments in solar and wind energy technologies (Alizadeh et al., 2020).

Pakistan can adopt similar solutions by diversifying funding sources, accessing climate funds and issuing green bonds to attract global investors focused on climate-resilient projects, leveraging platforms like the Green Climate Fund (GCF) to secure low-interest financing and encouraging domestic production of renewable energy equipment to mitigate currency fluctuation risks.

5.3.2 Lack of Digitalization: A Technological Gap

Lack of digitalization and technological integration was ranked as a low-priority variable (priority vector: 0.0254, HVI: 0.06005), but its transformative potential cannot be ignored. Pakistan’s reliance on manual monitoring systems increases inefficiencies and operational delays.

The National Smart Grid Mission of India introduced digital tools to optimize electricity distribution, improving grid stability and reducing losses (Mythreyee & Anandan, 2024). The UK invested heavily in smart grid technologies, integrating distributed renewable energy sources and reducing transmission losses (Kiasari et al., 2024).Germany’s digital tools for solar energy monitoring enhanced project transparency and increased investor confidence (Uzondu & Lele, 2024).

Collaboration with international technology providers to make digital solutions affordable, leveraging open-source software for energy planning and monitoring, and capacity-building programs to equip staff to use digital technologies effectively can help Pakistan modernize its energy sector.

5.4 Policy Challenges

5.4.1 Political Interference: A Challenge to Continuity

Political interference ranked as the second most significant barrier (priority vector: 0.3009, HVI: 0.21985). It disrupts long-term planning, deters investor confidence, and often results in stalled or abandoned projects.

The **Kalabagh Dam** of Pakistan has been stalled for decades due to political disputes between provinces, despite its potential to generate 3,600 MW of electricity (Ayaz & Farooq, 2020). Political lobbying in the **Thar Coal Power Project** has also delayed operations, with conflicting interests between local governments and private stakeholders (Babar & Waleed, 2024). Inconsistent policies on feed-in tariffs for renewable energy projects have deterred international investors, delaying Bangladesh's transition to solar energy (Akash et al., 2024).

Denmark overcame political disputes in the energy sector by establishing a transparent and inclusive policy framework for offshore wind energy (Zavadskas & Turskis, 2011). By involving stakeholders and ensuring policy continuity, Denmark now generates over 40% of its electricity from wind power. Despite being a developing country, Ethiopia successfully insulated its energy projects from political interference by establishing an independent regulatory authority. This attracted $1.8 billion in foreign investment for the **Grand Renaissance Dam** (Yihdego et al., 2017).

Similar to Ethiopia, creating autonomous energy bodies, Pakistan can ensure continuity and transparency. Adopting Denmark's inclusive policymaking approach can build investor trust and minimize political risks.

5.4.2 Cross-Investor Differences: Stakeholder Misalignment

Cross-investor differences (Priority vector: 0.1817, HVI: 0.2207) create delays and increase project costs. Misaligned goals and risk-sharing disputes are prevalent in Pakistan.

The **CPEC Energy Projects** have faced disputes between Chinese investors and the Pakistani government over tariff structures and risk-sharing mechanisms, delaying solar and coal power initiatives. India's renewable energy auctions have been disrupted by tariff disagreements between private developers and state governments, slowing project implementation (Sinha et al., 2011). The Netherlands centralized grid planning for offshore wind energy, ensuring equitable resource allocation and reducing conflicts among investors (Musial & Ram, 2010). Standardized contracts for geothermal energy projects in Indonesia aligned stakeholder priorities, streamlining development and minimizing delays.

Pakistan can resolve investor disputes by defining clear risk-sharing and revenue mechanisms for energy projects. Similar to the Netherlands, a centralized approach to grid access and resource allocation can reduce conflicts.

5.5 Cross-Cutting Insights for Pakistan

Policy stability is a crucial requirement for the development of Pakistan’s energy sector. The recurring political disputes, such as those surrounding the Kalabagh Dam, highlight the detrimental impact of governance instability on energy projects. Despite its potential to generate 3,600 MW of electricity and address water management issues, the Kalabagh Dam has been stalled for decades due to inter-provincial disagreements. This lack of consensus has not only delayed progress but also discouraged local and foreign investors.

Establishing an independent regulatory framework, free from political interference, could provide the stability needed to move such projects forward while ensuring long-term planning and consistency in policy implementation. The lack of stable governments, corruption, and the involvement of powerful individuals in state-owned businesses have been significant impediments to the progress and success of energy projects in Pakistan. These systemic issues create an environment of uncertainty, mismanagement, and inefficiency, often resulting in delays, cost overruns, or the outright failure of critical infrastructure projects. Unstable governments have led to frequent policy shifts, making it challenging for long-term energy projects to achieve continuity. Successive governments in Pakistan have often altered or reversed energy policies to align with their political agendas, creating inconsistencies that deter both domestic and foreign investors. For example, renewable energy policies have suffered from abrupt changes in tariff structures and project approvals, causing significant delays and uncertainty. The lack of a stable governance framework has stalled critical projects, such as the Kalabagh Dam, which remains a victim of political disagreements despite its immense potential to address the country’s water and energy needs. Corruption has been another pervasive issue, deeply embedded in Pakistan’s energy sector. Large-scale projects often involve kickbacks, embezzlement, and favoritism, leading to misallocation of funds and poor-quality execution. For instance, the **Nandipur Power Project**, which was initially touted as a solution to Pakistan’s energy crisis, became infamous for corruption scandals that inflated its costs and significantly delayed its operational timeline. Such practices not only waste public funds but also erode trust among investors and stakeholders. The involvement of powerful individuals and elites in state-owned energy businesses further exacerbates the problem. Many state-run enterprises are controlled by influential figures who prioritize personal or political gains over the public good. Nepotism in appointments, overstaffing, and misuse of resources have rendered these entities inefficient and unprofitable. The monopolistic control of influential individuals in energy projects often results in inflated tariffs and limited transparency. In cases where vested interests conflict with national priorities, projects are delayed or halted altogether. This is evident in various CPEC-related energy initiatives, where disputes over tariff structures and revenue-sharing mechanisms between private investors and government officials have slowed progress. Addressing these challenges requires significant reforms. Establishing independent regulatory authorities free from political influence can ensure transparency and accountability in the energy sector. Anti-corruption measures, including strict oversight of project financing and implementation, must be enforced to curb embezzlement and favoritism. Furthermore, depoliticizing state-owned enterprises and introducing merit-based management can enhance their efficiency and profitability. By tackling these systemic issues, Pakistan can create a stable and transparent environment conducive to the successful execution of energy projects and sustainable development.

Pakistan's dependency on the International Monetary Fund (IMF) for economic stability has created significant challenges in prioritizing long-term sustainability initiatives, such as green hydrogen projects. The IMF’s financial assistance packages often require the government to adopt fiscal consolidation measures, including subsidy cuts, austerity policies, and strict debt repayment schedules. These restrictions severely limit Pakistan's ability to allocate resources for innovative and capital-intensive projects like green hydrogen production, which require significant upfront investment in infrastructure, technology, and capacity building. Green hydrogen production and storage is currently an expensive endeavor, primarily due to the high costs of electrolyzers, which are critical for splitting water into hydrogen and oxygen. In a resource-constrained economy like Pakistan’s, where the government struggles to manage existing energy challenges such as circular debt and power outages, prioritizing an emerging and costly technology is not feasible in the short term. Additionally, the lack of infrastructure for hydrogen storage, transportation, and distribution adds another layer of financial and logistical complexity. Despite these challenges, there is hope for future adoption if global advancements in green hydrogen technology drive down costs. Countries like Germany, Japan, and Australia are leading the way in scaling up green hydrogen production and storage, which is expected to reduce the cost of electrolyzers through economies of scale, technological innovation, and market competition. As these advancements make the technology more affordable, Pakistan could explore green hydrogen as a viable option for meeting its energy and sustainability goals.

Furthermore, international collaboration and funding mechanisms could play a critical role in bridging the gap. For instance, technology transfer programs under the United Nations Framework Convention on Climate Change (UNFCCC) or other global sustainability initiatives could provide Pakistan with the technical expertise and financial support needed to adopt green hydrogen in the future. Participation in regional or global hydrogen alliances could also help Pakistan access cost-effective technologies and build partnerships with countries advancing in this field. In the short term, Pakistan can focus on preparatory measures to position itself for a potential hydrogen economy. This includes piloting small-scale green hydrogen projects, investing in research and development, and building technical expertise in renewable energy technologies. These initiatives would not require large-scale financial commitments but would prepare the groundwork for larger investments when economic conditions improve and global technology becomes more accessible. While green hydrogen remains a distant priority for Pakistan under current economic constraints, global advancements and cost reductions could make it a feasible option in the medium to long term. Until then, the government must focus on stabilizing its economy and preparing for future opportunities in the sustainable energy sector. Diversifying financing mechanisms is essential to reduce Pakistan's reliance on unstable foreign funding and to safeguard energy projects against economic downturns. The country’s current dependence on international loans and grants makes its energy sector vulnerable to financial shocks. By issuing green bonds or leveraging international climate funds, Pakistan can create more sustainable and diversified funding streams. This approach can provide the necessary capital for renewable energy initiatives such as solar and wind projects, which have often been delayed due to budget constraints.

Regional heterogeneity in Pakistan, characterized by disparities in awareness, acceptance, administrative capacities, and geographical resources, has significantly impacted energy development. Provinces like Sindh and Punjab have advanced in renewable energy projects due to better governance and awareness, while regions like Baluchistan and KP face challenges from weak institutions, limited community acceptance, and underutilized resources. Geographical differences also exacerbate inequalities, with energy-rich provinces like Baluchistan lacking infrastructure and investment despite their potential. The 18th Amendment to Pakistan's

Constitution, passed in 2010, decentralized power, granting provinces autonomy over their resources. This has enabled provinces to tailor energy initiatives to their unique needs, reducing inter-provincial conflicts. For instance, Sindh has expanded wind energy, and KP has focused on small hydropower projects. While challenges persist, the 18th Amendment fosters hope for improved cooperation and equitable energy development. Collaborative efforts, supported by federal capacity-building and funding, can help address regional disparities and transform heterogeneity into a driver of progress.

Technology adoption offers significant potential to transform the efficiency of Pakistan's energy infrastructure. The lack of digital monitoring systems in power transmission and renewable energy projects leads to inefficiencies and delays. For example, outdated manual systems in the National Transmission and Dispatch Company (NTDC) contribute to frequent power outages and operational challenges. By investing in affordable digital technologies and training programs for workers, Pakistan can enhance transparency and optimize the management of energy resources. Digital solutions can streamline project monitoring and improve decision-making, ensuring timely project completion and better energy distribution.

Workforce safety is another critical area that requires immediate attention in Pakistan. Frequent safety incidents at facilities like the Hub Power Plant and in coal mines supplying energy plants reflect systemic issues in enforcing OHS standards. These incidents not only delay projects but also increase operational costs and reduce worker morale. A significant barrier to Pakistan's adoption of green hydrogen storage technology is the lack of a skilled workforce and limited awareness of OHS practices. The hydrogen industry requires specialized knowledge for handling complex processes, including electrolyzer operation, storage management, and transportation. However, the workforce in Pakistan often lacks the technical expertise needed for such advanced energy systems. This skills gap can result in inefficiencies and heightened safety risks. Hydrogen, while a promising clean energy solution, is highly flammable and can lead to catastrophic accidents if mishandled. Leaks, poor storage conditions, or inadequately trained personnel can result in severe explosions or fires, endangering lives and infrastructure. The lack of emphasis on OHS practices in Pakistan further exacerbates these risks, as safety measures are often undervalued due to limited awareness of the potential dangers. This mindset poses a significant challenge in an industry where even minor lapses can have disastrous consequences. To address this, workforce training is crucial. Technical training programs must focus on equipping workers with the skills to operate and maintain hydrogen production and storage systems. Awareness campaigns on OHS practices should highlight the importance of safety protocols and the risks associated with hydrogen. Certification programs and partnerships with international organizations can further enhance workforce competency and ensure adherence to global safety standards. Building a skilled and safety-conscious workforce is essential for the successful and secure adoption of green hydrogen technology in Pakistan. Without such measures, the risks of accidents and inefficiencies may outweigh the benefits of this clean energy solution, making workforce development a critical priority alongside technological advancements. By enforcing strict OHS regulations, providing safety training, and incentivizing investments in modern safety technologies, Pakistan can reduce workplace accidents and improve productivity. Prioritizing worker safety will also foster a more reliable and sustainable energy workforce, ensuring that projects are completed efficiently and on time.

In Pakistan, a prevalent mindset within the industrial sector prioritizes survival over sustainability. Many industry leaders perceive sustainability initiatives, such as green energy projects, waste management systems, or emissions reductions, as luxuries that the country cannot afford in its current economic condition. This viewpoint is rooted in the nation’s broader economic challenges, including high levels of debt, inflation, and energy crises, which compel businesses to focus on short-term survival strategies rather than long-term sustainability goals. A key factor reinforcing this mindset is the financial instability faced by Pakistan's industries. With rising operational costs, frequent power outages, and an unstable regulatory environment, many businesses are struggling to maintain profitability. Sustainability projects, which often require substantial upfront investments, are viewed as additional burdens rather than opportunities for growth or cost savings in the long run. This belief is particularly evident in energy-intensive sectors such as textiles, cement, and manufacturing, where the focus remains on minimizing production costs to stay competitive in local and international markets.

Studies have highlighted this mindset in Pakistan's industrial landscape. According to Lin (2018), the majority of businesses in Pakistan prioritize economic survival over environmental considerations, citing financial constraints and an unpredictable economic environment as the primary reasons. Similarly, Khan et al. (2020) note that while many industrialists recognize the importance of sustainability, they believe it is a secondary priority compared to immediate survival needs, particularly in an economy plagued by energy crises and fiscal instability. This survival-over-sustainability mindset poses significant challenges to Pakistan’s progress in achieving environmental goals and adopting modern green technologies like hydrogen production. However, addressing this requires a shift in policy and mindset. The government must create targeted incentives, such as subsidies for renewable energy adoption, tax breaks for green initiatives, or low-interest loans for sustainability projects, to encourage industries to integrate sustainable practices without compromising their economic stability. Furthermore, raising awareness about the long-term financial and environmental benefits of sustainability is crucial. Highlighting case studies where green investments have led to cost savings and improved efficiency can help reshape perceptions and demonstrate that sustainability is not a luxury but a necessity for long-term survival.

Pakistan’s energy sector faces interconnected socio-economic, technological, and policy challenges. However, by learning from global best practices—such as Ethiopia’s governance reforms, Kenya’s digitalization initiatives, and Norway’s safety standards—Pakistan can address these challenges and accelerate its transition to a sustainable energy future. International collaboration, capacity building, and innovative solutions tailored to local needs will be key to overcoming these challenges.

5.6 Practical Implications

The findings of this study offer a strategic roadmap for Pakistan's manufacturing sector to leverage green hydrogen storage technologies effectively while addressing key challenges. The results indicate that **economic recession** and **political interference** emerged as the most critical challenges, emphasizing the need of **financial stability** and **regulatory consistency** as foundational steps for large-scale development. From an **economic standpoint**, industries can benefit from mechanisms like **debt-for-climate swaps** and dedicated green energy investment funds, which can alleviate financial strain while enabling infrastructure expansion (Losos et al., 2024). Government-backed financial guarantees and risk-sharing models, such as **Minimum Revenue Guarantees and Revenue Caps**, can encourage industrial participation (Biancardi et al., 2024). By fostering transparency, building institutional capacity, and enhancing stakeholder coordination, it is possible to mitigate the cascading effects of challenges and create a more resilient and sustainable energy storage system as confirmed by Lebedeva & Shkuropadska (2024) and Akinwale Omowumi Ishola et al., (2024). On the **technological front**, the results emphasize the importance of advancing storage technologies and modernizing infrastructure to improve operational efficiency. **R&D programs** for storage optimization and process automation is necessary. An automated energy monitoring and targeting system, compatible with ISO50001 and integrating SCADA and Soft-PLC technologies, can further optimize energy use and operational efficiency (Castro et al., 2013). **Regional implementation** strategies should be tailored by introducing **incentive packages**, localized infrastructure projects, and workforce capacity-building initiatives to ensure more balanced progress and optimize socio-economic benefits (Sarafinchan & Bilyk, 2022).

To address the pressing need for reducing global carbon emissions, the European Union (EU) has proposed the Carbon Border Adjustment Mechanism (CBAM) (Zhong & Pei, 2024). This policy aims to mitigate carbon leakage and promote fair competition by imposing import taxes or offering export subsidies based on the carbon footprint of goods originating from countries with less stringent carbon policies. CBAM is expected to raise product prices in high-emission sectors, prompting industries to adopt cleaner technologies (Shidiq et al., 2024).

The process to finalize the Carbon Border Adjustment Mechanism (CBAM) is almost complete. The European Commission's proposal includes key features like requiring importers to buy allowances tied to the EU’s carbon pricing system (ETS) and calculating taxes based on the exporter’s carbon emissions. It also plans to adjust for any carbon costs already paid by exporters in their own countries. Over the next ten years, free allowances will be gradually reduced and replaced by the CBAM. The funds collected through this mechanism will go into the EU budget to help tackle challenges from the COVID-19 pandemic and to support investments in green and digital technologies. CBAM will begin in October 2023 with a two-year transition phase, during which only reporting will be required. Full implementation, including the gradual phase-out of free allowances, is planned for the 2026–2034 period. This timeline ensures a structured rollout, allowing industries to adapt to the new requirements. This policy aims to reduce carbon emissions while encouraging a shift towards more sustainable practices (Bellora & Fontagné, 2023).

The legal impacts and risks of the Carbon Border Adjustment Mechanism (CBAM) will depend on the method used for its implementation. The European Commission has proposed four main options (European Commission, 2020a):

1. Introducing a carbon tax that applies to both imported and domestic goods.
2. Implementing a carbon customs duty or tax specifically on imports.
3. Extending the EU Emissions Trading System (ETS) to include imports.
4. Creating a separate system where importers must purchase carbon allowances at a price matching the EU's carbon market.

The choice among these approaches will influence how effective CBAM is, how it impacts trade, and whether it aligns with international regulations.

If implemented, CBAM could significantly reshape industrial practices, compelling industries to transition towards cleaner and more sustainable energy sources, such as green hydrogen, to remain competitive in global markets. By incentivizing such shifts, the policy could catalyze the adoption of green hydrogen storage, fostering innovation and reducing reliance on carbon-intensive processes. This aligns with the broader objective of decarbonizing industries and combating climate change effectively.

Green hydrogen storage could play a critical role in achieving these targets. The Paris Agreement is a legally binding international treaty on climate change. It was adopted by 196 Parties at the UN Climate Change Conference (COP21) in Paris, France, on December 12, 2015, and entered into force on November 4, 2016.Its main goal is to keep the global average temperature increase to well below 2°C above pre-industrial levels, with an aim to limit the increase to 1.5°C above pre-industrial levels. The agreement aims to strengthen nations’ ability to address the impacts of climate change and align financial flows with low greenhouse gas emissions and climate-resilient pathways. To achieve these goals, adequate financial resources must be mobilized, along with new technology frameworks and expanded capacity building, particularly for developing and vulnerable countries. The Paris Agreement requires all Parties to regularly report on their emissions and implementation activities, and conduct a global stock-take every five years to review collective progress and inform future individual actions (Abbass et al., 2022). It emphasizes that developed countries should take the lead in providing financial support to less developed and more vulnerable countries. For the first time, it also encourages voluntary contributions from other Parties.

The Framework for implementing the National Climate Change Policy for the period 2014-2030 aims to integrate climate-friendly policies into national and economic planning. Pakistan’s “Vision 2025” sets out a long-term strategic plan for sustainable development, emphasizing climate action as a key priority. To support these goals, the Climate Finance Unit (CFU) has been established to facilitate sustained implementation of Pakistan’s climate policy, its Nationally Determined Contributions (NDCs), and programs under the Global Environment Facility (GEF) and Green Climate Fund (GCF). Additionally, the Prime Minister launched the “Clean Green Pakistan Movement,” a nationwide initiative aimed at promoting environmentally friendly practices across all sectors. This movement aligns with Pakistan’s Vision 2025 and the Power Policy 2015, which seek to enhance access to affordable, reliable, sustainable, and modern energy, in line with the SDGs (H. Aslam et al., 2020). In October 2021, Oracle Power announced its Green Hydrogen project in the Jhimpir Wind Corridor in Sindh, Pakistan. In March 2022, Oracle Power established a joint venture (JV) with His Highness Shaikh Ahmed Dalmook Al Maktoum to expedite the development of the project. The company has acquired 7,000 acres (28.3 km²) of land in the wind corridor of Jhimpir, which features an annual wind power generation capacity exceeding 50,000 MW and average wind speeds of up to 8 m/s. It has received a Letter of Intent (LOI) from the government, allowing the production of 1.2 GW of hybrid power. The project aims to generate approximately 55,000 tonnes of high-purity green hydrogen or 275,000 tonnes of green ammonia annually. This will potentially involve 400 MW electrolyzers, 500 MW wind power, 800 MW solar power, and adequate battery storage (Oracle Power, 2024).

From 1947 to the 1980s, agriculture was a cornerstone of Pakistan's economy, contributing significantly to output, employment, and trade. The country's early economic progress, starting in the 1950s, was largely supported by the 1960 Indus River basin agreement with India, which facilitated the construction of the Tarbela Dam and other key irrigation projects (Spielman & Malik, 2017). Pakistan's economy has historically relied on agriculture as a cornerstone, contributing approximately 23.37% to the GDP and employing 37.4% of the labor force (Statista, 2023). However, this sector faces significant challenges due to climate change and the ongoing energy crisis. Energy shortages directly impact agricultural productivity, exacerbating the economic strain on a country where agriculture is integral to livelihoods and food security. This dependency underscores the critical need for sustainable energy solutions and climate resilience strategies to support the sector. Moreover, the fertilizer industry emerges as a key area for implementing green hydrogen technology. Fertilizer production, particularly ammonia, is highly energy-intensive and traditionally reliant on natural gas. Transitioning to green hydrogen could enhance sustainability and efficiency in this sector, reducing greenhouse gas emissions and supporting environmental conservation. The production cost of green ammonia can be competitive with gray ammonia, especially when electricity prices are low. For instance, at RMB 0.1/kWh, green ammonia production costs can drop to RMB 1,115/t (Yue et al., 2024).

Other industries, such as the cement and steel sectors, also contribute significantly to environmental pollution. The cement industry accounts for about 5.3% of the global economy and consumes approximately 13% of the total industrial energy (Prachi Patel, 2024). However, this sector remains reliant on fossil fuels despite efforts to decarbonize through renewable energy and carbon capture technologies. Similarly, the steel industry predominantly produces secondary steel, involving the recycling of scrap metal. While less energy-intensive than primary production, it still contributes to environmental degradation. Green hydrogen adoption in these industries is limited, with the fertilizer sector presenting the most viable opportunity for meaningful impact. The challenges facing Pakistan's agriculture and industrial sectors highlight the need for integrated strategies to address energy shortages and climate change. Investing in renewable energy, fostering collaboration among stakeholders, and leveraging technologies like green hydrogen are essential steps toward building a resilient and sustainable economy.

Pakistan's economy is struggling with high inflation, low growth, and financial losses in government-owned businesses. Heavy debt, rising costs of loan repayments, expensive essential goods, and repeated failed IMF bailouts have worsened the situation (Naz & Riaz, 2024). The commitments of foreign aid for Pakistan have now surpassed the $200 billion mark (Haque et al., 2024). While IMF programs have assisted Pakistan in achieving some of its short-term fiscal goals, they have also contributed to the decline in other economic indicators. These include rising inflation rates, reductions in social expenditures, and increased poverty levels (Ullah et al., 2024).Debt-related challenges are seen as significant challenges to the growth of clean energy programs. External debt can limit renewable energy consumption, while key factors like institutional quality, educational spending, banking development, and economic growth are crucial for promoting green energy initiatives (Sadiq et al., 2024).Debt-for-nature swap financing is a method used to address environmental challenges in developing countries. It involves converting part of a country’s foreign debt into funding for environmental conservation efforts, including projects like reforestation, habitat preservation, and wildlife protection (U. S. Ahmad et al., 2024). Strengthening domestic renewable energy markets and promoting international cooperation through initiatives such as debt-for-climate swaps could help ease the financial pressure on renewable energy investments. These efforts can provide additional resources and support for green energy projects, alleviating financial constraints and encouraging sustainable development.

Addressing ground-level business environment issues requires a multi-faceted approach aimed at simplifying regulatory procedures, reducing the time needed to obtain permits and licenses, and ensuring transparency to effectively tackle corruption. Additionally, improving the efficiency of customs and border clearance procedures is crucial for fostering a more seamless business operation. These efforts collectively aim to create a supportive and efficient environment where businesses can operate with reduced bureaucratic hurdles, increased transparency, and enhanced operational efficiency (Bibi et al., 2024).

To overcome the challenges associated with green hydrogen adoption, robust policy support is essential. Pakistan could look to international best practices for guidance, such as Germany's Renewable Energy Sources Act, which includes feed-in tariffs that support renewable energy projects, or Japan's Green Innovation Fund, which directly backs hydrogen technology development. The Australian Hydrogen Centre reports that utilizing existing gas infrastructure for hydrogen distribution can create significant economic value, support job creation, and enhance energy security, making it a viable model for regional development and green hydrogen adoption (Sharpe & Raman, 2024). By establishing similar hubs, Pakistan could develop centers of expertise and infrastructure, fostering investment and regional economic growth. Public-private partnerships also play a critical role in mobilizing the resources necessary for large-scale hydrogen projects, bridging the gap between government support and private sector innovation.

Suggested **implementation timeline** spans multiple phases, beginning with short-term goals (0-2 years) focused on establishing regulatory frameworks and initiating pilot projects, progressing through medium-term objectives (2-5 years) centered on scaling successful initiatives and expanding infrastructure networks, and culminating in long-term aims (5+ years) targeting full-scale implementation and operational optimization. Success metrics, represented by several key performance indicators, collectively assess the effectiveness and impact of the green hydrogen transition. These metrics encompass adoption rates, investment levels, safety performance, regional progress, and both economic and environmental outcomes.

5.7 Limitations

One limitation that became evident during the course of research is the lack of attention to the perception of sustainability within Pakistan's industries. While various challenges to the implementation of green hydrogen storage in Pakistan were identified, it should be initially address whether industries are genuinely prioritizing sustainability. In the context of Pakistan's economic struggles, where the primary focus is on survival, many stakeholders seem to perceive sustainability efforts, including carbon neutrality, as a luxury. This perception, particularly within industries, stems from the belief that Pakistan's emissions are relatively low, and thus, the country is not obliged to adopt sustainability practices to the same extent as developed nations. However, Pakistan, despite having relatively low per capita greenhouse gas (GHG) emissions—ranking 135th globally—faces high vulnerability to climate change, placing it 8th in global vulnerability rankings (Idris, 2024).This gap in research emerged after conducting interviews and analyzing the data, where it came to light that many participants were concerned more about immediate survival and profit rather than long-term environmental goals. The reluctance to focus on sustainability, especially in terms of carbon neutrality, is a critical aspect that needs to be considered. There is a disconnect between the need for environmental consciousness and the industry's immediate economic concerns, which could hinder the successful implementation of sustainable technologies like green hydrogen. This lack of prioritization of sustainability is a limitation in research that requires deeper exploration to fully understand the challenges and potential solutions for green hydrogen adoption in Pakistan. The issue is further compounded by the notion that the country's economic situation may not allow the luxury of focusing on global environmental concerns. The lack of awareness and willingness to prioritize sustainability among industries in Pakistan is a significant limitation when considering the adoption of sustainable technologies like green hydrogen.

Another notable limitation is the polarized perspectives observed between the private and government sectors regarding the challenges to green hydrogen storage in Pakistan. The private sector tends to adopt a more pessimistic view, emphasizing the difficulties and challenges posed by various challenges. This sector often assigns excessive weight to each perceived obstacle, reflecting a mindset that focuses heavily on the immediate risks and constraints. Conversely, the government sector holds a much more optimistic outlook, frequently underestimating or even overlooking the challenges, and instead focusing on the potential opportunities and benefits associated with green hydrogen adoption. This stark contrast in perspectives between the two sectors introduces a bias into the research, making it difficult to derive a balanced or comprehensive understanding of the real challenges and their impact. The presence of such extreme viewpoints suggests that the actual challenges may lie somewhere in between, and therefore require a more nuanced and integrated approach for effective policy formulation and decision-making. This limitation highlights the need for further investigation into the nuances and intermediate positions between these two extremes to develop a more accurate and balanced assessment of the challenges to green hydrogen storage in Pakistan.

A third limitation of this research is the lack of real-world application of green hydrogen in Pakistan. While hydrogen is used in various processes within the country, particularly in the industrial sector, there are currently no active green hydrogen projects. This absence of practical implementation means that much of the research relies on assumptions and theoretical frameworks, rather than actual case studies or real-world data. Consequently, the findings of this study may not fully reflect the challenges, opportunities, or dynamics that would arise when green hydrogen is actively adopted in Pakistan's context. The real-world situation could differ significantly from the theoretical assumptions made in this research, and further studies will be needed to validate these assumptions and better understand the practical feasibility and implications of green hydrogen adoption in Pakistan.

5.8 Conclusion

Green hydrogen is a growing field of research, primarily focused on supporting Affordable and Clean Energy (SDG 7) and Climate Action (SDG 13). Between 2016 and 2021, 50% of publications on this topic appeared in the top 10% of journals, reflecting the high quality of research and significant interest from leading academic publications (Raman et al., 2022). Pakistan’s energy system planning also needs to account for long-term sustainability, focusing on improving efficiency, minimizing losses, and ensuring energy access for all. The "energy trilemma" – balancing security, affordability, and sustainability – is central to the country's energy strategy (Reza et al., 2024; Vandenberg, 2024). Macro-scale energy systems models, which incorporate temporal and spatial factors, are valuable tools, ensuring that investments in the energy system align with both immediate needs and long-term sustainability goals (Cevallos & Urquizo, 2024; H. Zhang et al., 2024).

The adoption of green hydrogen storage is a pivotal step toward achieving decarbonization and contributing to sustainable development. By transitioning to green hydrogen storage, Pakistan can substantially reduce the carbon footprint of its manufacturing sector while improving energy security and reducing dependence on imported fossil fuels. The adoption of green hydrogen also aligns with broader national goals of socio-economic development, job creation, and fostering technological innovation. However, to realize these benefits, Pakistan must address several challenges related to economic viability, political stability, technological readiness, and social acceptance.

This study used ABM to comprehensively analyze these challenges and to identify potential strategies to overcome them, thus contributing to the sustainable transformation of the manufacturing sector in Pakistan. Green hydrogen storage represents an environmentally sound alternative to conventional fossil fuels, with the capability to enhance energy security, promote sustainable practices in industry, and support socio-economic development. With the implementation of appropriate policies, investments, and technological advancements, green hydrogen storage can lead Pakistan towards a cleaner, more resilient, and sustainable future.

5.9 Future Research

Future research in the context of green hydrogen adoption in Pakistan should focus on understanding the underlying mindset of practitioners, which could provide critical insights into why sustainability is often not a primary concern. A key area of exploration is to conduct qualitative studies that examine the cultural, economic, and social factors influencing decision-making within both the private and public sectors. This research should aim to identify historical and economic narratives that might prioritize short-term survival and profit over long-term environmental goals, thus hindering the integration of sustainability into industry practices.

Additionally, future studies should assess the perception of long-term versus short-term objectives within Pakistani industries. This involves examining how industries weigh immediate financial concerns against long-term environmental benefits, particularly in the context of green technologies like hydrogen. Understanding the costs and perceived benefits associated with green hydrogen implementation, along with the factors that influence these perceptions, could help shift industry practices toward a more sustainable future.

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