

THE EVOLVING JOURNEY OF GREEN HYDROGEN IN INDIA'S PROGRESS
TOWARDS NET-ZERO CARBON EMISSIONS

by

Shivprasad M. Laud

DISSERTATION

Presented to the Swiss School of Business and Management, Geneva

In Partial Fulfilment

Of the Requirements

For the Degree

DOCTOR OF BUSINESS ADMINISTRATION

SWISS SCHOOL OF BUSINESS AND MANAGEMENT GENEVA

MARCH, 2026

THE EVOLVING JOURNEY OF GREEN HYDROGEN IN INDIA'S PROGRESS
TOWARDS NET-ZERO CARBON EMISSIONS

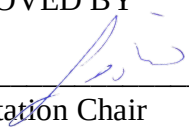
by

Shivprasad M. Laud

Supervised by

Dr. Anna Provodnikova

APPROVED BY



Dissertation Chair

RECEIVED/APPROVED BY:

Renee Goldstein Osmic

Admissions Director

Dedication

I dedicate this thesis to my beloved Parents, Late Madhao Krishnarao Laud and Late Rajani Madhao Laud, who have been a source of inspiration to me in my life.

Acknowledgements

I acknowledge the support of my wife Shibaani who has stood as a strong pillar behind me in encouraging me to complete this doctoral thesis in time.

ABSTRACT

THE EVOLVING JOURNEY OF GREEN HYDROGEN IN INDIA'S PROGRESS TOWARDS NET-ZERO CARBON EMISSIONS

Shivprasad M. Laud
2026

Dissertation Chair: <Chair's Name>
Co-Chair: <If applicable. Co-Chair's Name>

India is seeking a net-zero future, and Green Hydrogen (GH₂) has become one of the strategic pillars of decarbonising energy and industrial systems. Still, various systemic obstacles such as a lack of adoption preparedness, unclear policy effects, the infrastructural and investment gap, safety risks, and scalability issues remain a challenge to its mass adoption. The objective of the research is to evaluate the effect of Government policies, organisational preparedness, infrastructure facilitation, risk perception, scalability plans, and safety interventions in determining the evolving role and future of GH₂ in India.

A mixed-methods research design was employed. Data collection involved both structured surveys and interviews with respondents from Government authorities and Private organisations. In addition, a content analysis was performed on companies operating within the Green Hydrogen (GH₂) sector. This mixed-methods approach enabled a comprehensive understanding of the subject matter. Quantitative data were analysed using SPSS,

employing Spearman's correlation and logistic regression to explore relationships and predictive effects, while qualitative interview data were examined through thematic analysis.

Findings show that Government Policy effectiveness, clarity, and incentives had no statistically significant impact on adoption readiness ($p > 0.05$). However, technological readiness ($r = 0.435$, $p = 0.002$), financial readiness ($r = 0.542$, $p < 0.001$), and workforce readiness ($r = 0.467$, $p = 0.001$) were positively associated with industry collaboration. Financial support mechanisms significantly reduced risk perception ($r = 0.311$, $p = 0.028$), although infrastructure availability did not. Scalability showed strong associations with hydrogen storage capacity ($r = 0.633$, $p < 0.001$) and Government-Private Sector collaboration ($r = 0.659$, $p < 0.001$). Safety training showed significant predictive power in reducing safety incidents (Estimate = 0.811, $p = 0.019$), exceeding that of regulatory compliance alone.

Finally, the analysis suggests that a multi-pronged approach that includes investing in safety training, developing more storage infrastructure, increasing industry-policy alignment, and engaging more stakeholders is necessary. The results provide policymakers and industry leaders with guidelines that they can use to create a GH₂ ecosystem in India that is safer, scalable, and investor-friendly.

TABLE OF CONTENTS

List of Tables	ix
List of Figures	xi
List of Abbreviations.....	xv
CHAPTER I: INTRODUCTION	1
1.1 Introduction	1
1.2 Research Problem.....	22
1.3 Purpose of Research.....	23
1.4 Significance of the Study.....	24
1.5 Research Purpose and Questions	24
CHAPTER II: REVIEW OF LITERATURE	26
2.1 Introduction	26
2.2 The Green Hydrogen Economy in India.....	35
2.3 Need for Transition to Green Hydrogen	39
2.4 Challenges in Green Hydrogen Adoption	47
2.5 Role of Policy Initiatives in Accelerating Green Hydrogen Adoption.....	51
2.6 Public-Private Sector Contributions in Green Hydrogen Development.....	53
2.7 Renewable Energy and Green Hydrogen: Interdependencies	57
2.8 Socio-Economic and Environmental Benefits of Green Hydrogen.....	63
CHAPTER III: METHODOLOGY	69
3.1 Overview of the Research Problem	69
3.2 Operationalisation of Theoretical Constructs	70
3.3 Research Purpose and Questions	71
3.4 Research Design.....	72
3.5 Population and Sample	73
3.6 Participant Selection	73
3.7 Instrumentation.....	74
3.8 Data Collection Procedures	74
3.9 Data Analysis	76
3.10 Research Design Limitations	78
3.11 Conclusion.....	78
CHAPTER IV: RESULTS.....	80

4.1	Introduction	80
4.2	Installed Capacity and Ongoing Projects.....	80
4.3	Policy & Regulatory Measures	82
4.4	Cost Viability & Mobility Applications of Green Hydrogen in India	84
4.5	Findings of Company Analysis.....	84
4.6	Thematic Analysis of Green Hydrogen Stakeholder Perspectives	94
4.7	Findings of Respondents' Survey	98
4.8	Descriptive Analysis	161
4.9	Hypotheses Testing.....	163
CHAPTER V: DISCUSSION.....		173
5.1	Discussion of Results	173
5.2	Discussion of Research Question One (Effectiveness of Government Policies and Initiatives in Promoting Green Hydrogen)	174
5.3	Discussion of Research Question Two (Organisational Readiness for Green Hydrogen Adoption)	175
5.4	Discussion of Research Question Three (Infrastructure Requirements and Financial Measures by Producers, Banks, and Investors).....	176
5.5	Discussion of Research Question Four (Addressing the Challenge of Scalability and Hydrogen Storage)	177
5.6	Discussion of Research Question Five (Safety Measures for Hydrogen Handling, Storage, and Explosion Prevention)	178
CHAPTER VI: SUMMARY, IMPLICATIONS, AND RECOMMENDATIONS		181
6.1	Summary.....	181
6.2	Implications	182
6.3	Recommendations for Future Research.....	183
6.4	Conclusion	185
REFERENCES		188
APPENDIX: DATASET		210

LIST OF TABLES

Table 1.1: Global primary energy use projected from 1990 to 2040.	10
Table 1.2: Indian primary energy consumption (including renewables) projected from 2016–2040	11
Source: Author Generated.....	11
Table 1.3: Renewable energy usage in the BRIC nations plus the USA, expressed as a percentage, from 2015 to 2035.....	12
Table 1.4: Demand for electricity across several demand sectors.....	12
Table 1.5 Phased Approach	17
Table 3.1: Inclusion and Exclusion	73
Table 4.1: Selected Green Hydrogen Projects in India (Operational/Pilot)	82
Table 4.2: Per-km Fuel Cost Comparison.....	84
Table 4.3: JSW Energy	85
Table 4.4: Reliance Energy	86
Table 4.5: Adani Energy	88
Table 4.6: Greenko	89
Table 4.7: Hero Future Energies.....	91
Table 4.8: Industry Stakeholder Themes on Green Hydrogen Challenges and Strategies	95
Table 4.9: Institutional Stakeholder Themes on Policy, Infrastructure, and Investment.....	97
Table 4.10: Reliability Statistics.....	99
Table 4.11: Demographic Details.....	100
Table 4.12: Government Policies and Initiatives	108
Table 4.13: Readiness Level of Green Hydrogen	120
Table 4.14: Infrastructure & Investment Measures (for Green Hydrogen Producers, Banks, Private Equity, Venture Funds).....	130
Table 4.15: Scalability & Storage Challenges	141
Table 4.16: Safety Measures for Hydrogen Storage & Prevention of Explosions/Leakage.....	151
Table 4.17: Descriptive Statistics	162
Table 4.18: Model Fitting Summary for Factors Affecting Adoption Readiness	164

Table 4.19: Goodness-of-Fit Results for the Estimated Model	164
Table 4.20: Pseudo R-Square Statistics for Model Performance	165
Table 4.21: Parameter Estimates Reflecting Category Thresholds and Predictor Effects.....	165
Table 4.22: Spearman’s Correlation Matrix for Readiness Dimensions and Collaborative Outcomes.....	167
Table 4.23: Spearman’s Correlation Coefficients for Investment Risk Influencers	168
Table 4.24: Spearman’s Correlation Matrix for Scalability and Storage-Related Enablers.....	169
Table 4.25: Model Fitting Summary for Safety-Related Predictive Framework	170
Table 4.26: Goodness-of-Fit Results for Safety Measures Impact Model.....	170
Table 4.27: Pseudo R-Square Statistics for Safety-Oriented Predictive Model	171
Table 4.28: Parameter Estimates for Safety-Related Predictors and Response Thresholds.....	171

LIST OF FIGURES

Figure 1.1: Role of Green Hydrogen in a Net Zero Future.....	7
Figure 1.2: RE Capacity installed as of March 2024 (GW).....	13
Figure 1.3: Objectives of India's Green Hydrogen Mission.....	16
Figure 1.4: Share of Renewable Energy Sources in India's Energy Mix	20
Figure 4.1: Age	101
Figure 4.2: Gender.....	101
Figure 4.3: What is your highest level of education?	102
Figure 4.4: Which sector do you work in?	103
Figure 4.5: What is your current job title?	104
Figure 4.6: How many years of experience do you have in your industry?	105
Figure 4.7: Does your organisation have involvement in green hydrogen projects?	105
Figure 4.8: What is your organisation's primary role in the green hydrogen ecosystem?	106
Figure 4.9: Government policies effectively support the growth of Green Hydrogen.	109
Figure 4.10: Existing government policies are aligned with industry needs for Green Hydrogen.	110
Figure 4.11: The current regulatory framework for Green Hydrogen is clear and well-structured.	111
Figure 4.12: The regulatory approval process for Green Hydrogen projects is efficient and predictable.	112
Figure 4.13: The government provides adequate financial incentives to promote Green Hydrogen.	113
Figure 4.14: Subsidies and tax benefits are sufficient to encourage Green Hydrogen adoption.....	114
Figure 4.15: Bureaucratic processes help in the implementation of Green Hydrogen policies.	115
Figure 4.16: The existing policies need a clear roadmap for long-term Green Hydrogen development.	116
Figure 4.17: There is strong collaboration between the Government / Public Sector and the Private Sector in Green Hydrogen development.	117

Figure 4.18: Private sector companies receive adequate support from Government policies to scale Green Hydrogen initiatives.	118
Figure 4.19: Companies in India have access to the necessary technology for Green Hydrogen production.....	120
Figure 4.20: There is sufficient R&D investment in Green Hydrogen technologies	121
Figure 4.21: Investors are willing to fund Green Hydrogen-related initiatives in your sector.....	122
Figure 4.22: There is sufficient financial support from Banks and Financial institutions for Green Hydrogen projects.....	123
Figure 4.23: The organisation has a skilled workforce capable of handling Green Hydrogen technologies.....	124
Figure 4.24: Adequate training programs are available to develop expertise in Green Hydrogen technologies.	125
Figure 4.25: There is a strong commitment towards adopting Green Hydrogen solutions.	125
Figure 4.26: There is a clear roadmap in place for transitioning to Green Hydrogen-based operations.	126
Figure 4.27: There is strong industry-wide cooperation in India to advance Green Hydrogen adoption.	127
Figure 4.28: Partnerships and joint ventures are increasing to accelerate Green Hydrogen implementation.	128
Figure 4.29: The current infrastructure for Green Hydrogen production is adequate.	131
Figure 4.30: The existing Green Hydrogen infrastructure can support large-scale commercial adoption.	131
Figure 4.31: There are concrete plans to expand Green Hydrogen infrastructure.	132
Figure 4.32: Government and Private players are investing in large-scale hydrogen infrastructure projects.....	133
Figure 4.33: Private Equity and Venture Capital firms are actively funding Green Hydrogen startups and innovations.	134
Figure 4.34: Government incentives and subsidies play a crucial role in attracting Green	135
Figure 4.35: Investors perceive Green Hydrogen as a high-risk investment.....	136
Figure 4.36: Market uncertainty is not a significant barrier to securing Green Hydrogen investments.....	137

Figure 4.37: High initial capital costs are a major challenge for Green Hydrogen infrastructure expansion.	138
Figure 4.38: Land acquisition and approval processes affect the development of Green Hydrogen projects.	139
Figure 4.39: The current storage infrastructure is sufficient to meet the future demand for Green Hydrogen.	141
Figure 4.40: There is an urgent need to expand Green Hydrogen storage facilities to support large-scale adoption.	142
Figure 4.41: Organisation or industry has a clear strategy for scaling up Green Hydrogen production.	143
Figure 4.42: More investment is required in large-scale Green Hydrogen production and distribution facilities.	144
Figure 4.43: Transporting Green Hydrogen over long distances is currently inefficient and costly.	145
Figure 4.44: The development of Green Hydrogen transportation infrastructure is progressing at a satisfactory pace.	146
Figure 4.45: The demand for Green Hydrogen is growing significantly in domestic and international markets.	147
Figure 4.46: Policy and industrial mandates are playing a key role in increasing Green Hydrogen demand.	148
Figure 4.47: Government / Public Sector and Private sector collaboration is essential to scale up Green Hydrogen adoption.	149
Figure 4.48: Public-private partnerships (PPPs) are helping to overcome scalability challenges in the Green Hydrogen industry.	150
Figure 4.49: Organisations comply with all national and international safety regulations for Green Hydrogen storage.	152
Figure 4.50: Existing safety regulations for Green Hydrogen storage and handling are adequate and effective.	153
Figure 4.51: Well-defined emergency response plans are in place for Green Hydrogen leaks and explosions.	154
Figure 4.52: Green Hydrogen leak detection and response systems are effective in preventing major accidents.	155
Figure 4.53: Investments in hydrogen leak-proof storage systems have improved overall safety.	156
Figure 4.54: Infrastructure is equipped with advanced safety technologies for hydrogen storage.	157

Figure 4.55: Green Hydrogen safety awareness is a key part of your company policies and operational procedures.	158
Figure 4.56: There is a need for more specialised training programs on Green Hydrogen safety for all stakeholders.	159
Figure 4.57: Green Hydrogen-related safety incidents (such as leaks or explosions) are rare in the industry.	160
Figure 4.58: More stringent safety measures are required to address the risks of Green Hydrogen storage and transportation.	161

LIST OF ABBREVIATIONS

Abbreviation	Full Form
GH ₂	Green Hydrogen
NEP	National Energy Plan
CC	Climate Change
RE	Renewable Energy
NZEs	Net-Zero Emissions
CCUS	Carbon Capture, Utilisation, and Storage
TEC	Total Final Energy Consumption
CEA	Central Electricity Authority
NGHM	National Green Hydrogen Mission
PLI	Production-Linked Incentives
MTPA	Million Tonnes Per Annum
FEED	Front-End Engineering Design
ISTS	Inter-State Transmission System
ROE	Return on Equity
EPS	Earnings Per Share
ROCE	Return on Capital Employed
ROA	Return on Assets
HFE	Hero Future Energies
PPPs	Public-Private Partnerships
AHP	Analytical Hierarchy Process
ISM	Interpretive Structural Modelling
IFRM	Initial Fuzzy Reachability Matrix
SSIM	Structural Self-Interaction Matrix

BESS	Battery Energy Storage Systems
DARDLS	Dynamic Autoregressive Distributed Lag Simulations
HDI	Human Development Index
GHG	Greenhouse Gases
CO ₂	Carbon Dioxide
IETB	Institutional, Economic, Technological and Behavioural
SHIP	Strategic Hydrogen Innovation Partnership
IH2A	India Hydrogen Alliance
LCOE	Levelized Cost of Energy
HRES	Hybrid Renewable Energy Systems
MCDM	Multi-Criteria Decision-Making
SADC	Southern African Development Community

CHAPTER I: INTRODUCTION

1.1 Introduction

Natural gas, coal, and oil account for nearly a third of all greenhouse gas emissions worldwide, primarily due to the burning of fossil fuels for electricity production. More reliable and cleaner power is essential for improving the living standards of people. According to Von Zabeltitz (1994), India has ambitious plans for economic growth, which is driving up the Country's energy consumption. The economic development of a nation is largely reliant on its capacity to supply growing amounts of energy (Kumar, Kumar and Majid, 2019). The National Energy Plan (NEP) is a comprehensive 10-year strategy developed by the Ministry of Power (MoP) to supply energy throughout the nation. Furthermore, an additional strategy has been developed to ensure that residents are provided with power efficiently and affordably. According to the latest statistics from Worldometer, it was revealed that India is in third place with 6.99%, following China with 32.88% and the US with 12.6%. The delicate ecological balance of our planet is under jeopardy due to “Climate Change” (CC). A large number of nations have committed significant financial resources to international climate initiatives such as the Paris Agreement and the UN Framework Convention on Climate Change. As noted by Aggarwal (2017), these efforts aim to limit global warming to no more than 2 degrees Celsius. According to the World Energy Council (2013), global power demand is projected to reach its peak around the year 2030. Due to its position as a leading global coal-consuming Country with limited in-house deposits, India needs to import this costly fuel from outside sources. According to the International Energy Agency, 80.9% of global energy needs are fulfilled by fossil fuel-derived energy sources. According to a report published by The Economic Times, India’s coal imports rose by 7.7% to 268.24 million tonnes in FY24,

driven by softness in seaborne prices and the anticipated increase in power demand during the summer (The Economic Times, 2024). Urgently needed are novel approaches to electricity generation. A quick and global transition to “Renewable Energy” (RE) technology could lead us to the achievement of sustainable growth, and at the same time avoid catastrophic CC. The key to creating environmentally friendly power systems with decreased emissions involves RE (Kumar and Madlener, 2016). It is well-established that RE sources (RES) can reduce emissions and fulfil a significant amount of the Country's electrical demands. In recent years, the nation's energy supply has been trending towards more sustainable practices. One consequence of public awareness campaigns promoting energy efficiency is the increased use of RES. These include wind, waste, solar, biomass, and hydropower. RE's cheap prices and clear advantages are easy to see. According to PIB by 2030, India's renewable energy sector targets a total capacity of 500 GW, comprising 280 GW from solar power, 140 GW from wind power, 50 GW from biomass, and 70 GW from hydropower. Investors have committed to exceeding the lofty goals by more than 500 GW. In terms of contribution, the Indian Railways - 5 GW, private corporations 191 GW, international companies 58 GW, and the private sectors 18 GW (National Institute of Transforming India, 2022). According to recent forecasts, there will be more than 750 GW of solar power and 410 GW of wind power accessible in 2047 (Sholapurkar and Mahajan, 2015). To achieve the ambitious target of producing 175 GW of renewable energy by 2022, the Government needed to create approximately 330,000 new job opportunities and income streams. In addition, Harrison and Kostka (2014); Shukla, Sudhakar and Baredar (2017) mentioned that RE technology needs a mix of push rules, pull mechanisms, and focused activities to move forward faster. There are several possible paths toward energy and environmental conservation, such as technological development, suitable regulatory frameworks, and the efficient and quick utilisation of renewable resource reserves. Schmid

(2012) highlights the importance of expenditures on efficiency-enhancing research and development, tax incentives, and related measures. Consequently, strategies are outlined to boost funding for RES while simultaneously generating employment opportunities for technicians, contractors, and unskilled drivers (Khare, Nema, and Baredar 2013).

Many people are curious about hydrogen because it may be a sustainable fuel, and numerous countries aim to achieve zero emissions by 2050. Hydrogen has been proposed as a potential solution to the carbon footprint issue caused by industries such as transportation, heating, and heavy manufacturing. By 2050, the energy infrastructure must undergo a complete renovation using many technological options to achieve “Net-Zero Emissions” (NZE). The decarbonization of the global energy system requires improvements in energy efficiency, generation of electricity from RES, hydrogen (H₂) and fuels derived from hydrogen, changes in human behaviour, and carbon capture, utilisation, and storage (CCUS) (King, 2021). As its total final energy consumption (TFC) increases, hydrogen becomes increasingly crucial to the NZEs Scheme. A little under one percent of total fossil fuel consumption in 2020 came from hydrogen and hydrogen-based fuels. Their share of TFC is expected to rise from 2% in 2030 to 10% in 2050 (Dong et al., 2022; Ishaq & Dincer). However, the increase in demand is not enough to establish H₂ as an essential component in the decarbonization process. There has to be a dramatic improvement in the efficacy and carbon footprint of hydrogen production. For instance, in 2020, fossil fuels accounted for the vast majority (80%) of the 90 million tons of hydrogen produced, with the remaining share primarily derived from gases emitted by refining and petrochemical sectors. This production resulted in approximately 900 million tons of CO₂ emissions, an amount comparable to the combined emissions of countries such as the UK and Indonesia. Given India’s growing energy demand and hydrogen ambitions, addressing the carbon intensity of hydrogen production is critical for sustainable development (Pollitt and

Chyong, 2021; Slorach and Stamford, 2021). The NZE scenario would turn H₂ production into an unparalleled form. Around 70% of the world's hydrogen is expected to come from less CO₂-intensive systems, such as electrolysis or CCUS, by 2030, when worldwide hydrogen production exceeds 200 million tonnes (Mt). With less carbon-intensive technology, H₂ output is projected to surge to above 500 million tonnes (Mt) H₂ by 2050, with nearly full H₂ production. Bearing these objectives in mind, the predicted increases in electrolysis installed capacity are as follows: increased from 0.3 GW in 2018 to roughly 850 GW in 2030 and 3600 GW in 2050; and the quantity of CO₂ produced by hydrogen generation increased from 135 Mt in 2018 to 680 Mt in 2030 and 1800 Mt in 2050 (Yan *et al.*, 2020). By 2021–2050, H₂ and H₂-based fuels could reduce CO₂ emissions by 60 Gt, or 6.5% of the total, according to the NZEs Scenario, which accounts for rapid H₂ market expansion and the use of eco-friendly processing methods. Hydrogen fuel is particularly important for reducing emissions in businesses where direct power generation cannot be mandated, such as ships, heavy-duty road transport, aircraft, and heavy industries (especially chemical manufacturing and steel production). By facilitating seasonal grid storage and balancing the increasing shares of RE generation, hydrogen can make the power industry more flexible (French, 2020b; Schulthoff *et al.*, 2021).

The world's governments have come to a consensus that rapid action is necessary due to the vital role that emissions of GHG play in the current climate disaster. A major milestone in this regard was the Paris Climate Accord of 2015. The Paris Climate Accord, reached in 2015 by all participating nations, acknowledged the critical need to respond rapidly to the extraordinary climatic change brought about by emissions of GHG. The "Sustainable Development Goals" (SDGs) of the United Nations are greatly enhanced by the Paris Agreement, which aims to create a more equitable and environmentally friendly world. Accomplishing this objective will necessitate a mastery of resource extraction

techniques that do not jeopardise future generations' ability to live or contribute to their depletion (Ueckerdt *et al.*, 2021). To ensure a stable energy supply while reducing pollution from our current, cutting-edge, non-renewable power plants, we urgently require sustainable, scalable, and highly efficient energy sources. The majority of GHG emissions from many economic sectors, including power generation and transportation, are still caused by fossil fuels. In 1950, fossil fuels were responsible for 6 billion tonnes of CO₂ emissions worldwide. It had nearly quadrupled by 1990, reaching over 22 billion tonnes. Unprecedented political and economic prosperity, as well as greater civilisation and technical achievements, were all brought about by industrialisation in the nineteenth and twentieth centuries. Nevertheless, it was also the cause of widespread destruction of natural habitats and depletion of natural resource stocks (Martinez-Burgos *et al.*, 2019). The rate of emission growth has been steady, and the current annual emission level exceeds 34 billion tonnes (Ritchie, Roser and Rosado, 2020). The modern world could not function without energy and electricity. The methods used to produce it frequently endanger the continuity of our world.

The Paris Agreement of 2015 unites nations in their collective efforts to combat climate change (CC). Article 2.1 and 4.1 outline the Agreement's core objectives, which aim to mitigate the impacts of climate change by limiting the global temperature increase to well below 2°C above pre-industrial levels, with a concerted effort to restrict the rise to 1.5°C. These targets are intended to significantly reduce the risks and impacts associated with climate change (Rajamani and Werksman, 2018). As a result of its position as the source of more than three-quarters of all GHG emissions, the energy sector is well-positioned to lessen the impact of CC (Sokołowski, 2022). A complete paradigm shift in energy production and use is required if we are to achieve the NZE of CO₂ by 2050. While there is excellent cause for the increasing political consensus on the need to achieve NZE,

our current knowledge of the resources and technologies needed to achieve this goal is inadequate to support a global effort to achieve it by 2050. To achieve today's ambitious goals, an enormous amount of effort is needed, especially given the diverse situations among countries and their varying capabilities to implement the correct amendments. To mitigate the worst effects of global warming, both societies must undergo transformation, and growth must be sustainable. However, if trajectories considerably or entirely exceed 1.5 °C, more adaptation efforts, including critical adaptation, would be required to accommodate such a dramatic shift. Achieving the adaptation objectives outlined in the Paris Agreement and keeping global warming below its consequences will require more than the adaptation and mitigation pledges made by individual nations in recent years (van Soest, den Elzen and van Vuuren, 2021). To keep global warming below 1.5°C, a more comprehensive and rapid transformation of the world's energy, land, urban, and industrial systems is required, regardless of progress in individual countries (Kolb et al., 2021).

To meet the 1.5 °C target, it is necessary to have net zero CO₂ emissions globally by the middle of this century. Achieving NZE requires removing the same amount of carbon from the air as is lost in emissions. Fuhrman *et al.* (2023); Ampah *et al.* (2024) Carbon neutrality or net zero targets spanning 2040–2070 have been pledged by some nations, with more reportedly on the way. Research conducted by Ampah *et al.* (2023) and Wu *et al.* (2022) is mentioned. Achieving NZE, or carbon neutrality, requires cutting emissions through the use of RES.



Figure 1.1: Role of Green Hydrogen in a Net Zero Future

Source: Ampah *et al.* (2024)

Figure 1.1 offers a concise impression of the potential future contributions of GH₂ to the NZE. Consequently, hydrogen is vital for achieving the zero-energy transition by the year 2050. Global demand for hydrogen was around 90 MMT in 2020, with 80% of that amount being consumed as pure hydrogen and the remaining 20% being combined with carbon gases to produce steel and methanol. By 2050, in comparison with the year 2020, the need for hydrogen is projected to increase by about 500%, according to a net-zero scenario (Ampah *et al.*, 2024). To meet net-zero standards by the middle of the century, the production of GH₂, a by-product of renewable electrolysis, will need to increase significantly from its present 1% proportion.

The rapidly declining prices of renewable generation and energy storage have led to a growing consensus on the topic of how global power systems can decarbonise in the not-too-distant future. However, what about household heating, chemical fertiliser feedstocks, transportation fuel, and heating sources for metals and construction products?

In these areas, there is a widening gulf between proponents of hydrogen and electrification. According to their logic, both are essential to the emerging green economy and can help spur substantial economic growth. The potential of hydrogen, a clean-burning gas, to contribute to the decrease of emissions of GHG has been promoted for more than half a century. The concept of a "hydrogen economy" is currently trending upwards in popularity, but it will not solve all of society's problems by itself (Whitehead *et al.*, 2023). Amid the present excitement surrounding the subject, there has been scant consideration of when hydrogen technology can actually become economically feasible or how best to strategically use hydrogen to swiftly reduce global emissions. Considering the multitude of stakeholders and the various government agencies engaged in possible hydrogen applications, it is imperative to adopt a comprehensive approach to achieve strategic and efficient outcomes. Talking to larger groups of people, including businesses, academics, and members of the community, is also crucial. Countries need to be smart with their hydrogen usage if they don't want to encourage a global economy that uses a lot of energy for things that don't make financial or ecological sense.

1.1.1 The Role of Green Hydrogen in Decarbonization

Wind power's unsubsidised levelized cost fell by 70% between 2009 and 2019, while that of solar power fell by 89% in the same time period. The ever-changing renewable energy (RE) market is transforming the economics of electrical power generation (Mitchell, 2016). Coal is being replaced as the principal energy source by intermittent power from wind and solar, supplemented by rapidly dispatchable power from natural gas. At the same time, game-changing innovations in energy storage are driving long-established paradigm shifts across multiple sectors, including energy efficiency, chemical processing, power distribution, mining, manufacturing, agriculture, transportation, street lighting, consumer goods, and residential as well as commercial construction (Song, 2006;

Fumagalli, 2016; Needell *et al.*, 2016; Asensio and Delmas, 2017; Hittinger, 2017; Jamasb, 2017). Collectively, the various technical developments are reducing emissions of carbon dioxide. For example, between 2017 and 2040, the predicted decline in coal usage in Europe is 87%. A global peak in carbon emissions from power generation is expected in the 2020s. Similarly, impressive developments in CO₂ collection are necessary for the total eradication of carbon emissions from industrial sources. As things stand, monetary disincentives must be put in place before large-scale CO₂ capture can be considered feasible. Disincentives that are consistent across locations are limited, nevertheless, by political differences (Cl  men  on, 2016). The 2015 Paris Climate Accord goals will gain better viability when CO₂ capture technologies function harmoniously with existing economic dynamics. The management of CO₂ functions as a waste product that carries high economic expenses from storage and delivery costs. The present advancement of CO₂ capture technology operates under the expectation that ready geologic storage locations will accept this captured CO₂. The existing scenario dictates that CO₂ capture technologies will mainly serve to store captured CO₂, not to convert it into usable forms. The implementation of large-scale CO₂ capture will occur naturally through economic forces when new technology makes CO₂ valuable. A breakthrough in CO₂ conversion technologies would eliminate the necessity of international political agreements to pursue CO₂ solutions. Research into electrolysis of water shows progress towards converting it into H₂ and O₂ gases (Bertuccioli *et al.*, 2014; Tymoczko *et al.*, 2016) and alternative power sources; it is necessary to reconsider decarbonised process layouts. During photosynthesis, CO₂ is an essential component. Another product of breathing is carbon dioxide. Ostadi *et al.* (2020) report that CO₂ is converted into glucose and oxygen during photosynthesis. Vegetation stores carbohydrates, which are then used by many metabolic processes in both plants and animals. When atmospheric CO₂ levels rise unchecked, homeostasis (or

physiological balance) kicks in and stops the natural carbon cycle from regulating them. Rather, carbon is retained in some compacted forms, including biological stuff, carbonate rocks, and hydrocarbons. Carbon plays the part of a cyclic energy carrier in this context.

1.1.2 Projected Primary Energy Consumption in India

Power usage is proportionate to the number of people living in a nation and the rate at which that population is expanding. According to the previous statistics, with a total of 1,368,000,000 people in January 2019, India surpassed all but one country in terms of population. There is a 1.18% annual growth rate for this group, which accounts for approximately 17.74% of the world's inhabitants. A total of 1.512, 1.605, and 1.658 billion people will be residing in the nation by the year 2020. The corresponding years for these forecasts are 2020, 2030, 2040, and 2050. India boosts its total world population, with some Indian States having a total population that rivals that of other nations (Kumar and Majid, 2020).

Region	1990	1995	2000	2005	2010	2016	2020	2025	2030	2035	2040	Change (1990- 2016)	Change (2016- 2040)
Africa	222	244	274	327	389	440	509	603	710	840	1002	2.7	3.5
Brazil	126	158	188	211	268	298	330	378	419	451	477	3.4	2
China	683	889	1008	1800	2491	3053	3387	3753	4017	4207	4319	5.9	1.5
EU	1672	1661	1732	1819	1754	1642	1667	1623	1570	1513	1460	-0.1	-0.5
India	195	251	316	394	537	724	880	1118	1365	1624	1921	5.2	4.2
Middle East	264	351	423	565	734	895	980	1085	1189	1287	1382	4.8	1.8
Russia	865	662	620	647	673	674	711	720	723	722	716	-1	0.3
United States	1966	2119	2310	2349	2284	2273	2334	2344	2341	2325	2299	0.6	0

Table 1.1: Global primary energy use projected from 1990 to 2040.

Source: Petroleum (2018)

By 2040, India will have the quickest increase in energy consumption of any major country, with coal taking care of the mainstream of this need and RE coming in a far second. After gas and oil, renewables surpassed them as the country's second-largest generator of electricity by 2020. Table 1.2 shows that at a yearly growth rate of 12%, RE demand in India will increase from 17 Mtoe in 2016 to 256 Mtoe in 2040 (Rajesh and Majid, 2020).

Level (Mtoe)	1990	1995	2000	2005	2010	2016	2020	2025	2030	2035	2040	Change (1990-2016)	Change (2016-2040)
Total	195	251	316	394	537	724	880	1118	1365	1624	1921	5.2	4.2
Oil (Mb/dl)	58	75	106	122	155	212	251	308	359	419	485	5.1	3.5
Gas (Bcf/dl)	11	17	24	32	54	45	57	72	89	106	128	5.6	4.5
Coal	110	140	164	211	290	412	485	593	710	824	955	5.2	3.6
Nuclear	1	2	4	5	9	11	16	11	27	35	44	7.1	7
Hydro	15	17	17	22	25	29	36	43	47	50	52	2.6	2.5
Renewables	0	0	1	2	7	17	41	86	133	191	256	35.1	12

Table 1.2: Indian primary energy consumption (including renewables) projected from 2016–2040

Source: Rajesh and Majid (2020)

How renewable energy sources contribute to the energy demand in India

Despite India's impressive economic progress, energy remains a limited commodity. There has to be an increase in energy sources to meet the skyrocketing demand caused by India's booming economy. This nation is also grappling with the issue of sustainable development due to environmental degradation and population expansion. Future predictions indicate that the power supply-demand disparity will widen (Arto *et al.*, 2016).

In 2021 and 2022, the Central Electricity Authority (CEA) of India projects a highest electrical demand of 298 GW and an overall electrical energy demand of at least

1,915,000 TWh, as stated in the Load Generation and Balance Report (2016-2017). Rising incomes and urbanisation are driving up the demand for electrical appliances, which in turn increases the demand for power in the residential sector.

Country	2016	2040
India	2	13
China	3	18
United States	5	17
Russia	0	2
Brazil	13	24

Table 1.3: Renewable energy usage in the BRIC nations plus the USA, expressed as a percentage, from 2015 to 2035

Source: 2017 BP Energy Outlook

Industrial demand for power is being propelled by the proliferation of capital goods, transportation, construction, and infrastructure-related material needs. The agricultural sector's increasing reliance on machinery and the widespread adoption of irrigation using groundwater are driving up the demand for pumping and tractors, and by extension, substantial consumption of diesel and energy (Irena, 2017). The other businesses in Table 1.4 would see a substantial change in their electricity usage.

Sector	2012	2022	2030	2047
Industry	336	494	703	1366
Residential	175	480	842	1840
Commercial	86	142	238	771
Agriculture	136	245	336	501
Others	29	71	121	233
Total	762	1433	2239	4712

Table 1.4: Demand for electricity across several demand sectors.

Source: IRENA (2017)

1.1.3 India's Progress in Renewable Energy

Current Status

According to the “REN21 Renewables 2022 Global Status Report”, India ranks fourth for wind power capacity, fifth for solar power capacity, and sixth for RE installed capacity (including big hydro), in that order. With the support of COP26, the nation has promised to increase its RE output to 500 GW by 2030 (Pal, 2023). India's **Panchamrit** Plan represents the world's largest renewable energy (RE) expansion plan. Over the past nine years, India has achieved a 396% increase in its installed non-fossil fuel capacity.

India at the Top

- Ranked 4th in the world for the addition of total renewable power capacity.
- Ranked 4th for wind power capacity and
- Ranked 5th in the world for solar power capacity.
- The thirteenth IRENA Assembly was presided over by India.

A total of 190.57 GW of installed capacity is attributable to RES as of March 2024, and this includes massive hydropower. The RE capacity that has been installed is as follows:

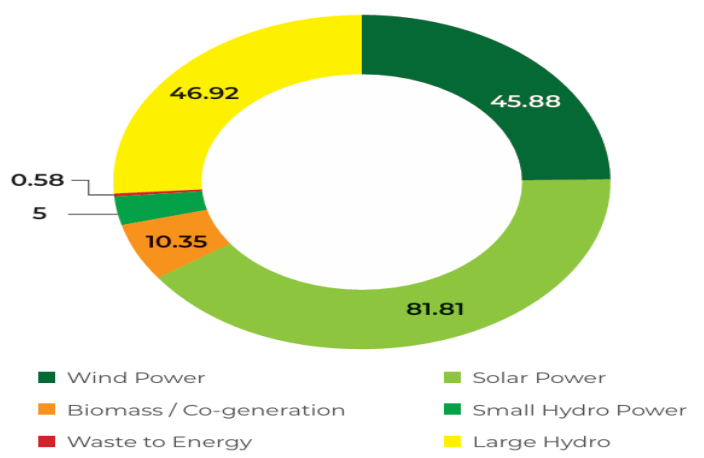


Figure 1.2: RE Capacity installed as of March 2024 (GW)

Source: (Approach, 2024)

Hydrogen, when created from low-carbon emitting sources, is a flexible energy source that can help decarbonise the world economy. According to Dey et al. (2022), Hydrogen is being considered as a potential feedstock and fuel by the Indian Government. This chapter aims to shed light on the global hydrogen ecosystem, talking about its main obstacles and offering suggestions for India to overcome them.

Why is India betting big on hydrogen?

- **Energy security:** As a result of the worldwide pandemic, countries have learned to diversify their energy consumption and geographic availability. Fuel price volatility is a direct result of the oil and gas market's ebb and flow, which has thrown off the supply-demand relationship. India and other developing nations must find a way to improve their energy security (Sheth, 2023).
- **Emission targets:** Third globally, India is responsible for approximately 7% of CO₂ emissions, behind only China and the US. The original goal of reducing emissions intensity by 33% to 35% was altered to 45% by 2030 as part of the Paris Agreement (Sheth, 2023).
- **Economic dependencies & balance of trade:** With an 80% reliance on imports, India ranks third among the world's top crude oil importers. Further impacting India's trade deficit is the Country's reliance on imports for 54% of its natural gas and 24% of its coal needs. The oil bill for India in FY19 was around US\$111.9 billion, whereas in FY20 it was around US\$101.4 billion (Shrivastava and Sharan, 2024; Thekkethil *et al.*, 2024).
- **Energy Subsidies:** Adding to the exorbitant cost of imported fuel, India spends almost US\$30 billion annually on energy subsidies for Oil & Gas (O&G), Coal, Transmission & Distribution, RE, and Electric Vehicles. A portion of these

subsidies can go towards fostering an ecology that runs on Hydrogen (Ministry of New and Renewable Energy, 2024b).

India's Potential as a World Leader in Green Hydrogen

Decarbonising several industrial sectors such as fertiliser, steel, refinery, petrochemicals, and mobility, utilising GH₂, it is far more feasible to reduce carbon emissions and attain energy independence all at once. India is projected to reduce its dependency on fossil fuel imports and eliminate fossil fuel imports totalling INR 1 trillion (US\$12.03 billion) by 2030 when its GH production capacity reaches 5 MMTPA. India could soon overtake China as the top global producer of GH. In addition to satisfying its own power needs, India aspires to join the global market as a supplier of GH electricity (Ministry of New and Renewable Energy, 2024b).

When it comes to the dream of India to become a global leader, the following are the primary factors:

1. Renewable power sources that are both plentiful and affordable
2. Legislative Backing
3. The stability of the grid
4. Ports and the coastline
5. Competence in Engineering, Purchasing, and Construction

1.1.4 India's Green Hydrogen Mission

The Indian Government recently implemented the “National GH₂ Mission (NGHM)”, an innovative energy transformation initiative, to decrease the dependence of the Nation on fossil fuel supply (Approach, 2024). Indian GH and its associated products will one day be a worldwide powerhouse. India aspires to achieve NZE and energy independence, and the Mission would help decarbonise the Country's efforts in that direction. So far, the production of electrolyzers (as part of the Make in India Initiative)

and GH has been advanced through several production-linked incentives (PLI) programs. The contracts for the establishment of electrolyser manufacture (totalling 1500 MW) and the production of GH (totalling 412 thousand Metric tonnes) were granted to a total of 10 businesses in January 2024, respectively. To attract businesses, various pilot projects in the shipping, steel, and mobility sectors have been publicised.



Figure 1.3: Objectives of India's Green Hydrogen Mission

Source: Approach (2024)

India plans to achieve Net Zero by the year 2070 and energy independence by the year 2047. The Indian Government has acknowledged GH's essential role in helping the Country reach its objective and fulfil its commitment. The abundance of RE resources in India allows the Country to produce GH for export. India presently spends more than USD 90 billion annually on energy imports, which accounts for more than 40% of its basic energy needs. Imported fossil fuels are crucial to key industries like transportation and manufacturing (MNRE, 2023). Some major economies have announced hydrogen policies as part of their more extensive efforts to address CC and promote RE.

Following the NGHM's lead, we intend to establish a GH ecosystem and initiate a concerted effort to take advantage of opportunities and circumvent challenges in this new sector (Pandey and Kumari, 2023). To launch the NGHM, the Union Cabinet gave its

approval on January 4, 2023. The Mission is set to begin with an initial expenditure of Rs. 19,744 crore. Out of this, ₹17,490 crores will go towards the SIGHT program and ₹1,466 crores will be distributed among pilot projects. Between 2029-30 and 2025-26, ₹455 crores will be used for low-carbon steel projects, ₹496 crores for mobility projects, and ₹115 crores for shipping projects. The budget includes ₹400 crore for Hubs and other projects until 2025–26, ₹400 crore for R&D, and ₹388 crore for the rest of the Mission.

The Scheme's implementation guidelines have been formulated by MNRE. The following are the anticipated results of the Mission by the year 2030:

1. Establishing an annual capacity for the production of GH equal to or greater than 5 MMT
2. A total of more than eight lakh crores of rupees in total investments
3. More than six lakh jobs would have been created.
4. A decrease in fossil fuel imports exceeding one lakh crore rupees
5. Reducing yearly emissions of greenhouse gases by approximately 50 MMT

Phase	Timeframe	Key Focus Areas
Phase I	2022-23 to 2025-26	Demand creation, domestic electrolyser production, pilot projects (steel, mobility, shipping), and regulatory setup.
Phase II	2026-27 to 2029-30	Cost competitiveness, commercial projects (steel, mobility, shipping), pilots (railways, aviation), R&D scaling.

Table 1.5 Phased Approach

Source: Author Generated

Integrated Mission Strategy

The Mission's overarching coordination and execution will be handled by the “Ministry of New and RE” (MNRE). With help of the Mission Secretariat at MNRE,

initiatives will be developed to incentivise the production, consumption, and export of GH and its byproducts through various financial schemes. The Ministry is responsible for coordinating the planned rollout of RE and GH capabilities, providing funding for pilot and research and development projects, increasing capacity, and promoting international cooperation. As part of its overall purpose, the Ministry will work closely with other public and private organisations to effectively grow the Country's GH ecosystem. To accomplish the Mission's goals, all relevant Central and State Government departments, agencies, and institutions will work together in a concentrated and coordinated effort (Pandey and Kumari, 2023).

Mission Components

Coordinated activities across several sectors are necessary to achieve the Mission's objectives.

As a result, the Mission's strategy includes interventions for:

- (i) Creating demand by making Indian-produced GH competitive for both domestic and export markets.
- (ii) using an incentive framework to handle supply-side limitations, and
- (iii) creating an ecosystem that facilitates growth and expansion (Pandey and Kumari, 2023).

1.1.5 GH₂ and Energy mix: Indian scenario

India ranks among the world's largest crude oil importers, sourcing approximately 85–88% of its oil requirements from overseas, with Russia alone accounting for around 35–39% of total imports (Raj, Lakhina, and Stranger, 2022). Furthermore, 54% of India's natural gas and 24% of its coal come from outside sources (Raj, Lakhina and Stranger, 2022). Energy imports cost India more than \$160 billion a year, and without RE alternatives, that number is expected to quadruple in the next fifteen years. Also, according

to Raj et al. (2022) India spends almost \$30 billion a year on energy subsidies for coal, RE, oil and gas (O&G), gearbox and distribution, and electric vehicles. As part of its plans to achieve energy independence by 2047 and NZE by 2070, India has projected that its annual energy consumption in the year 2070 will range from 18,900 to 22,300 TWh to 31,275 TWh. According to Bhattacharyya et al. (2022), the adoption of a Panchamrit action plan aims to expedite climate action and achieve a Green transformation (Goel, 2024). While maintaining economic growth, India is concentrating on decarbonising several industries to achieve its net-zero goal (Sambasivam and Balachandra, 2023). The nation has made great progress in the past ten years in incorporating more “Renewable Energy Sources” (RES) into its electrical industry (Balasubramanian and Balachandra, 2021b). After reaching 305 GW in 2015-16, India's installed power capacity has now increased to almost 442 GW. Power generation in India is dominated by coal, accounting for 48% (211 GW), with RES making for 32% (144 GW). As represented in Figure 1.4, the remaining portion is made up of hydropower at 11% (47 GW), gas at 6% (25 GW), and nuclear power at 2% (8 GW). At the same time, the share of installed capacity attributable to RES (including big hydro) rose from 89 GW to 191 GW. There are two main sources of RE in India: solar (57%, or 82 GW) and wind (32%, or 46 GW). As shown in Figure 1.4, the remaining individuals contribute little parts. The installation of 500 GW of renewable electricity capacity by 2030 is one of India's short-term goals. As a percentage of overall electricity generation, RE accounted for 16% in 2015–16. Balasubramanian and Balachandra (2021a) and rose to 23 percent in 2023–2024 (Ministry of Power, 2015). Additionally, by 2030, India wants to generate 50% of its electricity from RES (Balasubramanian and Balachandra, 2022). Solar and wind power, the two most common RES, are helping India speed up its energy transformation. In addition to targeting 30 GW of offshore wind power, India intends to construct 50 solar parks by 2030, with a total capacity of 37.49 GW. Wind

power reached 27 GW in 2015–16, while solar power reached 7 GW. Since then, it has grown to 46 GW and 82 GW (Ministry of Power, 2015). Accordingly, solar and wind power contributed 1% and 3% of total generation in 2015–16, respectively, and now account for 6% and 5% of total generation (Ministry of Power, 2015). Indian officials have set a goal of having 47.2 GW of battery storage capacity and 26.7 GW of pumped storage available by the year 2032.

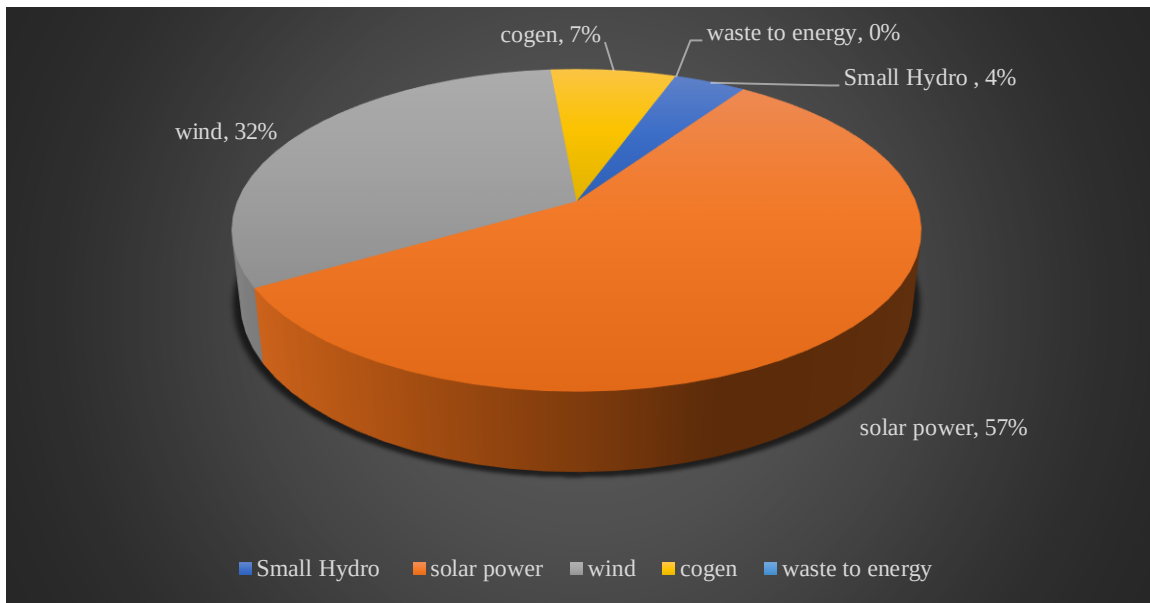


Figure 1.4: Share of Renewable Energy Sources in India's Energy Mix

Source: Ministry of Statistics and Programme Implementation (2024)

According to Guan et al. (2023), an important part of India's net-zero economy and sustainable development goals (Gupta *et al.*, 2024) is H₂ energy. The current GH₂ use in India is between 5 and 7 MMTPA, of which about 3 MMTPA is used as fuel by oil refineries for desulfurization and for processing into valuable end-products (Sambasivam and Sarma, 2024). The chlor-alkali and chemical industries use the remaining portions of approximately 2.5 MMTPA for ammonia production as fertiliser output, together with the ammonia production process (Sambasivam and Sarma, 2024). India will require 12 MMTPA of H₂ consumption by 2030, according to projections made by Sambasivam and

Sarma (2024), and this development is forecast to reduce annual fossil fuel importations by \$12 billion by that year (Raj, Lakhina and Stranger, 2022). In 2022, during the 75th-anniversary festivities, the Prime Minister of India unveiled the National Green Hydrogen Mission, a crucial step on the road to Net Zero Emissions for the Country.

H₂ types according to extraction techniques, as determined by India's NGHM (Sambasivam and Sarma, 2024) are:

- **Grey H₂**: It can be made by gasifying coal or lignite, which leaves behind brown or black residue, as an alternative to steam methane reformation, which turns methane and natural gas into grey gas. Carbon is an important component in most of these processes. **Blue H₂**: Its production involves reducing carbon emissions through the use of CCS or CCU technologies in conjunction with natural gas or coal gasification.
- **GH₂**: It is made by electrolysis using water using electricity that is generated by RES. i.e. a higher percentage of RE in the fuel mix for power plants results in "greener" hydrogen, which in turn increases the carbon intensity, which is directly proportional to the energy source's carbon neutrality. To clarify what is meant by "green" in GH₂, the MNRE of India published the GH₂ Standard for the Country in August 2023 and as per (Sambasivam and Sarma, 2024):
 - The maximum allowable level of carbon emissions during the production of GH₂ is from sustainable sources. It includes both routes that rely on biomass and those that use electrolysis.
 - The standard for GH₂ has been set at 2 kg CO₂ equivalent per kg of hydrogen gas formed, and this figure includes all processes from well to gate, such as electrolysis, drying, gas purification, and compression.

- The central agency in charge will be the Ministry of Power's Bureau of Energy Efficiency.

1.2 Research Problem

With the ambitious aim of achieving net-zero emissions by 2070, GH is rapidly becoming an integral component of India's plan to transform its energy landscape. A sustainable alternative to fossil fuels, GH is made by electrolysing water with RES. Several sectors can make use of it, including transportation, manufacturing, and power generation. There are a lot of moving parts when it comes to GH₂'s incorporation into India's energy grid, so it needs to be thoroughly investigated (Singh, 2024). The high energy needed to produce GH is a major cause for concern. The NGHM has set GH production targets of five million metric tonnes by 2030, which will necessitate an extra 125 GW of RE capacity. In addition, by 2030, India aims to have installed 500 GW of RE as part of its Nationally Determined Contributions (NDCs). That objective is expanded upon by this increment. To achieve these ambitious targets, renewable energy deployment must surge, particularly because India's solar and wind capacity will increase by just 15 GW in 2023 (Koshy, 2023).

Electrolysers also present possible environmental hazards due to their operational dynamics. Since electrolysers run continuously round the clock, it may be necessary to use power from the traditional grid, which is mainly composed of coal, particularly during the night when solar power isn't available. This dependence could unintentionally lead to higher carbon emissions, which would defeat the purpose of GH₂ as it helps the environment. Making sure that electrolysers can only be fuelled by renewable sources is crucial for the long-term viability of GH₂ production (Harichandan, Kar, and Rai, 2023).

Another key difficulty is the economic viability of GH₂. An important aspect determining GH₂'s viability compared to fossil fuels is the cost of electrolyser technology as well as renewable electricity. According to research, GH₂ can become more

economically viable as a result of improvements in electrolyser technology and economies of scale, which can reduce costs significantly. However, specific governmental actions, such as subsidies and incentives for the production and utilisation of GH₂, are necessary to achieve cost parity with conventional fuels (Madheswaran *et al.*, 2024). The shift to an environmentally friendly hydrogen economy can't happen without strong policy frameworks. Some stakeholders, including government ministries, research institutes, and industry participants, will need to work together for the NGHM's 2021 debut to be a success in promoting GH₂. Supporting the broad adoption of GH₂ technology requires clear legislative rules, infrastructural development, and funding mechanisms.

Furthermore, the environmental impact of hydrogen emissions themselves warrants attention. Hydrogen can act as an indirect greenhouse gas by influencing atmospheric chemistry and affecting the concentrations of other climate-related gases. To guarantee that the deployment of GH₂ positively impacts climate targets, it is important to address hydrogen emissions through strong monitoring and mitigation techniques. In conclusion, while GH₂ holds significant promise for aiding India's journey towards NZE, its integration into the energy system involves complex challenges related to energy infrastructure, environmental sustainability, economic viability, and policy implementation. For India's decarbonization efforts to fully benefit from GH₂, a comprehensive strategy that includes technological advancement, strategic policymaking, and environmental protection is necessary.

1.3 Purpose of Research

The Motive of this work is to assess how GH₂ can help India achieve NZE by 2070, focusing on its commercialisation challenges and strategic adoption pathways. It seeks to analyse barriers such as increased production costs, inadequate infrastructure, regulatory gaps, and stakeholder awareness while exploring policy effectiveness, industry readiness,

and financial sustainability. By combining literature reviews, policy analysis, and stakeholder surveys, the study will provide actionable recommendations to enhance GH₂ integration into India's energy and industrial sectors. The findings will contribute to informed decision-making, supporting India's sustainability goals and aligning with global best practices for a clean energy future.

1.4 Significance of the Study

This Research is significant for India's energy transition since it looks at the potential and risks of adopting GH₂. GH₂ has the potential to significantly decrease India's environmental influence and improve energy stability by decarbonising sectors like steel, transportation, and electricity that are notoriously challenging to control. The study provides policymakers with evidence-based insights to refine the NGHM, ensuring effective incentives and infrastructure development. For industries, it identifies investment risks and scalability strategies, fostering innovation and competitiveness. Academically, it enriches the discourse on sustainable energy transitions, while globally, it contributes to best practices for emerging economies pursuing net-zero goals.

1.5 Research Purpose and Questions

This research aims to assess the evolving role of GH₂ in India's progress towards Net Zero Carbon (NZC) emissions by analysing the challenges, opportunities, and strategic enablers for its large-scale uptake. This research intends to fill the existing gaps and barriers to policy development, industry adoption, and knowledge advancement towards the GH₂ ecosystem. The specific objectives include:

- Reviewing available literature
- Reviewing information on relevant websites of the Government of India's Ministries and Niti Aayog,

- Reviewing published Reports of a few Private Sector and Public Sector companies that have invested in the production of Green Hydrogen.
- Survey/Interviews of important stakeholders such as Policymakers, Experts, and Senior Leaders of Private and Public Companies to understand their perspective on:
 - Are Government's Policies and Initiatives effective enough in the area of Green Hydrogen?
 - What is the Readiness level of these companies?
 - What is the level of infrastructure required and measures being taken by Producers of Green Hydrogen, Banks and Finance Sector companies and Private Equity players, Venture Funds?
 - How is the Challenge of Scalability being addressed including Storage of Green Hydrogen?
 - What Safety measures are being implemented for prevention of explosions and leakage as Hydrogen is a highly volatile and inflammable?

CHAPTER II: REVIEW OF LITERATURE

2.1 Introduction

2.1.1 Overview of Green Hydrogen in India's Energy Transition

Rahul Tongia & Utkarsh Patel (2024) examined the costs and benefits of GH₂ production and consumption in India up until 2030. The goal of GH₂ is to reduce carbon emissions from "hard-to-abate" sectors, such as fertiliser and steel production, as well as certain transportation end-uses, including shipping and long-distance road freight. GH₂ is a new technology that is gaining momentum worldwide. By 2030, India aims to raise its domestic production of this energy from a few kilo-tonnes to five million tonnes per annum (Mtpa). Presently, steam reforming natural gas produces around 6 Mtpa of hydrogen, which is used mostly in fertiliser manufacture and oil refining in India. This hydrogen is made by burning fossil fuels. Although the price of GH₂ is predicted to fall from its present range of \$4–\$6 per kilogram in the next years, it is highly improbable that it will reach the often-stated goal of \$1 per kilogram by 2030 in India. In 2030, the input cost of RE for GH₂ generation would be at least \$1.4/kg (even after accounting for rupee depreciation), making up almost two-thirds of the overall production cost. This estimate is based on forward-looking estimates about electrolyser efficiency. The expenses associated with the electrolyser, its operation and maintenance and the cost of supplying pure water are additional charges. A reduction in the total cost to less than \$2/kg may be possible with the support of incentives offered by the Indian Government's National GH₂ Mission (NGHM) which includes capital incentives of up to 0.55 \$/kg for GH₂ generation and a suspension of interstate RE transmission rates.

According to Gupta, Kumar, and Kumar (2024), as a carbon-neutral fuel, GH₂ is essential in the fight against CC because of its ability to lower atmospheric concentrations

of greenhouse gases. It has enormous promise in renewable energy (RE)-rich Asian economies, but manufacturing has not yet begun due to issues with safety standards, available resources, appropriate Government incentives, and public acceptance. The five main potentials—social, technical, political, economic and environmental, are identified and prioritised in this study using three multi-criteria decision-making approaches: “Analytical Hierarchy Process” (AHP), fuzzy-AHP, and the test and evaluation laboratory for decision-making (DEMATEL). Next, it employs sensitivity analysis. Therefore, GH₂ and its 22 sub-potentials are the perfect renewable resources for India's sustainable development goal. The DEMATEL research found that among the predictors, social is the most important, with technical coming in last. According to the Fuzzy-TOPSIS algorithm, solar power is superior to wind, small hydro, and biomass as RE sources. Thus, to enhance output, particularly when taking solar energy into account, the government must intervene and establish strong policy frameworks. The outcomes of this study will be useful for governments, manufacturers, consumers, and environmental advocacy groups in their quest to find the most cost-effective RE source that can help achieve SDGs 5-7.

Dixit *et al.* (2024) evaluated that the use of GH₂ in India's transport industry holds great promise as a response to the Nation's pressing energy issues. Its widespread adoption is, however, impeded by a number of obstacles. The purpose of this research is to utilise Fuzzy Interpretive Structural Modelling (ISM) to identify the factors influencing the uptake of GH₂ and then examine these factors. They used “Initial Fuzzy Reachability Matrix” (IFRM) and “Structural Self-Interaction Matrix” (SSIM) to investigate the causal linkages between the obstacles. The resulting fuzzy reachability matrix was used with level partitioning to form a hierarchical framework. A cluster of barriers diagram was used to visually map the relationships, while a fuzzy digraph was employed to identify clusters based on driving power and reliance. A number of important obstacles, including

"Inadequate Regulatory Frameworks," "Technological Immaturity," and "Policy Inconsistencies," were recognised as fundamental problems. By removing these obstacles, the network as a whole will benefit greatly, and the transport sector in India will be able to embrace GH₂ more quickly. This study provides a road map for stakeholders and legislators to follow as they set priorities for initiatives involving this RE sector.

Ghosh and Roy (2024) summarised results of numerous pilot studies aimed at developing clean technologies worldwide and the intellectual community has concluded that GH₂ offers the best chance of meeting the world's sustainable energy goals by 2030. India has initiated an energy transition program with a budget of 19,744 crores of Indian rupees (INR) with the aim of achieving energy independence by 2047 and NZE by 2070. This program's goal is to curb the fast acceleration of CC targets. The author goes to examine the policies of GH₂-pioneering jurisdictions and determine, using sociodemographic characteristics as a basis, whether India can achieve energy sovereignty through a smart transitional plan. The current study evaluates the existing literature on interoperability mechanisms, investment opportunities, sustainable livelihoods, and local situations within India's policy framework. It then uses a semi-structured qualitative methodology to undertake a multivariate analysis of these factors. The goal is to build a mitigation policy framework. This research will add to the current body of knowledge on GH₂ by providing significant policy implications and will finish with a workable strategy for India to attain energy sovereignty. Global transition to GH₂ fundamentally faces production, regulation, and consumption behaviours scaling up across all sectors.

Janardhanan *et al.* (2024) noted that while India's Central Government strongly supports the Green Energy transition, including the development of Green Hydrogen (GH₂), the responsibility for driving its implementation will rest primarily with State governments rather than at the federal level. The study presents the case that the State and

regional governments of India may promote GH₂ as a means to increase employment opportunities, boost local economies, and make the most of their rich natural resource endowments. While subnational efforts to promote GH₂ face obstacles related to funding, infrastructure, and technology, the Central government must provide both direct and indirect assistance to overcome these obstacles. The research looks at advances in the hydrogen industry on a sub-national level by analysing three Indian states: Gujarat, Jharkhand, and Kerala. The research concludes with a six-point strategy to improve the multi-level cooperation essential for reaping the benefits of GH₂ to its maximum potential. The plan was broken down into the following steps: 1) adjusting skill development program so it better supports the GH₂ ecosystem; 2) filling in infrastructure gaps; 3) offering incentives to off-takers; 4) attracting investment and facilitating public-private partnerships; 5) promoting R&D; and 6) encouraging co-innovation. By implementing these six measures, India will be able to overcome the obstacles that come with a GH₂ transition and reach its full potential.

Bansal (2024) studied on CC, regulations and stakeholder demands, and that decarbonisation and sustainability must form the backbone of economic progress. This clean and sustainable development can be greatly aided by infrastructure that is adaptable to CC. The power industry is one of the important infrastructures that decarbonization relies on. In light of India's decarbonization problem, this study looks at the climate-resilience readiness of certain clean technologies. Utilising an exploratory secondary data, and descriptive research design, and the logic of deduction, this study examines battery energy storage systems (BESS), offshore wind and GH₂. The study outlines the challenges encountered by India's power sector throughout the transition to climate resilience, finds indicators to measure climate resilience, and evaluates the preparedness of certain technologies for India's energy transition in terms of climate resilience. There exist five

distinct categories of barriers, which include technological, financial, governmental, data and societal. Some of the numerous indicators of resilience are dependability, robustness, and resourcefulness. The resilience review discovered that BESS, offshore wind and GH₂ are resilient to the extent that they can withstand the CC storm. In its turn, lawmakers ought to fill some gaps. What matters with respect to renewable energy sources, is climate resilience but the four pillars of the energy transition, which are sustainable financing, technology, policy and regulation, and ESG considerations, will be equally significant.

Krishnan (2023) highlighted that the current trends in climate change and global warming necessitate a transition to more environmentally friendly energy sources. As an eco-friendly alternative to conventional hydrogen fuel, Green Hydrogen (GH₂) offers several advantages. With India's plans to expand GH₂ production, consumption, and exports, the Country has a significant opportunity to become a leader in this field. This study examines the infrastructural requirements, funding options and other conditions necessary for GH₂ adoption in India. It further emphasizes that transitioning from fossil fuels to GH₂ in key economic sectors such as transportation and energy would have both immediate and long-term environmental and financial impacts. The report concludes by outlining potential next steps for this transition providing a brief review of recent energy and GH₂-related provisions in the Union Budget.

Abhyankar *et al.* (2023) noted that the Foreign Exchange Reserves of India and its general inflation is influenced by the instability of the international energy markets due to India being one of the most dependent nations on imported oil (90%) and industrial coking coal (80%). Approximately 80 percent of the total energy consumption and CO₂ emissions of India in the energy sector are due to power, transportation, and industrial sectors. The study examines one of the possible solutions that India can adopt to address its growing energy demands and become energy independent with an almost 100 percent energy

independence by the year 2047. By reducing its reliance on fossil fuels by 90% (or \$240 billion), India may become energy independent with the accelerated implementation of clean technology, including electric vehicles, renewables and GH₂. Through clean energy projects, India will safeguard its energy spending against inflation, will save consumers \$2.5 trillion and also prevent over 4 million premature deaths due to air pollution by the year 2047. By 2047, the energy demand in India may have quadrupled to more than 6,500 TWh/yr. Energy-related CO₂ emissions in the power generation, transport, and industry will reach its peak in the early 2030s and then decrease to approximately 800 million tons/year. A significant rise in capital expenditures, totalling an extra \$1.5 trillion, will be required to implement RES. The clean energy transition cannot be managed without a fair transition, plans for the future of infrastructure, funding to help develop technologies, deployment mandates for efficient clean technologies, speeding up manufacturing at home and Government backing for these plans.

2.1.2 Importance of Green Hydrogen in Achieving Net-Zero Goals

According to Tiwari *et al.* (2024), the persistent threats of CC and environmental deterioration have prompted developing countries to seek ways to meet sustainability goals while simultaneously reducing their carbon emissions to zero. To do so, they need to switch from fossil fuels to RES. With South Asian countries like Bangladesh, India, Pakistan, and Malaysia aiming for zero emissions, the researchers looked at how the green energy industry and sustainable energy pricing are evolving. This study makes use of panel data collected between 1990 and 2018, utilising the “Dynamic Autoregressive Distributed Lag Simulations” (DARDLS) approach. The outcomes show that the market for Green Energy and sustainable development is positively correlated in the short term, but negatively correlated in the long term. As a corollary, the short-term inverse link between sustainable development emissions, NZE and price of green energy becomes stronger with

time. Findings indicate that South Asia is one area that will feel the effects of CC the most acutely. Governments in these nations should think about reducing tariffs, subsidising Green Energy technology, providing financial aid, and building robust sustainability frameworks and regulations to promote sustainable development.

Whitehead *et al.* (2023) noted that a number of futurists have long held the hydrogen economy in high regard as a means to remove human reliance on fossil fuels. The hydrogen economy, like many other worldviews, offers a holistic picture that allows one to appreciate all possible changes. As a result, it has a dedicated but somewhat dogmatic fan base. The research shows that electrification has gotten in the way of the hydrogen economy as originally planned. It then dissects what's left of the original plan to show how hydrogen can still play a niche but crucial role in helping the world reach its goal of an emissions-free economy. The firm believes that researchers, businesses, and government officials must all work together strategically to determine the optimal level of hydrogen adoption. They present a global framework for hydrogen development that aims to decarbonise industries that are difficult to electrify with renewable hydrogen. These industries include cement, steel, fertilisers, chemical feedstocks, shipping, and aviation, among others.

The research by Bhattacharyya *et al.* (2022) explored that among the most important tasks facing energy planners and policymakers operating under resource, environmental, and financial constraints is determining the minimal per capita energy consumption required to sustain high development. In a country's composite metrics, such as its human development index (HDI), energy consumption is positively connected with growth. This study estimated the lowest energy demand for India to achieve NZE and an HDI value of 0.9 by the year 2070. The final energy demand is estimated to be greater than three times the current demand, with a figure of about 18,900-22,300 TWh/yr.

Hydrogen may take up 30-40 percent of the total energy, with the rest of the energy being converted to electricity on the spot. At the beginning of rapid growth, it can be required an additional 4400-4800 TWh/yr to create the required infrastructure of high development and high digitisation.

The research by Patange *et al.* (2022) unveiled eliminating emissions from the energy sector is an essential step in limiting the rise in global temperature to "well below 2 °C." A significant amount of recent research has focused on attaining NZE by integrating bioenergy with carbon capture and storage (BECCS) into current energy systems. The CO₂-EOR initiative, which uses carbon dioxide to improve oil recovery from mature wells in western India, was just launched by the Indian Government. As part of this project, they hope to test the waters with a bioenergy-CO₂-EOR system to see whether BECCS can achieve zero emissions from power plants. Their method for matching CO₂ sources and links and bioenergy production, is mixed integer linear programming. When using CO₂ from bioethanol fermentation, the suggested system achieves break-even without a carbon tax at an oil price of about 56 USD/bbl. When employing bioelectricity plants, the break-even point is around 90 USD/bbl. Even with oil prices below \$45/bbl for the ethanol pathway, the system is still feasible with a carbon price ranging from \$20 to \$40/tonne of CO₂. After taking into consideration the emissions from the produced oil's lifecycle, the system's net CO₂ emissions are negative, presuming a sequestration rate of 0.5 tonne CO₂ per barrel of recovered oil. Additionally, the bioenergy-CO₂-EOR system lessens air pollution caused by burning crop residue in the fields, helps with ethanol blending, creates more localised revenue opportunities and decreases the need to import crude oil.

Saygin (2022) evaluated that as a flexible energy vector, hydrogen shows enormous potential and might help decarbonise many end-use sectors. At least two-thirds of the world's hydrogen production will be GH₂ by 2050, according to estimates, which supports

the shift to a NZE global energy system. This study lays forth a value chain methodology for determining which aspects of national hydrogen strategy development should receive the greatest attention from developing and emerging economies. In addition, based on eight case studies spanning industrial, transportation, and power-production applications, the analysis provides success determinants for GH₂ initiatives. This research compiles the key findings of the funding methods and enabling factors that can accelerate the development of the GH₂ market.

The study done by Chaturvedi (2021) revealed that achieving the aims of CC mitigation strategy requires an energy system that uses net zero energy. It is believed that India will have a significant impact on the mitigation discussion. Including topics pertaining to distribution corporations, labour unions, public sector undertakings, power market design and citizens, pricing and States dependent on fossil fuels, this perspective study outlines the essential institutional and infrastructure components of an energy system that is net-zero for India. It contends that going beyond co-benefits, pricing carbon, engaging the energy industry personnel, engaging people, and using low-cost finance are the five most important ways to make this vision a reality.

Research findings Honzák *et al.* (2019) showed that with the introduction of its net-zero objective for 2070, India has shown how powerful a credible policy signal can be and has altered the trajectory of the climate debate in India. Although the exact nature of the target has not been disclosed by the Government of India (GoI), the declaration marks a turning point in India's climate strategy. It all started with debates on how quickly or not India should decarbonise its economy, but today all of the Country's players are pulling in the same direction. The numerous modelling studies carried out by Indian institutions and scholars have made a significant involvement in guiding India's net-zero movement. There are some assessments of economy-wide net-zero models that are available, but what is

noticeably lacking is a comprehensive and integrated picture that has been cooperatively constructed by climate specialists in India. It is essential to supplement evaluations based on quantitative models with expert opinions on India's climate strategy. Insightful qualitative viewpoints from climate experts and quantitative assessments based on models could work together to help the Country reach its net-zero aim by identifying opportunities, mitigating risks, and understanding synergies. To fill a knowledge vacuum, this group of researchers examined the interconnected and cross-cutting dimensions of "national and sub-national perspectives," "sectoral and technological transitions," and "enablers" that would be necessary for India to achieve its net-zero goal. Even while the bigger net-zero discussion is about all GHG, the present endeavour was focused on carbon dioxide. The goal of the evaluation is to educate researchers, practitioners, and governments worldwide about the many facets of India's net-zero debate, which will benefit not only policymakers and stakeholders in India but also those in other countries.

2.2 The Green Hydrogen Economy in India

Bhati, Kumari and Biswas (2024) found that fossil fuel consumption contributes significantly to global warming due to the quantity of greenhouse gases (GHG) it generates. Energy's association with 74% of the SDG targets makes it evident that it is essential to attaining global sustainability. The use of GH₂ and other RES might drastically reduce these emissions and slow down global warming. At the 2015 United Nations Summit, a number of nations from the Asia-Pacific area announced ambitious goals for climate action. By 2070, India, a significant regional player, has promised to eradicate all carbon emissions. An extensive overview of India's GH₂ initiatives and their efforts to achieve this objective is given in this report. This addresses some of the major challenges that the development of a GH₂ economy encounters. These difficulties include material requirements, cost-effectiveness, and the footprints of water, energy, and land. India's

economy depends on a number of factors for its responsible and all-encompassing expansion.

Yesodharan *et al.* (2024) assessed that Heavy industry is vital to India's economic growth since it helps meet demand, which in turn boosts exports and GDP. In hard-to-abate industries, power is essential to the operation of every single functional unit in the production process. Coal is the main fuel for many heavy businesses, including those that produce electricity, steel, cement, research, and fertilisers. The combustion of coal produces a great deal of GHG, which contributes to the problem of inadequate energy conversion. It is critical to reduce carbon emissions as production capacity is raised to match increasing demand. The production process is being decarbonised in numerous ways by different sectors. Carbon capture, utilisation, and storage are among these, as is the usage of alternative fuels and the most up-to-date methods. After using most of these approaches, one will see favourable impacts. The study primarily focuses on the utilisation of GH₂ as a power source, but it also examines the production processes of each business to identify hotspots and the mitigation techniques employed by each. It goes into detail on GH₂'s production routes, the biggest obstacles in its implementation, the policymaking around GH₂ in India, its connection to heavy industries, and its role in achieving NZE.

Maurya *et al.* (2024) discovered that from 2019 to 2021, the global generation of solar power climbed by 47% and wind power by 31%. It is worth mentioning that to fulfil the increasing power demands and keep global warming below 1.5°, the proportion of RE globally must reach 75% by 2030. The difficulty of keeping warming below 1.5°C, as highlighted at COP 27, will persist so long as nations continue to update their targets. To achieve a future with zero emissions, India would need to reduce its reliance on coal and increase its use of RES, such as hydrogen, which may cost \$3 trillion spread out over 30 years. When it comes to reaching our net-zero goals, GH₂ will be a watershed moment. To

help India, become a hydrogen economy, the report reviews the Country's energy transition and stresses the importance of science, technology, and innovation policies. As a last point, the report stresses the importance of funding and better technologies to increase hydrogen production, particularly GH_2 . Technology, research and development, finance, and policy backing from the government, corporate entities, and academic institutions are all necessary for the lengthy process of transitioning to hydrogen energy in India.

Kar *et al.* (2023) uncovered that demand for energy in India's transportation, manufacturing, power generation, and cooling systems would rise in tandem with the Country's fast population expansion and continuous industrialisation. Reducing emissions of greenhouse gases is a priority for many countries, making fossil fuels an unattractive energy source. The transportation industry will drastically shift towards using green fuels, such as hydrogen. However, most hydrogen nowadays is produced by processes involving fossil fuels, such as partial oxidation, natural gas reforming, or coal gasification. The research looks at how hydrogen is being developed, stored, and sold in India throughout time. Hydrogen, due to its adaptability, will be essential in India's decarbonization efforts by the year 2050. The goal of India's hydrogen energy strategy was to have a fully functional hydrogen economy by the year 2020. The hydrogen roadmap's goals were not achieved. Their investigation into the causes of the hydrogen economy's downfall in India led them to the following conclusions: public ignorance, sluggish market preparation, poor infrastructure development, and a lack of proactive measures. To bring India's hydrogen sector back to life, the Country was considering launching a national hydrogen energy project. Hydrogen R&D, value chain development, and commercialisation of hydrogen technology should be the primary goals of all stakeholders.

Song *et al.* (2022) noted that a carbon-free energy future for India in the year 2050 is the focus of the study. Wind and solar power generated on land are anticipated to make

significant contributions towards this objective. According to these studies, these carbon-free energy sources will be crucial in producing so-called GH₂ through electrolysis. With this hydrogen source, we can make use of the complementary possibilities for power storage through batteries and pumped hydro, while also accommodating the inherent fluctuation of solar and wind generation. The current industrial uses of GH₂ might be substituted with “Grey Hydrogen”, which is mostly produced in India from natural gas and produces substantial amounts of CO₂ emissions. The research digs more into possible GH₂ uses to reduce emissions from the notoriously hard-to-regulate transport and industrial sectors. The study's overarching objective is to identify the best, most economical means by which India may realise its vision of a future free of carbon emissions.

The research done by Sontakke and Jaju (2021) explored There is a growing problem of excessive car emissions in India due to the country's expanding road network. These pollutants are mainly caused by the burning of the crude oil. India lacks sufficient amounts of crude oil in the country; hence it has to import crude oil from other oil-rich countries in order to meet the energy requirement of cars in the country. In order to overcome the problems that surround the oil import and the pollution caused by the emission of vehicles, we should find a carbon-free alternative fuel that will supply India with the energy on the local level and in adequate amounts. The green economy is an emerging and rapidly growing field that emphasises eco-friendly and sustainable practices. A carbon-free fuel, hydrogen is an ideal long-term energy storage option and a key component to the green economy's goals. When hydrogen is used in fuel cells, almost no emissions of greenhouse gases are produced; hence, it is a highly environmentally friendly fuel alternative. Even though free hydrogen is not sold, it can be generated by electrolyzers and other methods. In times of reduced demand, the increasing ability of India to produce RE can offer the benefit of generating hydrogen by renewable means such as wind and

solar. Since India stands to gain a lot in terms of energy security and a lower footprint in the transport sector with the implementation of GH₂, this assessment project focuses on the opportunities that India has in the production of GH₂.

Medisetty *et al.* (2020) identified industrial and automotive energy use is skyrocketing on a global scale. The increasing energy demand is outstripping the capacity of conventional sources, and the associated pollution is a major worry. Therefore, there is an urgent need for a car fuel substitute. Hydrogen and other RES, which are abundant in nature, are now the centre of attention. This review aims to cover the ever-changing technologies of hydrogen generation and storage in India. A review of recent research and continuing efforts allows us to make educated guesses about where hydrogen production, storage, and applications stand right now. Inadequate infrastructure, distribution problems, rules, expensive prices, and public opposition are among the potential roadblocks to the commercialisation of hydrogen-powered vehicles in India.

2.3 Need for Transition to Green Hydrogen

2.3.1 Role of Green Hydrogen in Reducing Carbon Emissions

Dorel *et al.* (2024) investigated GH₂'s function in mitigating CO₂ emissions during the shift to carbon neutrality, elucidating its advantages and disadvantages. The study begins with a discussion on GH₂ production from renewable sources and then gives a quick rundown of the main resource structures used to generate energy in EU nations, including Romania. Some nations' heavy use of fossil fuels persists despite advancements. Investigated are economically viable methods of producing GH₂, with the caveat that, because of the complexity and expense of the compression and storage processes involved, this will not be sufficient to resolve all problems. Impure GH₂, developed by processes such as fermentation, pyrolysis, biomass gasification, and wastewater purification, is also covered. Production trends in GH₂ and economic efficiency are detailed. In its last section,

the study examines combustion technologies that combine hydrogen and methane, providing a theoretical basis for making cost-effective use of GH₂ during the shift to a GH₂ economy.

Sebbagh *et al.* (2024) emphasised the rise of GH₂ as a RE carrier that is both environmentally beneficial and offers a great chance for a responsible energy transition in the future. The production procedure for GH₂ minimises CO₂ emissions because the electricity used to manufacture it comes from renewable sources. Carbon emission reduction, energy storage, and a wide range of potential uses are just a few of its many benefits. But there are still obstacles, especially with regard to R&D, infrastructure, logistics, and production costs. Notwithstanding this, GH₂ has tremendous promise in the battle against CC and for the promotion of more resilient energy systems; nevertheless, achieving this potential would necessitate international collaboration. The various aspects of GH₂ are examined in this review, including its production methods, infrastructure, advantages, disadvantages, and challenges. A thorough evaluation of the current hydrogen infrastructure is provided, with an emphasis on the transition from limited access to retail stations that are user-friendly for customers. Also covered are topics like energy density and infrastructural requirements as they pertain to the complicated relationship between hydrogen generation, storage, and delivery. Given the importance of advanced materials, safety, and life cycle evaluation in GH₂ production and utilisation, the study highlights the critical importance of research and development.

Kakran *et al.* (2023) explored several reasons, including natural processes, the combustion of fossil fuels, and deforestation, have contributed to the fast growth (by 50%) in atmospheric carbon dioxide (CO₂) levels since the 1750 industrial revolution. Extreme weather occurrences and climatic shifts are both brought about by human-caused global warming, to which carbon dioxide contributes. The world's energy consumption has

increased dramatically as a result of technology advancements and their usage. The study's originality comes from the fact that it tracks the present carbon emissions (by fuel type and industry) that are a result of the many ongoing hydrogen production projects, their uses, prices, and delivery times. It also delves into the impact of government policies and structural changes in the BRIC-S-US relationship over time. Institutional, economic, technological, and behavioural (IETB) logical comparison analysis has a conceptual model. Three key findings emerged from the study. To begin, while looking at countries side by side, it's clear that each one has its own set of advantages and disadvantages, as well as its unique dynamics. Secondly, while looking at development of hydrogen energy from a vertical perspective, it is clear that all countries are still in the quantitative stage, and they have not yet achieved the qualitative inflexion point. Third, from a strategic perspective, the energy transition is aided by creating hydrogen energy, which is a fundamental mission aspect. Nevertheless, research shows that CO₂ emissions are highest in China, with the US following closely behind. When it comes to hydrogen, China is both the biggest producer and user, at 2.4 million tonnes. Regardless, the world's biggest GH₂ facility is located in the USA, and it cranks out 3,800,000 kg of GH₂ each year, or 11,000 kg per day. This research elucidates potential avenues for future development despite existing limitations and is a great resource for fundamental scholars planning to build programs in developing nations (e.g., emerging and frontier economies) to fortify energy efficiency, conservation, and state policies.

Alzoubi (2023) Investigated in this study are the ways in which hydrogen production impacts the mitigation of carbon emissions. Concerning the function of hydrogen generation in reducing carbon emissions, the research investigates three theories in depth. Within the framework of GH₂, this study uses a system dynamics model to assess the effects on the environment, efficacy of production technologies, and role of policy

frameworks. The findings demonstrate that, with larger production, hydrogen technology could significantly decrease carbon emissions across all industries. In addition, the report highlights the importance of enabling economic policies and investments in IT scaling. In sum, the findings shed light on how hydrogen might contribute to a sustainable energy transition and give crucial data for planning future energy initiatives.

Nnabuife *et al.* (2023) examined that for 2020, the utilisation of hydrogen (H_2) was 90 (Mt), with nearly all of it going towards industrial and refining applications. Nearly 900 Mt of carbon dioxide was emitted as an outcome of this usage, as hydrogen was produced almost entirely from fossil fuels. However, H_2 has grown substantially in the last many years. The overall capacity of electrolyzers, which are necessary to produce hydrogen gas from electricity, has increased over the previous several years and is expected to surpass 300 MW by 2021. With 350 projects supposedly in the works, total capacity might reach 54 GW by 2030. An additional 40 projects with a combined output of over 35 GW are now being planned. Worldwide H_2 output from electrolyzers has the potential to surpass 8 Mt by 2030, assuming all of these projects are successfully executed. Here's a chance to capitalise on hydrogen's potential as an essential ingredient in a future that is clean, safe, and affordable. In its current state, the study evaluates H_2 and offers suggestions for its possible improvement in the future. According to the research, clean H_2 is undergoing an unprecedented level of commercial and political pressure, with number of legislation and projects worldwide increasing at a rapid pace. According to the study's findings, a dramatic uptick in technologies and a corresponding drop in costs are required to propel H_2 into the mainstream. Industry and government may make most of this increasing momentum with the help of the practical and actionable recommendations given to them.

Yu *et al.* (2021) look at several ways to make hydrogen with little carbon. Hydrogen gas (GH) generated from RES, blue hydrogen (H_2) produced from fossil fuels,

and aqua hydrogen (H_2) generated from fossil fuels using modern technology to reduce carbon dioxide emissions make up low-carbon hydrogen. GH_2 represents an expensive approach to producing hydrogen when compared with fossil-based hydrogen. The high implementation cost of CCUS technology blocks many advantages of blue hydrogen since blue hydrogen fails to be inherently carbon neutral. Engineering scientists dedicate efforts to establishing alternative low-cost and low-carbon hydrogen technologies because conventional production methods prove too expensive. Western Canada serves as the operational base for a novel, cost-effective method of extracting hydrogen from oil sands (natural bitumen) and oil fields. Hydrogen made with the new production method is marketed under the name Aqua Hydrogen. The hydrogen production method designated as Aqua combines elements of blue and GH_2 by avoiding CO_2 emissions similar to green and using fossil fuel energy like blue. Aqua hydrogen represents a transformative production process because it operates without releasing CO_2 emissions during the whole process, unlike the compensatory approach of blue hydrogen, which relies on CCUS. This study assesses the present state of affairs, looks ahead to potential developments, and offers policy suggestions for low-carbon hydrogen technologies like aqua, green, and blue hydrogen in an effort to foster the progress of the low-carbon hydrogen economy.

Valente *et al.* (2021) noted that future long-distance highway traffic will employ GH_2 , or hydrogen produced from sustainable resources, as an alternative fuel. The advantages of zero pollution at the utilisation stage may be offset when the upstream processes, which concern the raw materials and energy demands, are put into consideration. They assessed the environmental impacts of using hydrogen for heavy transportation across its whole life cycle under the framework of "Planetary Boundaries" (PBs) in order to better comprehend the practice's effects on the environment globally. These possibilities include hydrogen produced by solar, wind, nuclear, bioenergy with CCS, grid-powered

electrolysis, and biomass gasification (with or without CCS). This study shows that the heavy transport sector's existing reliance on diesel fuel is unsustainable because it breaches the PBs associated with CC, outperforming standalone by a factor of two in the global CC budget. Heavy transportation powered by hydrogen would lessen the strain on the CC-related PBs worldwide, assisting transportation industry in staying within the safe operating range, which is less than one-third of the global ecological budget when all eventualities are taken into account. However, the best CC scenarios, which are based on biomass, would transfer the costs to nitrogen flow PBs and the integrity of the biosphere. In contrast, there would be very little burden shifting in the electrolytic scenarios, and hydrogen produced from wind power would be a desirable option even if it would result in higher carbon emissions than the biomass approaches.

French (2020) observed that the pressure from the public is increasing on governments, lawmakers and regulators to find effective ways to keep global warming at 1.5°C over pre-industrial levels. It is estimated that by 2050, at least some countries will have committed to attaining zero net GHG emissions. To achieve zero emissions at the National, State, or regional level, a full plan is needed that will cover all the key factors that contribute to greenhouse gas emissions such as electricity production, transportation, manufacturing, and heating. With the need to plant billions of trees and modify meat consumption, efficient land use is critical. Hydrogen is increasingly recognised as a crucial tool for decarbonising sectors and applications, including industrial processes, heavy goods, power production and heating. Hydrogen storage enables increased use of renewable power generation, a crucial step towards the clean energy transition. Hydrogen can help decarbonise important segments and provide cross-sector coupling, allowing for synergies between key economic sectors. The study explores low-carbon hydrogen

production routes and its applications in reducing carbon dioxide and GHG emissions, highlighting its crucial role in energy transition and global climate stabilisation.

2.3.2 Economic and Geopolitical Aspirations of India

Braga *et al.* (2024) suggest that a new positive cycle of sustainable economic progress and development can be initiated on a global scale through the global GH₂ economy, potentially ushering in a new energy paradigm. The GH₂ economy tackles several of the 2030 agenda's "Sustainable Development Goals" (SDGs), including a pressing need for worldwide decarbonization. The potential benefits and obstacles of a worldwide GH₂ economy are discussed in the research. Green Power Shoring and Green Water Shoring are two novel concepts introduced in this study to assess the future of the global GH₂ sector and to identify the nations likely to dominate the global GH₂ market. Countries rich in RE resources and fresh water will have a distinct advantage over those that are not, as these resources are essential for GH₂ production. Therefore, a global GH₂ divide will inevitably be created, which will have numerous geopolitical and geo-economic ramifications around the world.

Nazeerudin (2023) evaluated that the manufacturing sector has failed to deliver, contributing just 20% of GDP, due to domestic demand being low, government decision-making being sluggish, infrastructure being clogged and interest rates being high. On the other hand, agriculture's share of India's GDP declined from 17.4% in 2006–07 to 14.2% in 2010–11. In addition, with industries like banking and real estate experiencing demand and investment limits, the service sector, which contributes approximately 65% of GDP, has also been seeing a decline in momentum. In addition, natural capital declined by 31% between 1990 and 2008, despite an astounding 120% increase in India's GDP per capita. This indicates that environmental degradation is a major consequence of economic growth. Furthermore, at now, India is using about double its biocapacity, which means that the

demand for resources from the ecosystem by the population is higher than the capacity of the ecosystem to replenish those resources. India must undergo critical changes if it wants to make sure that the social, economic and environmental facets of development are interconnected. As a result of increasing natural capital, a green economy boosts growth that benefits the poor and gives them more opportunities to make a living. In light of the above, the study's overarching goal is to investigate which Indian industries stand to benefit most from Government involvement and how they have become the driving forces behind green projects. While these industries have helped the economy expand, they have hurt the natural world. The second section of the research examines the six areas that might help strike a balance between sustainability's three tenets. The third section delves further into an analysis of the main obstacles encountered by certain projects and potential solutions to these problems. Lastly, it lays the groundwork for future studies and an understanding of the change agents that can bring about this shift.

Van de Graaf *et al.* (2020) observe that while studies on hydrogen have largely focused on the technological and financial barriers to its widespread adoption, comparatively little attention has been given to the geopolitical factors that could shape these developments. The infrastructures and technologies to sustain a hydrogen economy can be of any form, and different countries and interested parties are racing to find out the most suitable action plan. It is possible that in the longer perspective, international maritime trade of hydrogen can drastically change the world energy trade map, create a new circle of countries that produce energy and destabilise long-term established international unions and relations. It is hoped that worldwide regulation and investments in hydrogen value chains will lessen greater geo-economic competitiveness, market fragmentation and carbon lock-in.

Pflugmann and Blasio (2020) note that renewable hydrogen is gaining momentum in both governmental and corporate spheres. However, its effective deployment requires appropriate sizing, cost competitiveness, supportive infrastructure and the backing of suitable policies and market frameworks. As policymakers negotiate a new energy landscape, it is vital to investigate the geopolitical ramifications of renewable hydrogen, which may play a significant role in the carbon-free energy conundrum. It is important to think about technology, infrastructure, the environment, money, international markets and geopolitics. Research offers a technique to frame these variables, address the issues they cause, and identify potential solutions, with a focus on renewable hydrogen. They anticipate that, when implemented on a large scale, hydrogen markets will follow the same patterns as natural gas markets, including possible parallels in geopolitical dynamics. According to their findings, nations' responsibilities in future renewable hydrogen systems will vary according to their resource endowment and infrastructure potential.

2.4 Challenges in Green Hydrogen Adoption

Shin (2024) highlights that major economies in the Asia-Pacific region, including South Korea, China and Japan, are undergoing rapid urbanisation and industrialisation, leading to significant energy and environmental challenges. Green Hydrogen (GH₂), produced from renewable energy sources (RES), represents a pathway towards long-term sustainability. Produced from RES, GH₂ embodies long-term sustainability. With an emphasis on technical developments, national strategies and regional cooperation initiatives, this study investigates the difficulties posed by these technologies in the area. Support for and investments in GH₂ infrastructure are coming from countries like Japan, Australia and the Republic of Korea. Among the benefits for SMEs, are financial savings, long-term viability and the opening of new market niches. As long as investments keep coming in, new technologies keep appearing and policies keep encouraging growth, the

future looks bright. The Asia-Pacific region may overcome obstacles to the adoption of green ammonia and GH₂ technologies through regional cooperation, positioning it to become a leader in the industry.

Jayachandran *et al.* (2024) emphasise that decarbonising hard-to-abate industries is crucial to limiting global warming to below 2°C. Energy-intensive sectors such as cement, aluminium, chemicals, steel and transportation are actively exploring more sustainable fuel alternatives. One viable option is GH₂, which is produced by water electrolysis. Energy losses, exorbitant prices across supply chain, inadequate infrastructure and excessive power usage are among the obstacles to GH₂ production's scalability. Thus, this research aims to examine the difficulties inherent in GH₂ value chain, with an eye towards the creation of new technologies. By providing a thorough review of current research, this research looks at the potential consequences of GH₂ on hard-to-regulate industries, specifically looking at the expansion of RE infrastructure. The study delves into topics including assessments, sustainability, economic feasibility and carbon neutrality by way of an examination of novel renewable hydrogen technologies. Furthermore, the possibility of achieving net-zero energy targets and large-scale renewable power storage are also taken into account. This study's results provide hope for decarbonization efforts by indicating that new technology may one day greatly enhance GH₂ generation at a reasonable cost. The analysis confirms that by 2050, we might eliminate 60 gigatonnes of GHG emissions, which is 6% of the entire reduction in CO₂ emissions, and provide 24 percent of the world's energy. This research examines potential of three business models that place an emphasis on GH₂ production and distribution options to assess the overall effect of the GH₂ economy on ecosystem decarbonization. As a last step towards encouraging interdependent hydrogen ecosystems, the study suggests avenues for further investigation into hydrogen valleys.

Borowski and Karlikowska (2023) argue that the energy sector could benefit significantly from hydrogen, a novel fuel that facilitates greater integration of renewable sources. Their study examines the challenges that economies and businesses may face in the production and utilisation of hydrogen. By integrating hydrogen into energy, transportation and building industries, we can reach carbon neutrality by the year 2050. Utilising hydrogen for energy, transportation and buildings would allow for the attainment of climate neutrality, and the annual demand for hydrogen worldwide is projected to reach 614 million metric tonnes by 2050. Several categories can be identified, with corresponding colours, according to the means of hydrogen production, the procedures employed and the outcomes. New avenues for the manufacture of environmentally friendly hydrogen arise in this field. A multitude of factors influences the final price of hydrogen, such as the accessibility and affordability of carbon capture, utilisation, and storage systems, modes of transportation, rates of electrolyser energy consumption and network expenses. One US dollar is anticipated to be the cost of one kilogram of hydrogen. The study analysed a large amount of numerical and descriptive data because it used the desk research approach.

Sharma, Kumar and Jain (2023) note that the rising demand for energy is directly linked to modern human life, which is increasingly driven by advancing technological capabilities. Since fossil fuels are slowly running out, everyone is looking to RES to keep up with their ever-increasing energy needs. At the moment, RE is on the rise due to the fact that it lessens the impact on the environment caused by GHG emissions. Hydrogen, a novel technology that makes use of RES, is thus the centre of attention. India, like many other countries throughout the world, is concentrating on hydrogen development since it is one of the biggest producers of RE. A review of India's National Hydrogen Mission's plans up to 2050 and an evaluation of GH₂'s potential and applications in several fields are also on

the agenda for the study. In the wake of India's Hydrogen Mission launch, the transition to GH₂ appears to be within the realm of possibility for the industry. Problems with implementing and using GH₂ are also covered in the research.

Patange *et al.* (2022) report that a hydrogen-powered automobile was recently showcased at India's Parliament House, coinciding with the launch of the Ministry of Power's (MoP) 'Green Hydrogen Policy' on February 17, 2022. To achieve these goals, the Policy promotes clean energy and works to reduce emissions of greenhouse gases by highlighting GH₂ as a possible fuel for both commercial and residential use. Reducing reliance on fossil fuels and establishing India as a possible world leader in GH₂ production, are the goals of the Policy. The issue briefly delves into the essentials of India's GH₂ ambitions in this setting. Inadequate current supply chains, inadequate infrastructure, low domestic demand and an appropriate investment road plan are all obstacles to the efficient execution of the GH₂ Policy. In addition, this summary delves into the Policy's complexities by examining the position of stakeholders, economic ramifications and the shift away from a coal and natural gas-heavy economy.

AlZohbi (2022) emphasizes that decarbonizing the global economy is a critical challenge. One potential solution lies in expanding the use of renewable energy sources (RES) and integrating them across industries, transportation and the energy sector. This might be achieved by utilising GH₂. In addition to being a feedstock for numerous industrial processes and a transportation fuel, GH₂ can smooth out the fluctuations of solar and wind power. The study offered an overview of the numerous technologies utilised to generate GH₂. The study also provides a synopsis of the various challenges related to creating GH₂.

2.5 Role of Policy Initiatives in Accelerating Green Hydrogen Adoption

2.5.1 National Green Hydrogen Mission (NGHM)

By 2047, India hopes to achieve energy independence, and by 2070, NZE. It is anticipated that GH will be crucial to accomplishing these objectives. GH₂ is produced via the electrolysis process, which can be driven by hydropower, solar energy, or wind and splits water into its hydrogen and oxygen components. This method might produce clean, emission-free petrol, which would significantly reduce carbon emissions and replace fossil fuels. The process of gasifying biomass to create hydrogen is another way to make GH₂ from biomass. With its environmentally friendly and sustainable production methods, GH₂ is a great option for a future without carbon emissions. Rapidly increasing demand is driving GH₂'s price down as more and more industries consider its decarbonization potential. This includes steel, shipping and transportation. Traditional fossil fuels are a key contributor to transportation-related GHG emissions; however, GH₂ can eliminate this problem. Further, it can be used to make steel, methanol and ammonia, three industrial products that rely heavily on fossil fuels these days. In addition, GH₂ provides a reliable and steady energy source that can be used as a backup for RE facilities (Ministry of New and Renewable Energy, 2023).

GH₂ can be utilised in fuel cells to generate electricity and power automobiles, among other uses. Additionally, it can be utilised in fertiliser and chemical production as well as heating systems. Because of its high energy density and superior efficiency over conventional combustion engines, hydrogen fuel cells are a desirable alternative for vehicle power. Additionally, GH₂ can be utilised in microgrids to enable energy independence and to supply electricity to remote locations. It is impossible to overestimate GH₂'s significance in helping India become energy-independent. Energy security can be achieved by producing GH₂ utilising RES, including solar, wind, and hydropower, which lessen

reliance on fossil fuels and guarantees a steady and dependable supply of energy. Additionally, GH₂ can be made locally, negating the need for expensive and harmful imports. Further, GH₂ made from waste biomass gives local communities and farmers another source of income. India set up the National GH₂ Mission with a budget of Rs.19,744 crores so that the Country could generate 5 million metric tonnes of GH₂ per year.

To conclude, GH₂ offers a great deal of potential to attain energy independence, lower carbon emissions and decarbonise a number of sectors. As an enticing alternative to shift to a low-carbon future, GH₂ can be produced utilising RES, including solar, wind and hydropower. GH₂ is a reliable and steady energy source that can replace traditional fossil fuels in industrial and transportation settings. It is crucial for energy independence since it can lessen reliance on fossil fuels and offer a steady and dependable energy source (Ministry of New and Renewable Energy, 2023).

2.5.2 Incentives and Subsidies for Green Hydrogen Production and Use

As mentioned in a report by the Ministry of New and Renewable Energy (2024), it is the goal of the Indian Government to promote domestic manufacture of electrolyzers and GH₂ through initiatives such as the “Production-Linked Incentives” (PLI) program. Incentives and plans will evolve during the Mission's lifecycle in response to market demands and new technologies. To be eligible to participate in the competitive bidding procedure for the acquisition of GH₂ and its derivatives, the project must use equipment that has been licensed by the Indian Government and meets particular quality and performance standards.

Strategic investments and Public-Private Partnerships (PPPs) are important forces behind the advancement and application of GH₂ technology. The Government and business sector working together might spur innovation, lower costs and make it possible for GH₂

to be widely adopted in India. As GH₂ projects require a lot of capital, PPPs can close funding shortages, give stakeholders access to cutting-edge technologies and distribute risks (Singh, Ratn and Jha, 2024a).

With an initial expenditure of ₹19,744 crore (\$2.3 billion), the Indian Government's NGHM has set ambitious goals to create 5 million metric tonnes of GH₂ yearly by 2030. Through incentives, subsidies and policy frameworks, this program promotes private-sector participation (Ministry of New and Renewable Energy, 2023b). The storage, production and transportation infrastructure for GH₂ is receiving substantial investments from prominent companies like Adani Group, Reliance Industries and Indian Oil Corporation. For instance, GH₂ is one of several RE projects that Reliance Industries has committed to investing \$10 billion over the next three years (The Economic Times, 2024).

Prior studies concentrated on comprehending the Indian GH₂ economy, the necessity of switching to GH₂, examining obstacles and the necessity of policy initiatives as well as offering incentives and subsidies for the production and use of GH₂ in India. In addition, these are backed by R&D efforts and public-private collaborations to speed up the Country's shift to GH₂. Limited progress seems to have been made in understanding the impact of Policy interventions as well as the progress of the Public Sector (Government) / Private Sector in the production and consumption of GH₂ in India towards achieving goals of net zero and carbon neutrality. A new study examines India's potential for RE using current policies, initiatives and technologies. It concludes by highlighting the opportunities and difficulties of RE for India (Pal, Yadav and Tyagi, 2017; Singh, Ratn and Jha, 2024a).

2.6 Public-Private Sector Contributions in Green Hydrogen Development

The Mission will create a framework for R&D public-private partnerships - “Strategic Hydrogen Innovation Partnership” (SHIP). According to the framework,

industry and relevant Government organisations would contribute to the establishment of a special R&D fund. These organisations will combine their resources to work with the business sector to develop an all-encompassing, goal-oriented research and innovation agenda (Ministry Of New And Renewable Energy, 2024).

PPPs evaluate constraints in projects and business model development of repeatable project concepts by addressing particular challenges along the full GH₂ value chain (International Hydrogen Ramp, 2024), e.g.:

- Technical ideas along the relevant product chain, such as modes of transportation,
- markets for demand or
- The nation's particular framework circumstances

Financing

- The public can contribute a minimum of EUR 50,000 and a maximum of EUR 2,000,000 (International Hydrogen Ramp, 2024).
- The private partner (or consortia) is required to contribute a minimum of 50% of the PPP project's volume, which is EUR 50,000 (International Hydrogen Ramp, 2024).

On March 12, 2024, on behalf of the Standing Conference of Public Sector Enterprises (SCOPE), "Decarbonization of India's Public Sector Enterprises and Role of GH₂" was the subject of a workshop held at the SCOPE Complex. It was jointly organised by the Indo-German Energy Forum (IGEF-SO) and the Indo-German Support Project on Climate Action in India. The session gave Indian PSEs, an overview of the current decarbonization activities in the Country and a comprehension of climate co-benefits and how they can be used to fight against CC. Workshop attendees heard the results of PwC's "Decarbonising India - Potential for Electrification across India's Economy & Assessment of Electricity Needs," a report commissioned by IGEF-SO. Participants in the first session

discussed new laws and regulations that will hasten the production and usage of environmentally friendly hydrogen. Mr. Ajay Yadav, Joint Secretary for GH₂, International Relations & CC at India's Ministry of New and RE (MNRE), highlighted the importance of GH₂ in driving the Country's energy transition, who also detailed the Government initiatives that have been implemented since the National GH₂ Mission was established in 2022. He recognised the importance of the workshop in promoting ongoing initiatives and funding sources and fostering relationships between MNRE and PSEs. The Chairman of SCOPE and Chief Managing Director of GAIL, Mr. Sandeep Kumar Gupta, shared this view, emphasising the necessity of techno-commercial research and the role PSEs play in generating local GH₂ demand. The Indo-German Energy Forum (2024).

The importance of bilateral engagement between India and Germany in boosting PSE involvement and facilitating technology transfer and cross-industry learning was highlighted by Ms. Ruchika Drall, the Deputy Secretary of the Ministry of Environment, Forests, and CC (MoEFCC). Leadership for Industry Transition (Lead IT) 2.0 and the Avana Sustainability Fund were among the financial ideas she covered. Overall, by showcasing current GH₂ technologies and activities and introducing a novel low-carbon cement for decarbonization, the workshop represented a major step towards climate action for PSEs and demonstrated India's evident decarbonization efforts (The Indo-German Energy Forum, 2024)

As part of its efforts to create a more sustainable energy future, India has put GH₂ in the vanguard of its RE projects. The Country's GH₂ technology development and deployment successes are mostly attributable to strong Public-Private Partnerships (PPPs), which have become instrumental in driving innovation, infrastructure development and large-scale adoption.

Several notable PPPs have emerged in response to this mission. As an example, Larsen & Toubro (L&T) has committed to invest up to \$4 billion in GH₂ projects in the next 3 to 5 years in conjunction with Indian Oil Corporation and Renew Power, to name one. Part of this collaboration is manufacturing electrolyzers and then building the GH₂ plants to cater to domestic demand and expand to international markets as well. GH₂ cannot be readily developed without such investment in infrastructure and supply chains (Pathak, 2023).

State Governments too are getting engaged in PPPs promoting GH₂. In line with the India Hydrogen Alliance (IH₂A), Kerala State Government has mooted setting up a Kochi GH Hub. The GH₂ plant envisages a 150MW electrolyser yielding 60 tonnes per day envisioned to be built with an investment of about \$575 million (approx). The ambitious plan is to facilitate the development of a GH₂ production and utilisation ecosystem, particularly within the transportation sector to support California's net-zero ambitions (Luthra, 2022).

International collaborations further underscore the importance of PPPs in India's GH₂ landscape. French energy giant Total Energies has entered into a joint venture with Adani Green Energy Limited, investing \$444 million in a 1.150 MW solar power project in Gujarat. This partnership not only enhances RE capacity but also supports GH₂ production, aligning with India's broader energy transition goals (Adani Green Energy Limited, 2024)

Moreover, industry bodies like the India Hydrogen Alliance (IH₂A) have been instrumental in facilitating PPPs by submitting comprehensive development plans to the Government. IH₂A's proposal for the development of a \$5 billion National GH₂ Hub Economic Viability and Development Plan will see five large GH₂ hubs built by 2030 through public-private partnerships. The GH₂ technology would be made faster

commercially to accelerate the instrumentalization of GH₂ technology in India with public finance support, which can create the necessary infrastructure and stimulate private investment (GUPTA, 2024).

There are still issues, though, such as high cost of producing GH₂, inadequate infrastructure and unclear regulations. India will need to address these obstacles through strategic PPPs and focused investments to become a global leader in the production and transfer of GH₂, which will greatly advance its net-zero goals.

2.7 Renewable Energy and Green Hydrogen: Interdependencies

Basu (2024) observed that issues such as energy accessibility are currently key determinants of India's economic progress and the well-being of its population. In this context, assessing India's need for distributed renewable energy (RE) is essential. India has decided that clean and RES are its best bet in light of its Nationally Determined Contributions and its promises to address climate security. This has led India's Foreign Policy to focus on energy security above all, what with COVID-19 and the crisis between Russia and Ukraine. A rise in emissions wreaking havoc on the environment was caused by India's over-reliance on fossil fuels. India is bolstering its RE sector to avert these catastrophes, seeing it as the greatest alternative for a sustainable future. Also, through international partnerships like the International Solar Alliance, it has promoted RE to a greater extent. After revising its Nationally Determined Contributions in August of 2022, India boasted about its remarkable progress in RE at the 27th Conference of Parties (CoP-27) in Egypt in 2022. Consequently, the research provides a significant response to a pressing issue in the field of RE politics: "How has India connected climate diplomacy with energy security following COVID-19 through the advocacy of renewable sources on a global and national scale?" The study holds great importance for scholars who want to understand India's position in the post-pandemic global climate order as a pioneer in

promoting RES and bridging the gap between the South and the North. The study delves further into the interconnected nature of CC and energy security, which is of particular relevance in post-COVID-19 era when these two problems affect every continent.

Kaur & Rehman (2024) observed that the energy sector is the focal point of SDG 7—Affordable and Clean Energy, and, according to the IEA, it is responsible for around three-quarters of CC emissions. At its core, this conceptual study aims to comprehend the advances in the RE industry, particularly as they pertain to India and the present geopolitical climate. After that, the research will try to figure out what these changes mean for India and the rest of the globe. As a result of geopolitical tensions in Ukraine, global RE goals have lagged behind targets, particularly in India. India, the world's third-largest energy consumer and a net importer of power, has been attempting to satisfy its current energy demands while simultaneously investing extensively in RE to offer a sustainable and reliable supply of energy in the future. As a result, despite the present geopolitical crisis and its subsequent hurdles, India is rising to become one of the top five RE players, making a significant contribution to global sustainability and ensuring its energy security in the future.

Roy *et al.* (2024) present a comprehensive analysis of various energy system topologies for rural Indian villages that rely exclusively on renewable electricity. The gadgets can store extra electricity thanks to two energy storage options: lithium-ion batteries and GH_2 production utilising electrolysis. Configurations of “hybrid renewable energy systems” (HRES) have been sized by minimising the “levelized cost of energy” (LCOE). Using TOPSIS, a “multi-criteria decision-making” (MCDM) technique, economic and environmental performance parameters were examined to identify the optimal HRES configuration. System-1 was made up of the following parts: 310.24 kW photovoltaic panels, 690 kW wind turbines, 100 kW biogas generators, 174 kWh batteries,

150 kW electrolyzers, 120 kg hydrogen tanks, and 106.24 kW converters. It was determined to be the top-performing system. This was due to its lowest fuel consumption rate of 2.31 kg/kWh and highest relative closeness (RC) value of ~0.817. Among all the system configurations that were evaluated, system-6 displays the largest amount of CO₂ (143.97 kg/year). Optimal HRES configurations have also been the subject of extensive technical, economic, and environmental analyses. These estimates were \$1,960,584, \$0.44/kWh, and \$22.3/kg for System 1's cost of hydrogen (COH), LCOE and minimal net present cost (NPC), respectively.

SCHOLTEN (2024) noted that although energy geopolitics has a long history, it has entered a new phase of study. The urgency of transitioning to renewable energy sources (RES) and adopting other decarbonization strategies is driven by both environmental change and energy security concerns. There will be significant shifts in energy infrastructure, consumer preferences and trade patterns as a result of this development, which will impact both political and industrial dynamics. For instance, the current oligopolistic oil and natural gas markets could see a reduction in tensions due to the widespread availability of RE. Simultaneously, the energy transition is influenced by political factors on a worldwide scale. A great power competition affects the choices made in technology, the partnerships formed in trade, and the ability to reach and implement global agreements. The world's multiple regional and global powers vying for economic and political power makes a swift and equitable shift to RES seem unlikely. The outcome of this intricate and mutually beneficial relationship is uncertain. Are big power rivalries going to weaponize the energy transition or will it soothe global (energy) relations? Future historians will have to provide conclusive answers, but this brief lays out the major points about RE's impact on international politics, including the challenges nations confront in striking a balance between their own and other countries' interests.

A. Sharma *et al.* (2023) observed that India's energy demand is rising rapidly. At present, most of its energy is derived from fossil fuels, which harm the environment by contributing to greenhouse gas (GHG) emissions and accelerating climate change (CC). As RES provides GH₂ that is both clean and pollution-free, we can decrease our Nation's dependency on fossil fuels. The establishment of a GH₂ community in India can pave way for the Nation to attain NZE and sustainable growth. According to their analysis, GH₂ can be manufactured in India by the various regions' geographies that are abundant in RES like wind and solar. A lot of India's States are ideal for producing and distributing GH₂ because of their favourable solar energy prospects, strong wind speeds and established infrastructure and supply chain logistics. Government officials in India have designated several States—including Tamil Nadu, Andhra Pradesh, and Gujarat—as "RE clusters" that will facilitate the establishment of GH₂ projects. Another option for water for electrolysis is the seawater found along the coasts of India. The breezy coastlines are ideal for generating wind power, and the great ports and transportation infrastructure along these coasts make them ideal for transporting environmentally friendly hydrogen. Because of its favourable geographical characteristics and abundance of RES, India has limitless potential for GH₂ production. If the political and legislative conditions are favourable, India can take advantage of this opportunity to establish itself as a leading player in the global GH₂ industry.

Pandey and Kumari (2023) explore that for a sustainable future, India must address its varied energy demands, and GH₂ is quickly becoming a major player in this space, aligning perfectly with the Country's RE targets. With this background, the study delves into GH₂, the RE Policy of India, and the most recent GH₂ projects. The study demonstrates how GH₂ is an integral part of India's larger strategy for RE, which includes public-private partnerships. The study also examines the state of the GH₂ framework in

India as well as its problems and potential solutions. The study's methodology is centred on a thorough review of statutes, case law and legal documents, with an emphasis on judicial decisions and principles of law. The research indicates that GH₂ has great potential for India's energy future. It can supplement the Country's RE initiatives and provide practical answers to the problems caused by CC. As a result, it can help accomplish Sustainable Development Goal 7. With an optimistic ending, the research study suggests that GH₂ might be a critical instrument in combating environmental change and play an important role in India's RE regime, contributing to the accomplishment of SDG7.

Mneimneh *et al.* (2023) argue that the transition to renewable energy sources (RES) can be realized when communities rely on sustainable resources that meet basic needs and alleviate everyday challenges. The Sustainable Development Goals (SDGs) place these priorities—alongside urgent issues such as poverty, hunger, sanitation, economic hardship, climate change (CC) and greenhouse gas (GHG) emissions—at the centre of global action. Each of the 17 SDGs aims to address a specific sector and offers potential solutions to these catastrophic issues. Since hydrogen's use in various industries will lead to lower levels of GHG, contributing to the Earth's CC, it aids in accomplishing the objectives of these sustainable advancements. In addition, the development of numerous job possibilities will accompany the utilisation of these resources, which will boost the economy and elevate society's standing accordingly. Findings from the study differentiate between the four distinct varieties of hydrogen and place them in their proper classification. After that, the study goes on to stress how GH₂ is vital to the maritime sector, transportation and infrastructure, as well as to economic and social growth in the form of new job possibilities. In addition, the research comprises case studies that address GH₂ status in the UK, US, EU, UAE, Africa and Asia, among other regions. In the end, the difficulties and suggestions related to the GH₂ sector are covered. The study's

overarching objective is to pinpoint how GH₂ can help sources achieve both the immediate and long-term SDG objectives.

Marouani *et al.* (2023) noted that the development, advancement and cost reduction of Green Hydrogen (GH₂) are attracting significant attention from researchers, institutions, and governments worldwide. Their study examines the concept of GH₂ and its production using renewable energy (RES) across major countries and regions, including Japan, Australia, South Africa, India, Canada, the European Union, China, Russia, the United States, South Korea and several North African nations. These are promising areas to produce hydrogen, which is considered to be green, and this can facilitate a shift in polluting fuels towards RES that employ electrolysis. This study also looks at GH₂'s advantages as a potential fossil fuel replacement in the future, focusing on how it's better for the environment and how it produces no net greenhouse gas emissions. Furthermore, it delves into the possible benefits of GH₂ utilisation in several commercial, transportation and industrial domains. With the right applications, GH₂ has the potential to become the fuel of the future, according to the research. This might be due to advancements in storage and production methods, as well as increased efficiency in several fields. Maximising efficiency, minimising costs and reducing environmental impact can be achieved through the use of optimisation methodologies in the design and operation of GH₂ production systems. To advance this technology and reap its benefits to their maximum potential, global cooperation and joint endeavours are essential.

Dong *et al.* (2022) examined that as a possible alternative energy carrier that can help usher in a world without carbon emissions, hydrogen is quickly rising in favour of a sustainable energy option. It leaves almost no carbon footprint whatsoever. Still, the hydrogen economy isn't growing as quickly as it could be because of scaling up. In particular, the high transportation costs of GH₂ are limiting international trade and the

expansion of hydrogen's use for global carbon neutral goals. To investigate possible incentives for a worldwide hydrogen economy and to create new avenues for a carbon-emission-free future, this study suggests the concept of hydrogen credits and creates a system for trading them on the global market, similar to carbon credits. Instead of delving into the technical details of hydrogen generation, transportation and storage, this study aims to tackle the monetary component of GH₂ adoption. The presentation of case studies highlights the possibility of a worldwide hydrogen credit market and the practicality and efficacy of the current framework.

2.8 Socio-Economic and Environmental Benefits of Green Hydrogen

Verma, Sharma, and Mehta (2024) examined the impact of traditional energy sources being lessened while meeting current and future energy demands with the help of hydrogen, a promising new energy carrier. It is both efficient and attractive. Hydrogen is an excellent alternative to petrol since it is non-metallic, has no carbon in its composition, is nontoxic and has more specific energy per mass than petrol. A thorough analysis of systems that rely on hydrogen energy must take into account aspects related to hydrogen generation, storage, safety and consumption. This study examines the global and Indian GH₂ production scenarios through a comprehensive literature review that covers the technical, environmental and basic elements of various hydrogen applications and production methods. The majority of hydrogen is utilised in the chemical industry (40%) and metallurgical processes (33% of the global demand). Its secondary applications include the production of fuel, glass, welding and ingredients for food. Hydrogen is produced using a variety of feedstocks, such as natural gas (49%), crude oil (29%), coal (18%) and electrolysis (3%). Hydrocarbon and alcohol reformation, partial oxidation of fossil fuels and gasification (coal and fossil fuels) are the current methods for producing hydrogen. The problems that these methods address, nevertheless, include significant

amounts of carbon emissions and overall energy usage. Including only small hydroelectric projects, RES in India generated 12,610 MW of electricity, or around 9 percent of the Country's overall installed capacity. Large hydro projects and renewables account for almost 34% or 48,643 MW, of India's total installed capacity, which is 144,980 MW. Initiatives such as "National Green Hydrogen Mission" in 2021 and "GH₂ Policy" in 2022 demonstrated India's forward-thinking approach to hydrogen generation.

Gordon *et al.* (2024) observe that numerous National Hydrogen energy programs have been launched in recent years, reflecting the broad consensus that hydrogen technologies will play a central role in global decarbonization efforts. Remarkably, the Government of the United Kingdom published its Hydrogen Strategy in August 2021, which supports the decarbonization objectives and ambitions regarding energy security. The support of society will be needed to support the hopes of a hydrogen economy even though the techno-economic feasibility of hydrogen energy systems is a precondition of the possible transition. Nonetheless, sociological issues have not been considered in policy references yet. In the case of the so-called hydrogen homes, i.e. homes with low-carbon hydrogen appliances instead of natural gas boilers and stoves, it is extremely important to gain the approval of society. Hydrogen cooking and heating technologies are relatively young, and as such, not much research has been conducted about the factors that influence the opinion of people. Also, nothing is known about how the general public views the hydrogen economy or new national policies. Considering the lack of both theoretical and practical understanding, this research fills that gap by creating an integrated acceptance framework and then putting it through its paces with partial least squares structural equation modelling to measure its predictive capacity. The findings stress the significance of trust dynamics, perceived risk and emotional factors in influencing customer impressions. Firstly, the integration of hydrogen production from renewable sources with

local environmental and socio-economic benefits may hold the key to the possibility of large-scale hydrogen household deployment. To pave the road for socially acceptable transitions, policy recommendations should incorporate social considerations into the technical search for sustainable energy solutions on a large scale.

G. D. Sharma *et al.* (2023) highlight hydrogen as one of the most environmentally friendly fuel sources. Both developed and developing countries have established international frameworks to advance research, investment and policy on hydrogen. Their analysis of 610 peer-reviewed studies published over the past 50 years offer concrete, evidence-based insights into the hydrogen economy. According to the experts in the fields of RE and business, hydrogen will be a component of the energy revolution, which will begin in 2030. This research employs VOS viewer and Bibliometric R-tool, which are tools present in the Scopus database, to carry out a comprehensive literature review of the economic and societal impacts of hydrogen energy. Among the transdisciplinary difficulties that they found most studies focused on were generation, storage, transit, application, feasibility and policy formation. In addition, they show the conceptual framework that came from a thorough literature review and how ideas, themes and aggregate aspects are all connected to bring attention to research gaps and new trends. Future developments in GH₂ generation, risk assessment studies, blending, efficient storage and techno-economic viability will have an important influence on the socio-economic facets of study into hydrogen energy.

Bhatia (2023) identified that the power sector in India is currently experiencing a change that will greatly impact both the Country's development and the worldwide movement to reduce carbon emissions. Scholars working on the topic of sustainability transitions have argued that a multi-disciplinary approach to national energy transitions is essential. Bhatia (2023) notes that India's power sector is undergoing a transformation that

will significantly influence both the Country's development and global efforts to reduce carbon emissions. Scholars in the field of sustainability transitions argue that a multidisciplinary approach is essential for achieving effective national energy transitions. This research is a search-based narrative review study of academic and policy literature on the transformation of the Indian electricity sector between 2011 and 2022. It combines the contents under four aspects as demonstrated justice, techno-economic, socio-technical and political aspects. The study concludes that the pace of India's electrical transformation is controlled by the State, which has implemented pro-renewables laws and controls energy resources, assets and incumbents. Even while the policy mix has been essential in accelerating the deployment of RE, it has failed to encourage manufacturing. Although the thermal fleet is just starting out, there exist intricate political lock-ins beyond the employment factor, demand is uncertain, and integration with the grid is problematic; all of that is to the fact that we will be using coal even longer. Finally, it cites six information gaps pertaining to: (1) the role of Government; (2) incumbents and non-State actors; (3) green industrial policy; (4) key political organisations and groups; (5) social protection and economic diversification; and (6) the way to go forward in Indian development.

Jayakumar *et al.* (2022) evaluated hydrogen gas (H₂) with a critical eye on how it could be used extensively in future as a sustainable fuel in international mobility applications that involve India. Vehicles powered by hydrogen gas can be more economically and technologically beneficial when considered in conjunction with battery electric vehicles and conventional internal combustion engines. The present research reveals that the primary challenges are the expenses associated with producing, storing and delivering hydrogen and that an important advancement is still necessary for hydrogen to potentially compete with automobiles driven by internal combustion engines or electric vehicles powered by batteries. Additionally, the secondary obstacles have been proven, and

they consist of things like the fuel cell stack's price tag, the modifications needed for vehicles powered by internal combustion engines, and regulatory and safety worries that prevent H₂ from being used extensively. A national hydrogen energy roadmap is essential for India's policymakers to make sustainable transportation a reality. In consequence, this can help reach the goal of keeping H₂ costs at \$0.5/kg.

Hamukoshi *et al.* (2022) argue that, compared to the current fossil fuel industry, the Green Hydrogen (GH₂) economy's synthetic green energy offers far-reaching environmental benefits. Research on GH₂ in Southern Africa is still in its early stages, yet many resource-constrained regions are seeking to harness the advantages of sustainable green power. Due to how early this process is, the possible societal advantages are unclear. This is why it's crucial to investigate the monetary and social effects of GH₂ energy. This research summarises the possibilities for social and economic change within the Southern African Development Community (SADC) by surveying relevant literature. This research lends credence to the idea that GH₂ will be useful and might significantly alter the agricultural and industrial industries by bringing about highly sustainable shifts in production and processing. Additionally, the study delves into how sustainable GH₂ energy production in Southern Africa might contribute to global economic growth in the energy export industry while simultaneously lending assistance to CC activities. In addition, it delves into the effects of GH₂ value chain, the rise of green jobs, the necessity of related investments and legislative changes. Workers in sectors that rely on fossil fuels may have to retrain into green jobs if the GH₂ economy causes them to lose their jobs. Efforts to reduce poverty and boost the economy in SADC could be thwarted by such trades.

Bonesso *et al.* (2025) highlight that hydrogen, as an energy carrier, can support the development of flexible and environmentally sustainable power grids. However, meaningful decarbonization can only be achieved when energy is generated from

renewable sources and water resources are managed responsibly. A socioeconomic study of hydrogen production from a southern Italian integrated wind and electrolysis facility is the goal of this effort. In the most basic case, we predict a production of around 1.8 million kg with an LCOH of 3.60 €/kg. According to social research based on an online poll, there is a significant information gap; for example, just 27.5% of respondents say they are familiar with the distinction between green and GH₂. They have a minor tendency to put systems close to their houses, but that's likely to grow as they learn more about it. This study argues that sustainable habits should also be incorporated into everyday energy choices based on what respondents state. By outlining GH₂ as an operations approach that advances sustainable development, the report provides information to individuals, corporations and policymakers.

CHAPTER III: METHODOLOGY

3.1 Overview of the Research Problem

The manufacturing and utilisation of GH₂ as a carbon-free energy system was a critical aspect of the ambitious commitment of India for reaching a net-zero carbon footprint by 2070. GH₂ is a clean fuel; it does not have carbon emissions and could have decarbonised key industries like steel, cement, chemicals and transport (Griffiths *et al.*, 2021). In spite of its great potential, the implementation of GH₂ in India has been undermined by multiple obstacles, which are underdeveloped policies, lack of infrastructure enhancement, high production rates, low technological maturity, and the lack of involvement of the private sector.

The absence of an extensive policy framework and synchronisation among the public and private players is one of the significant drawbacks that India experienced in the GH₂ implementation (Ghosh and Roy, 2024). Despite initiatives by the Government of India, such as the launch of the “National Green Hydrogen Mission” (NGHM), the extent of financial incentives, subsidies, and regulatory frameworks required to enable large-scale production and consumption of green hydrogen remains uncertain. Moreover, the technological obstacles and the cost of production remained a major challenge since GH₂ at the time used costly electrolysis that was fuelled by RES.

From the perspective of the industry, investments in GH₂ projects were checked by public as well as private sector organisations (Singh, Ratn and Jha, 2024b). Nevertheless, the research that was utilised to examine the way their development, challenges, and plans of implementing GH₂ into the Energy Mix were addressed, was limited. Also, the perceptions of the key stakeholders about the role of GH₂ in the energy transition of India

was not extensively investigated and should be evaluated in a more comprehensive way (WEF, 2024).

This study is an attempt to understand more about the policy measures and to assess the progress in the public and the private sector activity, and to find out the views of the stakeholders with respect to the GH₂ ecosystem in India. In this study, the author attempted to present a broad perspective of the upcoming future of GH₂ in India in its journey towards a net zero carbon emission by integrating the reports made by the Government, industries and experts.

3.2 Operationalisation of Theoretical Constructs

To investigate the process of GH₂ uptake in India, the study translated the key theoretical constructs into visible elements that characterise both the macro-level politics and micro-level processes of implementation (Ng et al., 2024). The criteria of coherence and clarity of NGHMs, consistency of the regulatory frameworks, and the confidence of the stakeholders in the long-term support of the Government were used to quantify Policy Effectiveness (Baum et al., 2022). Industry Readiness was gauged by the presence of infrastructure, technological preparedness, R&D initiative, and patterns of public and private investment, the capacity of the industry to boost the output of and integrate the production of GH₂ (Gordon, Balta-Ozkan and Nabavi, 2022).

The barriers related to the adoptions were seen through structural and operational barriers as cost of production, unformed safety standards, weak market mechanisms, and infrastructure constraints discouraged commercialisation (Firoozi et al., 2024). Finally, comparative policy learning was reviewed by benchmarking India's policy efforts against world-class performers like the EU, Japan and others in the transfer of best practices in policy design, fiscal incentives among others. Each construct was systematically incorporated into the study's survey tools by means of particular questions and Likert scale

items. From the perspective of qualitative interview data, however, thematic analysis was performed to understand deeper layers of stakeholder perception and possible gaps in institutions, as well as strategic interconnectivity between the sectors (Jain, 2021). This complex operationalisation allowed a rigorous understanding of the GH₂ landscape in India.

3.3 Research Purpose and Questions

The aim of the study was to critically revisit the role of the GH₂ in the Indian transition to “Net Zero Carbon” (NZC) emissions. GH₂ became one of the areas of interest when the Country began to develop a low-carbon growth pathway since it was considered a clean energy vector that could be applied in the industrial, transport, and energy markets (Pandey, 2024). This study has investigated the horizon of the GH₂ Policy, industry preparedness, State preparedness, financial and scalability and safety implications of the deployment of GH₂. It was also the purpose of the study to determine the enablers and barriers to scaling up the GH₂ ecosystem by synthesising knowledge from literature, Government sources, corporate reports, and stakeholder perspectives. The findings were to guide strategic policy choices, investment patterns, and frameworks of implementation to align with India's ambitions to use GH₂ (Harichandan, Kar and Rai, 2023). The research questions are the following:

- Are the Government’s Policies and initiatives effective enough in the area of Green Hydrogen?
- What is the readiness level of the companies involved in the production of GH₂?
- What is the level of infrastructure required and measures being taken by Producers of Green Hydrogen, Banks and Finance Sector companies and Private Equity players, Venture Funds?

- How is the Challenge of Scalability being addressed including Storage of Green Hydrogen?
- What Safety measures are being implemented for prevention of explosions and leakage as Hydrogen is highly volatile and inflammable?

3.4 Research Design

In order to provide a holistic picture of GH₂'s importance in India during the net-zero carbon transition, the study used a mixed-method research strategy that combined quantitative and qualitative concepts (Raman *et al.*, 2022). It employed an exploratory and descriptive research design where it assessed policy reactions, industry trends, and the view of the stakeholders on the acceptance of GH₂.

The quantitative part contains survey of stakeholders who included policymakers, experts in the industry, and top managers of both publicly traded and privately owned firms (Bakhtiari *et al.*, 2024).

The qualitative part of the study, which included the literature review, policy analysis, and company reports, was aimed at discussing the regulatory environment, investment in the industry and best practices of GH₂ deployment (Vallejos-Romero *et al.*, 2023). In addition, some interviews, including energy policymakers, managers of the GH₂ industry, and financial-sector professionals, were conducted in-depth. The interviews were expected to give a deeper understanding of regulatory bottlenecks, investor moods, safety regulations and how the market will be scalable. The qualitative information supplemented the survey findings through the contextual and detailed information on the perspectives of stakeholders (Jain, 2021).

Such research design has embraced the strengths of a quantitative perspective of stakeholders and the qualitative perspective of policy-industry analysis to reach a balanced, data driven method of providing actionable recommendations to policymakers, businesses

and researchers in the domain of increasing the GH₂ adoption in India (Onifade *et al.*, 2024).

3.5 Population and Sample

The participants in the study will be the primary stakeholders in the development and adoption of GH₂ in India, such as policymakers, industry specialists, and top leaders of both governmental and business enterprises that work on hydrogen production, RE, and sustainability programs (Janardhanan *et al.*, 2024). This is a wide range of individuals who are the key actors and drivers of the direction of GH₂ adoption in India towards net-zero carbon emission.

3.6 Participant Selection

The participant selection of this study was based on the following Table 3.1:

Criteria	Inclusion	Exclusion
Expertise	Policymakers, industry experts, and senior leaders in GH ₂ and RE sectors	Individuals with no direct experience or expertise in GH ₂ or related fields
Affiliation	Officials from Government, public and private sector, energy research and sustainability professionals	Individuals from unrelated industries with no involvement in GH ₂ policy, production, or research
Geographical Scope	Participants based in India actively contributing to GH ₂ initiatives	Individuals from outside India not directly involved in India's GH ₂ sector
Decision-Making Role	Involvement in policy formulation, investment decisions, research, or implementation of GH ₂ projects	Entry-level employees or individuals without decision-making influence in the sector
Availability for Participation	Individuals willing to participate and share insights on GH ₂ adoption	Individuals unwilling to participate or unable to provide relevant insights

Table 3.1: Inclusion and Exclusion

Source: Author Generated

3.7 Instrumentation

In this study, two types of primary instruments were employed for data collection: a structured survey questionnaire and two semi-structured interview guides.

The survey instrument was a combination of Likert-scale and multiple-choice questions aimed at collecting quantitative data on such essential aspects as Policy clarity and effectiveness, infrastructure and industry readiness, investment feasibility, and safety concerns (Sadan, 2017; Sharma, 2022). It was targeted at a diverse set of stakeholders such as policymakers, industry leaders and energy experts to create quantifiable perceptions of the adoption of GH₂ in India. The survey was administered via Google Forms and disseminated through social media platforms to maximise reach

In addition, the semi-structured interview guide was designed to capture deeper qualitative insights from key informants across two stakeholder categories:

- Senior representatives from **Government departments/institutions**
- Senior representatives from **Private institutions**

Interview topics included regulatory perspectives, policy gaps, infrastructure and scalability challenges, financing barriers, safety frameworks and opportunities for public–private collaboration.

3.8 Data Collection Procedures

The study used mixed method of data collection that entailed the use of primary and secondary sources to give a general picture of how GH₂ can help India to attain net zero carbon emissions (Marouani *et al.*, 2023). The quantitative and qualitative data was used to merge the secondary information with the perspectives of the industry stakeholders that will be obtained through literature, policy statements and corporate reports and hence give a complete scenario of the sector.

- **Primary Data Collection**

To accomplish this, the formal survey was drawn to gather first-hand data of 50 major stakeholders, including policymakers, industry specialists and senior officials in both the government and private sector (Maurer *et al.*, 2022). The survey consisted of closed-ended and Likert scale questions covering key areas such as the effectiveness of policies, market challenges, investment patterns, and technological innovation in GH₂ (Leske, 2023). Convenience sampling was employed, with participants selected based on their relevance and availability to the research context. The survey was administered using Google Forms and disseminated via social media platforms to reach a diverse group of respondents.

In addition to the survey, four in-depth interviews were conducted — two with senior representatives from Government departments /institutions and two with senior representatives from private institutions. These interviews provided deeper qualitative insights into policy implementation, market readiness, safety frameworks, and public–private collaboration in GH₂ development.

- **Secondary Data Collection**

Besides collecting primary data, the study also made use of several official secondary sources to validate the research findings. Analysis of the regulations of the GH₂ industry and the industry reports and policy documents, and investment data were investigated thoroughly (Das, 2023).

Additional sources of secondary data consist of:

- **Government Reports and Policy Documents:** This was done by reviewing National Policies and Government announcements on the development of GH and the strategic roadmaps and incentives that are being offered by India through

the Ministry of New and RE (MNRE), NITI Aayog and other related Government agencies (Gesellschaft, 2024).

- **Corporate Reports and Sustainability Disclosures:** The reports of corporate investments in GH₂ from companies such as JSW Energy, Reliance Energy, Adani Energy, Greenko and Hero Future Energies were evaluated to provide a picture of industry support, funding behaviour, and production and consumption data in both the public and private sectors.
- **Academic Research and Industry Publications:** This study has examined academic journals and industry publications to acquire information on GH₂ technical issues, global best practices and new trends (Hassan *et al.*, 2024).

The combination of quantitative stakeholder surveys with qualitative analysis of Interview, Policy and industry trends created a complete approach to discerning the status of GH₂ in India and its obstacles (Kokkinos *et al.*, 2023). These results produced important information among the authorities, industrial directors, and scientists, who could use the information to enhance the rate at which GH₂ is adopted to ensure that India meets its goal of net-zero carbon emissions.

3.9 Data Analysis

This study integrated a mixed-method approach in the data analysis process to allow both quantitative and qualitative methods to obtain an informed conclusion of the primary and secondary sources of information (Ahmed, Pereira and Kimberly, 2023). The SPSS (Statistical Packages for Social Sciences) software was used to analyse the results of the quantitative data that was collected in the form of stakeholder surveys (Alili and Krstev, 2019). In order to sum up the answers and analyse the dependence of variables, evaluate the effect of policy initiatives, financial investment and technological preparedness on the

adoption of GH₂, the descriptive statistics, correlation, and regression analyses were performed. In this,

- **Descriptive Statistics** – Used to summarize and present the key characteristics of the collected data, providing an overview of trends, distributions and central tendencies (Mishra *et al.*, 2019).
- **Correlation Analysis** – Applied to measure the strength and direction of relationships between variables, helping identify potential associations (El-Hashash and Shiekh, 2022).
- **Regression Analysis** – Used to examine the predictive relationship between independent and dependent variables, enabling the assessment of how changes in one or more factors influence the outcome (Koletsis and Pandis, 2018).

In the qualitative component, the top concepts and thematic trends were identified and analysed through thematic analysis of the interview data. This plan assisted in recording critical issues and priorities of the key stakeholders on the topic of Policy gaps, funding obstacles, infrastructure readiness and safety concerns.

In addition, the financial and GH₂ related data from key contributors such as JSW Energy, Reliance Energy, Adani Energy, Greenko and Hero Future Energies was analysed in order to evaluate their operational and financial preparedness to assist India's clean energy transformation, as well as their strategic alignment with the National GH₂ Mission.

Also, secondary data like Government reports, corporate sustainability facts and academic research were used, and the qualitative content analysis was carried out to derive information on Policy effectiveness, trends in investment, global standards and industry failures. The research benchmarks India's GH₂ strategies against leading international practices (e.g., EU, Japan, Australia) to draw lessons and suggest strategic improvements

(Pinto, 2023). Based on quantitative trends and qualitative insights, the research aimed to provide practical recommendations to accelerate GH₂ adoption in India's transition to net-zero carbon emissions (Khadka, 2023).

3.10 Research Design Limitations

- **Convenience Sampling Bias:** Specifically, convenience sampling as a method of collecting primary data will provide selection bias and hence prevent their extension to the entire GH₂ sector.
- **Limited Sample Size:** With a small sample size, the study may not have fully captured the diverse perspectives of all stakeholders, which could affect the statistical robustness of the analysis.
- **Response Bias:** Social desirability bias occurs through self-reported survey data that participants respond based on what the industry thinks is good and not necessarily on what experiences they had.
- **Dependence on Secondary Data:** As the policies and investments in GH₂ are constantly evolving, relying on Government reports, corporate disclosures and literature from the industry may lead to including outdated or incomplete information.
- **Evolving Policy Landscape:** The relevance of some of the Policy assessments carried out during the study may be affected by any changes in Government regulations and international climate commitments.

3.11 Conclusion

The study examined the changing landscape of GH₂ adoption in India as a strategic choice on the road to NZC emissions. By combining industry survey statistics with qualitative impressions gained from interviews and other secondary evidence, the research created an all-rounded picture of the major enablers, barriers, and opportunities in the

Indian GH₂ ecosystem. The findings showed that despite evident Policy intents, captured in efforts such as NGHM, there will be a lot of differences in areas such as industry readiness, lack of finances, safety considerations, and scalable infrastructure. Prime stakeholders – Governments, private sector players and financial institutions understood the prospects of GH₂ but highlighted the requirement of common Policy, encouraged investments and strong risk management structures.

In addition, conducting comparative benchmarking of India's GH₂ strategy against the global best practices – like being followed by the EU, Japan, and Australia – revealed beneficial lessons in the area of continued policy commitment; facilitation of R&D; and cooperation across sectors. The interviews held and analysed through thematic analysis methods identified some of the recurring issues, which were ambiguity in policies, safety hazards, storage challenges and limitations to resources. At the same time, the content analysis of secondary data emphasised the necessity of synchronising industry efforts with policy targets with views of speeding up deployment. In conclusion, the study provides policy-relevant strategic pointers to policymakers, industry leaders, and researchers to ensure developing a more resilient and scalable GH₂ ecosystem, which is essential for India's decarbonisation and energy transition goals.

CHAPTER IV:

RESULTS

4.1 Introduction

The “National Green Hydrogen Mission” (NGHM) was initiated in January 2023 by the Indian Government with the goal of making India a leading global player in the production, use, and export of Green Hydrogen (GH₂). The Government is eager to expedite the implementation of the Mission (National Portal of India, 2023). To sustain the advancement of the sector, it is imperative to rationalise and harmonize safety and performance standards, approval procedures, and regulatory frameworks pertaining to GH₂ projects within India. According to the Ministry of New and Renewable Energy (2024), the initiative's goal is to produce 5 (MTPA) of GH₂ by 2030. This would put it third globally, after only the United States (US) and the European Union (EU).

The Mission’s comprehensive scope encompasses large-scale capacity auctions, Research and Development (R&D), and testing infrastructure, aiming to eliminate cost barriers, drive electrolyser manufacturing, and accelerate deployment across sectors such as mobility, industry, and ammonia export (Ministry of New and Renewable Energy, 2023).

4.2 Installed Capacity and Ongoing Projects

Companies in the conventional energy sector, especially those dealing with oil and gas, pose a threat to and an opportunity for the Hydrogen economy. The use of cleaner energy sources, such as Hydrogen, is being investigated by numerous well-established energy companies. Motivating their actions is the necessity to lessen environmental impacts without sacrificing profits, as well as the hope of capitalising on emerging energy market prospects.

Traditional energy players face numerous hurdles while transitioning to hydrogen. It takes a lot of capital and technical changes to convert current infrastructure to handle hydrogen, particularly for blue hydrogen generation that uses natural gas with “Carbon Capture and Storage” (CCS). Further complicating these transition efforts are regulatory uncertainty, especially with relation to carbon price and environmental requirements.

Key to a successful transition is a coordinated plan. Conventional energy providers, Government agencies, and academic organisations can share the financial and technical costs of implementing Hydrogen technology. Industry heavyweights form joint ventures to build large-scale GH₂ projects; examples include BP and Equinor in Europe.

Hydrogen is essential to India's long-standing energy transformation plan, which includes State-run enterprises. Major oil and gas companies are exploring the potential of hydrogen as an energy source, with investments in pilot projects and potential joint ventures being considered. This change allows these long-standing companies to compete in the energy market despite its fast evolution, while simultaneously lowering carbon emissions (Green H Electrolysis, 2025).

With a total projected capacity of 10.55 MTPA, 143 renewable or low-carbon Hydrogen projects in India were recorded in the S&P Global Hydrogen Production Assets database as of March 2025. Still, the vast majority have not even begun the front-end engineering design (FEED) or pre-construction phases. The NGHM program, which has funding of ₹197.44 billion (USD 2.37 billion) from the Indian Government, is crucial in promoting the production of renewable Hydrogen and ammonia, as well as the advancement of electrolysers and manufacturing centres (Bio Energy Times, 2025). Smaller operational projects in the pilot or early demonstration phase include:

Company / Entity	Location	Capacity (tpa or per day)
ACME Cleantech (green ammonia + H ₂)	Bikaner, Rajasthan	5 t/day ammonia + 500 Nm ³ /h (~15 tpa)
Bharat Petroleum Corporation Limited (BPCL)	Bina Refinery, Madhya Pradesh	0.7 ktpa
National Institute of Solar Energy	Gurugram, Haryana	10 Nm ³ /h (~0.3 tpa)
INOX India	Chittorgarh, Rajasthan	190 tpa
Hygenco Green Energies Pvt. Ltd. (3 plants)	Ujjain (16 tpa), Hisar (78 tpa), Sambhajinagar (230 tpa)	Total 324 tpa
SJVN – Nathpa Jhakri (fuel cell demo)	Himachal Pradesh	14 kg/day (~5 tpa)
THDC India	Rishikesh, Uttarakhand	50 kg/day (~18 tpa)
Larsen & Toubro Limited	Hazira, Gujarat	15 tpa
Oil India Limited	Assam	30 kg/day (~11 tpa)
Hero Future Energies	Tirupati, Andhra Pradesh	25 tpa
GAIL (India) Limited	Vijaipur, Madhya Pradesh	10 MW electrolyser (~3,500 tpa)
Adani New Industries Limited (pilot)	Kutch, Gujarat	5 MW (~1,750 tpa)
NTPC (multiple sites, incl. Leh)	Gujarat & Leh	Pilot-scale capacity

Table 4.1: Selected Green Hydrogen Projects in India (Operational/Pilot)

Source: Jha (2025)

Combined, these capacity figures total approximately 5–6 MW equivalent of electrolyser power, or around 3,000–4,000 tons per annum (tpa) of GH₂, with several additional hydrogen-buoyed ammonia plants in the planning pipeline (Jha, 2025).

4.3 Policy & Regulatory Measures

4.3.1 Financial Incentives

Under NGHM, the Government has launched the Scheme Implementation Guidelines (SIGHT), funding up to 862,000 tpa electrolyser capacity, and in FY 24–25

awarded ₹22.39 billion (~US\$261 million) for 450 ktpa, bringing the total capacity funded to 900 ktpa (Bio Energy Times, 2025).

In addition, auctions for “Mode 2B” GH₂ production, totalling 200 ktpa, offer incentives that scale down from ₹50/kg in Year 1 to ₹30/kg in Year 3. In a study Curcio, (2025) found that GH₂ cannot compete with hydrogen produced from fossil fuels in terms of cost unless renewable power costs fall below \$20–\$30/MWh. GH₂ costs should be lowered to \$1.00/kg by 2031, according to the DOE's Hydrogen Shot Initiative. This initiative highlights the importance of reducing capital expenditures, achieving economies of scale, and improving the efficiency of electrolyzers. Transport costs can be reduced by 50-70% through pipeline retrofitting; however, energy losses and conversion costs make liquid hydrogen and chemical carriers expensive. Infrastructure is still a major barrier. By 2035, GH₂ is estimated to have received more than \$250 billion in investment, much outpacing the \$100 billion forecasted for blue hydrogen. By 2030, the transition to low-carbon hydrogen will be hastened, as grey hydrogen will likely become uncompetitive due to carbon pricing exceeding \$100/ton CO₂, accelerated by the increasing cost of CO₂ emissions. With GH₂ set to play a pivotal role in the net-zero energy transition by 2035, the future of hydrogen looks bright, but only if prices continue to fall, incentives remain in place from policymakers and infrastructure continues to expand.

4.3.2 Transmission & Duty Waivers

Project developers gain a 25-year waiver from Inter-State Transmission System (ISTS) charges if the projects are commissioned before December 2030. Duty exemptions for Special Economic Zone-based GH₂ /ammonia plants further enhance economic viability (Bio Energy Times, 2025).

4.4 Cost Viability & Mobility Applications of Green Hydrogen in India

India's dynamic diesel pricing, currently averaging ₹87.62 per litre in Delhi and ₹90.03 in Mumbai as of July 24, 2025, underscores the expense of conventional fuels when taxation is factored in. At typical heavy-truck efficiency (~3 km/l), this translates to roughly ₹29–30 per kilometre.

GH₂, by contrast, is trading around ₹350 per kg (~US\$4.2)—a price trajectory confirmed in recent Indian auction bids (Mint, 2023). Fuel cell trucks currently consume approximately 9 kg per 100 km, reducing the per-km cost to ₹31.5, which is on par with diesel. However, with projected efficiency improvements (reaching 6.6 kg/100 km by 2030), the cost drops to ₹23 per km, nearly 25% lower than diesel (details in Table 4.2).

Fuel Type	Price Unit	Consumption per 100 km	Cost per km (₹)
Diesel	₹90/litre	33 litres	30.0
Green H ₂ (present)	₹350/kg	9 kg	31.5
Green H ₂ (2030 forecast)	₹350/kg	6.6 kg	23.1

Table 4.2: Per-km Fuel Cost Comparison

Source: Author Generated

Besides the economic aspect, the advantages of Hydrogen in its operation cannot be overestimated. In Delhi, four Hydrogen buses have shown a range of 350 km, and in Delhi, the Hydrogen buses are powered by four 30 kg tanks. The refuelling time has also been reduced, and now the four tanks will fill in 0-12 minutes. GH₂ is one hundred percent sustainable and does not produce gases that are polluting in its combustion or production phase (Mint, 2023).

4.5 Findings of Company Analysis

This section presents a comparative analysis of five major companies actively contributing to India's GH₂ ecosystem—JSW Energy, Reliance Energy, Adani Energy, Greenko and Hero Future Energies. It evaluates their annual investments in GH₂ projects,

share of renewables in total energy, capital expenditures, financial performance indicators (including ROE, ROA, EPS, ROCE), and leverage positions from 2021 to 2024. The analysis aims to assess their strategic alignment with the National GH₂ Mission and their operational and financial readiness to support India's clean energy transition.

Indicator	2024	2023	2022	2021
Annual investment in green hydrogen projects	Estimated ₹200 Cr	Estimated ₹150 Cr	Initial feasibility & infra	-
Share of total energy from renewables (%)	~65%	~61%	~55%	~30%
Capital Expenditure (₹ Cr)	₹6,130 Cr	₹4,835 Cr	₹3,270 Cr	₹2,140 Cr
Debt-to-Equity Ratio	0.5	0.51	0.59	0.65
Return on Equity (ROE)	10.40%	10.80%	10.20%	9.60%
Operating Profit Margin	38.70%	39.50%	37.40%	36.10%
Earnings Per Share (EPS)	₹12.9	₹12.2	₹11.1	₹10.0
Return on Capital Employed (ROCE)	12.10%	11.50%	10.90%	10.30%
Return on Assets (ROA)	5.10%	4.80%	4.20%	3.90%
Total Assets (₹ Cr)	₹42,320 Cr	₹39,770 Cr	₹35,650 Cr	₹31,980 Cr

Table 4.3: JSW Energy

Source: Author Generated

JSW Energy has been exhibiting a profitable and strategic transition towards sustainability and GH₂ preparedness from 2021-2024. In 2022, the Company initiated feasibility and infrastructure preparations for GH₂ and has gradually increased its planned expenditure to 200 crore INR by 2024, indicating an expanding interest in GH₂ development. At the same time, the proportion of renewables in overall energy production has increased by more than twofold, with the total percentage of energy produced by renewables rising to 65 percent in 2024, compared to 30 percent in 2021, marking a significant shift towards the production of clean energy. This is backed by a massive capital outlay increase in 2021 of 2,140 crore INR to a huge expenditure of 6,130 crore INR in 2024, possibly indicating intensive development of infrastructure and perhaps correlating

with its RE and hydrogen plans. The Company has also recorded positive financial performance indicators during this transition. There was consistently a lower debt-to-equity ratio, which was 0.65 in 2012 and 0.50 in 2013, showing a healthier balance sheet and less financial risk. Even after its incremental investment, JSW was in good shape with its ROE remaining between 1011%, as well as its operation profit margin always remained healthy with an average margin of nearly 39 %. Moreover, the earnings per share (EPS) went up by ₹2.9 (2021-2024), ROCE and ROA improved steadily, indicating better capital efficiency and better asset utilisation. This growth of 32% or more reflects the increase in total asset base, which went up to 42,320 crores in the period from 31,980 crores in 2021, a terrific base to scale up. On the whole, JSW Energy appears financially robust and operationally well-positioned to lead the Indian GH₂ ecosystem, with its planning efforts aligned with the goals of the National GH₂ Mission and the overall net-zero transition.

Indicator	2024	2023	2022	2021
Annual investment in green hydrogen projects	Part of ₹1,31,769 Cr capex (not separately given)	Giga Complex investment underway	\$10 Bn announced (₹75,000 Cr over 3 yrs)	Initial planning phase
Share of total energy from renewables (%)	~1.35%	~0.83%	~0.67%	-
Capital Expenditure	₹1,31,769 Cr	₹1,16,961 Cr	₹99,472 Cr	₹76,400 Cr
Debt-to-Equity Ratio	0.44	0.44	0.34	0.36
Return on Equity (ROE)	8.8%	~11.0%	~10.5%	12.50%
Operating Profit Margin	15.6%	15.8%	~15.9%	11.90%
EPS	₹103.9	₹98.0	₹92.0	₹76.4
ROCE	~9.4%	~11.0%	~10.2%	~9.5%
ROA	~4.6%	~4.7%	~4.6%	~3.4%
Total Asset	₹16,00,000 Cr	₹15,77,093 Cr	₹14,48,323 Cr	₹13,15,998 Cr

Table 4.4: Reliance Energy

Source: Author Generated

Between 2021 and 2024, Reliance Energy has made substantial strides toward positioning itself as a major player in India's GH₂ transition, backed by massive capital commitments and infrastructure planning. Beginning with strategic planning in 2021, the company formally announced a \$10 billion (approximately ₹75,000 crore) green energy investment in 2022 and has since been deploying capital under this umbrella, including in the Giga Complex initiatives. By 2024, Reliance had committed ₹1,31,769 crore in capital expenditure, although exact GH₂ investment figures were not separately disclosed. Despite the scale of investment, the share of total energy from renewables remains relatively modest, increasing gradually from under 1% in 2021 to approximately 1.35% in 2024, indicating the early-stage integration of renewable sources within a vast energy portfolio. Financial indicators suggest stable profitability and operational efficiency: ROE ranged from 12.5% in 2021 to approximately 8.8% in 2024, and the operating profit margin remained consistently strong at around 15.6%–15.9%, despite large-scale investments. The Earnings Per Share (EPS) steadily grew from ₹76.4 in 2021 to ₹103.9 in 2024, reflecting enhanced shareholder returns. ROCE and “Return on Assets” (ROA) remained within healthy margins, suggesting prudent asset utilisation and capital efficiency. The company's Debt-to-Equity ratio stayed stable at around 0.44 from 2023 to 2024, indicating controlled leverage while scaling operations. Meanwhile, Reliance's total asset base expanded significantly, from ₹13.15 lakh crore in 2021 to over ₹16 lakh crore in 2024, underscoring the company's aggressive growth strategy. In general, although current penetration of RES by Reliance Energy remains at initial phases, the financial capabilities, development of an infrastructure, and top-level determination make it one of the key players in the GH₂ economy of India in the future, as outlined by the National GH₂ Mission.

Indicator	2024	2023	2022	2021
Annual investment in green hydrogen projects	₹100 billion (group-level pledge)	₹100 billion (pledged)	Not specifically mentioned	Not specifically mentioned
Share of total energy from renewables (%)	100%	100%	100%	100%
Capital Expenditure	₹20,124 Cr	₹15,769 Cr	₹10,987 Cr	₹8,735 Cr
Debt-to-Equity Ratio	4.0	5.4	~5.6	~6.0
Return on Equity (ROE)	0.174	0.131	0.125	0.109
Operating Profit Margin	92%	0.9	0.89	0.85
EPS	₹11.4	₹9.1	₹7.3	₹5.8
ROCE	0.129	0.103	0.094	0.076
ROA	0.052	0.043	0.037	0.031
Total Asset	₹1,42,193 Cr	₹1,09,312 Cr	₹91,202 Cr	₹72,450 Cr

Table 4.5: Adani Energy

Source: Author Generated

Adani Energy has made a bold commitment towards GH₂ by pledging ₹100 billion at the group level starting in 2023, although specific deployment figures remain limited. This pledge reflects an ambitious strategic vision to lead in the renewable hydrogen space. Notably, Adani Green Energy Limited operates as a 100% RE company, highlighting full alignment with clean energy generation, unlike its peers, who are still transitioning from fossil fuel portfolios. Capital expenditure has grown substantially over the years—from ₹8,735 crore in 2021 to ₹20,124 crore in 2024—indicating a strong build-out of infrastructure to support renewable expansion and potentially GH₂. Financially, the company shows improving profitability and returns, with Earnings Per Share (EPS) doubling from ₹5.8 in 2021 to approximately ₹11.4 in 2024, and ROE rising from 10.9% to 17.4% over the same period, reflecting growing investor value and improving internal efficiency. ROCE and “Return on Assets” (ROA) also exhibit a consistent upward trend,

albeit modest, rising from 7.6% and 3.1% in 2021 to 12.9% and 5.2% in 2024, respectively. A critical point of concern remains the Company's high leverage, with the Net Debt to EBITDA ratio at 4.0x in 2024, down from 6.0x in 2021, which still signals a reliance on debt-fuelled growth. However, this reduction over time demonstrates improving capital management. The EBITDA margin has remained extraordinarily high, reported at 92% in 2024, reflecting the efficiency of its operational model in the renewable energy sector. Furthermore, the total asset base has doubled from ₹72,450 crore in 2021 to ₹1,42,193 crore in 2024, supporting the group's rapid capacity expansion and infrastructure development. Overall, Adani Energy stands out as a fully renewable enterprise with an aggressive capital and GH₂ commitment, but it must manage its high debt profile carefully to ensure long-term sustainability. Its strong growth trajectory and operational scale position it as a critical contributor to India's net-zero transition and the GH₂ ecosystem.

Indicator	2024	2023	2022	2021
Annual investment in green hydrogen projects	\$20 B planned (3–5 yrs)	Part of the long-term energy transition	\$8.1 B cumulative till date	Not explicitly mentioned
Share of total energy from renewables (%)	100%	100%	100%	100%
Capital Expenditure	₹5,778 Cr	₹5,528 Cr	₹5,000 Cr	₹4,286 Cr
Debt-to-Equity Ratio	3.9	4.1	4.2	4.5
Return on Equity (ROE)	0.102	0.093	0.081	0.078
Operating Profit Margin	84.6%	0.837	0.829	0.812
EPS	₹7.3	₹6.8	₹6.3	₹5.5
ROCE	0.089	0.081	0.076	0.068
ROA	0.039	0.036	0.032	0.029
Total Asset	₹94,752 Cr	₹84,231 Cr	₹76,540 Cr	₹68,120 Cr

Table 4.6: Greenko

Source: Author Generated

Greenko has positioned itself as a leading pure-play RE company with a strong long-term vision for GH₂ integration. By 2024, the company had announced a planned investment of \$20 billion over the next 3–5 years specifically aimed at energy transition, including GH₂ infrastructure, building on the \$8.1 billion already invested cumulatively by 2022. With a 100% RE portfolio throughout the period, Greenko exemplifies a full commitment to clean energy, unlike several peers that are still undergoing a renewable shift. Its capital expenditure has steadily increased from approximately ₹4,286 crore in 2021 to ₹5,778 crore in 2024, demonstrating sustained infrastructure development to support its energy and hydrogen goals. Financially, Greenko has shown consistent, though moderate, improvement in returns: ROE has increased from 7.8% in 2021 to 10.2% in 2024, and Earnings Per Share (EPS) grew from ₹5.5 to ₹7.3 over the same period. However, its Return on Assets (ROA) and ROCE remain relatively low (ROA: 3.9% in 2024, ROCE: 8.9%), suggesting continued high capital intensity. The Company's EBITDA margin remains robust at around 84.6%, reflecting strong operational performance; however, its financial structure is heavily leveraged, with a Net Debt-to-Equity ratio of 3.9x in 2024—a slight improvement but still indicative of significant borrowing. It is important to note that the total asset base of Greenko has grown by ₹68,120 crores in the year 2021, to ₹94,752 crores by the year 2024, which is also an indication of scale-up and asset backed-growth. All in all, with the well-established renewable base, ambitious hydrogen investment strategy, and robust operational performance, Greenko is an essential contributor to the journey towards GH₂ in India. Financial prudence will be critical however in maintaining its high leverage as it continues to fulfil its green infrastructure aspirations.

Indicator	2024	2023	2022	2021
Annual investment in green hydrogen projects	Pilot project in progress (Hydrogen Valley)	MoUs and pilot strategy initiated	R&D phase only	Not reported
Share of total energy from renewables (%)	~100%	~100%	~100%	~100%
Capital Expenditure	₹298.99 Mn	₹62.16 Mn	450 Mn	176 Mn
Debt-to-Equity Ratio	2.33	3.61	3.45	0.8
Return on Equity (ROE)	5%	-30%	-116.18%	-
Operating Profit Margin	22.50%	21%	-	-40.80%
EPS	₹0.43	₹0.06	-	-
ROCE	2%	4%	-37.13%	3.34%
ROA	-	-	-	-
Total Asset	₹1,08,874 Mn	₹1,24,426 Mn	₹1,36,080 Mn	₹1,12,500 Mn

Table 4.7: Hero Future Energies

Source: Author Generated

Hero Future Energies (HFE) has adopted a calculated approach to developing GH₂, first undertaking R&D in 2022, which is expected to be followed by pilot projects by 2024. This will commence with the establishment of a pilot plant within the Hydrogen Valley project. Compared with larger players, the company is still in its early days of achievement, but the undertaking is a clear sign of long-term commitments toward GH₂ integration. HFE does not expect to face RE bleeding during the next 5 years (2021-2024), which is completely in line with India's clean energy prospect and net-zero goal. Nevertheless, its financial trend shows serious fluctuations. There has been unstable capital expenditure with a high of 450 million rupees in 2022 and a decline to 62.16 million rupees in 2023 and then it rises to a high of 298.99 rupees in 2024- thus indicating spurts of investment, which may be due to funding capacity or time of the project. Performance metrics have also been affected, with a highly negative ROE figure of - 116.18 in 2022 with an improvement at - 30% in 2023, and positive in 2024 (5%), which shows a gradual healing of previous losses

of operation or investments. In the same vein, ROCE also reversed its 2022 figure of -37.13 to a 2024 figure of 2. The operating profit margin is also increasing, shifting to 22.5 percent in 2024 after recording a substantial negative value in 2021, which indicates greater cost discipline or improved revenue. Earnings Per Share (EPS) is low at 0.43 in 2024, but the figure is in a steady progression, which was close to zero in the previous year. Its debt-to-equity ratio in 2023 recorded 3.61, lowering to 2.33 in the following year, yet showing significant leverage in comparison to its equity. Interestingly, although the performance is fluctuating, the total asset base has decreased since 2022 (1,36,080 million to 1,08,874 million), possibly reflecting either asset revaluation, divestments, or financial reorganization. Comprehensively, Hero Future Energies is a committed renewable energy company whose rising Hydrogen roadmap holds promise; however, its financial integrity and capital capacity will be pivotal to expanding GH₂ deployments and surviving in India's fast-changing clean power environment.

4.5.1 Corporate Readiness and Investment Trends in Green Hydrogen Transition

The comparative performance analysis of leading Indian energy companies reveals significant variations in their approach to GH₂ adoption, RE integration, and financial sustainability. Each Company's trajectory offers insights into its current readiness and long-term viability in contributing to India's National GH₂ Mission and net-zero targets.

Green Hydrogen Investment and Strategy: Among the companies evaluated, Reliance Energy and Greenko have so far announced the largest financial commitments to Green Hydrogen (GH₂). Reliance has pledged over ₹1.3 lakh crore in capital expenditure under its clean energy program, with GH₂ being a core pillar. Greenko, a fully renewable energy operator, has outlined a \$20 billion investment plan focused on the energy transition, including Hydrogen, reflecting its long-term strategic intent. In contrast, Adani Energy has committed ₹100 billion at the group level but without clear project-level

allocations, suggesting the plans are still in early execution stages. JSW Energy has gradually increased its annual investments (₹150–₹200 crore by 2024), positioning itself as an emerging hydrogen player. Meanwhile, Hero Future Energies, although a 100% renewable company, is at a pilot and R&D stage with limited financial outlay, indicating cautious entry.

Renewable Energy Share: Both Greenko and Hero Future Energies have maintained a 100% RE portfolio, offering them a natural platform for GH₂ integration. JSW Energy has also demonstrated a significant increase in its renewable share, rising from 30% in 2021 to 65% in 2024, highlighting its rapid diversification. In contrast, Reliance's renewable contribution remains below 2%, underscoring that its portfolio is still dominated by conventional energy and that hydrogen development is more investment-driven than operationally embedded. Adani Energy, through Adani Green, also reports full renewable generation within that entity, aligning its platform with the future GH₂ market.

Financial Health and Sustainability: JSW Energy emerges as the most financially balanced entity, with steady improvements in profitability, capital efficiency (ROCE 12.1%), and declining debt ratios, all while expanding its renewable base. Reliance, with massive asset size and consistent EPS growth, is well-capitalised but shows only marginal improvement in ROA and ROCE, suggesting ongoing high capital intensity. Adani Energy and Greenko, though aggressively expanding, have notably high debt-to-equity ratios (4.0x and 3.9x respectively), signalling elevated financial risk despite growing returns. Hero Future Energies has faced the most volatility, with erratic capital investment and severe negative ROE and ROCE until a slight recovery in 2024, pointing to structural financial instability that could hinder its hydrogen ambitions.

Operational Efficiency: From an operational standpoint, Adani and Greenko exhibit industry-leading EBITDA margins (~92% and ~85% respectively), indicating lean

and profitable models, possibly due to asset-heavy long-term contracts. JSW maintains healthy but more moderate profit margins (~38%), while Hero Future Energies operates at lower efficiency (~22.5% OPM), although it has improved from previous losses. Reliance, due to its diversified portfolio, maintains an average OPM (~15.6%).

4.6 Thematic Analysis of Green Hydrogen Stakeholder Perspectives

This section presents insights from qualitative interviews with key representatives from both Government and Private institutions involved in India's GH₂ ecosystem. The analysis highlights major thematic areas, including policy effectiveness, infrastructure readiness, investment climate, technological gaps, and safety preparedness. The themes have been organised in structured tables and are interpreted to reflect current realities, perceived challenges, coping mechanisms and stakeholder outlooks.

4.6.1 Thematic Analysis – Interview 1 and 2 (Government Department / Institutions)

This sub-section provides a thematic breakdown of feedback from senior representatives within Government departments / affiliated bodies overseeing GH₂ development. The stakeholders outline institutional challenges in market development, regulatory implementation, cost structures, and coordination with private entities.

Key Challenge	Perception of Policy Effectiveness	Effects on Readiness/ Implementation	Coping/Strategic Measures	Organisational/ Govt Support	Outlook/ Attitude
Supply-demand mismatch, offtake gaps	Government policies moderately effective, some gaps remain	Slow adoption due to lack of market security	Demand aggregation, tender mechanisms, gradual investment	PLI schemes, limited policy clarity	Cautiously optimistic about future scale-up

Unclear regulations, approval delays	Regulatory clarity lacking, slows project execution	Barriers in project execution and safety compliance	Focusing on regulatory consultation and pilot models	Supportive intent, but inconsistent follow-through	Realistic, requires more robust frameworks
High tech and infra cost for scaling	Policy is catalytic but does not fully address cost-side	Delayed readiness due to funding and capex concerns	Cost reduction in manufacturing, internal capacity building	Limited subsidies, early-stage policy mechanisms	Hopeful, but demands stronger government incentives
Limited stakeholder coordination	Early-stage coordination across actors	Collaboration exists, but lacks structure	Viability-gap funding proposed, private consultations	Consultations happening, but too dispersed	Believes structured PPPs can unlock scale
Investor hesitation and credit concerns	Financial ecosystem not fully aligned	Risk-averse investment environment delays deployment	Focus on credible offtake models and performance guarantees	PE/VCs show interest, but seek more confidence	Needs de-risking to inspire institutional commitment
Raw material supply, storage tech gaps	Infrastructure is bottleneck	Tech readiness is hindered by supply and storage limits	Investing in upstream material chain, basic safety adoption	Government facilitator role acknowledged	Warns delays without infra overhaul
Volatility and safety risks	Standards adopted internally, but the general framework lacks maturity	Operational risk remains high without standardisation	Following global safety norms, some internal audits	No formalised safety compliance system yet	Alert but confident with internal control

Table 4.8: Institutional Stakeholder Themes on Green Hydrogen Challenges and Strategies

Source: Author Generated

Table 4.8 Institutional Stakeholder Themes on GH₂ Challenges and Strategies, sheds light on the complex landscape of challenges, perceptions, and strategic responses

shaping India's GH₂ ecosystem. Among the most pressing issues identified are persistent supply-demand mismatches and offtake uncertainties, which hinder market security and scale-up confidence. Stakeholders perceive Government Policies as moderately effective, with schemes like the Production Linked Incentive (PLI) offering some momentum, but a lack of policy clarity and consistent implementation slows down real progress. Regulatory bottlenecks and approval delays further exacerbate project execution risks, prompting organisations to engage in regulatory consultations, pilot project testing, and internal risk mitigation practices. High capital expenditure requirements and infrastructure costs remain significant barriers, particularly in scaling hydrogen production and storage systems, where early-stage policy incentives are insufficient to bridge funding gaps. Coordination across stakeholders is recognised as essential but remains fragmented, with many calling for structured public-private partnerships (PPPs) to ensure collective progress. Investor hesitancy, largely driven by credit risks and uncertain returns, continues to delay capital inflow, even as private equity and venture capital firms express growing interest. Additionally, challenges in raw material availability and underdeveloped storage technologies are slowing technical readiness, while safety risks persist due to the absence of a formalised national safety compliance framework. Nonetheless, the stakeholders maintain a cautiously optimistic stance, grounded in the belief that with stronger government facilitation, targeted incentives, de-risking strategies, and robust stakeholder collaboration, the GH₂ sector can achieve scalable and sustainable growth in the coming years.

4.6.2 Thematic Analysis – Interviews 3 and 4 (Private Sector)

This sub-section focuses on the viewpoint of private sector leaders engaged in renewable and hydrogen innovation. The respondents evaluate current Government schemes, infrastructure gaps, and regulatory limitations while also emphasising the need

for evolved safety frameworks and risk-sharing models. The private institutions see significant potential but urge a more synchronised public-private approach to accelerate readiness and deployment.

Key Challenge	Perception of Policy Effectiveness	Effects on Readiness/ Implementation	Coping/ Strategic Measures	Organisational/ Govt Support	Outlook/ Attitude
Early-stage policy maturity	Policies just starting to catalyse growth	Implementation is cautious and fragmented	Aligning with NGHM, initial investments and pilots	Government equity support, targeted schemes	Optimistic if momentum sustains
Ambiguous regulations, safety codes	Major gaps in regulatory framework, esp. safety	Barrier to scaling and stakeholder trust	Methanol use suggested as interim hydrogen carrier	Public sector lacks evolved compliance guidelines	Awaiting clearer policy evolution
Technological lag and infra shortfalls	Supportive stance, but practical readiness is low	Capacity constraints slow down production chain	Planning for electrolyser scale-up, land identification	Government targets 5 MMT but infra gaps remain	Needs immediate action for industrial-scale shift
Weak PPP engagement	Collaboration is nascent, trust building needed	Coordination issues and project risks remain	Seek structured PPPs and long-term policy confidence	Current initiatives fragmented; clarity needed	Sees opportunity, but only with joint accountability
Investor interest vs. technology risk	Positive long-term outlook, but concern over tech maturity	Investment delayed due to uncertainties in viability	Highlighting ROI in clean-tech roadshows, risk sharing	Policy-level incentives exist, but limited traction	Bullish on future, cautious now
Electrolyser and storage infra gaps	Recognition of infra gap in production ecosystem	Hinders speed of adoption and safe rollout	Public-private R&D encouraged, grid plans in early stages	Stronger logistics coordination needed	Practical, sees infra as core issue
Lack of evolved safety ecosystem	Acknowledges safety as underdeveloped policy-wise	Delays in scale and increased operating risk	International benchmarking and protocols being initiated	Some PSUs proactive, others lagging	Believes safety culture must precede scale

Table 4.9: Industry Stakeholder Themes on Policy, Infrastructure, and Investment

Source: Author Generated

Table 4.9 Industry Stakeholder Themes on Policy, Infrastructure, and Investment, highlights the perspectives of key stakeholders on the current state of India's GH₂ ecosystem. The respondents emphasised that while the National GH₂ Mission (NGHM) and related Government initiatives are starting to generate momentum, Policy maturity remains at an early stage, resulting in cautious and fragmented implementation. Ambiguities in regulatory and safety codes, particularly for hydrogen storage and transport, continue to serve as major bottlenecks, restricting stakeholder trust and slowing project scalability. Although Government equity support and targeted schemes are acknowledged, these are seen as insufficient for industrial-level deployment due to the lack of a robust safety and compliance framework. Technological readiness and infrastructure development, especially for electrolysers and hydrogen storage systems, are seen as underdeveloped, with immediate action required to achieve national production targets. The respondents also pointed out that PPP engagement remains nascent and unstructured, which limits coordinated execution and increases risk exposure. Investment appetite exists, but it is tempered by concerns about technology maturity and return on investment. To cope with these challenges, the stakeholders advocate for structured PPP models, international benchmarking of safety standards, and increased public-private R&D collaboration. Overall, while the interviewees maintain a cautiously optimistic outlook, they emphasize that accelerated progress depends on regulatory clarity, infrastructure build-out, trust-building mechanisms, and a proactive safety culture that must precede large-scale adoption.

4.7 Findings of Respondents' Survey

This section presents the key insights obtained from a structured survey of respondents comprising professionals, executives, policymakers, researchers, and investors engaged in the GH₂ ecosystem in India. The survey explores their perceptions on

policy effectiveness, investment readiness, infrastructure bottlenecks, technological constraints, safety considerations, and organisational involvement in GH₂ initiatives. These responses serve as the foundation for correlation and regression analyses in subsequent sections.

4.7.1 Reliability Analysis

The reliability of the survey instrument was evaluated using Cronbach's Alpha to ensure internal consistency among the survey items.

Cronbach's Alpha	N of Items
.942	50

Table 4.10: Reliability Statistics

Source: Author Generated

Table 4.10 presents statistics on the Survey's reliability that were used for the research. A total of fifty respondents has an outstanding degree of internal consistency and reliability, as indicated by the Cronbach's Alpha score of 0.942. Items within the instrument are strongly associated and consistently measure the underlying construct if Cronbach's Alpha is over 0.9, which is generally considered very trustworthy. The acquired data can be confidently used for additional statistical analysis and interpretations thanks to this high reliability.

4.7.2 Demographic Details of Respondents

This section outlines the demographic distribution of survey participants, covering aspects such as age, gender, education level, professional sector, designation, years of experience, and organisational involvement in GH₂ initiatives.

Demographic	Category	Frequency	Percent
What is your age group?	26 – 35 Years	16	32
	36 – 45 Years	9	18
	46 – 55 Years	11	22
	56 Years and above	14	28
What is your gender?	Male	39	78

	Female	11	22
What is your highest level of education?	Bachelor's Degree	4	8
	Engineering Degree	8	16
	Master's degree	26	52
	Professional Qualification (CA/CS/CMA/Law/Medicine)	7	14
	Doctorate (Ph.D. / DBA)	5	10
Which sector do you work in?	Government & Policy (Ministry / Regulatory Bodies)	10	20
	Energy Sector (Renewable / Hydrogen Production)	8	16
	Industrial Sector (Steel /Cement / Power / Transportation)	2	4
	Finance & Investment (Banks / Financial Institutions/ Venture Capital / Private Equity)	19	38
	Research & Academia	4	8
	Consultancy & Advisory Services	5	10
	Other	2	4
What is your current job title?	CXO / Senior Management	13	26
	Mid-level Management	19	38
	Technical / Engineer / Specialist/ Consultant / Advisor	4	8
	Researcher / Academic	3	6
	Other	11	22
How many years of experience do you have in your industry?	Less than 1 Year	3	6
	1 – 5 Years	8	16
	6 – 10 Years	5	10
	11 – 20 Years	6	12
	More than 20 Years	28	56
Does your organisation have involvement in green hydrogen projects?	Yes	19	38
	No	31	62
What is your organisation's primary role in the green hydrogen ecosystem?	Policy Making & Regulation	5	10
	Advisory/Consulting	6	12
	Academia	1	2
	Green Hydrogen Production	4	8
	Infrastructure Development (Storage, Distribution)	3	6
	End-User Industry (Steel, Cement, Transport, etc.)	1	2
	Investment & Funding	17	34
	Research & Development	1	2
	Other	12	24

Table 4.11: Demographic Details

Source: Author Generated

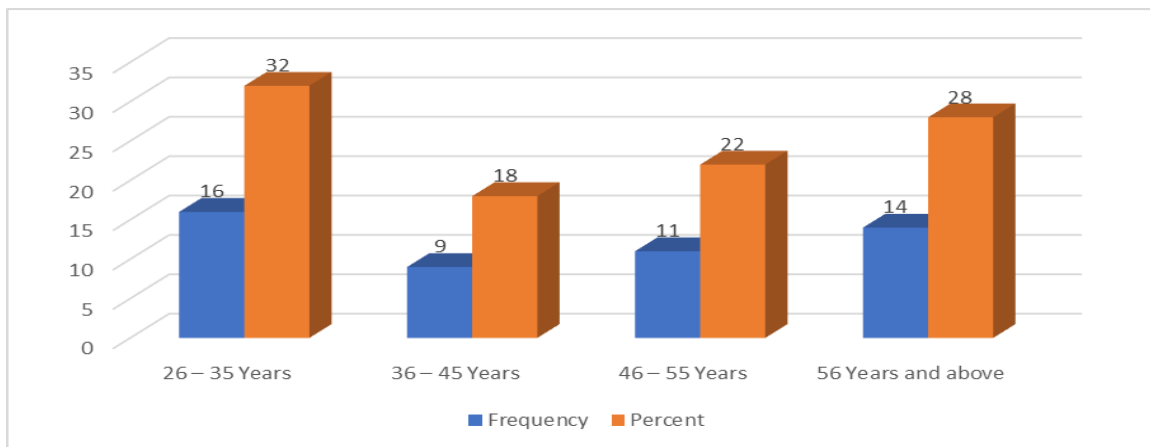


Figure 4.1: Age

Source: Author Generated

Figure 4.1 illustrates the age distribution of the respondents participating in the study. The majority of respondents (32%) fall within the 26–35 years age group, followed by 28% in the 56 years and above category. Respondents aged 46–55 years make up 22%, while the 36–45 years group accounts for 18%. This distribution indicates a diverse representation across different age brackets, with a notable concentration in both the younger (26–35) and older (56+) age groups, offering balanced insights from a multigenerational workforce.

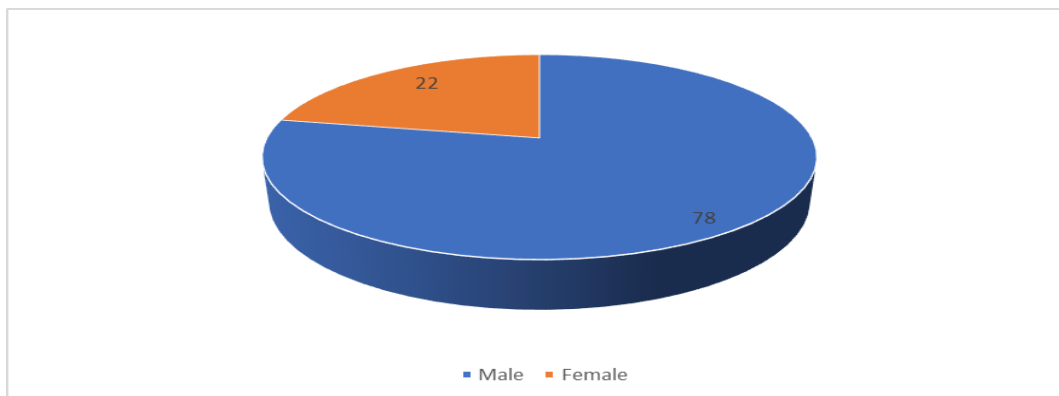


Figure 4.2: Gender

Source: Author Generated

Figure 4.2 presents the gender distribution of the respondents. Out of the total 50 participants, 78% are male (39 respondents) and 22% are female (11 respondents). This indicates a significant gender imbalance among the respondents, with male participants forming a substantial majority. The disparity suggests that the sector or sample surveyed may have a predominantly male representation, which could influence perspectives and responses in the study.

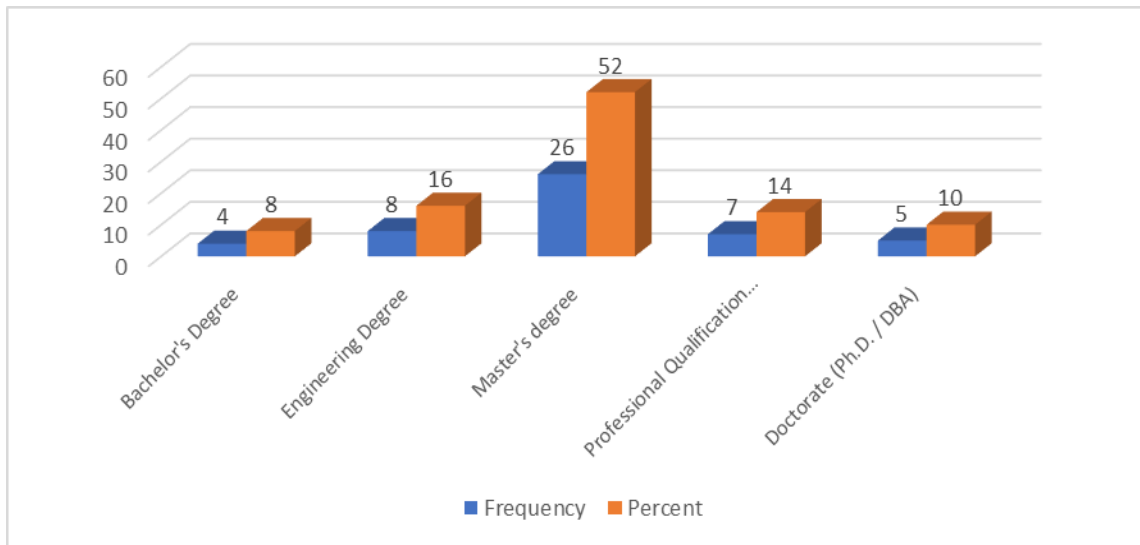


Figure 4.3: What is your highest level of education?

Source: Author Generated

Figure 4.3 depicts the educational qualifications of the respondents. A majority of 52% hold a Master's degree, followed by 16% with an Engineering degree and 14% possessing Professional Qualifications such as CA, CS, CMA, Law, or Medicine. Additionally, 10% of the respondents have completed a Doctorate, while 8% hold a Bachelor's degree. This distribution indicates a highly educated respondent pool, with a strong concentration of postgraduate and professionally qualified individuals, suggesting that the data gathered comes from respondents with substantial academic and professional backgrounds.

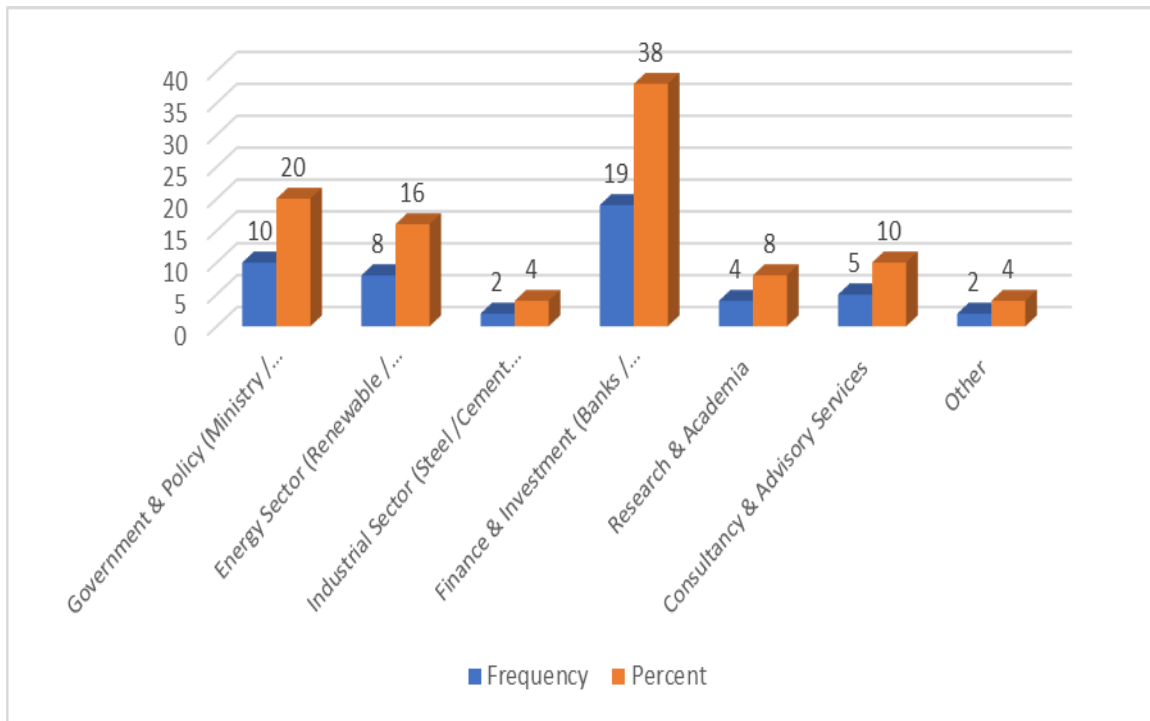


Figure 4.4: Which sector do you work in?

Source: Author Generated

Figure 4.4 displays the sector-wise distribution of respondents. The largest share of participants, 38%, are employed in the Finance & Investment sector, including banks, financial institutions, venture capital, and private equity. This is followed by 20% from Government & Policy roles such as ministries and regulatory bodies, and 16% from the Energy Sector, specifically RE and hydrogen production. Respondents from Consultancy & Advisory Services make up 10%, while Research & Academia account for 8%. The Industrial Sector and Other categories each represent 4% of the sample. This diverse sectoral representation suggests a broad spectrum of perspectives, particularly weighted toward financial and policy-driven domains.

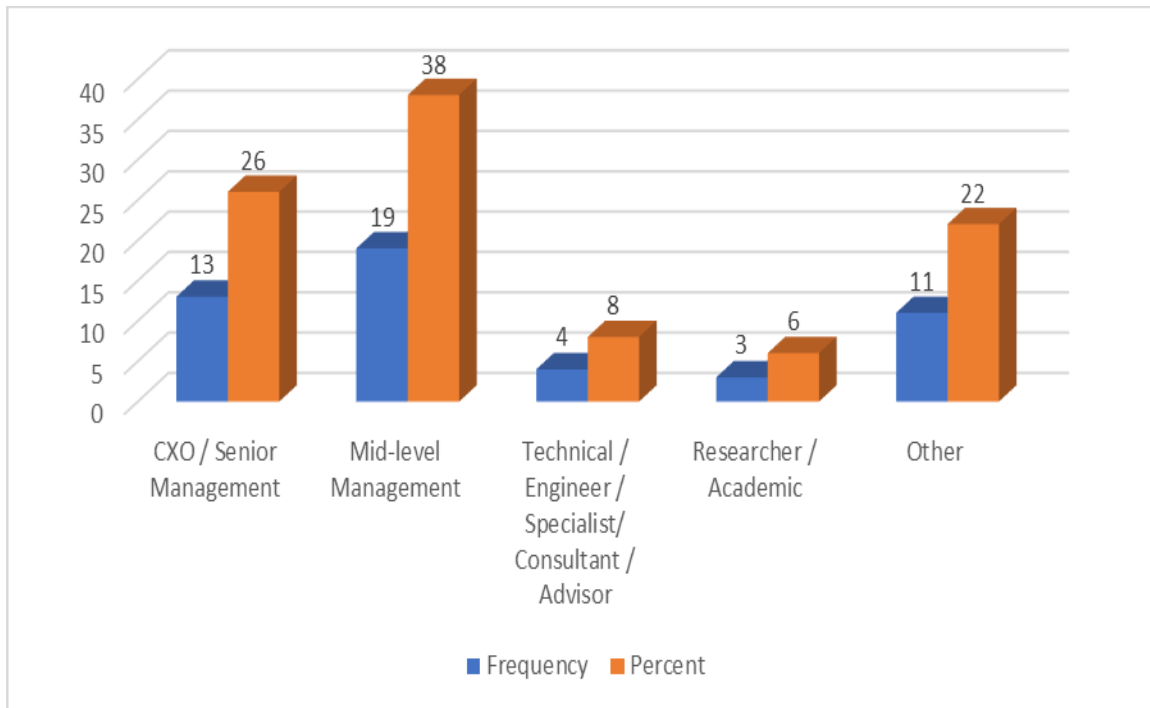


Figure 4.5: What is your current job title?

Source: Author Generated

Figure 4.5 presents the distribution of respondents based on their current job titles. The largest group, comprising 38%, holds mid-level management positions, followed by 26% in CXO or senior management roles. Additionally, 22% fall under the ‘Other’ category, which may include roles not specifically listed. Respondents working as technical professionals, engineers, specialists, consultants, or advisors make up 8%, while 6% are engaged in research or academic roles. This indicates that a significant portion of the respondents are in leadership and decision-making positions, contributing experienced and strategic perspectives to the study.

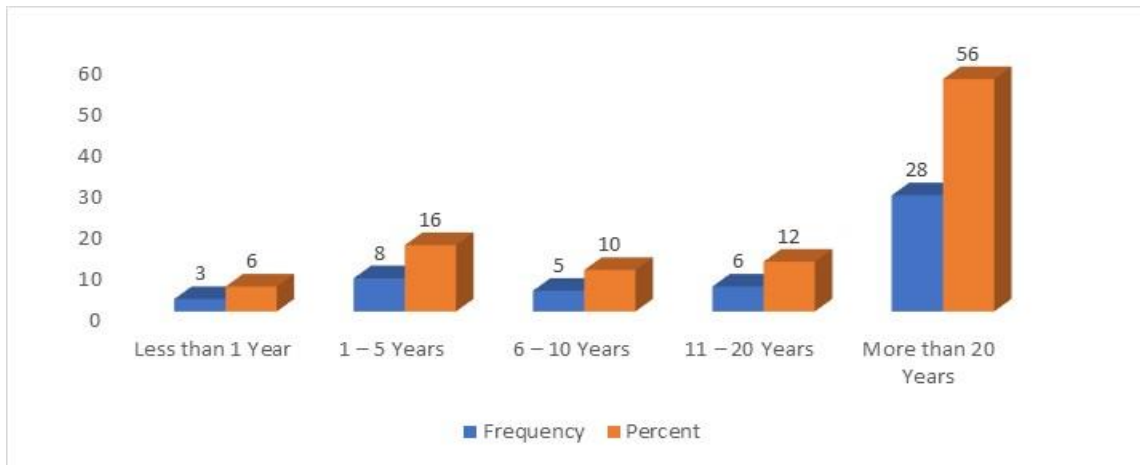


Figure 4.6: How many years of experience do you have in your industry?

Source: Author Generated

Figure 4.6 illustrates the respondents' years of experience in their respective industries. A majority, 56%, have more than 20 years of industry experience, indicating a highly seasoned and knowledgeable participant base. This is followed by 16% with 1–5 years of experience, 12% with 11–20 years of experience, 10% with 6–10 years of experience, and only 6% with less than 1 year of experience. The dominance of respondents with extensive experience enhances the credibility of the insights gathered, reflecting a deep understanding of the industry and long-term professional engagement.

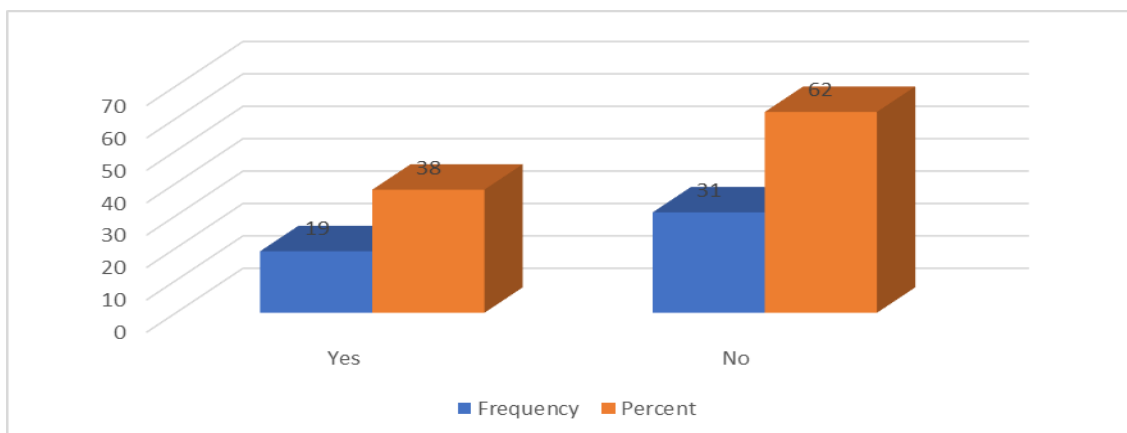


Figure 4.7: Does your organisation have involvement in green hydrogen projects?

Source: Author Generated

Figure 4.7 shows the organisational involvement of respondents in GH₂ projects. Out of the 50 participants, 38% reported that their organisation is involved in GH₂ initiatives, while the remaining 62% indicated no involvement. This suggests that although there is growing interest and participation in GH₂, a significant portion of organisations have yet to engage in such projects, highlighting both the emerging nature of the sector and potential areas for future expansion and investment.

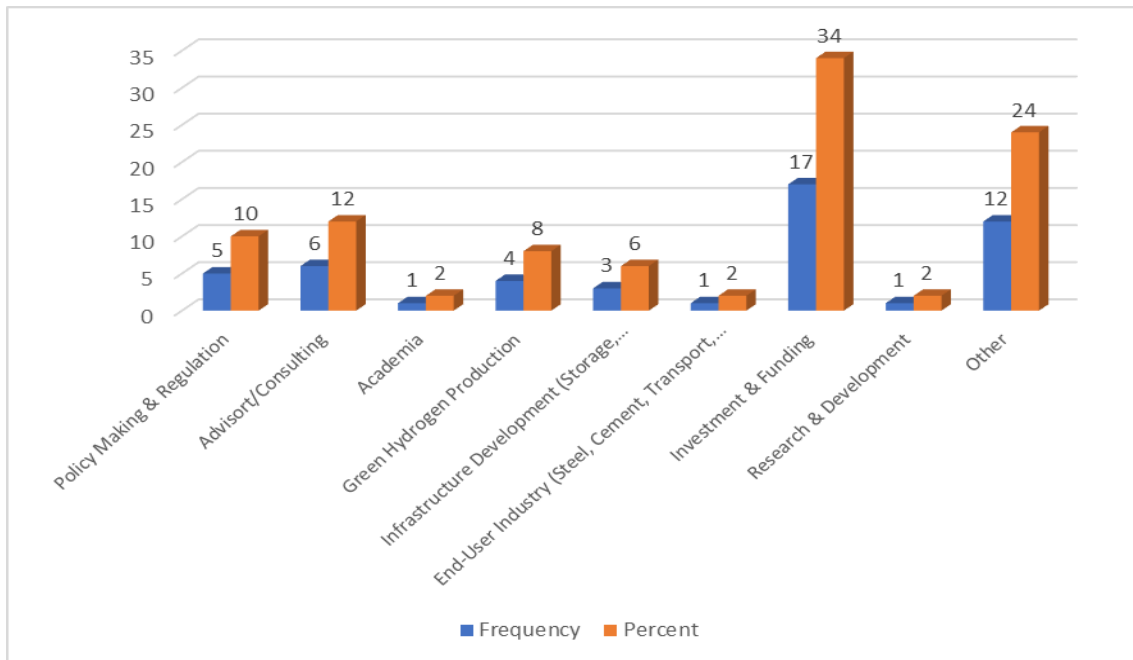


Figure 4.8: What is your organisation's primary role in the green hydrogen ecosystem?

Source: Author Generated

Figure 4.8 illustrates the primary roles of respondents' organisations within the GH₂ ecosystem. The largest share, 34%, represents entities involved in investment and funding, highlighting the financial sector's key role in driving GH₂ initiatives. This is followed by 24% in the 'Other' category, suggesting a wide range of roles not specifically listed. Advisory and consulting firms account for 12%, while policy-making and regulatory bodies contribute 10%. Organisations engaged in GH₂ production make up 8%, and those in infrastructure development comprise 6%. Meanwhile, academia, end-user industries,

and research & development each represent 2%. This diverse distribution underscores the multifaceted nature of the GH₂ value chain, with finance and advisory services playing particularly prominent roles.

4.7.3 Government Policies and Initiatives

This section evaluates respondents' perceptions of the effectiveness, clarity, and implementation of Government policies related to GH₂. It also assesses the adequacy of public-private partnerships (PPPs) and financial incentives in driving hydrogen adoption in India.

			Strongly Disagree (SD)	Disagree (D)	Neutral (N)	Agree (A)	Strongly Agree (SA)
Effectiveness of Policies	Government policies effectively support the growth of Green Hydrogen.	Frequency	0	4	16	13	17
		Percent	0	8	32	26	34
	Existing Government policies are aligned with industry needs for Green Hydrogen.	Frequency	0	8	19	17	6
		Percent	0	16	38	34	12
Clarity of Regulations	The current regulatory framework for Green Hydrogen is clear and well-structured.	Frequency	1	8	22	14	5
		Percent	2	16	44	28	10
	The regulatory approval process for Green Hydrogen projects is efficient and predictable.	Frequency	3	10	22	11	4
		Percent	6	20	44	22	8
Incentives & Subsidies	The Government provides adequate financial incentives to	Frequency	2	14	20	9	5

	promote Green Hydrogen.	Percent	4	28	40	18	10
	Subsidies and tax benefits are sufficient to encourage Green Hydrogen adoption.	Frequency	3	13	25	6	3
		Percent	6	26	50	12	6
Policy Implementation Challenges	Bureaucratic processes help in the implementation of Green Hydrogen policies.	Frequency	2	9	18	14	7
		Percent	4	18	36	28	14
	The existing policies need a clear roadmap for long-term Green Hydrogen development.	Frequency	3	9	19	11	8
		Percent	6	18	38	22	16
Public-Private Partnerships (PPP) in Green Hydrogen	There is strong collaboration between the Government / Public Sector and Private sector in Green Hydrogen development.	Frequency	0	10	25	10	5
		Percent	0	20	50	20	10
	Private sector companies receive adequate support from Government policies to scale Green Hydrogen initiatives.	Frequency	1	16	24	6	3
		Percent	2	32	48	12	6

Table 4.12: Government Policies and Initiatives

Source: Author Generated

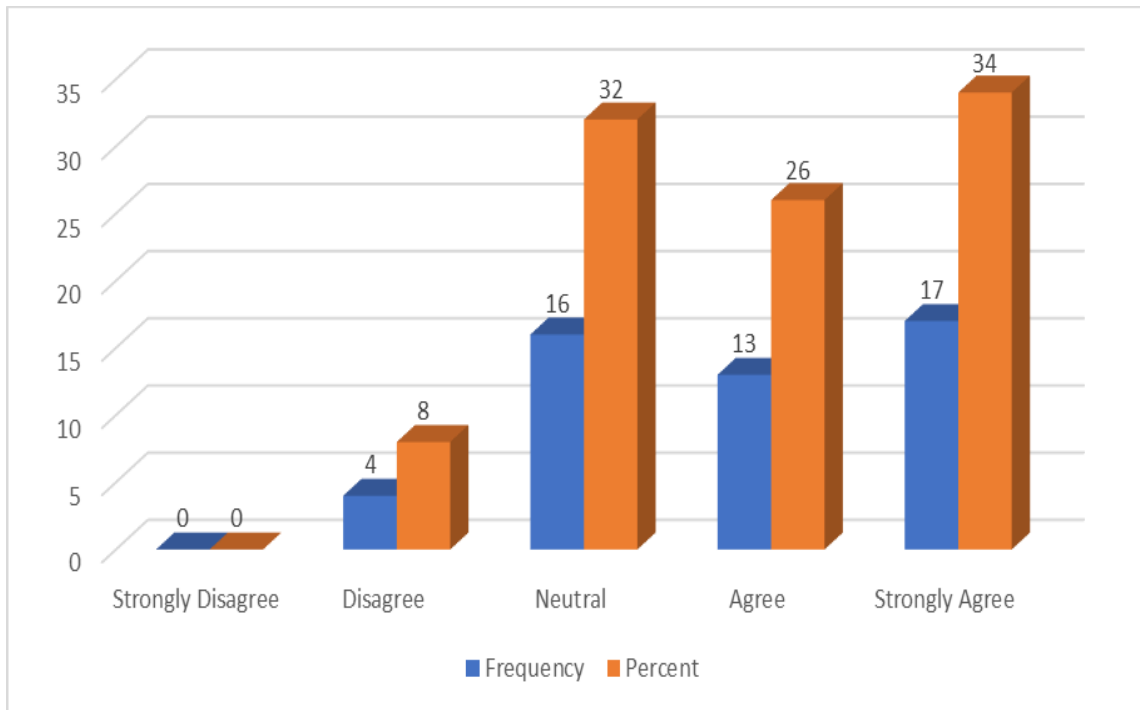


Figure 4.9: Government policies effectively support the growth of Green Hydrogen.

Source: Author Generated

Figure 4.9 presents respondents' perceptions regarding the effectiveness of government policies in supporting the growth of GH₂. A combined 60% of respondents either A (26%) or SA (34%) that government policies are supportive, indicating a generally positive outlook on policy frameworks. However, 32% remain N, suggesting some uncertainty or mixed experiences, while a small segment, 8%, D, with the statement. Overall, the data reflects a majority belief in the constructive role of government policy, while also pointing to the need for clearer, more impactful, or better-communicated regulatory initiatives to convert N observers into supporters.

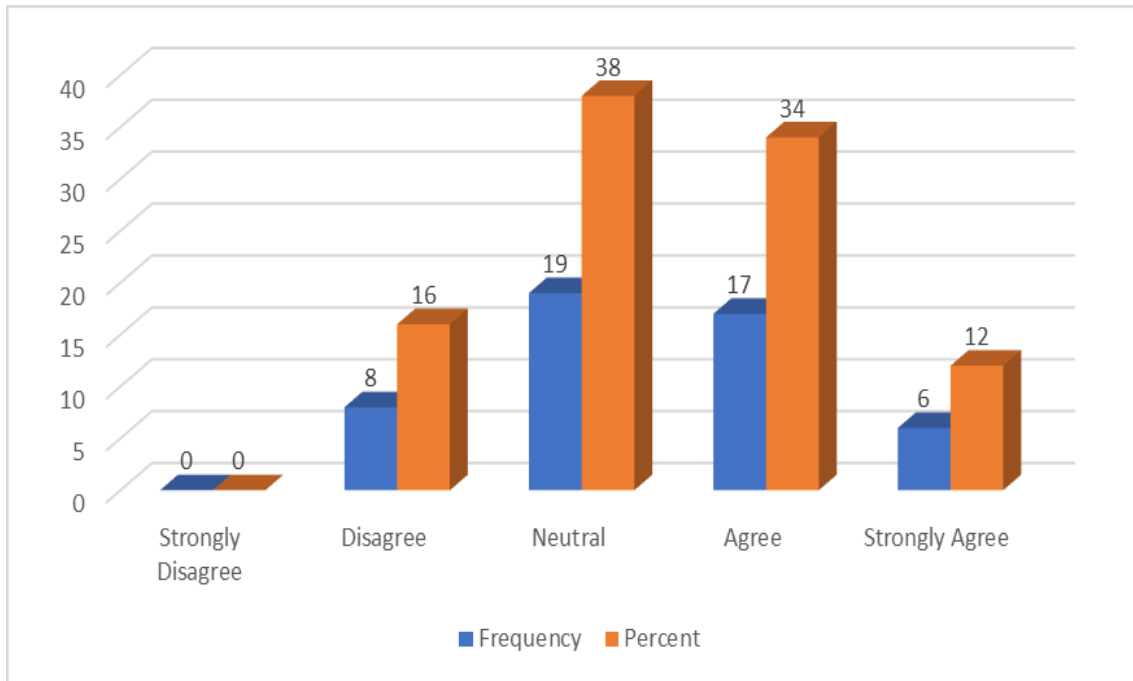


Figure 4.10: Existing Government policies are aligned with industry needs for Green Hydrogen.

Source: Author Generated

Figure 4.10 illustrates respondents' views on the alignment of existing Government policies with industry needs for GH₂. A combined 46% of participants either A (34%) or SA (12%) that current policies are in line with industry requirements. However, a significant portion, 38%, selected N, indicating uncertainty or a lack of strong opinion on the matter. Meanwhile, 16% D, suggesting that some respondents perceive a misalignment between policy frameworks and practical industry needs. Overall, while there is a generally positive sentiment, the high N response highlights an opportunity for better clarity, engagement, or alignment between policymakers and industry stakeholders.

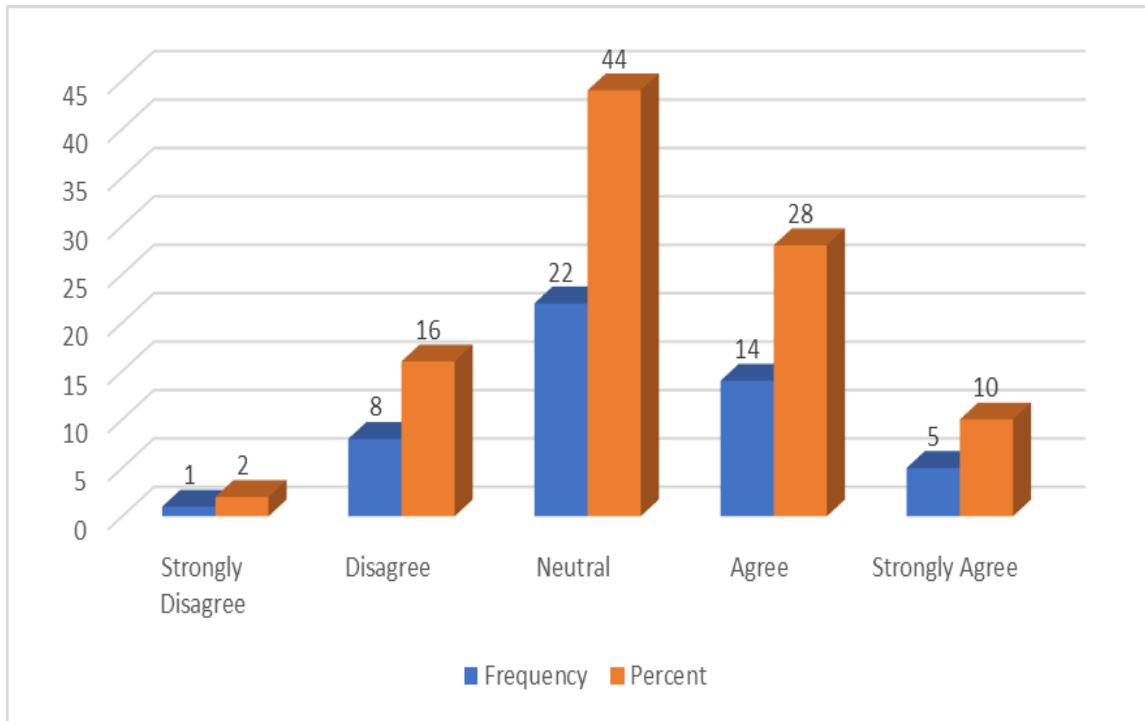


Figure 4.11: The current regulatory framework for Green Hydrogen is clear and well-structured.

Source: Author Generated

Figure 4.11 presents the respondents' perceptions of the clarity and structure of the current regulatory framework for GH₂. A total of 38% either A (28%) or SA (10%) that the regulatory framework is clear and well-structured. However, the largest group, 44%, remain N, indicating uncertainty or limited exposure to the regulatory specifics. Additionally, 16% D and 2% SD, reflecting concerns about ambiguity or gaps in the framework. These responses suggest that while a portion of stakeholders see positive progress, there is a prevailing need for greater transparency, simplification, and communication of regulatory policies in the GH₂ space.

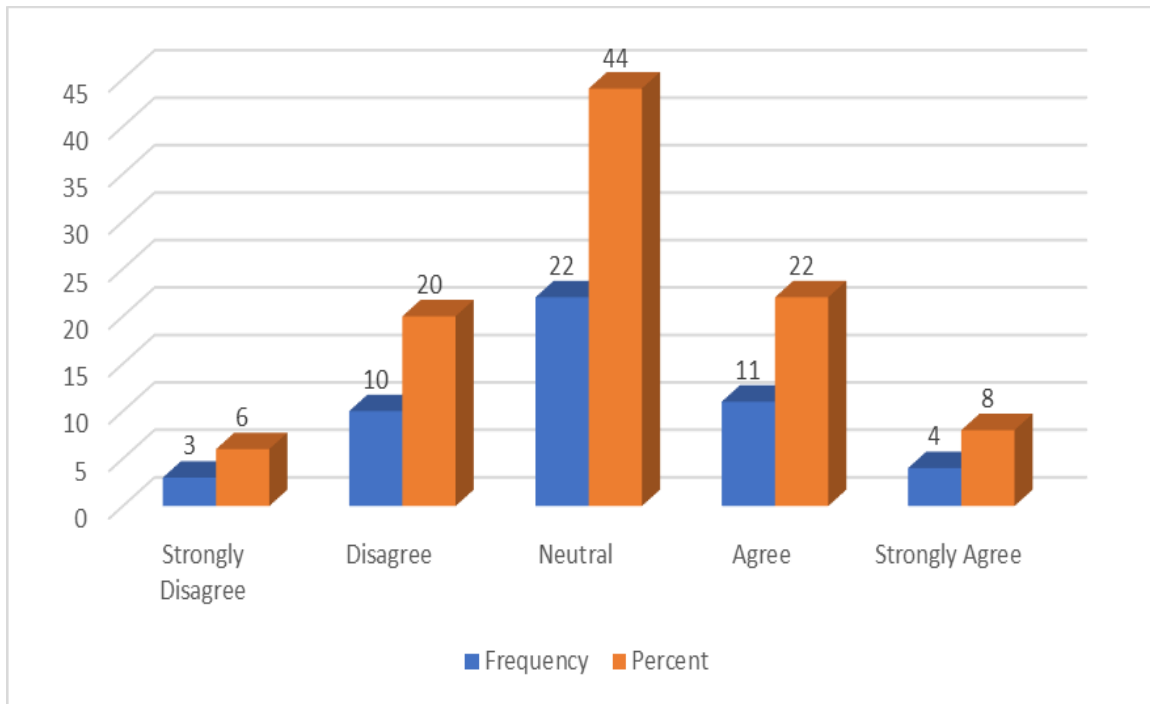


Figure 4.12: The regulatory approval process for Green Hydrogen projects is efficient and predictable.

Source: Author Generated

Figure 4.12 displays the respondents' opinions on the efficiency and predictability of the regulatory approval process for GH₂ projects. A combined 30% of respondents A (22%) or SA (8%) that the process is efficient and predictable. However, a significant portion, 44%, selected N, indicating either uncertainty or a lack of direct experience with the approval process. On the other hand, 26% of participants expressed dissatisfaction, with 20% D and 6% SD. These results suggest that while there is some confidence in the system, a substantial number of stakeholders are either uncertain or critical, highlighting the need for improvements in regulatory transparency, timelines, and procedural clarity.

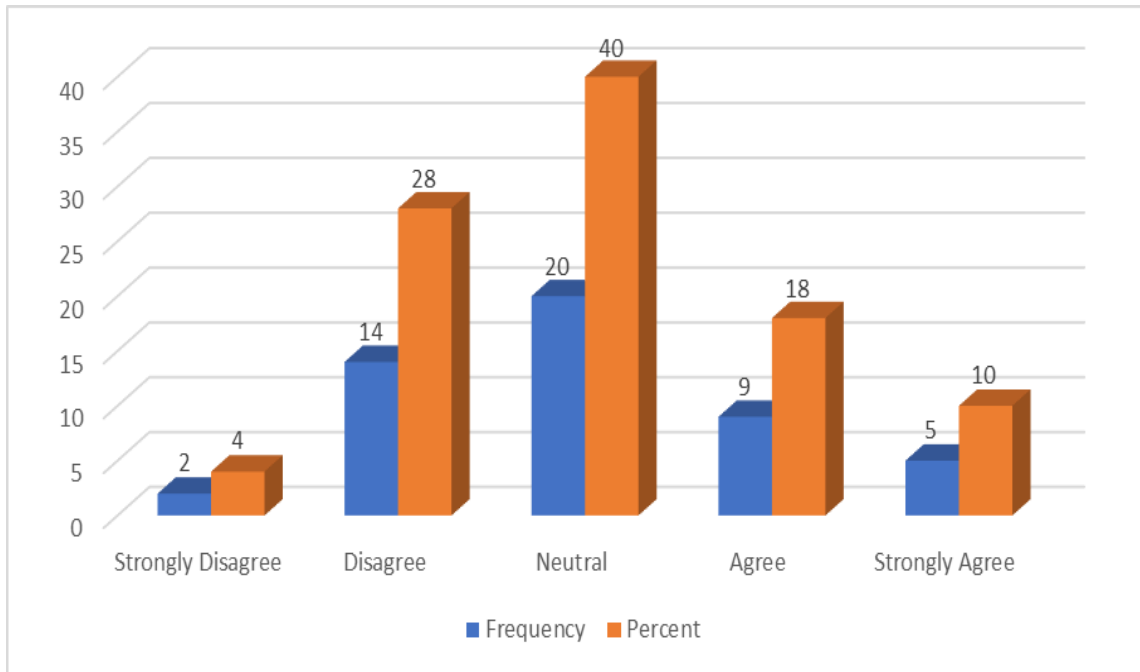


Figure 4.13: The Government provides adequate financial incentives to promote Green Hydrogen.

Source: Author Generated

According to Figure 4.13, respondents hold mixed views on the adequacy of Government-provided financial incentives for promoting GH₂. A significant portion, 40%, remained N, indicating either limited awareness or uncertainty about the incentive mechanisms currently in place. Meanwhile, a notable 32% of respondents expressed dissatisfaction, with 28% D and 4% SD, suggesting that many believe the financial support is insufficient or poorly targeted. On the other hand, only 18% A and 10% SA, reflecting that a smaller group finds the existing incentives satisfactory. Overall, the responses suggest a perceived gap between Policy intent and on-ground financial facilitation, emphasising the need for more visible, accessible, and impactful incentive programs to support the GH₂ ecosystem.

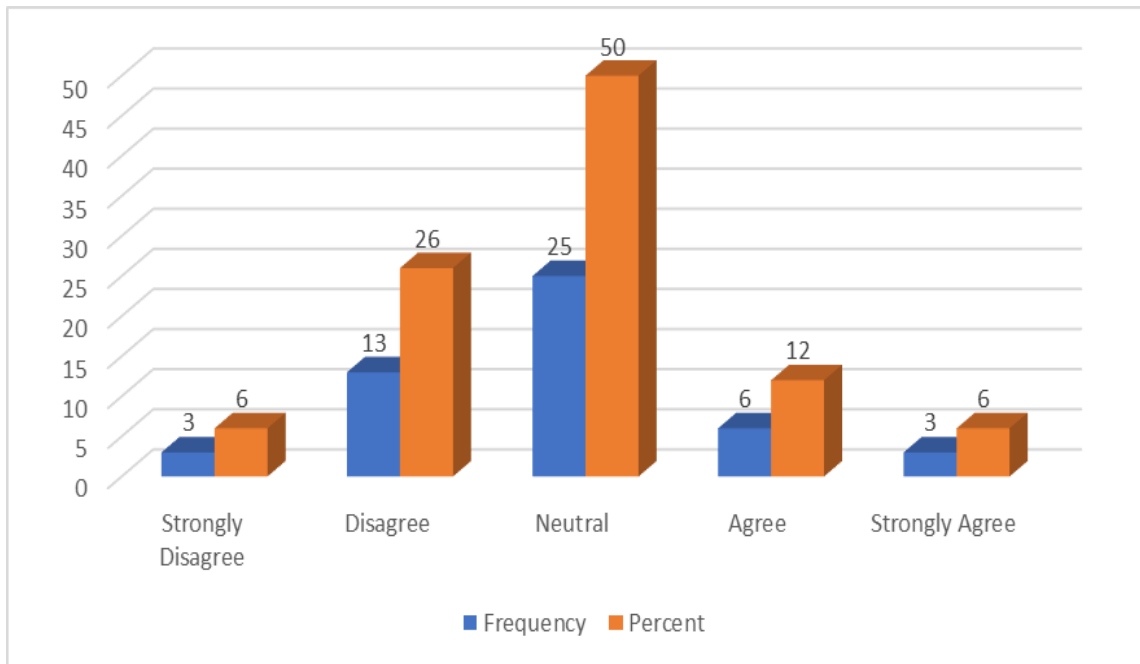


Figure 4.14: Subsidies and tax benefits are sufficient to encourage Green Hydrogen adoption.

Source: Author Generated

As shown in Figure 4.14, opinions on the sufficiency of subsidies and tax benefits to encourage GH₂ adoption are largely N or critical. Half of the respondents (50%) selected N, indicating uncertainty or limited exposure to existing fiscal incentives. A combined 32% expressed disagreement, with 26% D and 6% SD, suggesting a widespread perception that current subsidies and tax benefits are not robust or attractive enough to accelerate adoption. In contrast, only 18% of respondents expressed a positive view (12% A, 6% SA), reflecting a relatively small share of stakeholders who find the current incentives sufficient. This distribution highlights a policy perception gap, where the existing financial mechanisms may either be lacking clarity, scale, or accessibility, thereby limiting their effectiveness in driving meaningful GH₂ adoption.

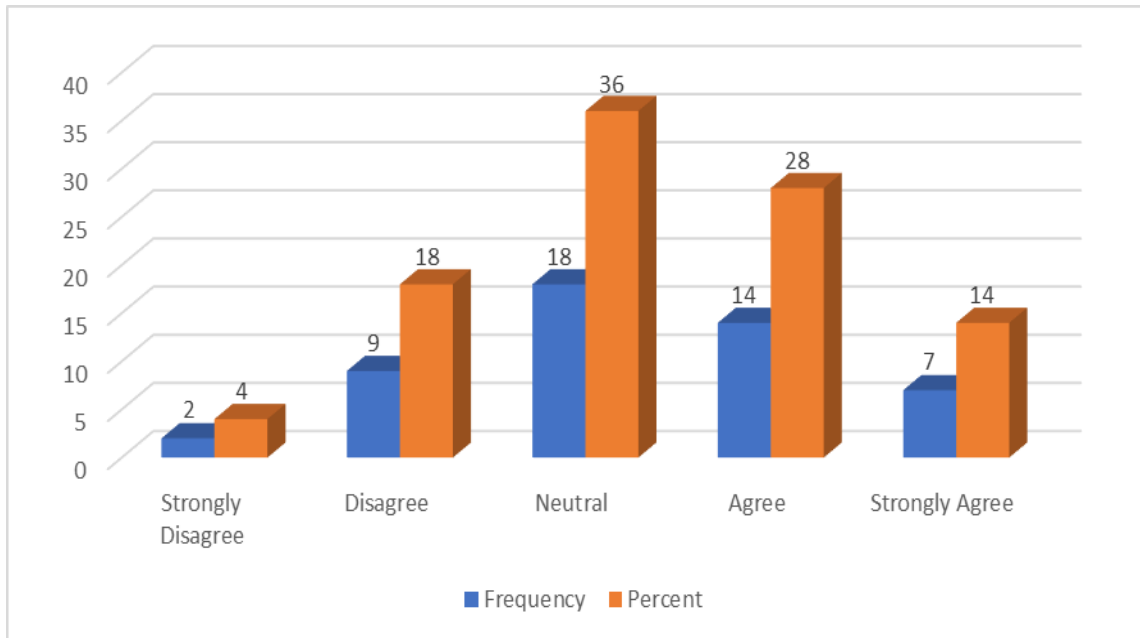


Figure 4.15: Bureaucratic processes help in the implementation of Green Hydrogen policies.

Source: Author Generated

Figure 4.15 highlights respondents' perspectives on whether bureaucratic processes support the implementation of GH₂ policies. The responses reveal a mixed sentiment, with 42% of participants expressing a positive view, 28% A and 14% SA, indicating that a fair number of respondents believe that bureaucratic systems are playing a facilitative role. However, 36% remained N, suggesting uncertainty, possible lack of direct interaction with bureaucratic mechanisms, or varied experiences. On the other hand, 22% of respondents, 18% D and 4% SD, perceive bureaucratic processes as possibly inefficient or obstructive. Overall, the data implies that while some stakeholders recognise the value of bureaucracy in policy execution, others find its effectiveness to be inconsistent or unclear, pointing to the need for more streamlined, responsive, and transparent administrative processes to enhance policy implementation.

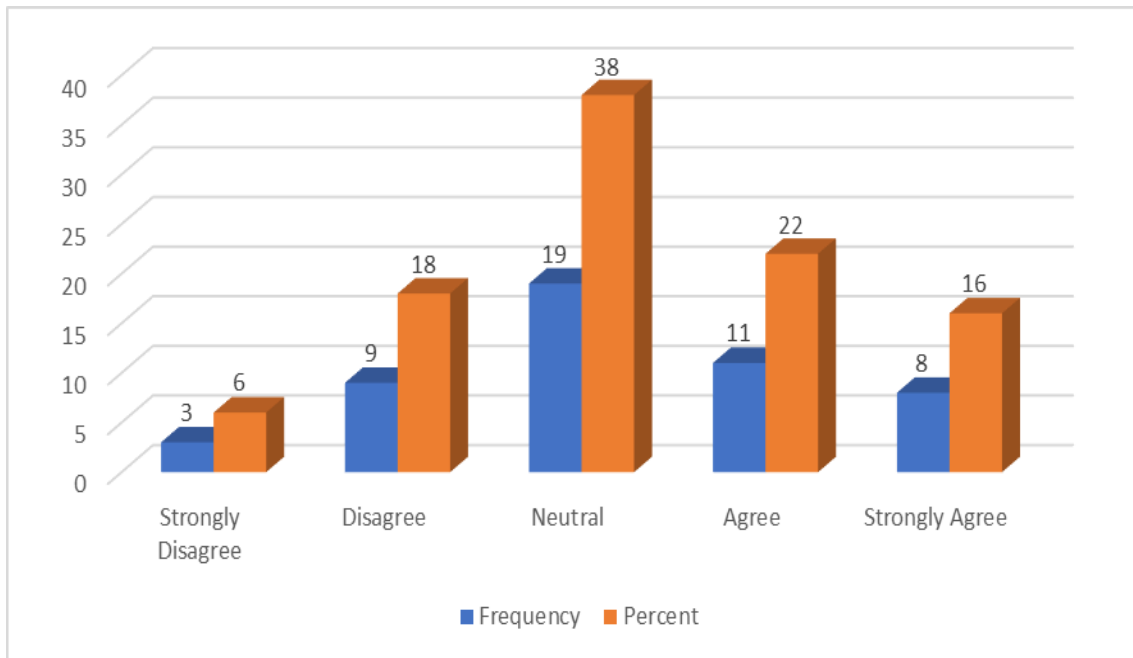


Figure 4.16: The existing policies need a clear roadmap for long-term Green Hydrogen development.

Source: Author Generated

According to Figure 4.16, the responses on whether existing policies require a clearer roadmap for long-term GH₂ development reveal a broad spectrum of opinions. While 38% of respondents selected N, indicating either uncertainty or mixed exposure to policy details, a notable 38% also expressed agreement (22% A, 16% SA), suggesting that a significant portion of stakeholders recognise the need for more structured, long-term policy planning. On the other hand, 24% of respondents, 18% D and 6% SD, believe that current policies are sufficiently clear or already provide direction. This spread of views suggests that although some progress is acknowledged, there is a prevailing demand for a more transparent, forward-looking policy framework that outlines implementation phases, investment priorities, and sectoral targets to guide the sustainable development of GH₂ in the coming decades.

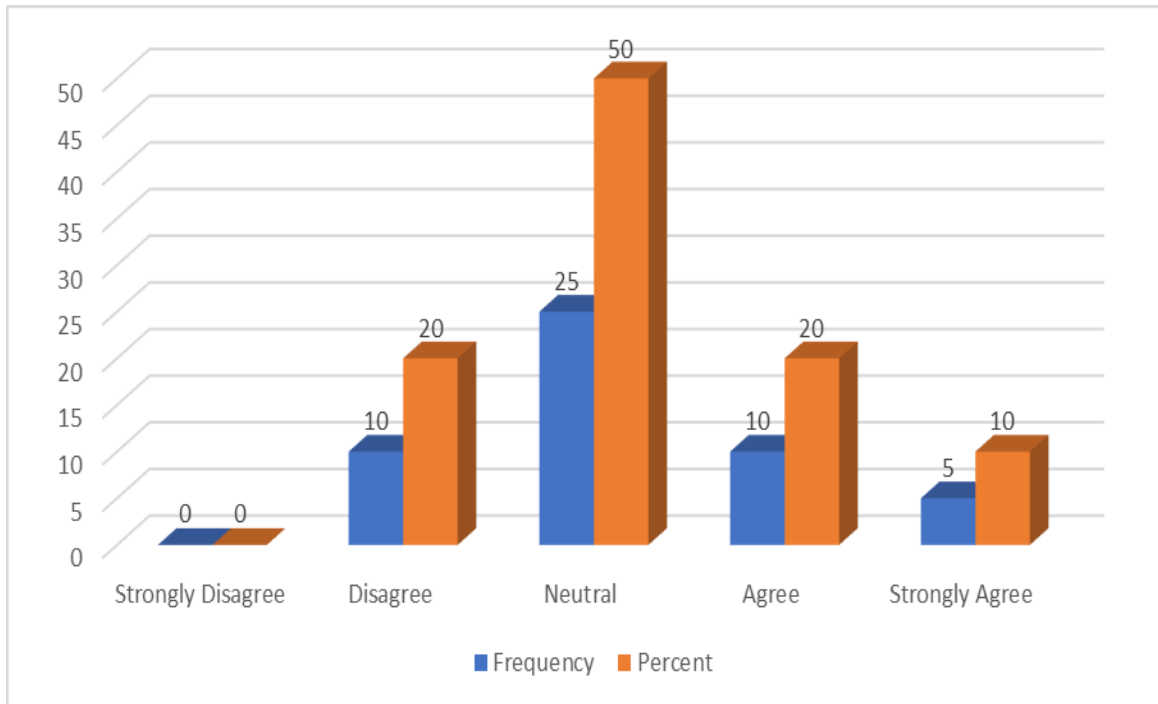


Figure 4.17: There is strong collaboration between the Government / Public Sector and the Private Sector in Green Hydrogen development.

Source: Author Generated

Figure 4.17 reflects a lack of strong consensus among respondents regarding the collaboration between the Government/public sector and the private sector in the GH₂ space. While 30% of respondents believe that such collaboration is happening effectively (20% A, 10% SA), an equal proportion, 20%, D, pointing toward perceived disconnects or missed opportunities in joint efforts. Notably, half of the participants (50%) chose the N option, suggesting either a limited awareness of such collaborations or an experience of only fragmented and informal partnerships. These insights highlight a critical area for improvement—strengthening institutional frameworks and engagement platforms to foster more visible, transparent, and impactful public-private cooperation in advancing the GH₂ agenda.

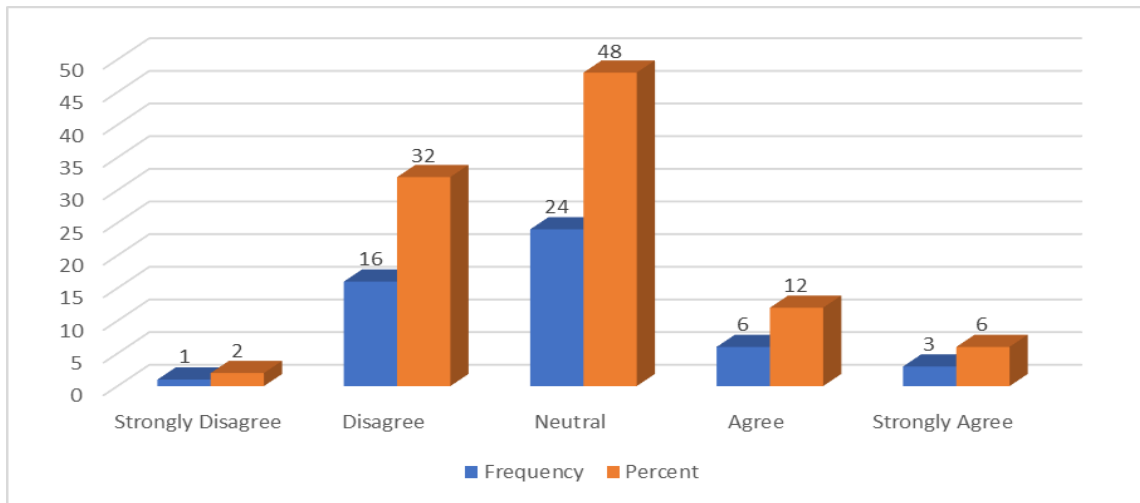


Figure 4.18: Private sector companies receive adequate support from Government policies to scale Green Hydrogen initiatives.

Source: Author Generated

Figure 4.18 captures respondents' perceptions regarding the adequacy of Government policy support for private sector companies in scaling GH₂ initiatives. A significant portion, 48%, selected N, indicating either limited awareness of support mechanisms or varied experiences across organizations. However, 34% of respondents expressed dissatisfaction, with 32% D and 2% SD, suggesting that many in the private sector feel that current Government policies fall short in offering sufficient support, whether in terms of funding, infrastructure, or regulatory facilitation. On the positive side, only 18% felt supported (12% A, 6% SA), highlighting a minority who perceive current policies as enabling growth. These findings point to a clear gap between policy intent and on-ground impact, emphasizing the need for more targeted, accessible, and practical support systems to empower the private sector's role in advancing GH₂ development.

4.7.4 Readiness Level of Green Hydrogen

This section explores technological, financial, workforce, and adoption readiness levels in the GH₂ sector. Respondents also rated industry-wide collaboration and the availability of training programs.

			SD	D	N	A	SA
Technological Readiness	Companies in India have access to the necessary technology for Green Hydrogen production.	Frequency	12	13	17	6	2
		Percent	24	26	34	12	4
	There is sufficient R&D investment in Green Hydrogen technologies	Frequency	16	9	19	4	2
		Percent	32	18	38	8	4
Financial Readiness	Investors are willing to fund Green Hydrogen-related initiatives in your sector.	Frequency	4	15	20	10	1
		Percent	8	30	40	20	2
	There is sufficient financial support from Banks and Financial institutions for Green Hydrogen projects.	Frequency	7	19	19	4	1
		Percent	14	38	38	8	2
Workforce Readiness	Organisations in India have a skilled workforce capable of handling Green Hydrogen technologies.	Frequency	14	18	12	4	2
		Percent	28	36	24	8	4
	Adequate training programs are available to develop expertise in Green Hydrogen technologies.	Frequency	14	18	13	4	1
		Percent	28	36	26	8	2
Adoption Readiness	There is a strong commitment towards adopting Green Hydrogen solutions.	Frequency	7	8	23	9	3
		Percent	14	16	46	18	6
	There is a clear roadmap in place for transitioning to Green	Frequency	9	19	17	3	2
		Percent	18	38	34	6	4

	Hydrogen-based operations.						
Industry Collaboration Readiness	There is strong industry-wide cooperation in India to advance Green Hydrogen adoption.	Frequency	5	18	22	4	1
		Percent	10	36	44	8	2
	Partnerships and joint ventures are increasing to accelerate Green Hydrogen implementation.	Frequency	4	8	19	14	5
		Percent	8	16	38	28	10

Table 4.13: Readiness Level of Green Hydrogen

Source: Author Generated

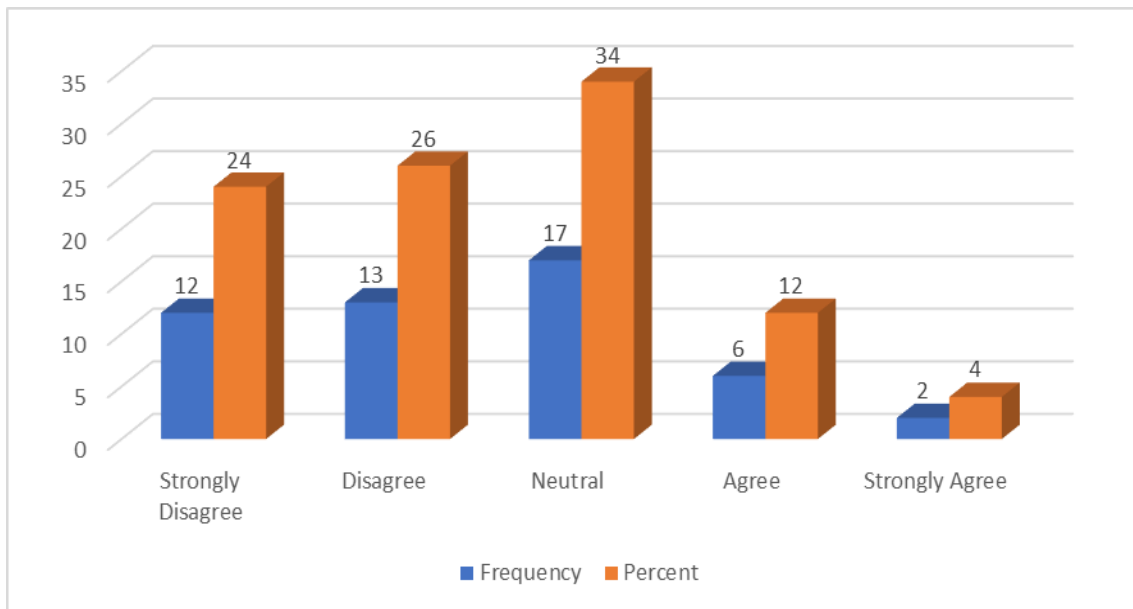


Figure 4.19: Companies in India have access to the necessary technology for Green Hydrogen production.

Source: Author Generated

Access to advanced technology remains a key concern for GH₂ production in India, as reflected in the responses shown in Figure 4.19. A significant 50% of participants either D (26%) or SD (24%) that companies have access to the necessary technology, indicating

that half of the respondents believe India faces major technological limitations in this area. Additionally, 34% selected N, which may suggest uncertainty, limited awareness, or a lack of direct involvement with the technology landscape. Only 16% of respondents expressed confidence (12% A, 4% SA) that the technology is currently accessible. These findings point to a critical need for enhanced R&D efforts, stronger international collaborations, and technology transfer frameworks to ensure that Indian companies are adequately equipped to lead in the GH₂ sector.

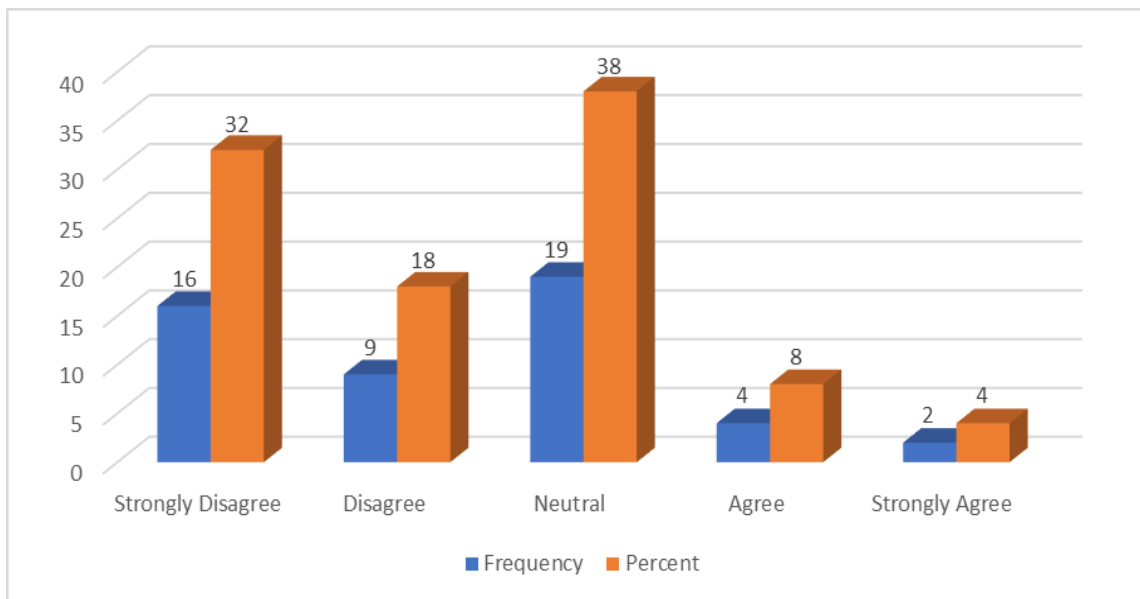


Figure 4.20: There is sufficient R&D investment in Green Hydrogen technologies

Source: Author Generated

As shown in Figure 4.20, the majority of respondents believe that R&D investment in GH₂ technologies is currently insufficient in India. A combined 50% either SD (32%) or D (18%), indicating widespread concern about the lack of robust funding and focus in this critical area. Additionally, 38% selected N, suggesting uncertainty or possibly limited visibility into the scale and impact of existing R&D efforts. Only 12% expressed a positive view (8% A, 4% SA) that adequate investment is being made. This distribution highlights a clear perception gap and points to the urgent need for increased public and private sector

investment in research and innovation to accelerate the development and deployment of GH₂ technologies in the Country.

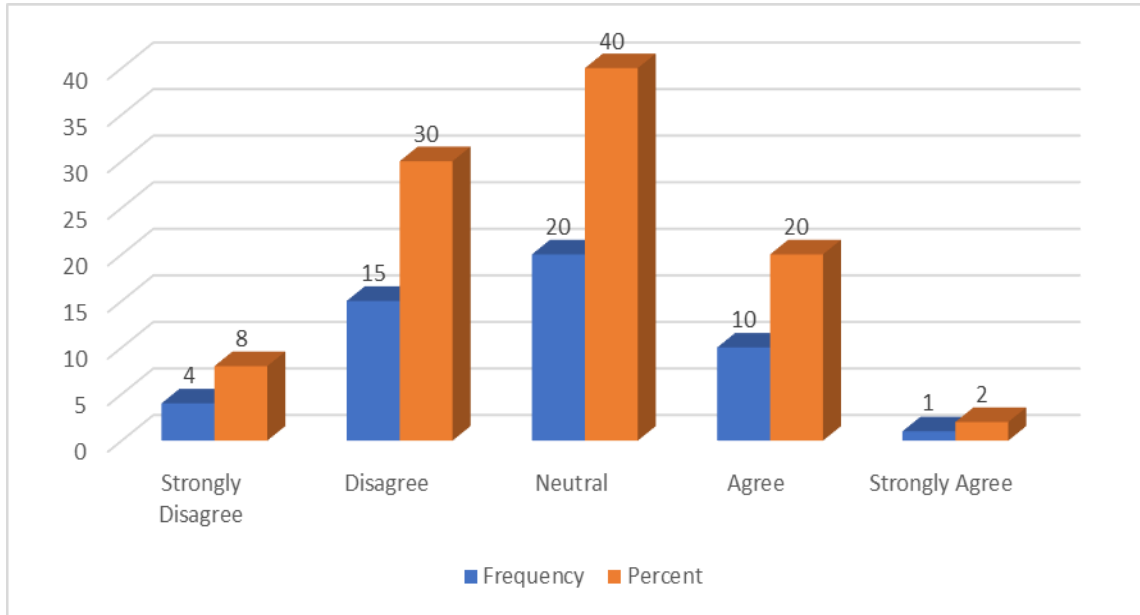


Figure 4.21: Investors are willing to fund Green Hydrogen-related initiatives in your sector.

Source: Author Generated

Figure 4.21 highlights the respondents' perceptions of investor willingness to fund GH₂-related initiatives in their respective sectors. The responses suggest a generally cautious investment environment, with 38% expressing doubt—30% D and 8% SD—about investor readiness. A large portion, 40%, chose the N option, reflecting uncertainty or possibly a lack of visibility into ongoing funding trends. In contrast, only 22% of respondents showed optimism (20% A, 2% SA) about investor interest. These results indicate that while there is some level of investment activity, confidence in widespread investor enthusiasm remains limited, pointing to the need for stronger policy signals, risk mitigation mechanisms and clearer returns on investment to attract and mobilise capital in the GH₂ space.

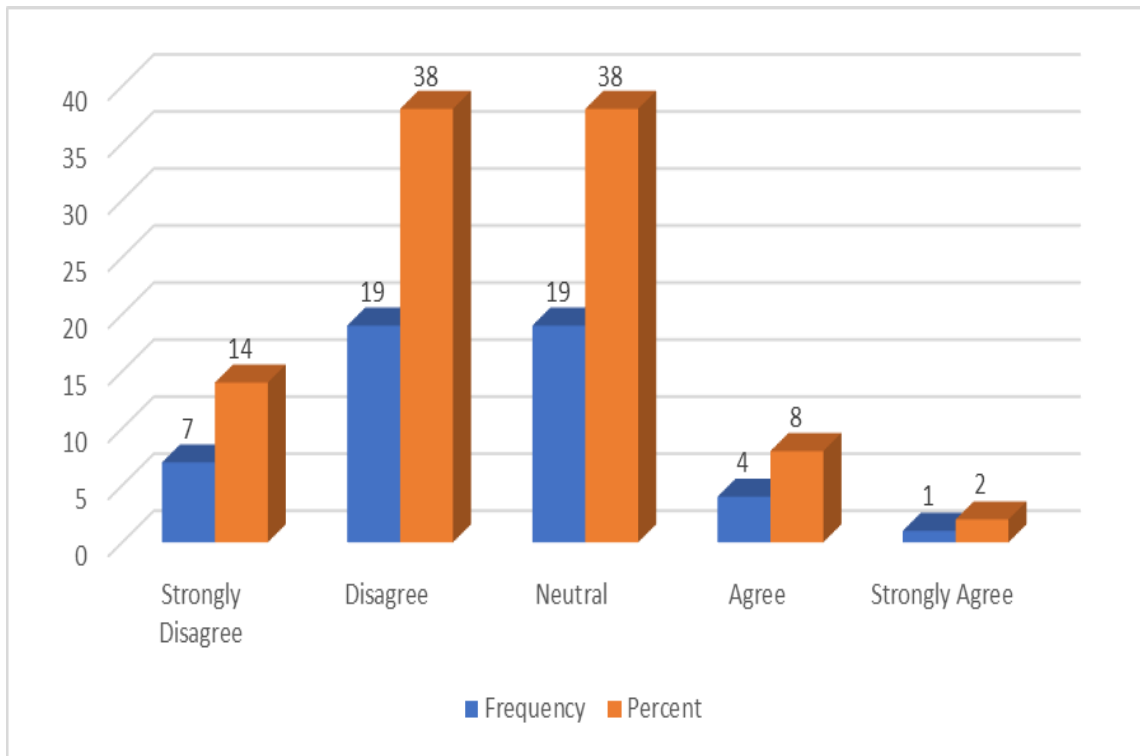


Figure 4.22: There is sufficient financial support from Banks and Financial institutions for Green Hydrogen projects.

Source: Author Generated

Figure 4.22 reveals a prevailing sense of inadequate financial support from banks and financial institutions for GH₂ projects in India. A combined 52% of respondents either D (38%) or SD (14%), indicate that more than half of the participants perceive a lack of accessible or sufficient funding avenues through traditional financial channels. Additionally, 38% selected N, suggesting uncertainty or limited exposure to GH₂ financing mechanisms. Only a small fraction—10%—expressed a positive outlook (8% A, 2% SA) on the availability of financial backing. These insights highlight a significant financing gap, underscoring the need for dedicated green finance schemes, concessional lending, and risk-sharing instruments to encourage institutional support for GH₂ development.

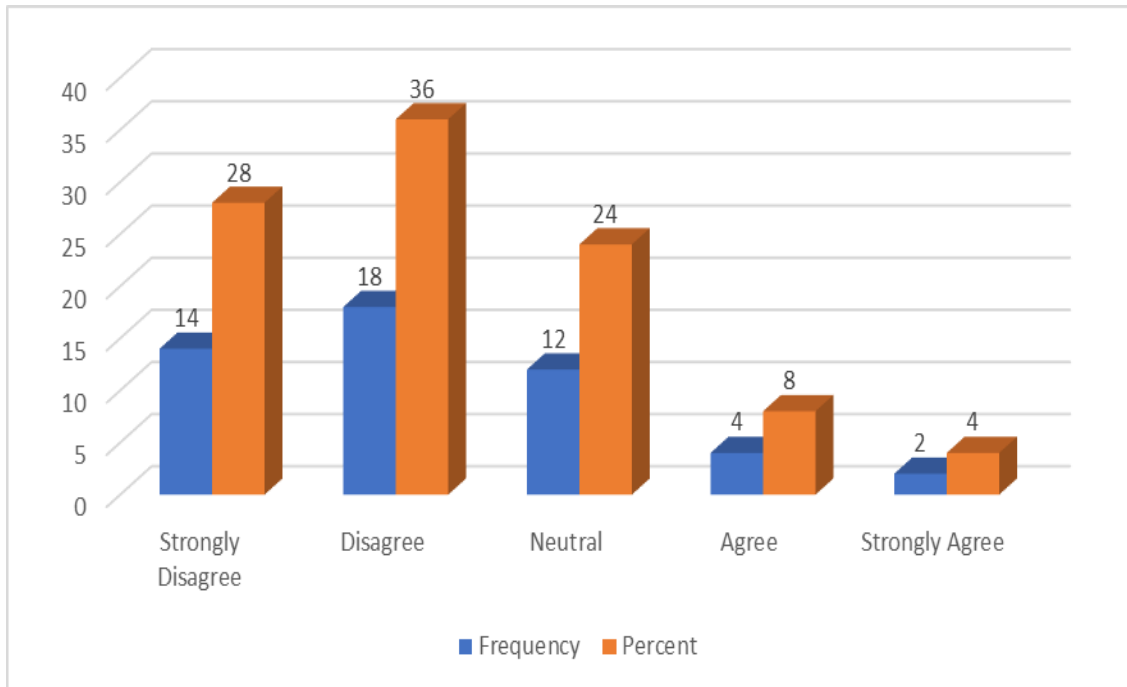


Figure 4.23: The organisation has a skilled workforce capable of handling Green Hydrogen technologies.

Source: Author Generated

The responses shown in Figure 4.23 indicate a significant skills gap in the workforce needed to support GH₂ technologies. With 36% D and an additional 28% SD, a clear majority (64%) of respondents believe that their organisations lack the necessary technical expertise. This concern is further emphasised by the fact that only 12% of participants expressed agreement or strong agreement, pointing to very limited confidence in current workforce capabilities. The 24% who responded neutrally may reflect organisations that are still evaluating their preparedness or have mixed levels of skill availability. These results signal a critical need for strategic investments in human capital, including technical education, industry-led certification programs, and practical skill-building to ensure organisations are ready for the challenges and demands of GH₂ implementation.

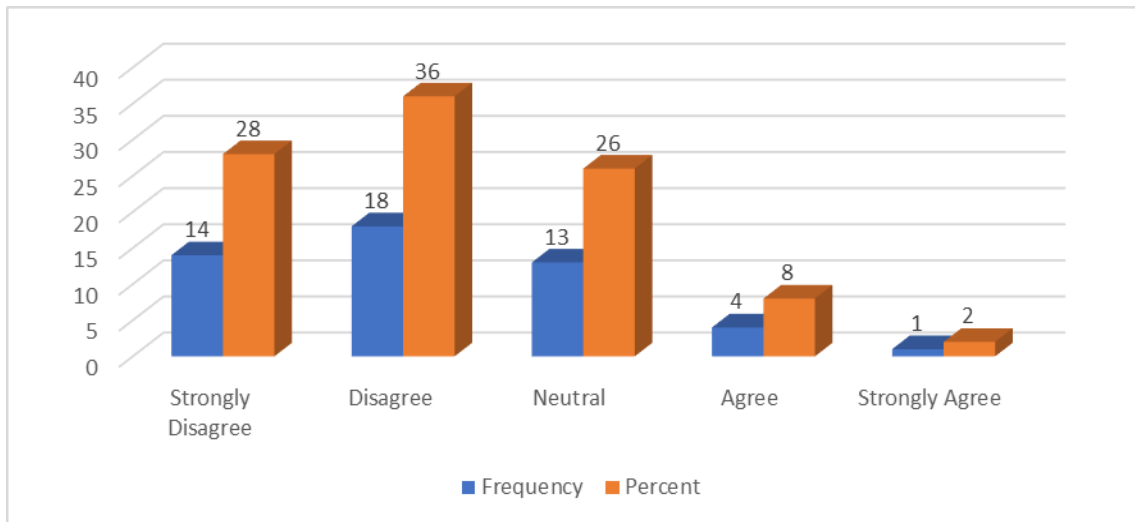


Figure 4.24: Adequate training programs are available to develop expertise in Green Hydrogen technologies.

Source: Author Generated

Figure 4.24 reveals a clear gap in training infrastructure for GH₂ technologies. A combined 64% of respondents either SD (28%) or D (36%) with the statement that adequate training programs are available. Only 10% A or SA, while 26% remained N. These results indicate that training opportunities are perceived as insufficient, which could hinder workforce development and slow down the adoption of GH₂ solutions in India.

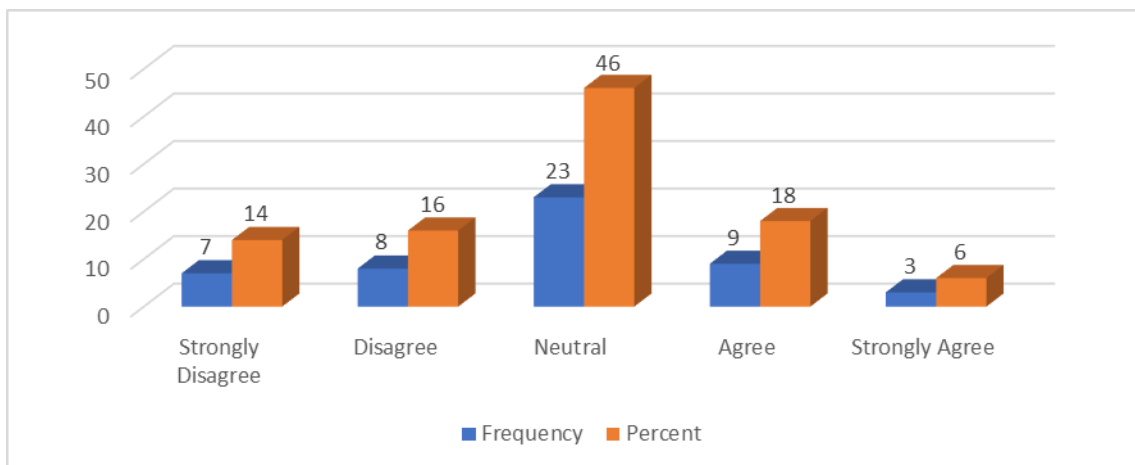


Figure 4.25: There is a strong commitment towards adopting Green Hydrogen solutions.

Source: Author Generated

The data presented in Figure 4.25 indicates a moderate level of commitment toward adopting GH₂ solutions. While 18% A and 6% SA with the statement, a significant portion (46%) remained N, suggesting uncertainty or lack of clarity regarding organisational priorities. Meanwhile, 30% of respondents expressed disagreement to varying degrees. This distribution reflects that while some positive inclination exists, there is no overwhelming consensus or strong momentum, highlighting the need for clearer direction and stronger leadership commitment in promoting GH₂ adoption.

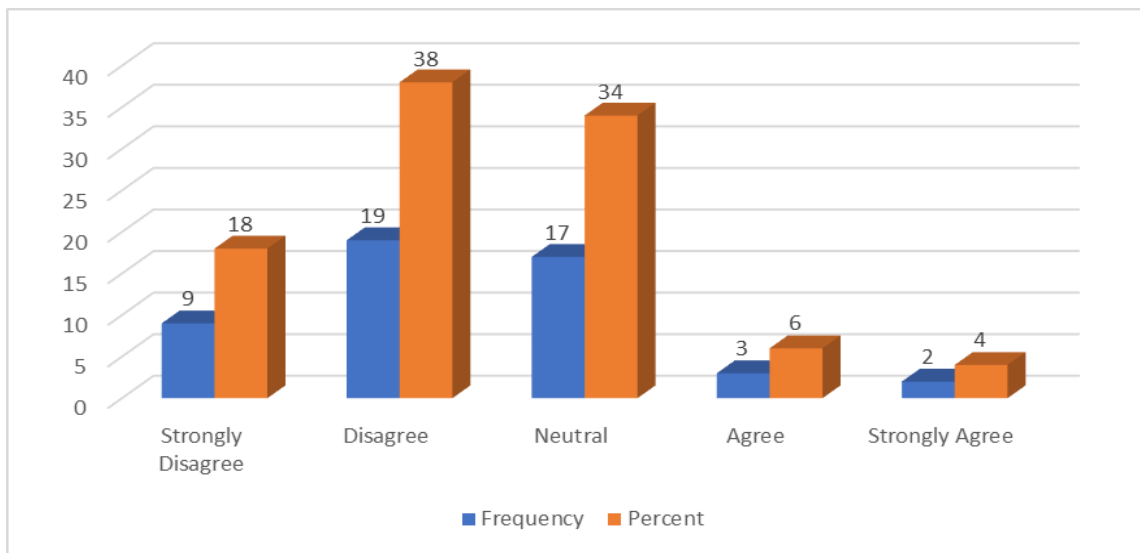


Figure 4.26: There is a clear roadmap in place for transitioning to Green Hydrogen-based operations.

Source: Author Generated

The responses depicted in Figure 4.26 highlight a lack of clarity and direction regarding the roadmap for transitioning to GH₂-based operations. A combined 56% of respondents either D (38%) or SD (18%) with the presence of a clear roadmap, indicating concerns over strategic planning and guidance. Additionally, 34% remained N, suggesting a degree of uncertainty or lack of awareness. Only a small proportion—6% A and 4% SA—perceived a clear plan in place. This suggests a pressing need for organisations and

policymakers to articulate a more defined and transparent roadmap to enable effective GH₂ adoption.

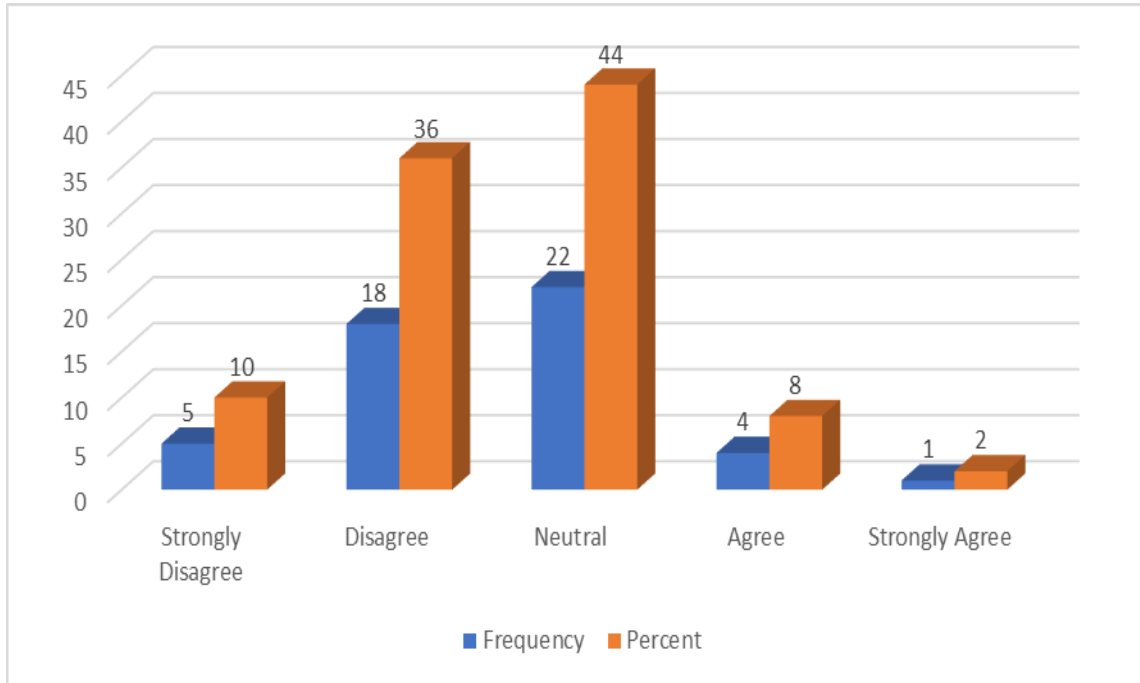


Figure 4.27: There is strong industry-wide cooperation in India to advance Green Hydrogen adoption.

Source: Author Generated

The data presented in Figure 4.27 illustrates a notable gap in industry-wide cooperation for advancing GH₂ adoption in India. A significant portion of respondents—36% D and 10% SD—indicates that collaboration across sectors is perceived as weak. Moreover, 44% of participants remained N, suggesting either a lack of awareness or unclear visibility into cooperative efforts. Only a small segment—8% A and 2% SA—recognized any strong collaborative drive. These findings point to the need for enhanced synergy and collective action among industry players to foster a more unified approach to scaling GH₂ initiatives.

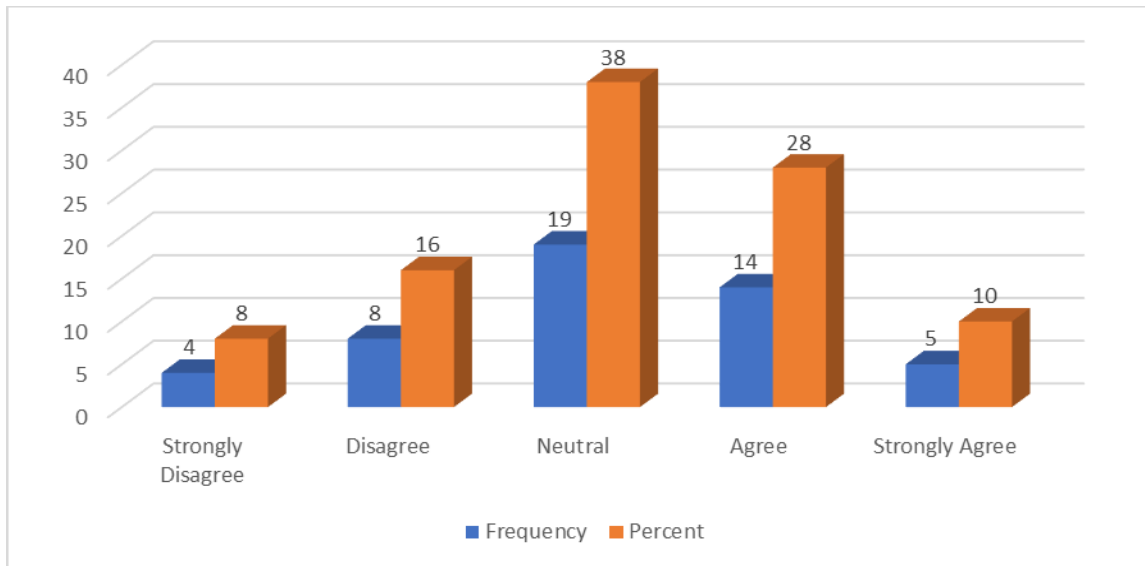


Figure 4.28: Partnerships and joint ventures are increasing to accelerate Green Hydrogen implementation.

Source: Author Generated

As illustrated in Figure 4.28, responses regarding the rise of partnerships and joint ventures to accelerate GH₂ implementation reveal a moderately positive trend. While 38% of respondents remained N, indicating uncertainty or limited awareness, a considerable 28% A and 10% SA that such collaborations are indeed increasing. On the contrary, 16% D and 8% SD, pointing to some scepticism about the extent or effectiveness of these efforts. Overall, the data suggests growing momentum in strategic alliances, but also highlights the need for more visible and impactful partnerships to build confidence across the sector.

4.7.5 Infrastructure & Investment Measures (for Green Hydrogen Producers, Banks, Private Equity, Venture Funds)

Here, the focus is on how well the current infrastructure and investment ecosystem supports GH₂ development. Key insights are drawn on infrastructure availability, investment plans, financial support mechanisms, risk perception, and development challenges.

			SD	D	N	A	SA
Existing Infrastructure Availability	The current infrastructure for Green Hydrogen production is adequate.	Frequency	13	17	17	1	2
		Percent	26	34	34	2	4
	The existing Green Hydrogen infrastructure can support large-scale commercial adoption.	Frequency	13	19	17	0	1
		Percent	26	38	34	0	2
Infrastructure Investment Plans	There are concrete plans to expand Green Hydrogen infrastructure.	Frequency	8	11	28	2	1
		Percent	16	22	56	4	2
	Government and Private players are investing in large-scale hydrogen infrastructure projects.	Frequency	3	13	22	9	3
		Percent	6	26	44	18	6
Financial Support Mechanisms	Private Equity and Venture Capital firms are actively funding Green Hydrogen startups and innovations.	Frequency	5	16	22	6	1
		Percent	10	32	44	12	2
	Government incentives and subsidies play a crucial role in attracting Green Hydrogen investments.	Frequency	1	6	13	13	17
		Percent	2	12	26	26	34
		Frequency	3	7	13	15	12

Risk Perception in Green Hydrogen Investments	Investors perceive Green Hydrogen as a high-risk investment.	Percent	6	14	26	30	24
	Market uncertainty is not a significant barrier to securing Green Hydrogen investments.	Frequency	5	10	17	9	9
		Percent	10	20	34	18	18
Infrastructure Development Challenges	High initial capital costs are a major challenge for Green Hydrogen infrastructure expansion.	Frequency	1	3	11	21	14
		Percent	2	6	22	42	28
	Land acquisition and approval processes affect the development of Green Hydrogen projects.	Frequency	0	6	16	16	12
		Percent	0	12	32	32	24

Table 4.14: Infrastructure & Investment Measures (for Green Hydrogen Producers, Banks, Private Equity, Venture Funds)

Source: Author Generated

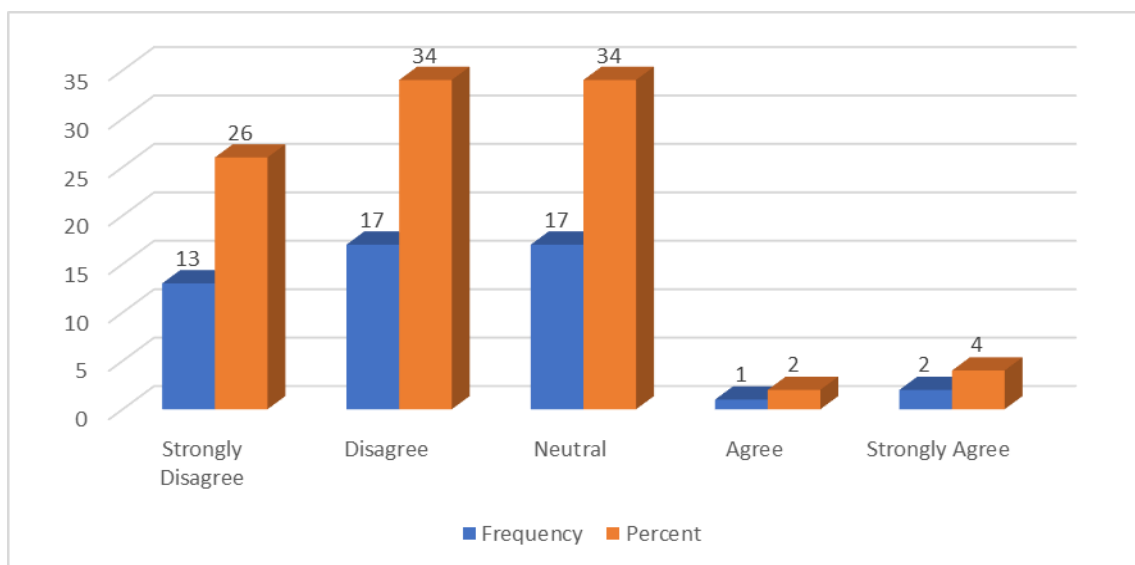


Figure 4.29: The current infrastructure for Green Hydrogen production is adequate.

Source: Author Generated

The perception of adequacy in the current infrastructure for GH₂ production appears largely unfavourable, as depicted in Figure 4.29. A combined 60% of respondents either D (34%) or SD (26%) with the statement, indicate significant concerns about the preparedness of existing infrastructure. Meanwhile, 34% remained N, possibly reflecting uncertainty or limited exposure to operational facilities. Only a marginal 6% expressed A or SA. These findings suggest a critical gap in infrastructure development, underscoring the need for substantial investment and policy support to build a robust foundation for GH₂ scalability in India.

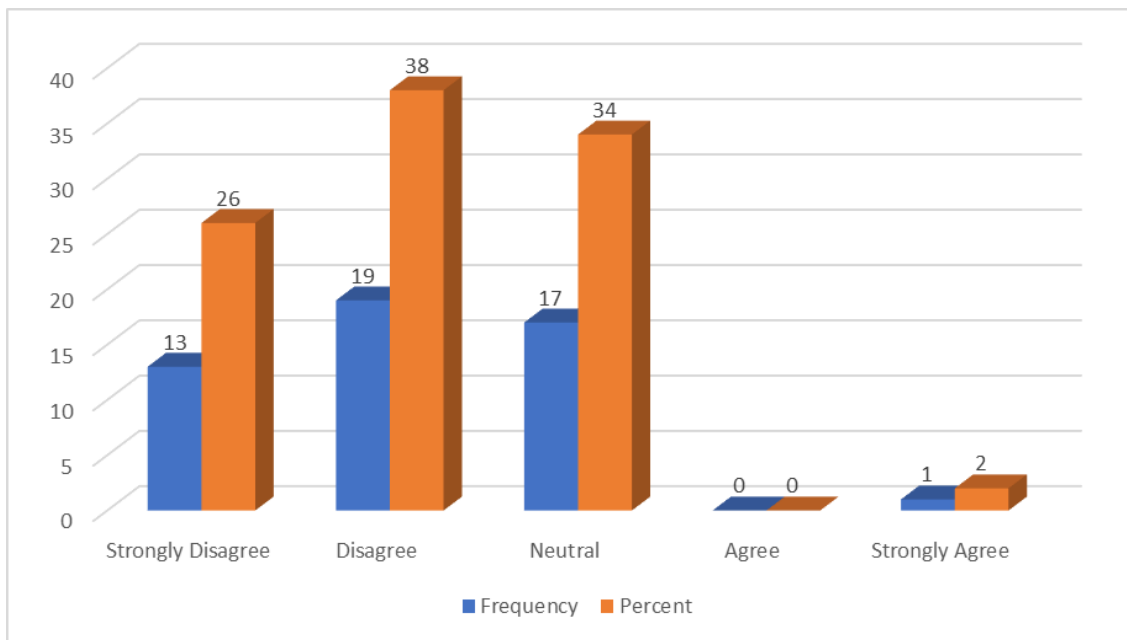


Figure 4.30: The existing Green Hydrogen infrastructure can support large-scale commercial adoption.

Source: Author Generated

The data in Figure 4.30 highlights a predominantly negative outlook regarding the capability of existing GH₂ infrastructure to support large-scale commercial adoption. A significant 64% of respondents either D (38%) or SD (26%) with the statement, indicate

widespread scepticism about the current system's readiness. Meanwhile, 34% remained N, possibly pointing to uncertainty or lack of awareness, and only 2% SA that the infrastructure is sufficient. This suggests a pressing need for substantial infrastructural upgrades and investments to enable commercial viability and scalability of GH₂ solutions in India.

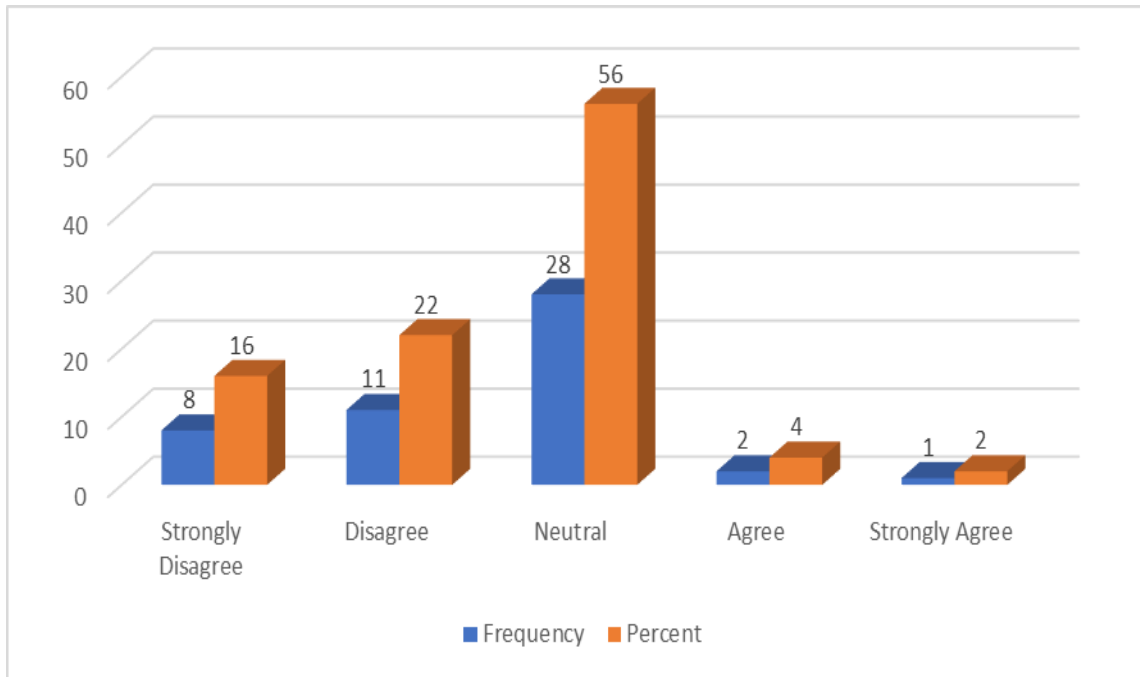


Figure 4.31: There are concrete plans to expand Green Hydrogen infrastructure.

Source: Author Generated

Figure 4.31 reveals a largely uncertain perception regarding the existence of concrete plans to expand GH₂ infrastructure in India. A majority of respondents (56%) remained N, suggested limited awareness or clarity about such initiatives. Additionally, 38% of participants expressed scepticism, with 16% SD and 22% D, indicating that clear and communicated expansion strategies are either lacking or not reaching key stakeholders. Only 6% of the respondents showed agreement, with 4% A and 2% SA. These findings

underscore the need for transparent and actionable infrastructure development plans to foster confidence in the sector’s growth trajectory.

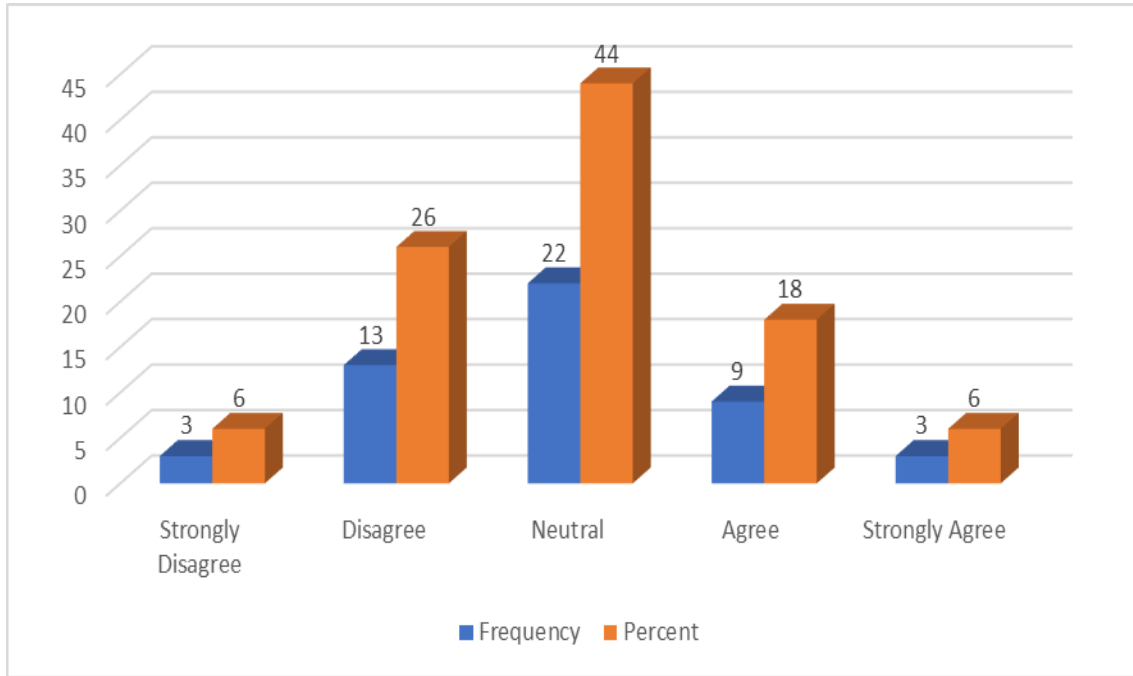


Figure 4.32: Government and Private players are investing in large-scale hydrogen infrastructure projects.

Source: Author Generated

Figure 4.32 highlights a mixed perception regarding investments by the Government and private players in large-scale hydrogen infrastructure projects. While a significant portion of respondents (44%) remained *N*, indicating either limited awareness or ambiguity about such investments, a combined 24% (18% *A* and 6% *SA*) acknowledged that such initiatives are indeed underway. However, 32% of respondents expressed disagreement (26% *D* and 6% *SD*), reflecting scepticism about the visibility or scale of current investment efforts. Overall, the responses suggest that while some progress is perceived, greater transparency and communication regarding large-scale hydrogen investments are essential to build stakeholder confidence.

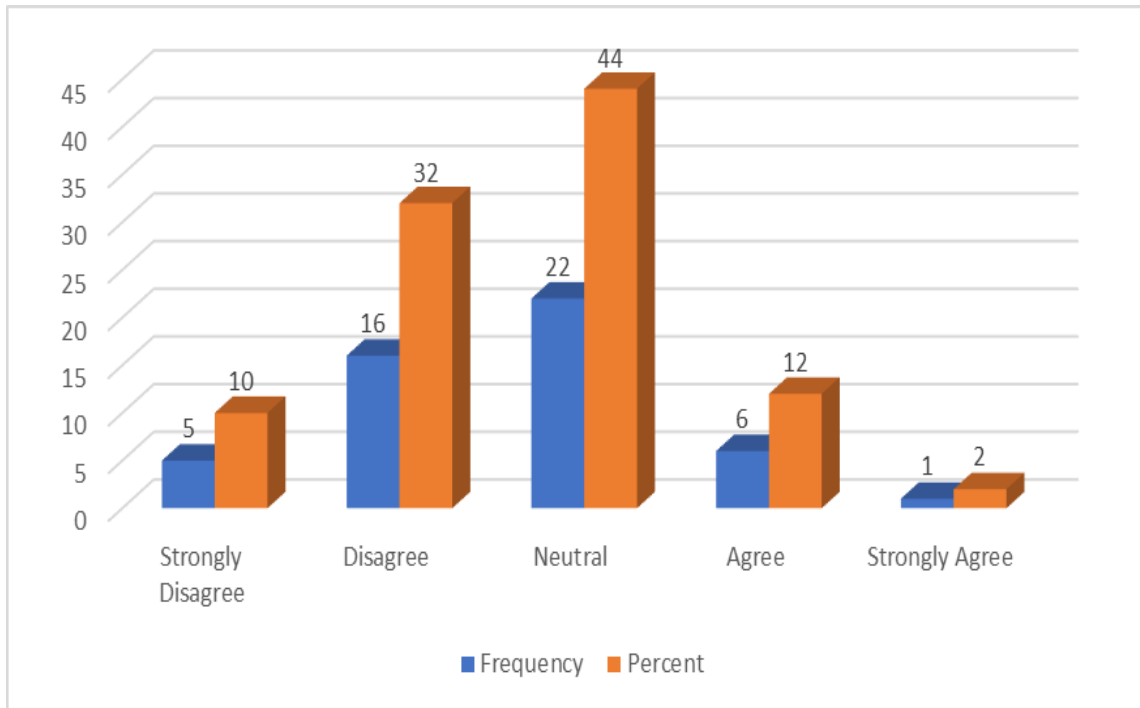


Figure 4.33: Private Equity and Venture Capital firms are actively funding Green Hydrogen startups and innovations.

Source: Author Generated

Figure 4.33 presents insights into perceptions regarding the involvement of private equity and venture capital firms in funding GH₂ startups and innovations. A large portion of respondents (44%) maintained a *neutral* stance, indicating uncertainty or limited knowledge about such funding activities. Meanwhile, 42% expressed scepticism, with 32% *D* and 10% *SD*, suggesting that many do not perceive active financial backing from these investors. Only 14% of participants acknowledged some level of support (12% *A* and 2% *SA*). This distribution reflects a general lack of visibility or perceived momentum in venture capital engagement within the GH₂ sector, highlighting a need for increased awareness or actual investment activity in this space.

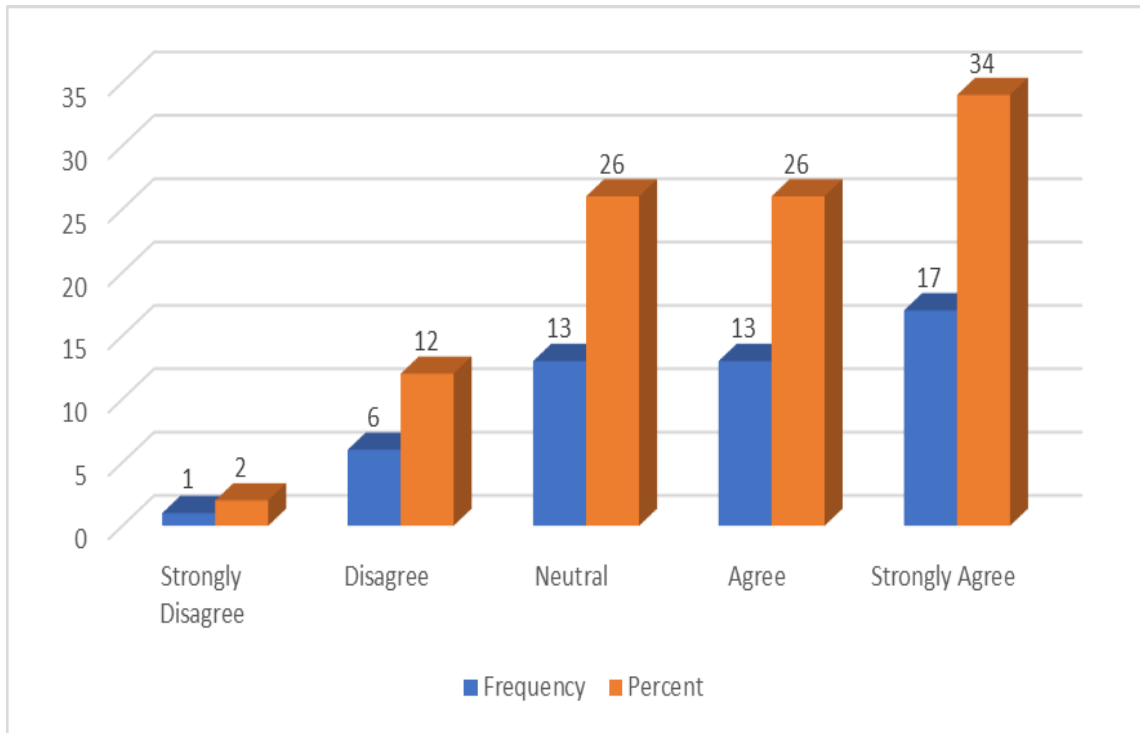


Figure 4.34: Government incentives and subsidies play a crucial role in attracting Green

Source: Author Generated

Figure 4.34 depicts participants' perceptions regarding the influence of Government incentives and subsidies on GH₂ investments. A combined 60% of respondents expressed positive agreement (26% A and 34% SA), highlighting that policy support is widely seen as a key enabler for sectoral growth. Meanwhile, 26% of the respondents remained N, possibly reflecting limited exposure to the policy impact or a wait-and-watch approach. On the other hand, only 14% (12% D and 2% SD) expressed scepticism. This distribution reflects broad confidence in the Government's fiscal role in promoting hydrogen innovation and infrastructure.

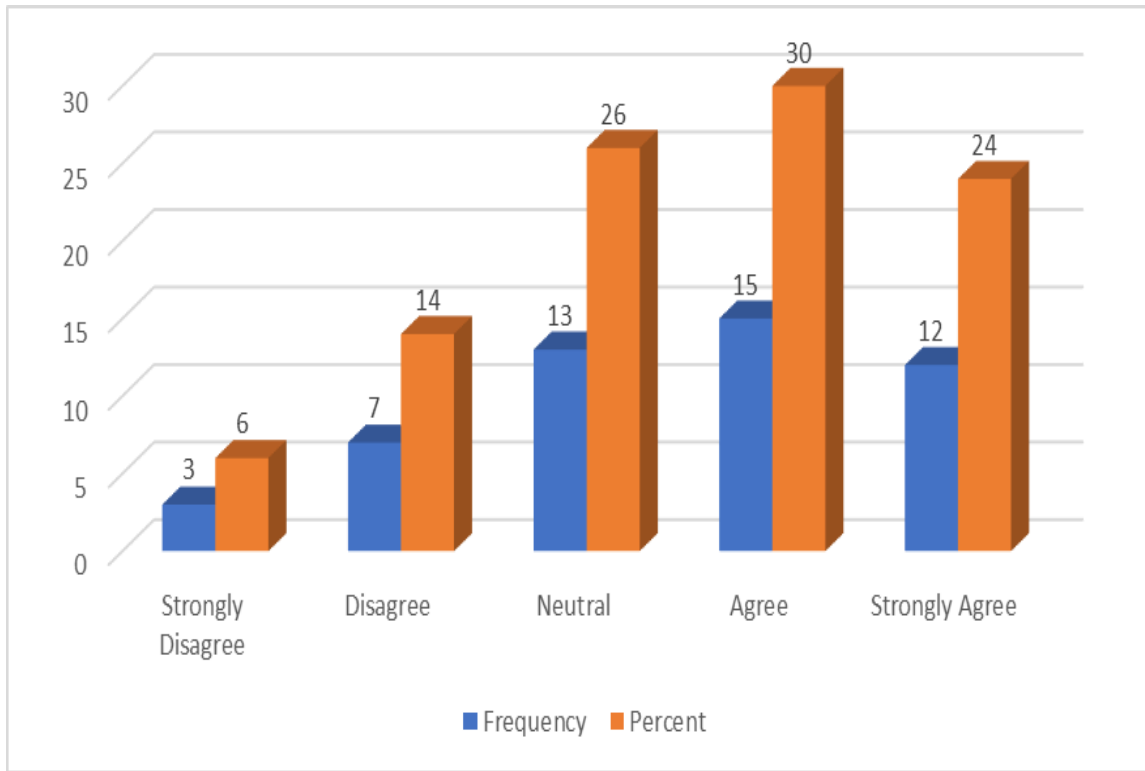


Figure 4.35: Investors perceive Green Hydrogen as a high-risk investment.

Source: Author Generated

Figure 4.35 shows the perception of respondents regarding the risk associated with GH₂ investments. A majority of the participants, 54% (30% A and 24% SA), feel that investors perceive GH₂ as a high-risk investment. About 26% of respondents remained N, possibly indicating uncertainty or lack of awareness. On the other hand, 20% (14% D and 6% SD) do not consider it to be a high-risk investment. This indicates that while there is growing interest, concerns about risk continue to influence investment decisions in this sector.

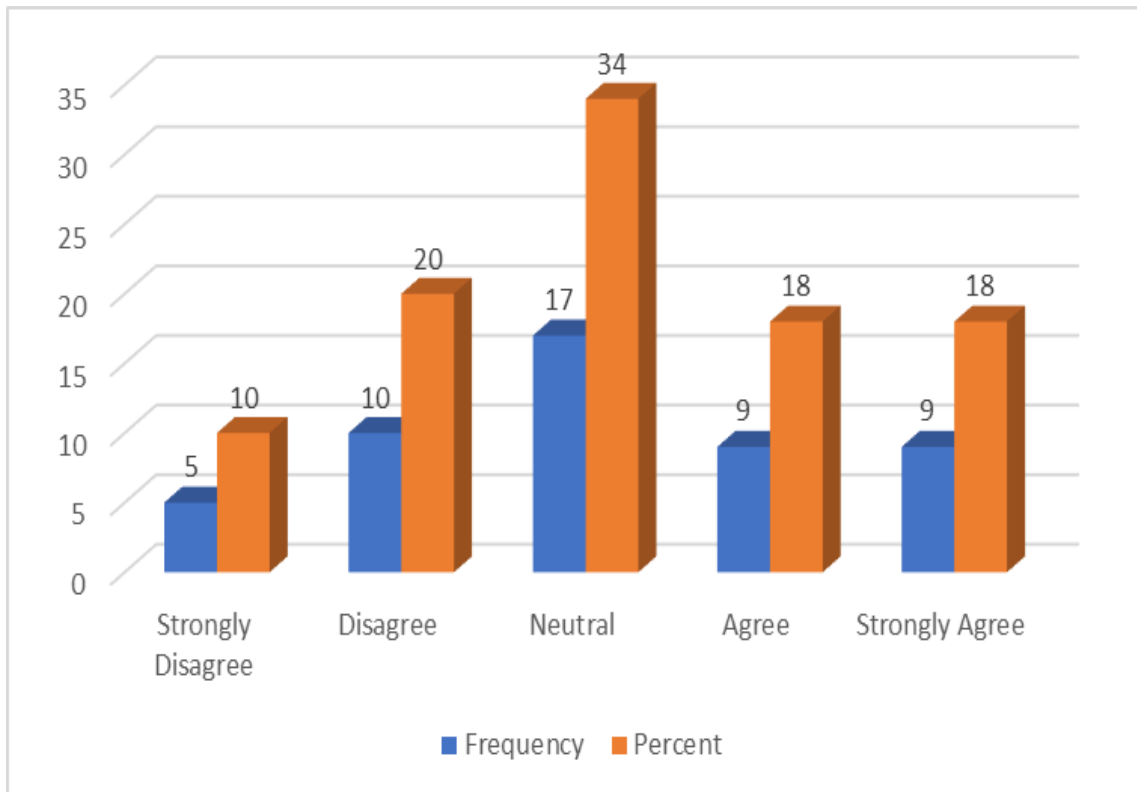


Figure 4.36: Market uncertainty is not a significant barrier to securing Green Hydrogen investments.

Source: Author Generated

According to Figure 4.36, the responses regarding whether market uncertainty is a significant barrier to securing GH₂ investments show a mixed perspective. About 36% of the respondents (18% A and 18% SA) believe that market uncertainty is not a major obstacle. On the other hand, 30% (10% SD and 20% D) feel that uncertainty does pose a challenge. A considerable 34% of participants remained N. This suggests that while a portion of stakeholders is optimistic about market stability, a significant number still express caution or uncertainty.

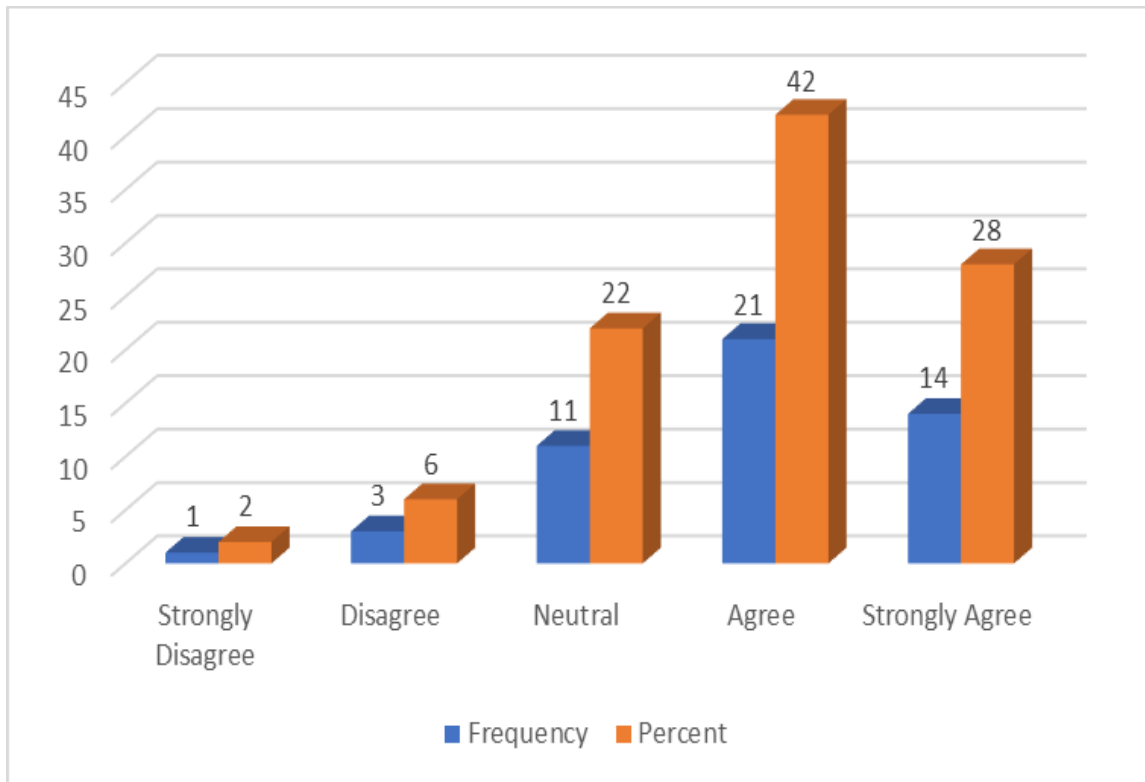


Figure 4.37: High initial capital costs are a major challenge for Green Hydrogen infrastructure expansion.

Source: Author Generated

According to Figure 4.37, a significant majority of respondents perceive high initial capital costs as a major challenge for the expansion of GH₂ infrastructure. Specifically, 42% of the participants agreed and 28% SA with this statement, indicating that 70% acknowledge the financial burden involved. Only 8% of respondents D or SD, while 22% remained N. This highlights that upfront investment requirements are a widely recognised barrier to scaling up GH₂ initiatives.

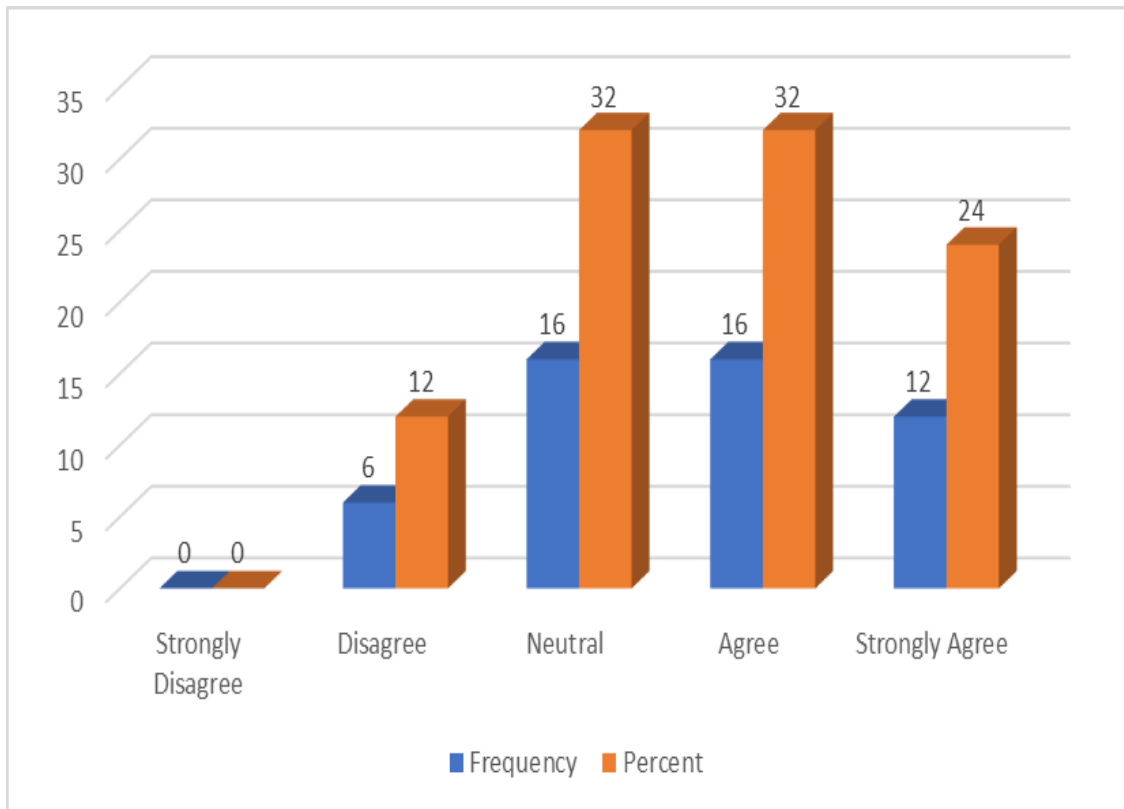


Figure 4.38: Land acquisition and approval processes affect the development of Green Hydrogen projects.

Source: Author Generated

As shown in Figure 4.38, land acquisition and approval processes are considered significant factors affecting the development of GH₂ projects. A combined 56% of respondents A (32%) or SA (24%) agree with this statement, indicating that bureaucratic and regulatory hurdles are perceived as real challenges. While 32% of the participants remained N, only 12% D. These findings suggest that streamlining land and regulatory clearances could be crucial to accelerating the implementation of GH₂ projects.

4.7.6 Scalability & Storage Challenges

This section investigates the technical and logistical issues related to scaling up GH₂ in India, particularly in storage infrastructure, transport, market demand, and the role of Government-Private cooperation.

			SD	D	N	A	SA
Hydrogen Storage Capacity	The current storage infrastructure is sufficient to meet the future demand for Green Hydrogen.	Frequency	15	16	14	2	3
		Percent	30	32	28	4	6
	There is an urgent need to expand Green Hydrogen storage facilities to support large-scale adoption.	Frequency	3	2	10	16	19
		Percent	6	4	20	32	38
Scalability Strategies	The organisation or industry has a clear strategy for scaling up Green Hydrogen production.	Frequency	6	14	23	4	3
		Percent	12	28	46	8	6
	More investment is required in large-scale Green Hydrogen production and distribution facilities.	Frequency	0	3	9	16	22
		Percent	0	6	18	32	44
Transportation & Logistics Challenges	Transporting Green Hydrogen over long distances is currently inefficient and costly.	Frequency	1	2	11	15	21
		Percent	2	4	22	30	42
	The development of Green Hydrogen transportation infrastructure is progressing at a satisfactory pace.	Frequency	7	18	21	1	3
		Percent	14	36	42	2	6
Market Demand for Green Hydrogen	The demand for Green Hydrogen is growing significantly in domestic and international markets.	Frequency	3	8	23	12	4
		Percent	6	16	46	24	8
	Policy and industrial mandates are playing a key role in increasing Green Hydrogen demand.	Frequency	1	8	18	12	11
		Percent	2	16	36	24	22
Government & Private Sector Collaboration for Scalability	Government / Public Sector and Private sector collaboration is essential to scale up Green Hydrogen adoption.	Frequency	0	1	9	13	27
		Percent	0	2	18	26	54

	Public-Private partnerships (PPPs) are helping to overcome scalability challenges in the Green Hydrogen industry.	Frequency	1	2	20	16	11
		Percent	2	4	40	32	22

Table 4.15: Scalability & Storage Challenges

Source: Author Generated

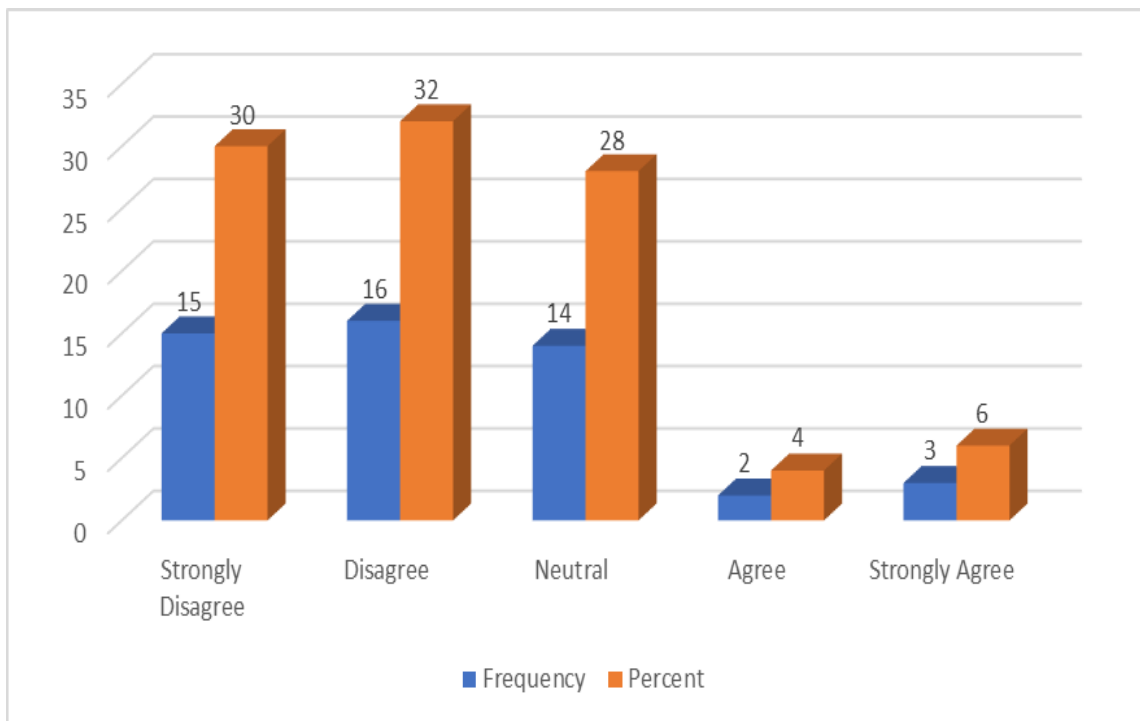


Figure 4.39: The current storage infrastructure is sufficient to meet the future demand for Green Hydrogen.

Source: Author Generated

According to Figure 4.39, a significant proportion of respondents expressed scepticism regarding the adequacy of the current storage infrastructure for meeting future GH₂ demand. A combined 62% either SD (30%) or D (32%) with the statement, while 28% maintained a N stance. Only a small fraction, 10%, A or SA. This data indicates a prevailing concern that existing storage capacities may be insufficient to support the anticipated scale of future GH₂ deployment, emphasising the need for strategic infrastructure upgrades.

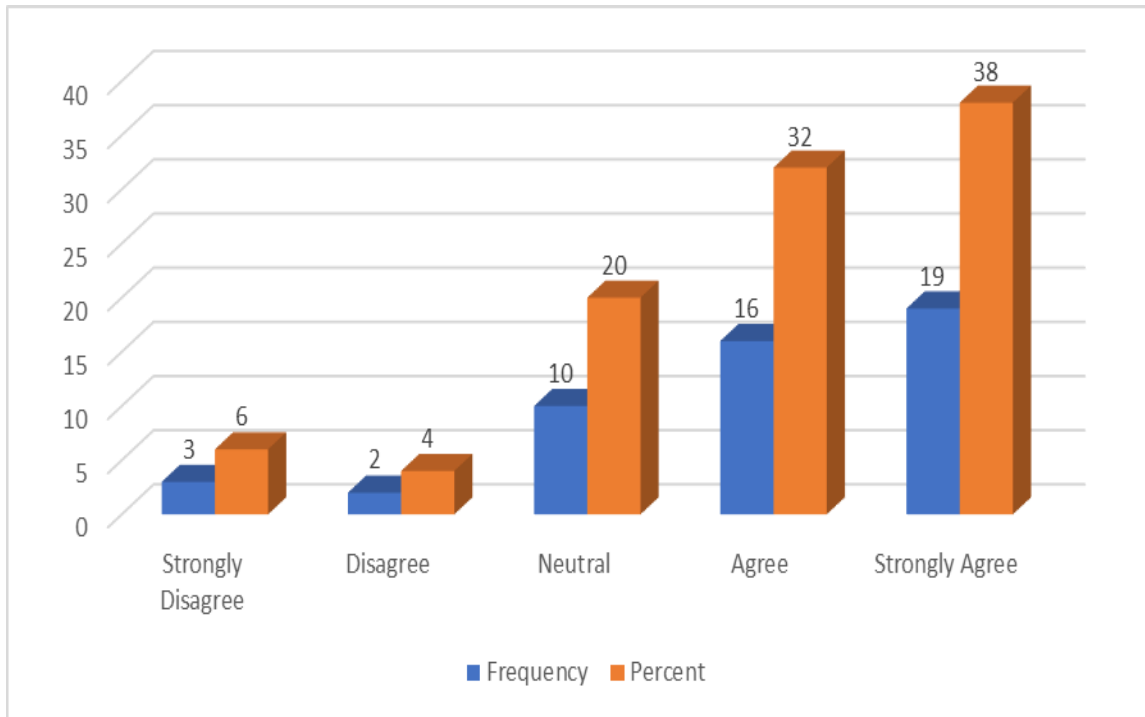


Figure 4.40: There is an urgent need to expand Green Hydrogen storage facilities to support large-scale adoption.

Source: Author Generated

As shown in Figure 4.40, the majority of respondents emphasised the urgent necessity to expand GH₂ storage facilities for enabling large-scale adoption. A combined 70% either A (32%) or SA (38%) with this viewpoint, indicate strong support for infrastructure development. Meanwhile, 20% remained N, and only 10% D or SD. This response pattern clearly highlights a widespread perception that current storage infrastructure is inadequate and that immediate investments and expansion are essential to meet future demand and scalability in the GH₂ sector.

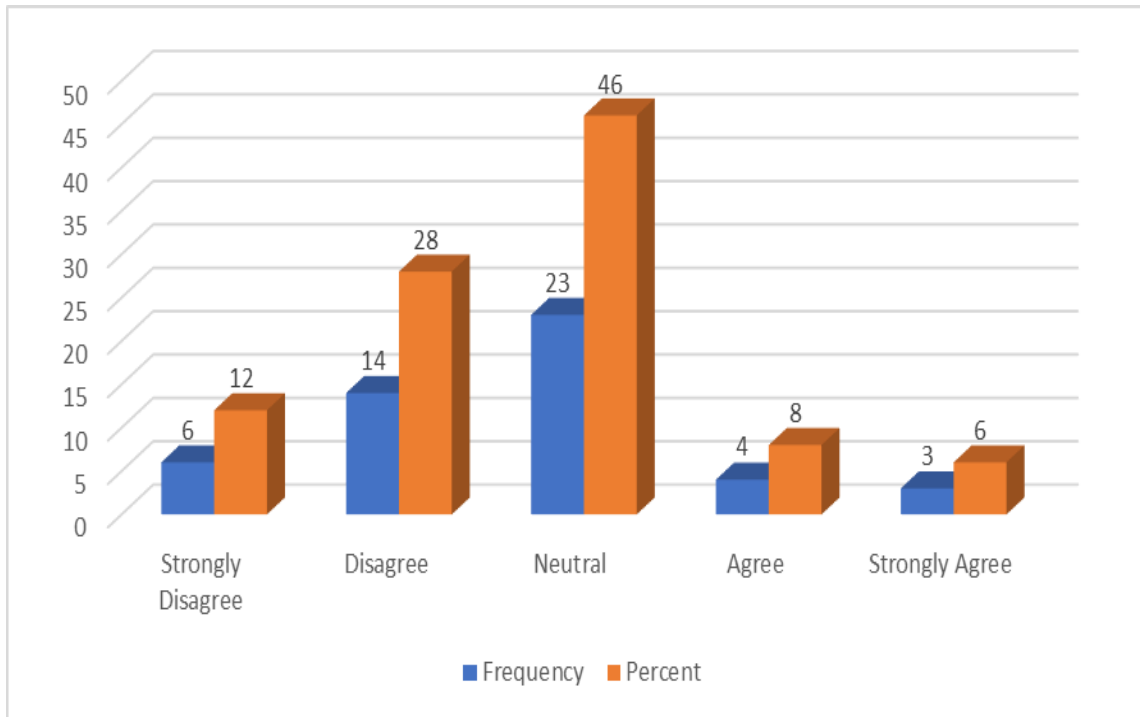


Figure 4.41: Organisation or industry has a clear strategy for scaling up Green Hydrogen production.

Source: Author Generated

As shown in Figure 4.41, a substantial portion of respondents (46%) remained N on whether their organisation or industry has a clear strategy for scaling up GH₂ production, suggesting a lack of clear communication or awareness regarding long-term planning. Additionally, 40% expressed disagreement (with 28% D and 12% SD), indicating concern over the absence of defined strategic direction. Only 14% of respondents A or SA opine that a clear strategy exists. These findings suggest that while there may be discussions or intentions surrounding GH₂ expansion, concrete and well-communicated strategies for scaling up GH₂ production are still lacking within most organisations.

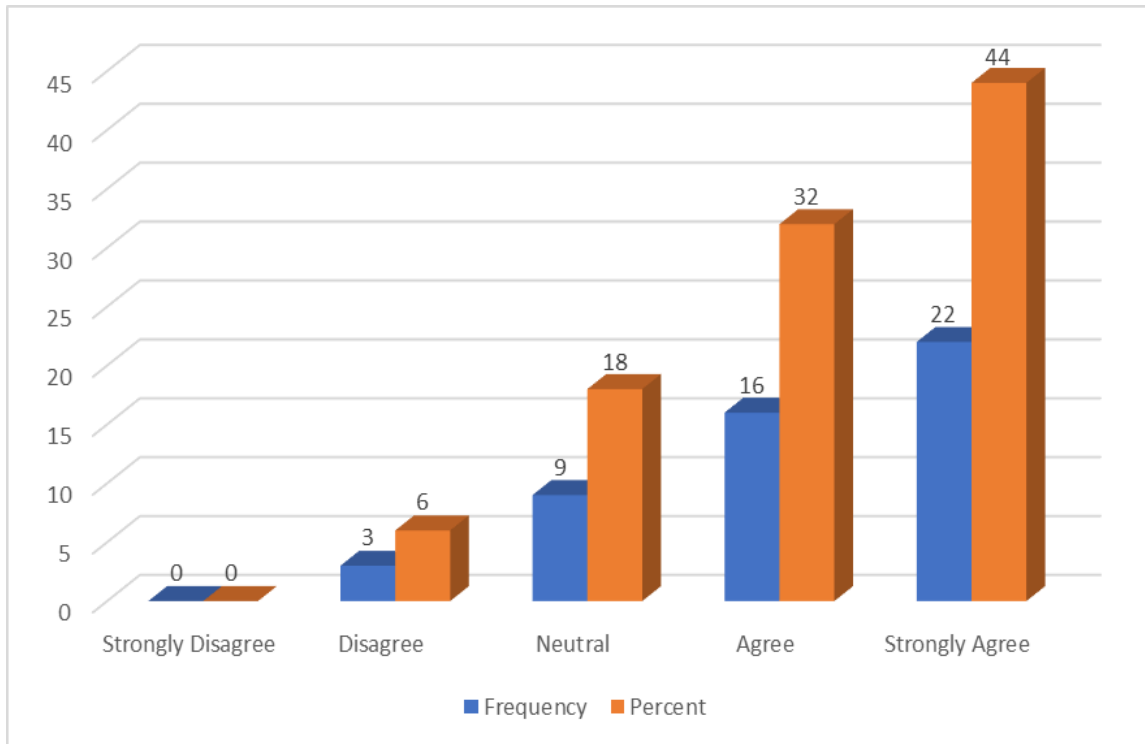


Figure 4.42: More investment is required in large-scale Green Hydrogen production and distribution facilities.

Source: Author Generated

As shown in Figure 4.42, a significant majority of respondents (76%) agreed that more investment is needed in large-scale GH₂ production and distribution facilities, with 32% A and 44% SA. This indicates a strong consensus on the necessity of enhancing funding to scale up infrastructure for broader adoption. Only a small fraction (6%) D, while 18% remained N. The data reflects a clear perception among stakeholders that increased financial investment in large scale GH₂ production and distribution facilities is essential for accelerating the GH₂ transition and meeting future energy demands.

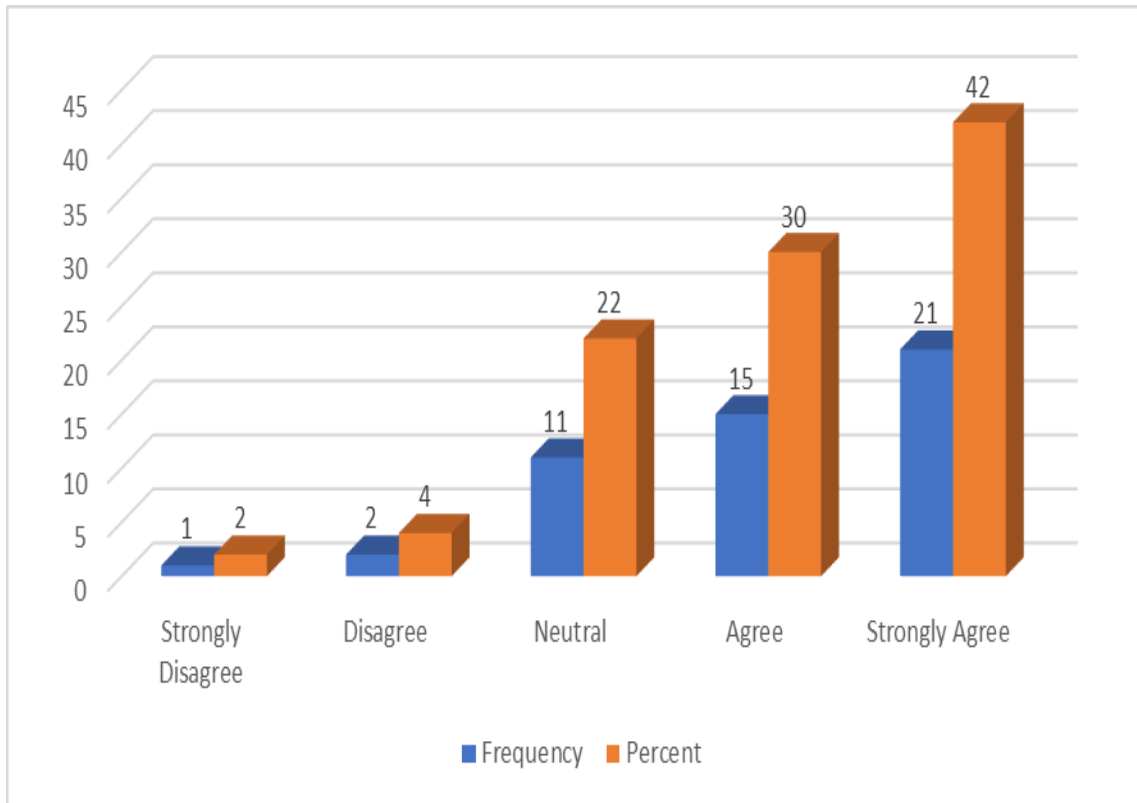


Figure 4.43: Transporting Green Hydrogen over long distances is currently inefficient and costly.

Source: Author Generated

According to Figure 4.43, most respondents perceive long-distance transportation of GH₂ as both inefficient and costly. A combined 72% of the participants expressed agreement with this view—30% A, while 42% SA. Meanwhile, 22% maintained a N stance, and only 6% (D and SD combined) felt otherwise. These insights underscore the need for technological and infrastructural improvements in hydrogen transport systems to support broader adoption.

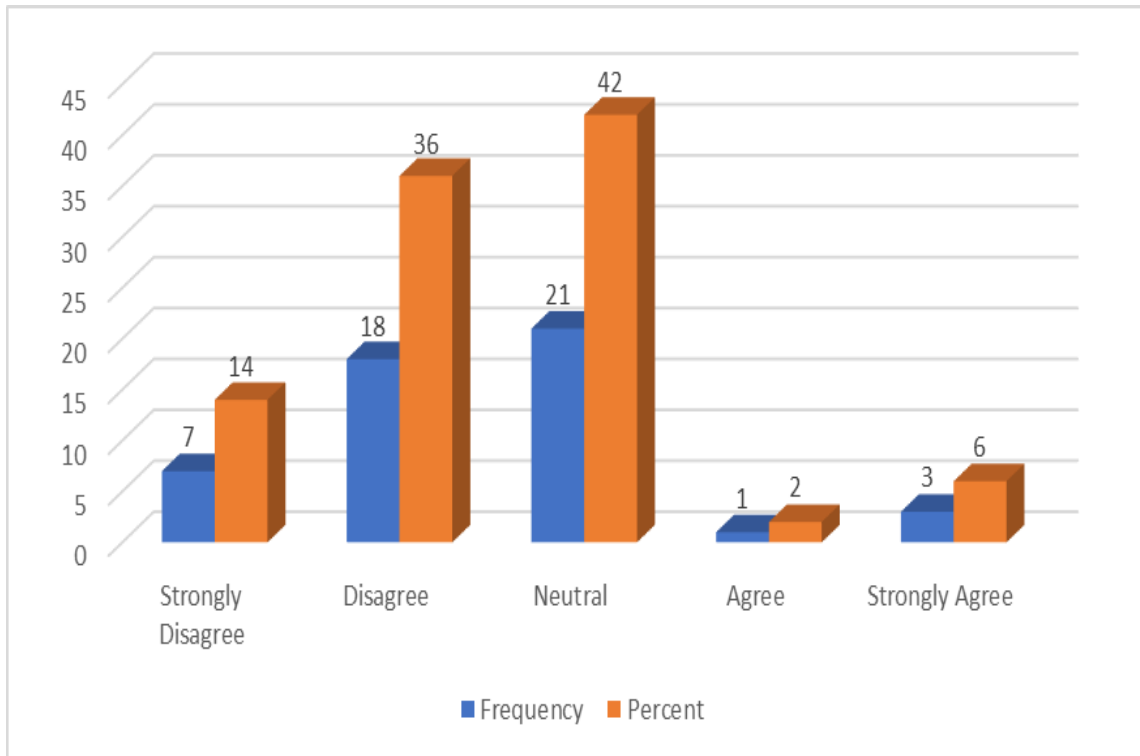


Figure 4.44: The development of Green Hydrogen transportation infrastructure is progressing at a satisfactory pace.

Source: Author Generated

As shown in Figure 4.44, the majority of respondents do not perceive the development of GH₂ transportation infrastructure to be progressing satisfactorily. A combined 50% of participants either D (36%) or SD (14%) with the statement, indicating a lack of confidence in the current pace of infrastructure advancement. 42% of the respondents remained N, suggesting uncertainty or limited awareness, while only 8% expressed agreement. This highlights a critical gap that needs to be addressed through more focused policy support and accelerated infrastructure development.

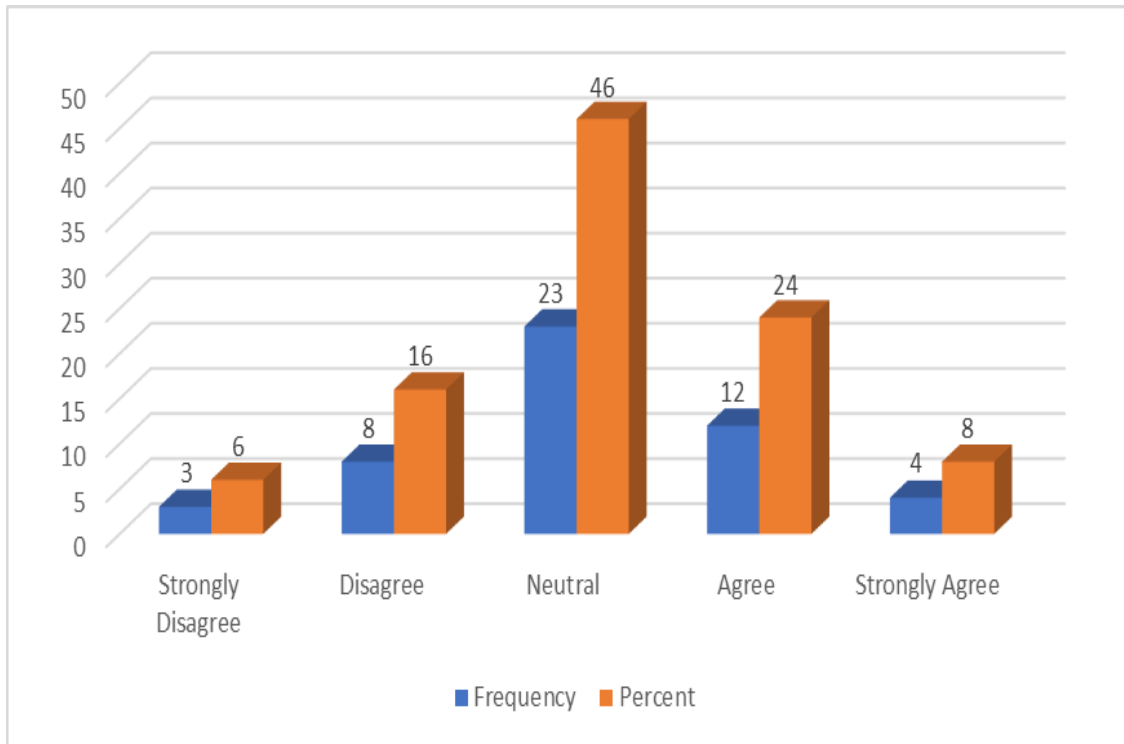


Figure 4.45: The demand for Green Hydrogen is growing significantly in domestic and international markets.

Source: Author Generated

According to Figure 4.45, perceptions about the growing demand for GH₂ in domestic and international markets are mixed. A significant portion of respondents (46%) chose a N stance, indicating uncertainty or lack of direct exposure to demand trends. However, 32% of the participants A (24%) or SA (8%) that demand is rising, reflecting an awareness of increasing interest in GH₂. On the other hand, 22% of respondents expressed disagreement (including 6% SD), suggesting scepticism about the pace or scale of demand growth. These varied responses highlight the need for clearer market signals and broader communication regarding GH₂ demand trajectories.

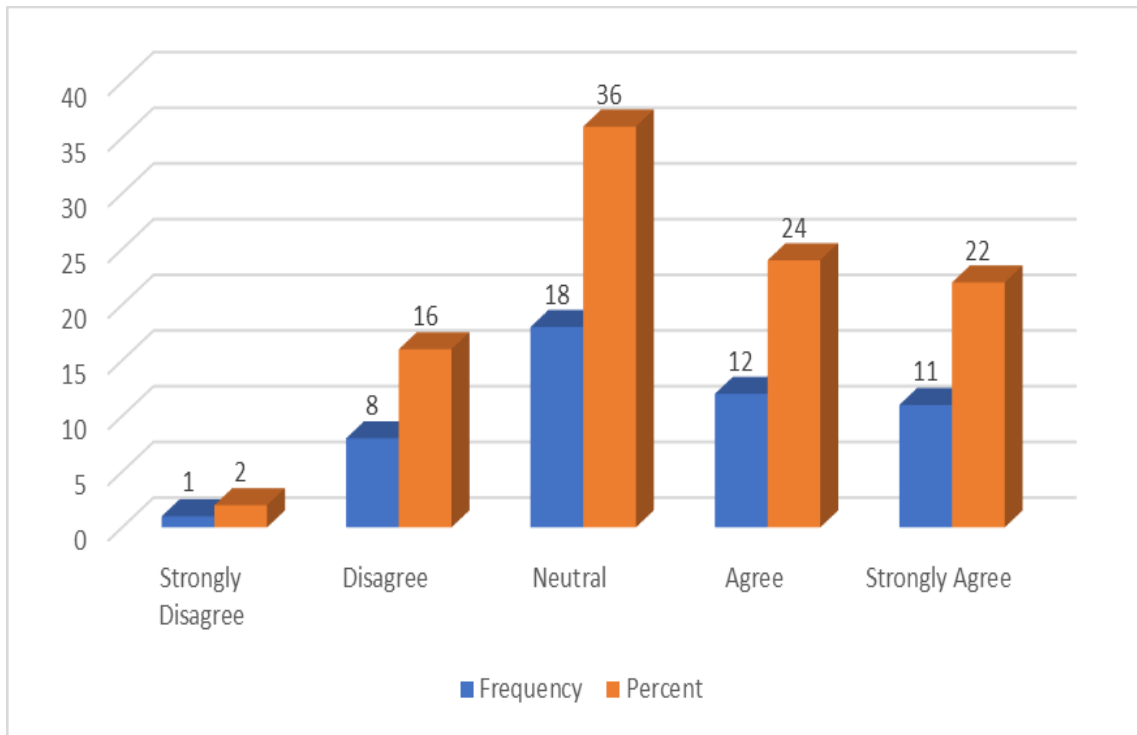


Figure 4.46: Policy and industrial mandates are playing a key role in increasing Green Hydrogen demand.

Source: Author Generated

As shown in Figure 4.46, responses indicate a moderate consensus regarding the role of policy and industrial mandates in boosting GH₂ demand. A combined 46% of respondents A (24%) or SA (22%), acknowledging the influence of regulatory frameworks and industrial strategies. Meanwhile, 36% remained N, suggesting either limited knowledge or mixed evidence about the effectiveness of these mandates. A smaller segment, 18%, expressed disagreement (including 2% SD), reflecting some doubt about the impact of current policies. Overall, while supportive policies appear to be recognized as important drivers, their perceived effectiveness still varies among stakeholders.

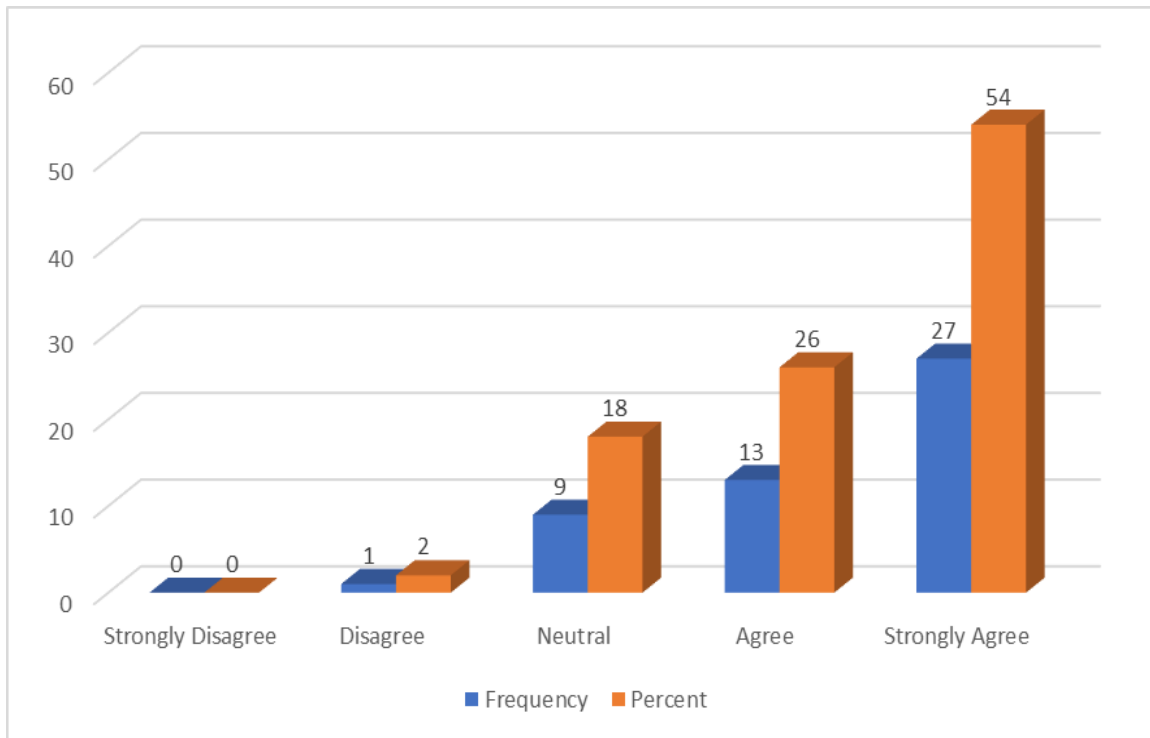


Figure 4.47: Government / Public Sector and Private sector collaboration is essential to scale up Green Hydrogen adoption.

Source: Author Generated

As presented in Figure 4.47, the vast majority of respondents recognize the crucial need for collaboration between the Government/Public sector and Private sector to scale up GH₂ adoption. A significant 54% SA and 26% A, together forming 80% of the sample affirm the importance of public-private partnerships in advancing the GH₂ agenda. Only 18% remained N, and a mere 2% D, indicating an overwhelmingly positive consensus on the necessity of coordinated efforts between sectors to overcome infrastructure, policy, and investment-related challenges in this emerging energy domain.

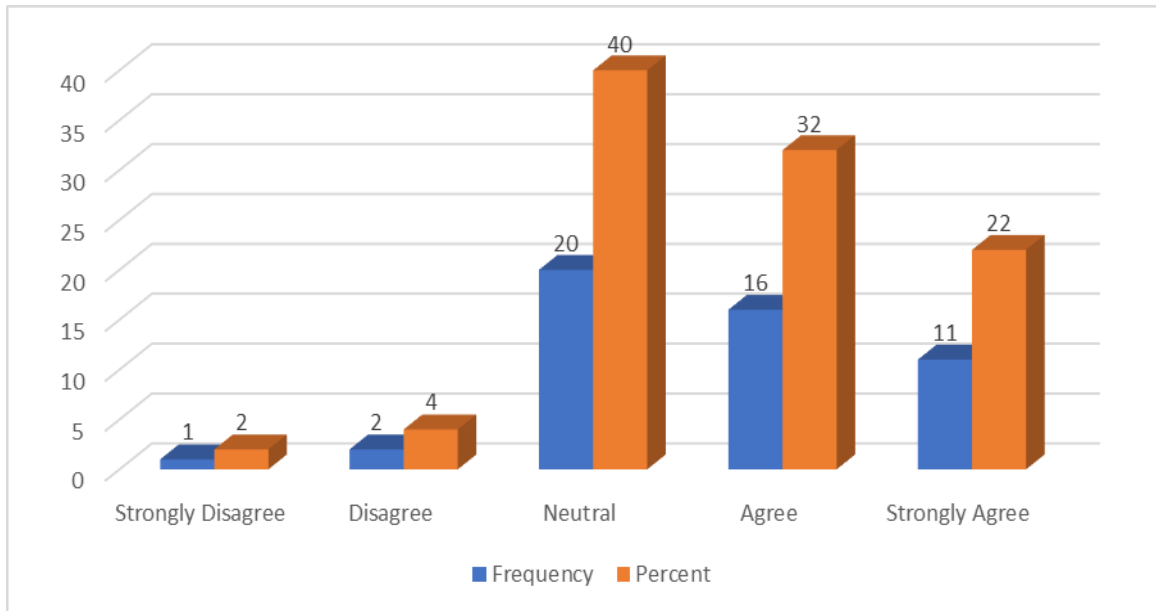


Figure 4.48: Public-Private Partnerships (PPPs) are helping to overcome scalability challenges in the Green Hydrogen industry.

Source: Author Generated

As shown in Figure 4.48, respondents expressed a moderately positive outlook regarding the role of Public-Private Partnerships (PPPs) in addressing scalability challenges within the GH₂ industry. A combined 54% (32% A and 22% SA) believe that PPPs are contributing to overcoming scalability issues. Meanwhile, 40% remained N, indicating some uncertainty or lack of direct exposure to such partnerships. Only a small proportion—4% D and 2% SD—suggested scepticism. Overall, the findings reflect growing confidence in PPPs as a strategic approach to accelerating industry-wide adoption and infrastructure development.

4.7.7 Safety Measures for Hydrogen Storage & Prevention of Explosions/Leakage

This final subsection assesses respondents' views on compliance with safety regulations, emergency response readiness, awareness and training efforts, and the adequacy of infrastructure upgrades to prevent safety incidents in GH₂ operations.

			SD	D	N	A	SA
Safety Protocols & Regulations	Organizations comply with all national and international safety regulations for Green Hydrogen storage.	Frequency	6	4	26	10	4
		Percent	12	8	52	20	8
	Existing safety regulations for Green Hydrogen storage and handling are adequate and effective.	Frequency	7	11	22	7	3
		Percent	14	22	44	14	6
Emergency Response Mechanisms	Well-defined emergency response plans are in place for Green Hydrogen leaks and explosions.	Frequency	11	11	22	5	1
		Percent	22	22	44	10	2
	Green Hydrogen leak detection and response systems are effective in preventing major accidents.	Frequency	9	12	18	6	5
		Percent	18	24	36	12	10
Infrastructure Safety Upgrades	Investments in hydrogen leak-proof storage systems have improved overall safety.	Frequency	7	8	20	10	5
		Percent	14	16	40	20	10
	Infrastructure is equipped with advanced safety technologies for hydrogen storage.	Frequency	11	12	18	6	3
		Percent	22	24	36	12	6
Awareness & Training on Safety Measures	Green Hydrogen safety awareness is a key part of your company policies and operational procedures.	Frequency	7	6	16	12	9
		Percent	14	12	32	24	18
	There is a need for more specialized training programs on Green Hydrogen safety for all stakeholders.	Frequency	7	8	20	10	5
		Percent	14	16	40	20	10
Safety Incidents & Challenges	Green Hydrogen-related safety incidents (such as leaks or explosions) are rare in the industry.	Frequency	2	10	19	6	13
		Percent	4	20	38	12	26
	More stringent safety measures are required to address the risks of Green Hydrogen storage and transportation.	Frequency	2	1	9	13	25
		Percent	4	2	18	26	50

Table 4.16: Safety Measures for Hydrogen Storage & Prevention of Explosions/Leakage

Source: Author Generated

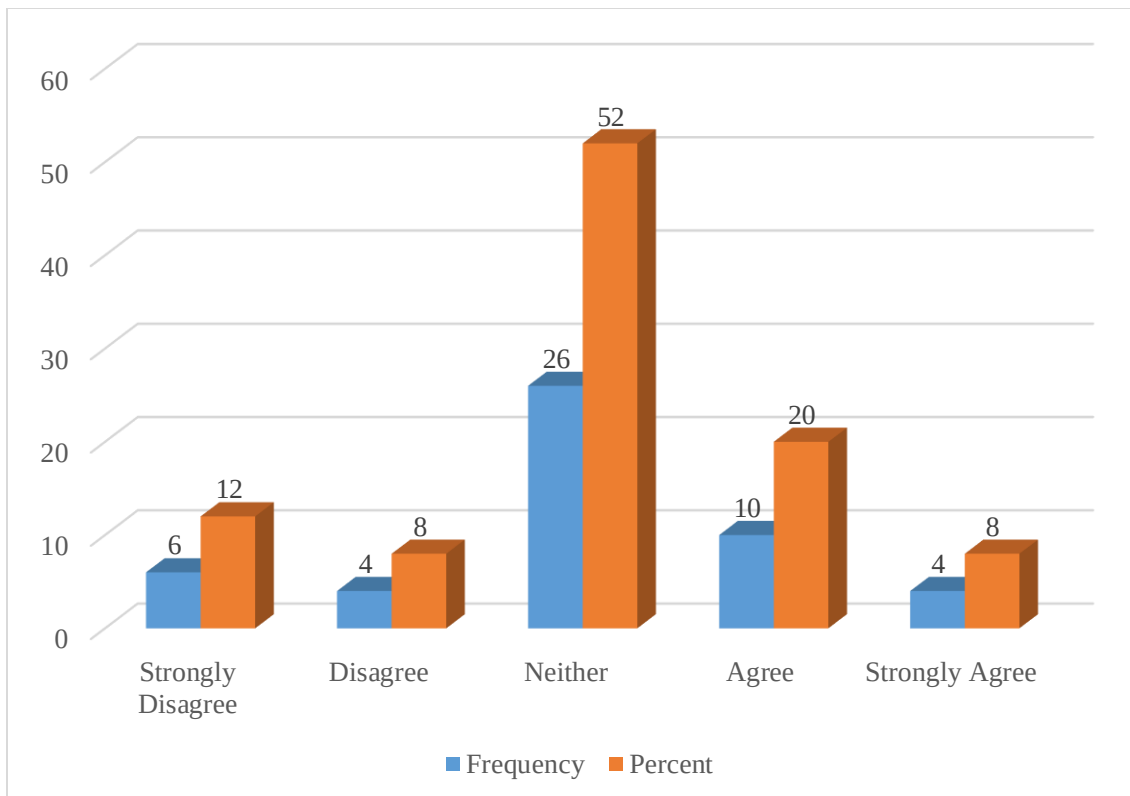


Figure 4.49: Organisations comply with all national and international safety regulations for Green Hydrogen storage.

Source: Author Generated

As illustrated in Figure 4.49, perceptions regarding organisational compliance with national and international safety regulations for GH₂ storage are largely N or uncertain. A majority of respondents—52%—chose the N option, indicating either a lack of awareness or mixed experiences. On the positive side, 28% (20% A and 8% SA) believe that organisations are indeed complying with safety standards. However, a notable 20% (12% SD and 8% D) expressed concern or scepticism about full compliance. This suggests that while some progress is acknowledged, there is still a need for greater transparency and assurance regarding safety practices in the sector.

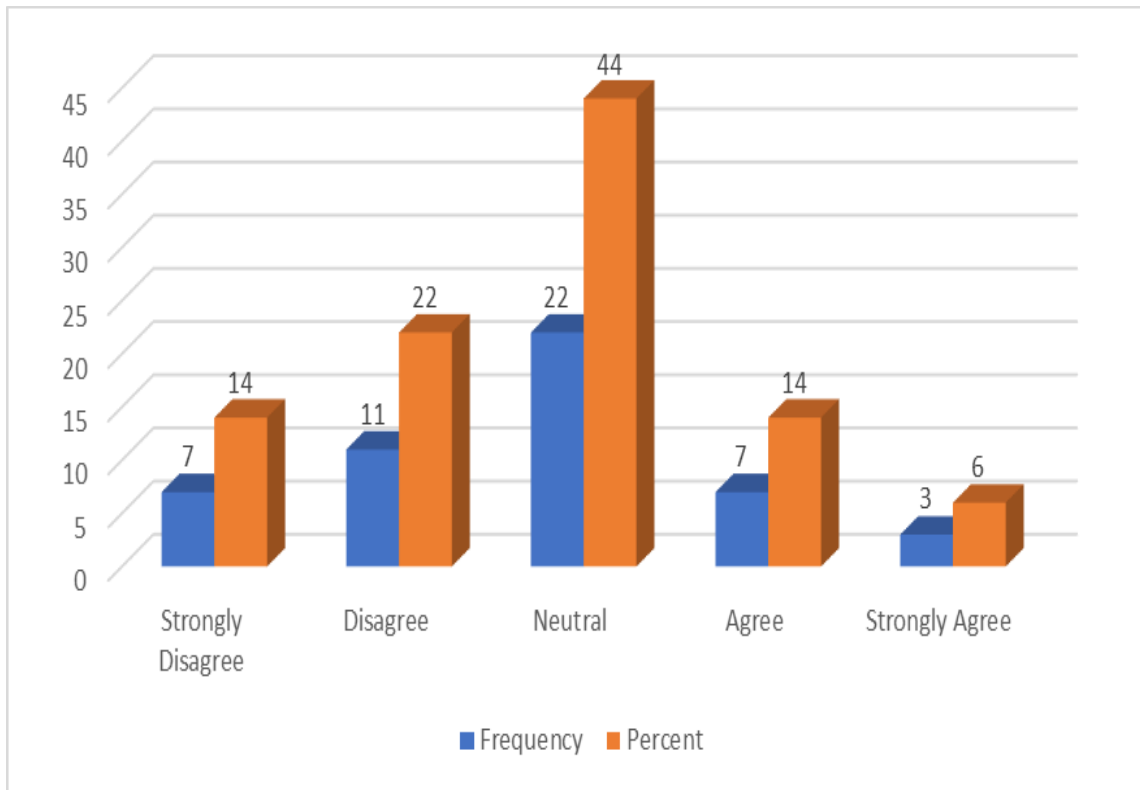


Figure 4.50: Existing safety regulations for Green Hydrogen storage and handling are adequate and effective.

Source: Author Generated

As shown in Figure 4.50, respondents expressed mixed opinions regarding the adequacy and effectiveness of existing safety regulations for GH₂ storage and handling. A significant portion—44%—remained N, suggesting uncertainty or limited exposure to the regulatory framework. Meanwhile, 36% (14% SD and 22% D) believed that the current regulations are inadequate, reflecting concerns about safety oversight or enforcement gaps. Only 20% (14% A and 6% SA) viewed the existing regulations as sufficient and effective. These responses highlight the need for stronger communication, regulatory updates, and stakeholder confidence-building in safety protocols.

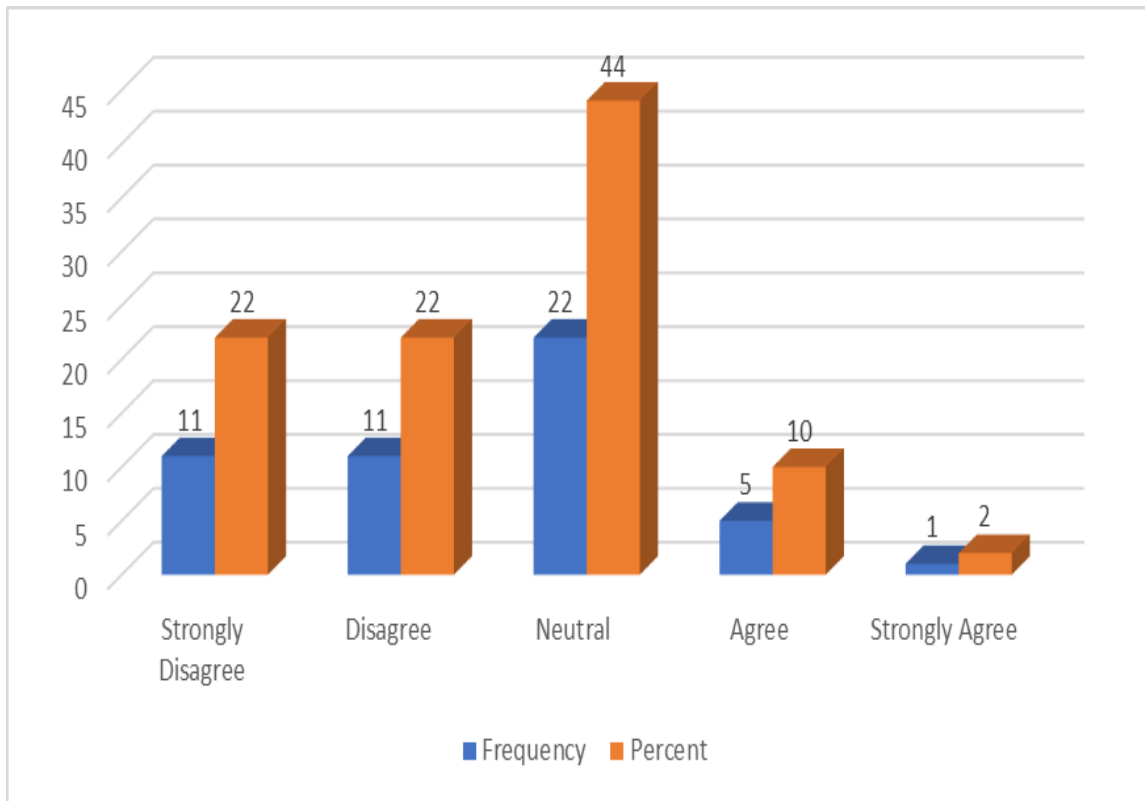


Figure 4.51: Well-defined emergency response plans are in place for Green Hydrogen leaks and explosions.

Source: Author Generated

As shown in Figure 4.51, responses indicate significant concerns regarding the availability of well-defined emergency response plans for GH₂ leaks and explosions. A combined 44% of respondents either SD (22%) or D (22%) agreed with the statement, reflecting a perceived lack of preparedness for potential hazards. Meanwhile, 44% remained N, possibly due to limited awareness or uncertainty about the current protocols in place. Only a small fraction—12% (10% A, 2% SA)—affirmed the existence of effective emergency plans. This suggests a critical gap in safety preparedness that organisations need to address urgently to ensure risk mitigation and crisis readiness.

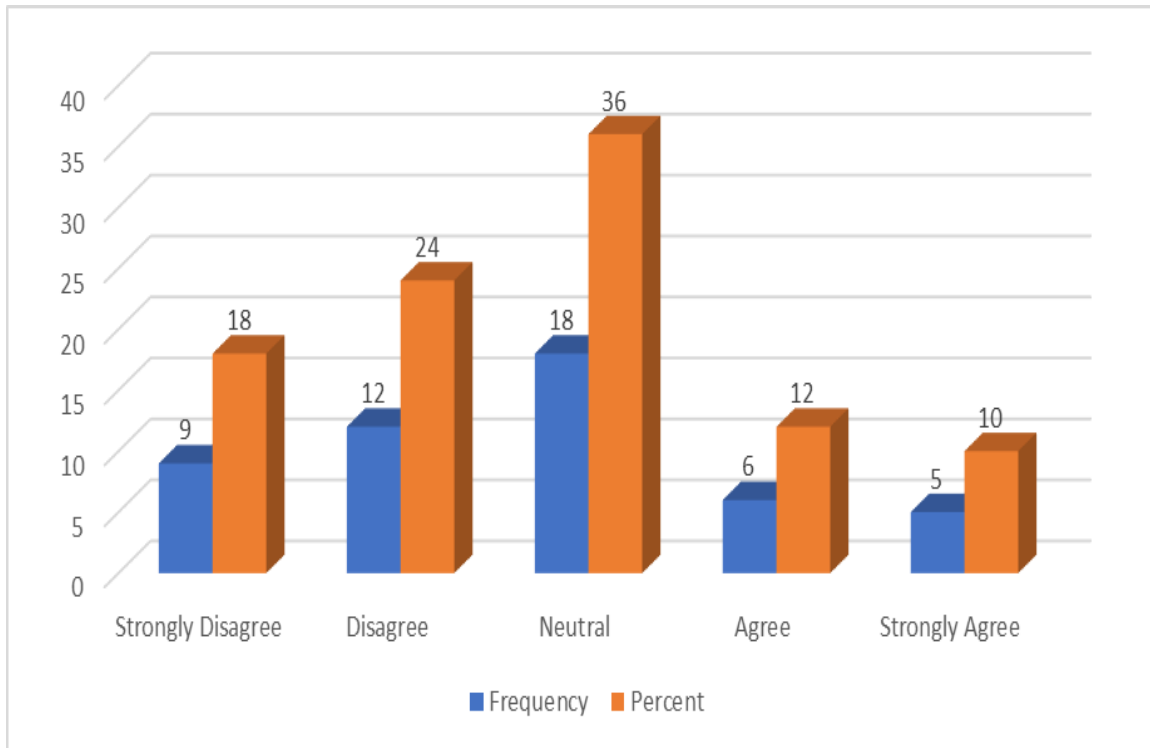


Figure 4.52: Green Hydrogen leak detection and response systems are effective in preventing major accidents.

Source: Author Generated

As presented in Figure 4.52, the effectiveness of GH₂ leak detection and response systems appears to be a subject of concern among respondents. A combined 42% of participants expressed scepticism, with 18% SD and 24% D that these systems are effective in preventing major accidents. Additionally, 36% of respondents remained N, suggesting a lack of clarity or limited exposure to existing safety mechanisms. In contrast, only 22% agreed to some extent (12% A, 10% SA) with the statement. These findings indicate that confidence in current leak detection and emergency response infrastructure is relatively low, highlighting the need for stronger systems, awareness, and transparent safety protocols in the GH₂ sector.

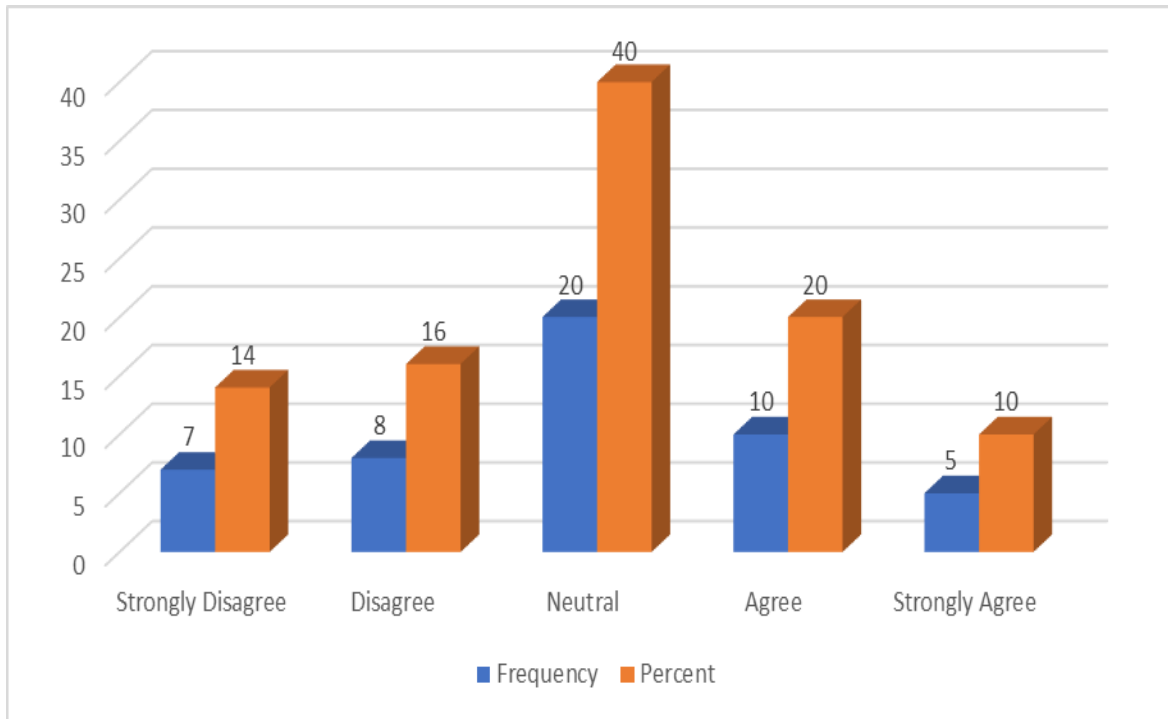


Figure 4.53: Investments in hydrogen leak-proof storage systems have improved overall safety.

Source: Author Generated

As illustrated in Figure 4.53, perceptions regarding the effectiveness of investments in hydrogen leak-proof storage systems are mixed. A significant portion of respondents (40%) chose the N option, indicating uncertainty or lack of clear visibility on safety improvements. Meanwhile, 30% expressed a positive outlook, with 20% A and 10% SA that such investments have enhanced overall safety. On the other hand, a notable 30% expressed disagreement (14% SD and 16% D), reflecting concerns or scepticism about the real-world impact of these safety investments. These results suggest a divided perception, highlighting the need for better communication and demonstrable outcomes from safety-related investments in hydrogen storage systems.

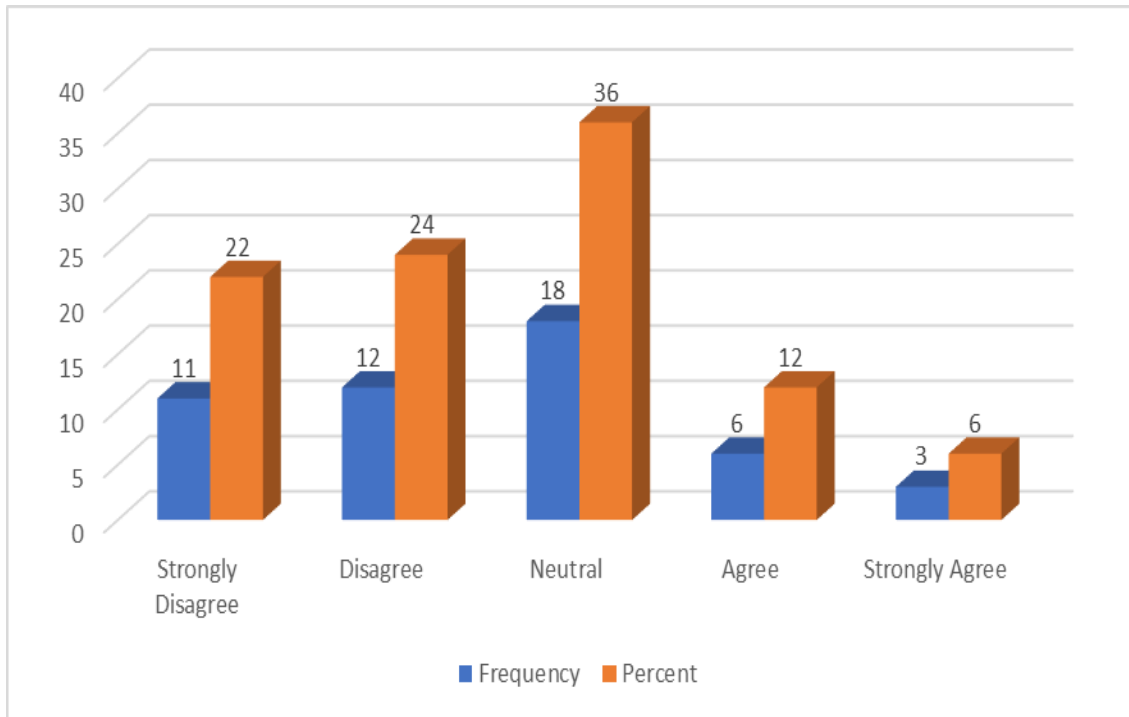


Figure 4.54: Infrastructure is equipped with advanced safety technologies for hydrogen storage.

Source: Author Generated

As shown in Figure 4.54, responses regarding the presence of advanced safety technologies in hydrogen storage infrastructure are skewed towards scepticism or uncertainty. A combined 46% of respondents either SD (22%) or D (24%), indicate significant doubt about the adequacy of safety technologies currently in use. Meanwhile, 36% remained N, reflecting either a lack of awareness or inconclusive experiences. Only 12% A and 6% SA, suggesting that few respondents have observed or are confident in the integration of advanced safety features. These results point to a perceived gap in technological readiness or visibility of safety enhancements in hydrogen storage infrastructure.

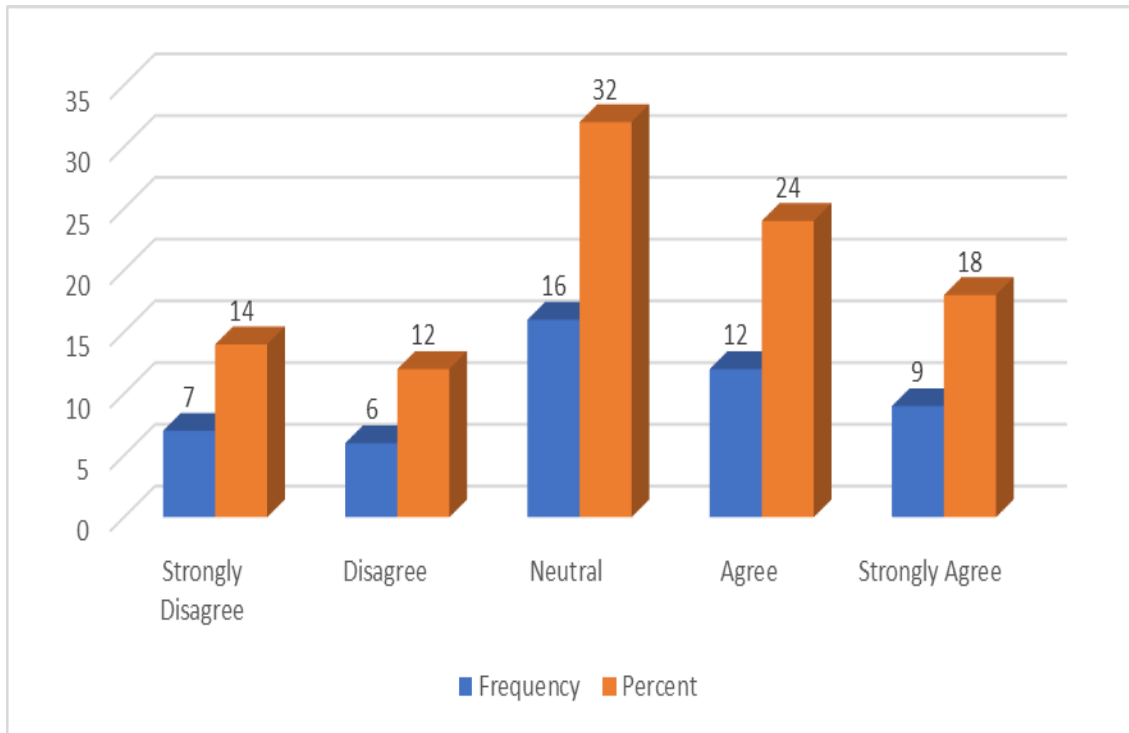


Figure 4.55: Green Hydrogen safety awareness is a key part of your company policies and operational procedures.

Source: Author Generated

As illustrated in Figure 4.55, perceptions on whether GH₂ safety awareness is a key part of company policies and operational procedures appear mixed. While 24% A and 18% SA, indicate that some organisations prioritise safety integration, a significant proportion of respondents were N (32%), suggesting uncertainty or inconsistency in implementation. Additionally, 14% SD and 12% D, reflecting notable concern regarding the lack of structured safety awareness initiatives. These findings suggest that while awareness efforts exist, there is room for broader and more consistent policy integration across organisations.

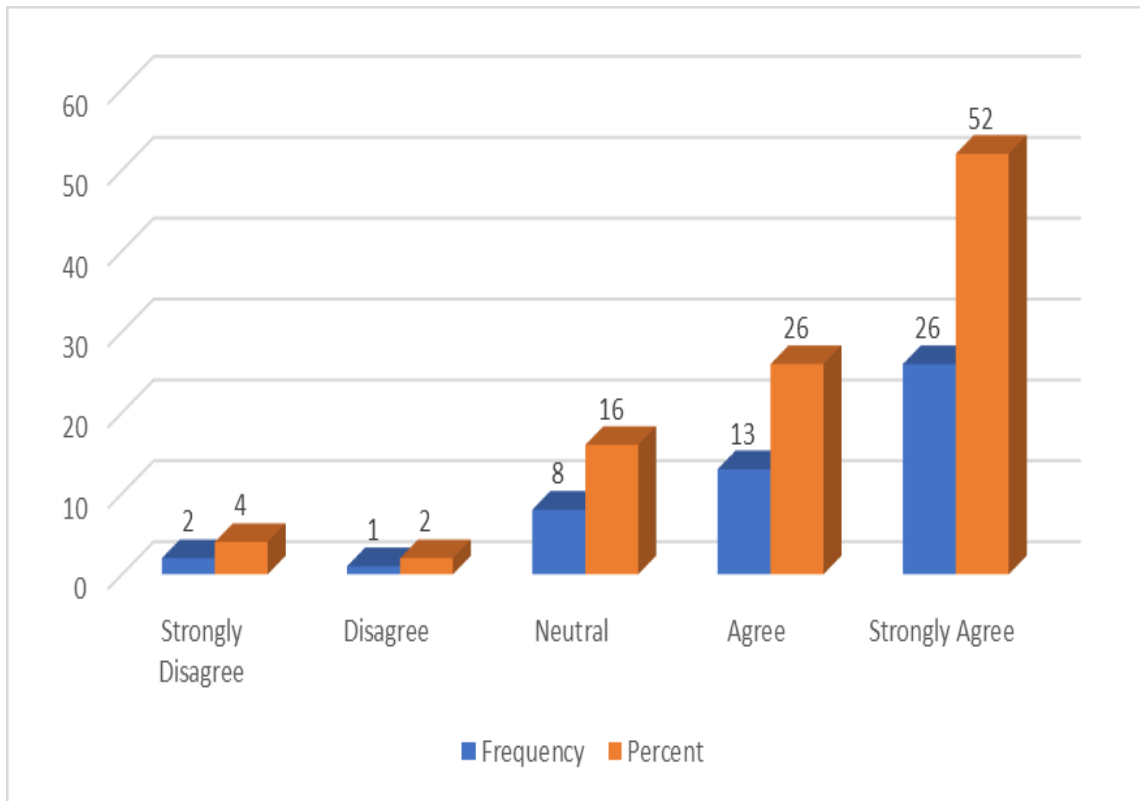


Figure 4.56: There is a need for more specialised training programs on Green Hydrogen safety for all stakeholders.

Source: Author Generated

As shown in Figure 4.56, there is strong consensus among respondents on the importance of specialized training programs focused on GH₂ safety. A significant majority — 52% SA and 26% agreed that more such programs are necessary for all stakeholders. Only a small portion of participants D (2%) or SD (4%), while 16% remained N. This highlights a clear recognition of the growing need to enhance safety knowledge and preparedness through targeted training as GH₂ initiatives scale up.

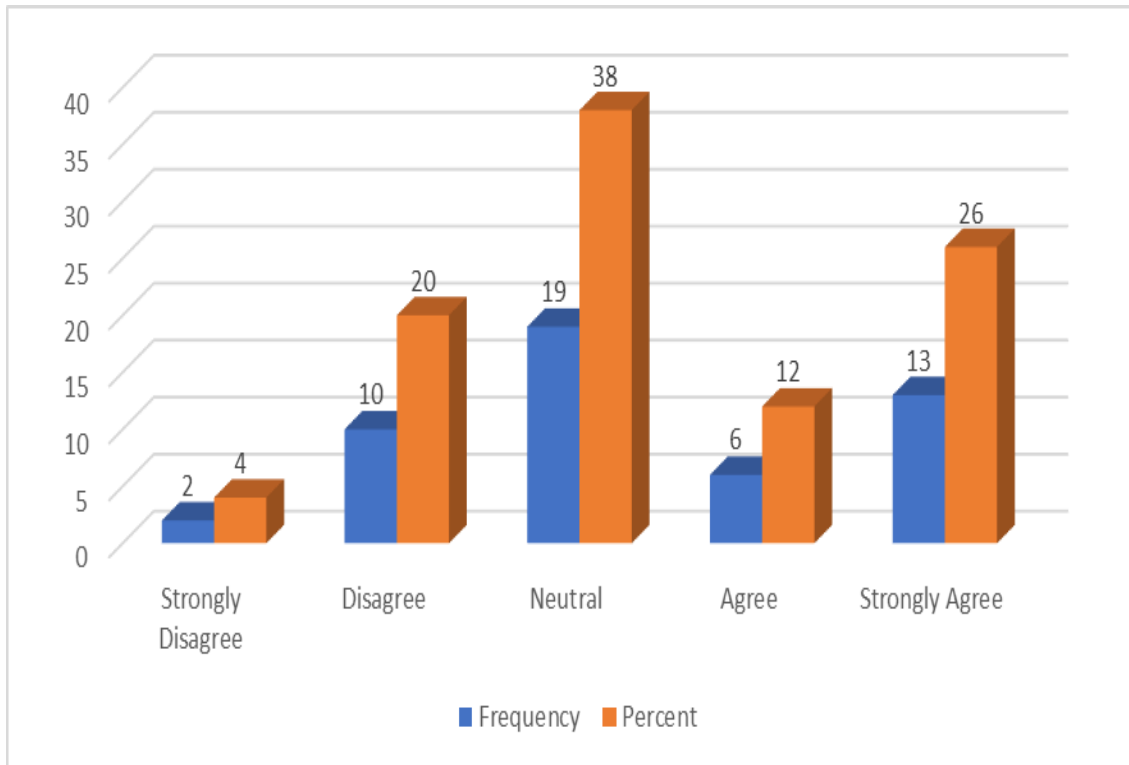


Figure 4.57: Green Hydrogen-related safety incidents (such as leaks or explosions) are rare in the industry.

Source: Author Generated

As presented in Figure 4.57, respondents expressed mixed views regarding the rarity of GH₂-related safety incidents such as leaks or explosions. While 26% SA and 12% A that such incidents are rare in the industry, a notable 20% D and 4% SD, indicated scepticism about safety consistency. Additionally, 38% remained N, reflecting uncertainty or limited firsthand experience. Overall, the data suggests a general but cautious belief that major safety incidents in the GH₂ sector are infrequent, although concerns persist among a portion of the respondents.

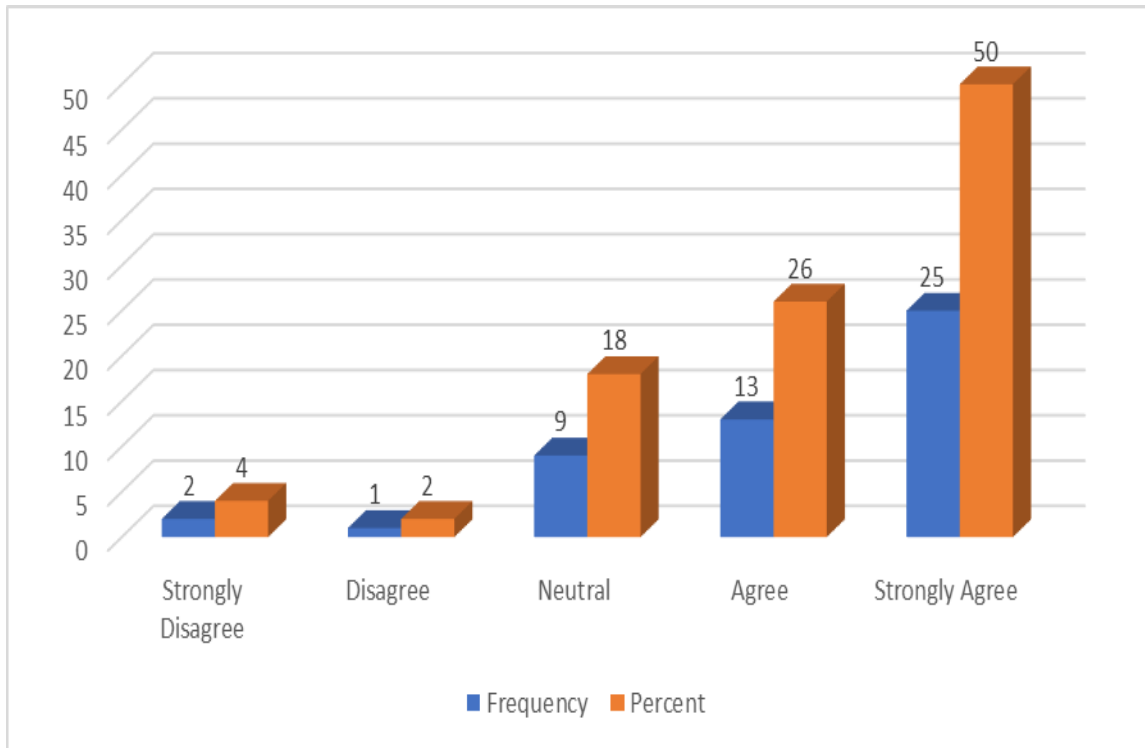


Figure 4.58: More stringent safety measures are required to address the risks of Green Hydrogen storage and transportation.

Source: Author Generated

As shown in Figure 4.58, a significant majority of respondents emphasised the need for more stringent safety measures to address the risks associated with GH₂ storage and transportation. Half of the participants (50%) SA and an additional 26% A, indicate widespread concern over current safety protocols. Only a small portion of the sample D (2%) or SD (4%), while 18% maintained a N stance. These findings clearly reflect a growing consensus among stakeholders for enhancing safety regulations to ensure the secure handling and movement of GH₂.

4.8 Descriptive Analysis

This section presents the descriptive statistics of key variables related to Government policies, readiness levels, infrastructure and investment measures, scalability and storage challenges and safety protocols in the GH₂ ecosystem.

Key Variables	Category	Mean	Mean Std. Error	Std. Deviation	Variance
Government Policies and Initiatives	Effectiveness of Policies	3.84	0.1351	0.95533	0.913
	Clarity of Regulations	3.36	0.11697	0.82709	0.684
	Incentives & Subsidies	3.1	0.12536	0.88641	0.786
	Policy Implementation Challenges	3.4	0.13093	0.92582	0.857
	Public-Private Partnerships (PPP) in Green Hydrogen	3.26	0.11714	0.82833	0.686
Readiness Level of Companies	Technological Readiness	2.54	0.15175	1.07305	1.151
	Financial Readiness	2.86	0.12125	0.85738	0.735
	Workforce Readiness	2.36	0.13927	0.98478	0.97
	Adoption Readiness	2.78	0.13788	0.97499	0.951
	Industry Collaboration Readiness	3.04	0.12441	0.8797	0.774
Infrastructure & Investment Measures	Existing Infrastructure Availability	2.36	0.13018	0.92051	0.847
	Infrastructure Investment Plans	2.88	0.1298	0.91785	0.842
	Financial Support Mechanisms	3.44	0.12506	0.88433	0.782
	Risk Perception in Green Hydrogen Investments	3.52	0.14636	1.0349	1.071
	Infrastructure Development Challenges	3.94	0.12908	0.91272	0.833
Scalability & Storage Challenges	Hydrogen Storage Capacity	3.24	0.11627	0.82214	0.676
	Scalability Strategies	3.56	0.10751	0.76024	0.578
	Transportation & Logistics Challenges	3.48	0.11154	0.7887	0.622
	Market Demand for Green Hydrogen	3.48	0.13168	0.9311	0.867
	Government & Private Sector Collaboration for Scalability	4.16	0.11198	0.79179	0.627
Safety Measures for Hydrogen Storage & Prevention of Explosions/Leakage	Safety Protocols & Regulations	3.1	0.14639	1.0351	1.071
	Emergency Response Mechanisms	2.7	0.14639	1.0351	1.071
	Infrastructure Safety Upgrades	2.88	0.15555	1.09991	1.21
	Awareness & Training on Safety Measures	3.86	0.14289	1.01035	1.021
	Safety Incidents & Challenges	3.94	0.12908	0.91272	0.833

Table 4.17: Descriptive Statistics

Source: Author Generated

The descriptive statistics (Table 4.17) provide key insights into stakeholder perceptions surrounding the development of GH₂ in India. Among policy-related factors, “Effectiveness of Policies” (Mean = 3.84) and “Policy Implementation Challenges” (Mean = 3.40) indicate a moderately positive but cautious sentiment toward Government’s efforts. However, the relatively lower mean for “Incentives & Subsidies” (3.10) and “Clarity of Regulations” (3.36) reveals that stakeholders find current policies partially supportive but lacking in comprehensive structure and economic stimulus. In terms of readiness, the technological readiness (2.54) and workforce readiness (2.36) scores are particularly low, highlighting a major bottleneck in R&D access and skilled labour availability. On the other hand, financial readiness (2.86) and industry collaboration (3.04) show slightly better prospects, albeit still below optimal. Encouragingly, collaboration between Government and Private sector for scalability recorded a high mean score of 4.16, indicating strong support for PPP-driven scale-up strategies. However, emergency response mechanisms (2.70) and infrastructure safety (2.88) highlight gaps in operational preparedness and safety systems, suggesting a need for improved training and investment. Overall, the statistics underscore the sector’s optimism towards long-term potential, while also revealing pressing concerns around technological maturity, infrastructure and policy clarity that must be addressed to enable sustainable growth.

4.9 Hypotheses Testing

This section presents the results of hypothesis testing conducted to examine the relationships between key variables such as Government policies, company readiness, infrastructure investment, scalability and safety measures in the GH₂ sector. Using statistical tools like correlation and regression analysis, the study evaluates the strength and direction of association among variables. The findings offer empirical support for assessing

the effectiveness of Policy frameworks and organisational preparedness in driving GH₂ adoption in India.

4.9.1 Hypothesis 1:

- **Null Hypothesis (H₀):** The effectiveness of policies, clarity of regulations, and incentives & subsidies do not significantly influence the adoption readiness of Green Hydrogen among industries.
- **Alternative Hypothesis (H₁):** The effectiveness of policies, clarity of regulations, and incentives & subsidies significantly influence the adoption readiness of Green Hydrogen among industries.

Model	-2 Log Likelihood	Chi-Square	Df	Sig.
Intercept Only	93.271			
Final	87.020	6.251	3	.100
Link function: Logit.				

Table 4.18: Model Fitting Summary for Factors Affecting Adoption Readiness

Source: Author Generated

Table 4.18 presents the model fitting summary assessing the factors influencing industrial readiness for new energy integration. The final model shows a reduced -2 Log Likelihood value (87.020) compared to the intercept-only model (93.271), with a chi-square value of 6.251 (df = 3, p = .100). Although the model indicates slight improvement, the statistical insignificance reflects a limited impact of the examined drivers on readiness levels.

	Chi-Square	Df	Sig.
Pearson	72.172	73	.505
Deviance	62.003	73	.817
Link function: Logit.			

Table 4.19: Goodness-of-Fit Results for the Estimated Model

Source: Author Generated

Table 4.19 outlines the goodness-of-fit indicators evaluating the factors shaping readiness levels for sustainable energy transition. The Pearson chi-square value (72.172, df = 73, p = .505) and deviance score (62.003, p = .817) demonstrate a strong model fit. These outcomes reflect that the tested variables align well with observed data, suggesting consistent predictive capacity in gauging industry preparedness.

Cox and Snell	.118
Nagelkerke	.126
McFadden	.047
Link function: Logit.	

Table 4.20: Pseudo R-Square Statistics for Model Performance

Source: Author Generated

Table 4.20 shows model performance metrics exploring the impact of institutional and regulatory support on industry readiness. The Nagelkerke value of 0.126 and McFadden's R^2 of 0.047 indicate a modest yet meaningful explanatory power. These figures suggest that while Policy clarity and incentive mechanisms do contribute to shaping adoption intent, their influence remains moderate, pointing towards the need for broader systemic enablers to accelerate GH₂ uptake in India's net-zero journey.

		Estimate	Std. Error	Wald	df	Sig.	95% Confidence Interval	
							Lower Bound	Upper Bound
Threshold	[RLGH_AR = 1.00]	1.124	1.274	.778	1	.378	-1.373	3.621
	[RLGH_AR = 2.00]	2.463	1.280	3.703	1	.054	-.045	4.971
	[RLGH_AR = 3.00]	4.976	1.447	11.828	1	.001	2.140	7.812
	[RLGH_AR = 4.00]	6.700	1.612	17.287	1	.000	3.542	9.859
Location	GPI_EP	.314	.377	.692	1	.405	-.425	1.052
	GPI_CR	.422	.493	.733	1	.392	-.544	1.389
	GPI_IS	.225	.423	.284	1	.594	-.603	1.054
Link function: Logit.								

Table 4.21: Parameter Estimates Reflecting Category Thresholds and Predictor Effects

Source: Author Generated

Table 4.21 outlines the parameter estimates for assessing the influence of policy, regulatory clarity, and incentives on industry readiness for GH₂ adoption. Despite positive coefficient estimates—such as 0.314 for policy effectiveness and 0.422 for regulatory clarity—their significance levels ($p = .405$ and $.392$, respectively) indicate limited statistical impact. While adoption likelihood improves across thresholds (e.g., 4.976 at level 3, $p = .001$), the predictors show only marginal direct influence, suggesting other factors may also play a role in India's GH₂ transition.

This shows that the effectiveness of policies, clarity of regulations, and incentives & subsidies do not significantly influence the adoption readiness of GH₂ among industries.

4.9.2 Hypothesis 2:

- **Null Hypothesis (H_{02}):** Higher levels of technological, financial, and workforce readiness are **not** positively associated with industry collaboration readiness in the Green Hydrogen sector.
- **Alternative Hypothesis (H_{12}):** Higher levels of technological, financial, and workforce readiness are positively associated with industry collaboration readiness in the Green Hydrogen sector.

			Technological Readiness	Financial Readiness	Workforce Readiness	Industry Collaboration Readiness
Spearman's rho	Technological Readiness	Correlation Coefficient	1.000	.324*	.588**	.435**
		Sig. (2-tailed)	.	.022	.000	.002
		N	50	50	50	50
	Financial Readiness	Correlation Coefficient	.324*	1.000	.231	.542**
		Sig. (2-tailed)	.022	.	.106	.000
		N	50	50	50	50
	Workforce Readiness	Correlation Coefficient	.588**	.231	1.000	.467**
		Sig. (2-tailed)	.000	.106	.	.001

	N	50	50	50	50
Industry Collaboration Readiness	Correlation Coefficient	.435**	.542**	.467**	1.000
	Sig. (2-tailed)	.002	.000	.001	.
	N	50	50	50	50
*. Correlation is significant at the 0.05 level (2-tailed).					
**. Correlation is significant at the 0.01 level (2-tailed).					

Table 4.22: Spearman's Correlation Matrix for Readiness Dimensions and Collaborative Outcomes

Source: Author Generated

Table 4.22 presents the Spearman's correlation analysis supporting the hypothesis that higher levels of technological, financial, and workforce readiness are positively associated with industry collaboration readiness in the GH₂ sector. The results reveal significant positive correlations: technological readiness ($r = .435$, $p = .002$), financial readiness ($r = .542$, $p = .000$), and workforce readiness ($r = .467$, $p = .001$) with collaboration outcomes. These findings affirm that enhanced readiness across key domains plays a pivotal role in fostering collaborative efforts essential to advancing India's GH₂ ambitions towards a net-zero future.

Hence, higher levels of technological, financial, and workforce readiness are positively associated with industry collaboration readiness in the GH₂ sector.

4.9.3 Hypothesis 3:

- **Null Hypothesis (H₀₃):** Existing infrastructure availability and financial support mechanisms do **not** significantly reduce risk perception in Green Hydrogen investments.
- **Alternative Hypothesis (H₁₃):** Existing infrastructure availability and financial support mechanisms significantly reduce risk perception in Green Hydrogen investments.

			Existing Infrastructure Availability	Financial Support Mechanisms	Risk Perception in Green Hydrogen Investments
Spearman's rho	Existing Infrastructure Availability	Correlation Coefficient	1.000	.261	-.067
		Sig. (2-tailed)	.	.067	.645
		N	50	50	50
	Financial Support Mechanisms	Correlation Coefficient	.261	1.000	.311*
		Sig. (2-tailed)	.067	.	.028
		N	50	50	50
	Risk Perception in Green Hydrogen Investments	Correlation Coefficient	-.067	.311*	1.000
		Sig. (2-tailed)	.645	.028	.
		N	50	50	50
*. Correlation is significant at the 0.05 level (2-tailed).					

Table 4.23: Spearman's Correlation Coefficients for Investment Risk Influencers

Source: Author Generated

Table 4.23 provides insights from the Spearman's correlation analysis aligned with the assumption that infrastructure availability and financial support influence risk perception in GH₂ investments. The results show a weak and non-significant correlation between infrastructure availability and risk perception ($r = -.067$, $p = .645$), suggesting minimal direct impact. However, financial support mechanisms exhibit a modest yet significant negative relationship with investment risk perception ($r = .311$, $p = .028$). This highlights that robust financial frameworks can moderately ease investor concerns, aiding India's GH₂ journey towards a resilient, net-zero future

4.9.4 Hypothesis 4:

- **Null Hypothesis (H₀₄):** Hydrogen storage capacity, scalability strategies, and Government–Private sector collaboration do **not** significantly improve scalability of Green Hydrogen projects.

- **Alternative Hypothesis (H₁₄):** Hydrogen storage capacity, scalability strategies, and Government–Private sector collaboration significantly improve scalability of Green Hydrogen projects.

			Scalability Strategies	Hydrogen Storage Capacity	Government & Private Sector Collaboration for Scalability
Spearman's rho	Scalability Strategies	Correlation Coefficient	1.000	.633**	.659**
		Sig. (2-tailed)	.	.000	.000
		N	50	50	50
	Hydrogen Storage Capacity	Correlation Coefficient	.633**	1.000	.465**
		Sig. (2-tailed)	.000	.	.001
		N	50	50	50
	Government & Private Sector Collaboration for Scalability	Correlation Coefficient	.659**	.465**	1.000
		Sig. (2-tailed)	.000	.001	.
		N	50	50	50
**. Correlation is significant at the 0.01 level (2-tailed).					

Table 4.24: Spearman's Correlation Matrix for Scalability and Storage-Related Enablers

Source: Author Generated

Table 4.24 illustrates the correlation outcomes assessing the influence of enablers on GH₂ scalability and storage advancement. Strong positive correlations were observed— .633 between scalability strategies and storage capacity, and .659 between scalability strategies and collaborative efforts (both $p < .001$). These results highlight that robust planning, storage infrastructure, and synergistic efforts significantly mitigate scalability challenges, reinforcing India's journey towards a sustainable and net-zero hydrogen economy.

Hence, hydrogen storage capacity, scalability strategies and Government–Private sector collaboration significantly improve scalability of GH₂ projects.

4.9.5 Hypothesis 5:

- **Null Hypothesis (H_{0s}):** Safety protocols, emergency response mechanisms, and training on safety measures do not significantly reduce safety incidents and challenges in handling of Green Hydrogen. **Alternative Hypothesis (H_{1s}):** Safety protocols, emergency response mechanisms, and training on safety measures significantly reduce safety incidents and challenges in the handling of Green Hydrogen.

Model	-2 Log Likelihood	Chi-Square	Df	Sig.
Intercept Only	93.445			
Final	84.261	9.184	3	.027
Link function: Logit.				

Table 4.25: Model Fitting Summary for Safety-Related Predictive Framework

Source: Author Generated

Table 4.25 presents the model fitting results evaluating the impact of safety practices on reducing incidents in GH₂ operations. The final model shows a statistically significant improvement over the intercept-only model (Chi-Square = 9.184, df = 3, p = .027), indicating that structured safety protocols, response mechanisms, and training initiatives play a meaningful role in minimising safety challenges, thereby supporting India's secure transition toward a net-zero future.

	Chi-Square	Df	Sig.
Pearson	72.074	81	.750
Deviance	65.654	81	.892
Link function: Logit.			

Table 4.26: Goodness-of-Fit Results for Safety Measures Impact Model

Source: Author Generated

Table 4.26 provides the goodness-of-fit assessment for the model evaluating the role of safety interventions in mitigating risks in GH₂ handling. The Pearson Chi-Square

value of 72.074 (df = 81, p = .750) and Deviance value of 65.654 (p = .892) indicate a good model fit. These findings highlight that robust safety protocols, emergency mechanisms, and training contribute effectively to managing safety challenges in India's GH₂ transition.

Cox and Snell	.168
Nagelkerke	.183
McFadden	.074
Link function: Logit.	

Table 4.27: Pseudo R-Square Statistics for Safety-Oriented Predictive Model

Source: Author Generated

Table 4.27 outlines the Pseudo R-Square values for the model assessing safety interventions in GH₂ handling. With Nagelkerke at 0.183 and McFadden at 0.074, the model demonstrates modest explanatory power. These values suggest that structured safety protocols, emergency response systems, and targeted training contribute meaningfully to minimising safety incidents—reinforcing the importance of risk management in India's GH₂ journey toward net-zero goals.

		Estimate	Std. Error	Wald	df	Sig.	95% Confidence Interval	
							Lower Bound	Upper Bound
Threshold	[SMHSPE_SIC = 1.00]	-.542	1.436	.143	1	.706	-3.357	2.272
	[SMHSPE_SIC = 2.00]	.320	1.250	.066	1	.798	-2.129	2.770
	[SMHSPE_SIC = 3.00]	3.001	1.240	5.860	1	.015	.571	5.430
	[SMHSPE_SIC = 4.00]	4.899	1.355	13.067	1	.000	2.243	7.556
Location	SMHSPE_SPR	.637	.371	2.952	1	.086	-.090	1.364
	SMHSPE_ERM	-.479	.408	1.380	1	.240	-1.278	.320
	SMHSPE_ATSM	.811	.345	5.541	1	.019	.136	1.487
Link function: Logit.								

Table 4.28: Parameter Estimates for Safety-Related Predictors and Response Thresholds

Source: Author Generated

Table 4.28 presents the parameter estimates associated with safety-related factors influencing incidents in GH₂ handling. This analysis aligns with the examined hypothesis, emphasising the role of safety protocols, emergency mechanisms, and training in reducing operational risks. Notably, training on safety measures (Estimate = 0.811, p = .019) shows a statistically significant effect. Additionally, higher safety response thresholds, such as [SMHSPE_SIC = 4.00] with an estimate of 4.899 (p = .000), reflect a strong predictive relationship. These insights highlight the critical importance of structured safety systems in India's transition to a net-zero GH₂ ecosystem.

This shows that safety protocols, emergency response mechanisms, and training on safety measures do not significantly reduce safety incidents and challenges in GH₂ handling.

CHAPTER V:

DISCUSSION

5.1 Discussion of Results

This study has explored key facilitators in India's transition towards NZE through the adoption of GH₂. It was found that policy frameworks, incentive schemes, and regulatory structures exist, but their immediate influence on industrial readiness remains moderate. Despite the strategic guidance provided by Government initiatives like the National GH₂ Mission (NGHM), implementation gaps, delays in execution, and an unclear marketplace continue to hinder widespread adoption. Beyond policies, technological maturity, financial capacity, and the preparedness of a skilled workforce emerged as crucial factors enabling firms to participate in joint ventures and industry-wide innovation. These findings support the idea that institutional support combined with private sector readiness is driving progress in GH₂ development in India.

Additionally, the research emphasises the importance of scalability, infrastructure, and safety systems in establishing a sustainable GH₂ economy. An effective scalability plan, hydrogen storage capacity, and partnerships between Government and Private sectors have proven to be highly successful in progressing from pilot projects to large-scale deployment. Similarly, well-designed safety protocols, emergency response plans, and training programmes significantly reduce operational risks, underscoring the need for strict standards given hydrogen's highly explosive nature. A consistent theme across all findings is the necessity for an integrated, systems-level approach that aligns infrastructure development, risk mitigation, policy implementation, and stakeholder collaboration. The Indian GH₂ journey will require balancing these interdependent factors to develop a sustainable and scalable hydrogen ecosystem that achieves its net-zero goals.

5.2 Discussion of Research Question One (Effectiveness of Government Policies and Initiatives in Promoting Green Hydrogen)

The research study aims to determine whether existing Governmental measures, including policies, regulatory programs, and incentive programs, are effective in enhancing the preparedness of industries to adopt GH₂ technologies. It discusses the role of institutional processes in shaping the emerging hydrogen ecosystem in India within the context of the net-zero energy transition.

The results indicate that though the Governmental activity is oriented correctly in terms of encouraging the use of GH₂, their impact on industrial preparedness is statistically small. This is consistent with the results of Sharma, Kumar and Jain, (2023), who noted that even though policy frameworks in India are now mature, their effects are regularly neutralised by the deficiencies in implementation and transparency. The existence of a well-fitted model and a weak predictor significance are indicative of the fact that institutional support needs to be implemented, yet it is not sufficient.

This, in turn, supports the claims of Agency et al., (2021) that even such policy support is not enough without market certainty and infrastructure development to transition industries to cleaner products. Lack of synchronisation between policies that are announced and operational on-ground incentives is frequently pointed out as a bottleneck in the Indian context. Therefore, despite such controls, there is still a perception of high risk in adoption by industries because the long-term benefits of cost are not clear or adequate implementation advice is lacking.

In addition, the moderate explanatory power leads to the conclusion that industries can also react to other predisposing forces, such as technological maturity, global supply chain trends, and stakeholder pressure, in addition to Governmental stimulation. This is analogous to the report of Odenweller and Ueckerdt (2025) that highlighted that the

ambitious NGHM of India is dependent on establishing interconnected ecosystems and minimising systemic uncertainty. The dynamic GH₂ in India represents the progress that has not been completed yet not only as a process of structural change but through independent policies.

5.3 Discussion of Research Question Two (Organisational Readiness for Green Hydrogen Adoption)

This study recognizes that the preparedness of firms involved in the GH₂ industry in India is key to evaluating their potential in collaborative industry undertakings. In this context, the answers focus on the level of technological, financial, and workforce capacity in relation to the overall objectives of building successful collaborations within the GH₂ ecosystem. These dimensions constitute the operational fabric of the GH₂ innovations and implementation as India moves towards net-zero goals.

As the results show, a company with a good technological base is more likely to participate in GH₂ industry cooperation. This is in harmony with Rey, Segura and Andújar, (2023), which highlight that, technological maturity enables shared Research and Development (R&D), cross-sector innovations, and integration of infrastructure, which are necessary in the scaling of hydrogen solutions. The transformative role of digital platforms and process automation in hydrogen generation further supports the view that cooperative ventures are underpinned by technological readiness.

The financial readiness became another one of the collaboration enablers which is consistent with what Anjanappa, (2025) stated in the study that fiscal resilience helps companies to absorb the risk of joint ventures, pilot projects, and long-term green investments. Companies with financial capabilities can obtain subsidies, tender for national hydrogen projects, and access international green finance, making them more appealing to collaborations with both Governmental and business entities.

The workforce readiness which has been a perennial oversight has turned out to be just as important. This correlation is reflected in the results of Henry Ebini (2024), who emphasized the key role of specialized human capital needed to be able to successfully operate GH₂ projects, such as engineers, hydrogen technologists, and sustainability managers. The strong workforce will facilitate the process of cooperation since it will help to eliminate the divide between planning and practical application in the field and eventually bring the Indian GH₂ mission one step closer to the net-zero solution that can be scaled.

5.4 Discussion of Research Question Three (Infrastructure Requirements and Financial Measures by Producers, Banks, and Investors)

This research question examines the readiness and willingness of key stakeholders in GH₂ production, including financial institutions, private equity, and venture capitalists, to establish the required infrastructure and financial systems that can reduce the risks involved in investments. The emphasis is placed on the importance of learning the implications of structural and economic preparedness on risk perception, which is critical in the development of the sector and the net-zero efforts of India.

The results imply that the current infrastructure might not play a major role in investor confidence and this confirms the findings of J. Gulia et al. (2024), who stated that the GH₂ sector in India remains at an early stage, with infrastructure frequently disjointed or locally disparate. The absence of combined pipelines, storage, and distribution infrastructure will cause the stakeholders to consider infrastructure to be inadequate in de-risking investments. Physical readiness is, therefore a long-term issue that needs a united front in both the private and the public sectors.

On the other hand, the study under discussion points out that the financial support mechanisms play a significant role in reducing perceived risk. This is in line with OECD,

(2024) which noted that the de-risking instruments, including viability gap funding, sovereign guarantees and preferential tariffs are a key to attracting institutional capital. The more that these mechanisms are strong and clear, the more investors, particularly those in the private equity and venture capital funds, will be willing to invest in early-stage GH₂ projects in India.

On a larger scale, these findings reveal that the GH₂ scalability and decarbonization process in India is less dependent on current resources and more on prospective fiscal policy and investor-guarantee tools. The works of OECD (2024) also tend to support the idea that the risk-sharing framework, green bonds, and concessional lending could be used to move towards commercial-level projects. The key in long-standing investor confidence and the rapid GH₂ value chain lies in the reinforcement of these financial ecosystems.

5.5 Discussion of Research Question Four (Addressing the Challenge of Scalability and Hydrogen Storage)

This research question explores how the potential problematic issue of scalability and storage is being solved in the GH₂ environment in India. The key issue is the realisation of how the strategic planning of scalability, storage infrastructure, and collaborative structures can impact the ability of the GH₂ sector to shift pilot projects towards large-scale deployment in line with net-zero targets.

The results indicate that the scalability strategies and storage capacity have a strong interdependence, and this brings out the necessity of well-integrated infrastructure planning. This is in line with Kar et al. (2023), who added that scalable models demand parallel development of transport and storage systems in order to prevent future bottlenecks. The existing pilot projects in India are not usually modular in scale, which implies that a system level approach to storage should be integrated at the very beginning.

In the absence of focused storage innovation, long-term viability of hydrogen may be stunted by occasional production and distribution inefficiencies.

In addition, the Government-Private sector joint structures were also established to have strong correlations with improved scalability. This affirms the opinions of Gupta and Sneha Sinha (2024) who provide that policy co-design, joint ventures, and financial co-investment platforms are key to breaking down the early-stage inertia. As the Government and Private sectors agree upon their models of executions and cost-sharing, accelerating the project becomes easier. In the case of India, the RE growth path is being implemented through the increasing use of public-private partnerships (PPPs) as a way of de-risking the infrastructure development path, which is mainly investment-heavy.

All of these findings support the notion that scalability cannot be looked at in a vacuum. As Gupta and Sneha Sinha (2024) claim, the GH₂ scale-up needs to be carried out through coordinated advancement in the spheres of planning, technologies, and policies. The National Green Hydrogen Mission in India should focus on long-term storage and institutionalise the channels of working together to enable the commercial feasibility. The path towards net-zero therefore, requires technical innovation but more so, combining the interests of multiple stakeholders to have scalable, safe and sustainable GH₂ ecosystems.

5.6 Discussion of Research Question Five (Safety Measures for Hydrogen Handling, Storage, and Explosion Prevention)

This research question examines how India is addressing the critical safety concerns associated with hydrogen handling, storage, and the prevention of explosions or leakage. Safety is a paramount challenge in the GH₂ ecosystem due to the high flammability, low ignition energy and high diffusivity of hydrogen gas. These properties necessitate rigorous safety standards and robust regulatory mechanisms.

The findings of this study indicate that safety protocols and emergency preparedness are strongly associated with the overall organisational readiness for hydrogen adoption. The findings of the hypothesis show that strategic planning, good storage systems and close coordination of Government and the private players are very vital in clearing these obstacles. When properly aligned, these enablers will help create an ecosystem that will be able to support large-scale production and deployment of GH₂.

The safety of storing hydrogen has become one of the most vigilantly watched aspects in the public and the privately owned sectors. It was identified in the study that firms using high pressure gas cylinders, cryogenic liquid hydrogen tanks, and solid-state storage technologies were required to install massive protection mechanisms including automated shut-off valves, ventilation, and hazard zoning requirements. This can be attributed to the best practices in the world especially in countries such as Japan and South Korea whereby strict regulations regarding storage safety is a condition of rolling out the infrastructure to the people.

The hydrogen storage capacity became another critical variable that was related positively with the strategies of scalability. This complements the findings of Poll, Araujo and Keoleian (2025) which underscored that supply-demand mismatch can be managed by having substantial storage infrastructure as a core pillar of continuous availability of hydrogen. In India, the variability of RE is a logistic challenge where advanced storage solutions including solid state or high-pressure tank storage are essential. Just like what has been observed in Germany and Japan, countries that have invested early in hydrogen storage technologies have developed a pivotal lead in realising hydrogen integration. Similarly, the roadmap of India is based on the perspective of prioritizing the storage as a means of facilitating flexible and scalable hydrogen systems.

The cooperation between Government and Private sector also plays a major role in increasing the efforts towards scalability as the correlation of the data points to positive values. This is consistent with findings of Raj, Lakhina and Stranger (2022) and Atul Raizada (2025) who observed that policy-supported investment models, public-private partnerships (PPPs), and synchronized infrastructure deployment stimulate the adoption of technology. To illustrate, the National GH₂ Mission in India has prepared the groundwork of such cooperation, provided subsidies and brought about demand incentives. Nevertheless, the actualisation of scalability remains subject to the extent of productiveness in the convergence of both the Private innovation and Government facilitation of ground-level implementation in various regions and sectors.

In addition, the interactivity of scalability strategies and other enablers implies that a systems approach is critical to success. As Harichandan, Kar and Rai (2023) noted, GH₂ cannot be scaled independently; they will need to develop the logistics of transportation and the efficiency of electrolysis, funding mechanisms, and the training of personnel.

In conclusion, Hydrogen safety is not merely a technical obligation but a foundational enabler for sector-wide adoption. It requires a systemic approach—combining Government regulation, industrial innovation, cross-sectoral partnerships, and continuous capacity-building. India's GH₂ strategy must prioritise risk mitigation, enforceable standards and scalable safety infrastructure to establish a secure, reliable, and socially accepted hydrogen ecosystem.

CHAPTER VI: SUMMARY, IMPLICATIONS, AND RECOMMENDATIONS

6.1 Summary

This study critically examines the evolving role of GH₂ in India's journey towards NZE, focusing on policy efforts, industry involvement, and operational facilitators. The findings illustrate that national missions and regulatory systems provide a necessary level of support, but their success depends on effective implementation, financial incentives, and technological adoption. Policies alone do not guarantee industry uptake; rather, internal factors such as technical skills, skilled human resources, and firms' financial readiness reinforce their effectiveness. The results indicate that collaboration and innovation are more feasible when these internal enablers are in place, enabling stakeholders to address early-stage uncertainties and promote a large-scale GH₂ approach aligned with Sustainable Development Goals.

Furthermore, the study emphasises that overcoming the scalability challenges of GH₂ requires an ecosystem approach. This involves robust storage infrastructure, coordinated partnerships between the Private and Public sectors, and long-term financial mechanisms. Storage capacity, combined with institutional collaboration, is identified as a key factor in scaling GH₂ technologies. The findings support the view that infrastructure alone cannot drive adoption; instead, a synergy of regulation, technology, capital and workforce is essential for developing a comprehensive hydrogen economy in India beyond pilot projects. Through such multi-dimensional integration, India can establish a sustainable and internationally viable GH₂ ecosystem, contributing meaningfully to its net-zero ambitions.

6.2 Implications

The findings of this study, the transition to net-zero in India by using GH₂, appears to be a policy statement since it will need detailed and executable plans that will take into consideration the realities on the ground in terms of the industries. Though the strategic framework has been offered by national policy, like the National GH₂ Mission, which can be directly linked to industrial readiness, there is an obvious lack of direct connection between policy intent and action. This poses an urgent implication on policymakers to shift the vision statement on the macro-level to the micro-level implementation plans, where there exists clarity, consistency and measures of progress. The multi-tiered governance system, which has more Centre-State convergence and specific execution agencies, will be critical to reducing the execution gap and fostering trust among the industries that are expected to invest in hydrogen adoption and infrastructure building.

The study also highlights the fact that industrial collaboration is anchored on domestic readiness, especially on the aspects of technology, finance and skilled manpower. This observation has an obvious message to the key players in the Industry and the education-policy planners. It is required to increase industrial capacity through Research and Development (R&D) investments, scale up indigenous technology platforms and develop a talent pipeline dedicated to hydrogen-related work. Unless it has an experienced and financially robust industrial base, collaborative innovation will be slow. The Private sector would thus have to incorporate Green Hydrogen into its long-run sustainability and investment strategies, and the Government should also give special support to bolster technical institutions, vocational training and Green financing platforms within the various sectors.

The other major implication is in the infrastructural and funding ecosystems. These findings indicate that the current existing physical infrastructure is insufficient to de-risk

investments and thus India's transition will rely on future-oriented financial devices rather than the present availability of assets. To make hydrogen commercially viable, policymakers need to ramp up financial innovation (e.g., Green Bonds, concessional loans, and risk-sharing platforms) to help access long-term capital. Moreover, the disjointed nature of the infrastructure environment requires coordinated planning of the energy, transport and industrial corridors. Such coordination is only possible when Government institutions work with financial stakeholders and developers in the early stages of the project lifecycle to ensure compatibility between infrastructure deployment and investment certainty.

Finally, the systemic significance of safety measures, storage plans and stakeholder integration suggests that the GH₂ industry in India will need to develop as an orchestrated system, rather than a series of policy tests. Without being robust, the safety measures will erode the faith of the people and investors in hydrogen as a clean fuel. Poorly developed storage will generate supply chain bottlenecks and inefficiencies. Therefore, the broader implication is that India should develop a hydrogen economy using systems thinking, which involves an interdependent approach to policy, infrastructure, finance, training and innovation. The importance of this ecosystem-based development model to India lies not only in scaling up hydrogen production but also in ensuring that it is done in a reliable, inclusive and net-zero-compatible manner.

6.3 Recommendations for Future Research

Based on the analysis and the findings within this study, several research initiatives that can be taken to further advance the knowledge base on GH₂ transition in India are proposed:

1. Examine policy execution gaps across Central and State levels to evaluate how regulatory intentions translate into industry-level implementation and investment behaviour.
2. Investigate region-specific GH₂ readiness, focusing on States or industrial zones with varying infrastructure and resource availability to identify scalable models.
3. Assess workforce development needs in depth, including curriculum, vocational training and industry-academia collaboration to align talent pipelines with hydrogen sector demands.
4. Explore financing innovations, such as Green Bonds, Carbon Credits or blended finance, to determine their effectiveness in de-risking hydrogen investments.
5. Study end-use sector integration, particularly in mobility, refining and fertiliser industries, to measure the techno-economic feasibility and emission-reduction impact.
6. Evaluate Public-Private Partnership (PPP) models to identify governance frameworks that facilitate long-term infrastructure development and technology scaling.
7. Analyse safety and storage innovations, particularly those tailored to Indian conditions, for their role in building trust, reducing volatility and supporting reliability.

Future research should adopt a more longitudinal and sector-specific approach to monitoring the development of India's GH₂ ecosystem over time and across various sectors, including transportation, manufacturing and power. Since the current study only gives a cross-sectional picture, future research would be able to trace the industrial preparedness, safety levels and economic sustainability through the lens of policy influence over 5-10 years. Such activities can assist in determining the actual rate of technological penetration

and the stakeholder engagement in accordance with the net-zero plan of India. Case studies of sectors, particularly those that have looked into early adopters, will be useful in learning lessons regarding barriers and accelerators in the move towards commercial scale following pilot projects.

In addition to that, benchmarking may be done through comparative international studies to compare the Hydrogen strategies in India with those of the global front runners such as Germany, Japan and Australia. These comparative studies would reveal India's position in terms of technology development, conformity with regulations and infrastructure integration. Studies could also be done on cross-border Hydrogen trade and geopolitical supply chains, and electrolyser manufacturing ecosystems that would help India in the international GH₂ market. Not only would this information help policymakers further streamline national policies, but it would also enable investors and industries to make sound, long-term decisions in a clean energy economy that is becoming increasingly interdependent globally.

6.4 Conclusion

This Study has demonstrated that, on the one hand, the National policy frameworks and incentive schemes can create an initial drive, but on the other hand, their practical efficacy in terms of industry preparation is relatively still not very high. Regulatory certainty, uniformity and conformity to market forces are currently not at levels where these can propel industrial-scale adoption. The institutional support has to be developed between strategic intent and operational performance. As it is also proven, it is the policies coupled with enabling conditions - technology maturity, risk mitigation instruments and skilled manpower, which are really the determinants of industrial readiness. The shift to a GH₂ economy in India will have to involve a rebalanced strategy that combines top-down and bottom-up policy guidance, as well as industrial innovation and responsiveness.

The ability to utilise technology, financial resources, and workforce readiness have become the three key factors of industrial preparedness, shaping collaborative behaviour and innovative activity in the hydrogen value chain. Organisations with high technological maturity and strong fiscal stability are more likely to engage in strategic partnerships, receive subsidies and bear the risks of early-stage deployment. Similarly, workforce capabilities including engineering, systems design and implementation, are required to achieve the vision. These enablers are not merely operational necessities but strategic catalysts. The combined effort of these roles emphasises that the adoption of GH₂ in India relies as much on how different elements are brought together to initiate movement as it does on isolated breakthroughs. This alignment will be vital for India's progression towards scaling up Green Hydrogen deployment to establish net-zero aligned industrial ecosystems.

The Study has also identified that infrastructure and financial systems exert more than a fair share of influence on stakeholder confidence, particularly that of the private equity investors and hydrogen producers. The currently available infrastructure is expanding but it is not integrated, and it cannot fully support end-to-end hydrogen supply chains. Nonetheless, strong financial interventions, including viability gap funding, Green Bonds and public guarantees, are already demonstrating significant changes in reducing the perceived risks and opening the flow of capital. This twofold discovery implies that the fate of GH₂ in India will depend not only on the construction of physical infrastructure but also on the design of stable and favourable financial conditions. Clear strategy, transparent de-risking instruments and persistence of Policy will be important to invite and maintain domestic and international investments.

Finally, scalability and safety are the key drivers of continuing the GH₂ adoption movement. Harmonised storage infrastructure, regulatory agility and collaboration of public and private organisations are necessary to achieve scalable deployment. The

uncertainties in supply and inefficiencies may hinder national goals without specific planning for hydrogen storage. Similarly, it was found that well-organised safety procedures and training sessions lead to a considerable decrease in the risks of the operation, so these will be essential in a hydrogen-based energy future. These results are leading to the direction of integrated ecosystem that highlights safety, scalability, technology, financing and policy not as parallel initiatives but as interdependent pillars. Finally, coordination, innovation and inclusion are key factors that need to guide India's GH₂ path towards achieving a resilient and economically feasible net-zero transition.

It is pertinent to add that the Prime Minister of India, during his address to the Nation on 15th August, 2025 (79th Independence Day), has reiterated the Government's commitment to Green Hydrogen being a source of clean energy with his mention that "...With Mission Green Hydrogen, Bharat (India) is investing thousands of crores of rupees".

REFERENCES

- Abhyankar, N. *et al.* (2023) 'India's path towards energy independence and a clean future: Harnessing india's renewable edge for cost-effective energy independence by 2047', *The Electricity Journal*, 36(5), p. 107273. Available at: <https://doi.org/10.1016/j.tej.2023.107273>.
- Adani Green Energy Limited (2024) *Adani Green And TotalEnergies Strengthen Partnership With Strategic Joint Venture, Adani Green Energy Limited*.
- Agency, I.E. *et al.* (2021) 'IEA Global Hydrogen Review Paris 2021'.
- Aggarwal, P. (2017) '2°C target, India's climate action plan and urban transport sector', *Travel Behaviour and Society*, 6, pp. 110–116. Available at: <https://doi.org/10.1016/j.tbs.2016.11.001>.
- Ahmed, A., Pereira, L. and Kimberly, J. (2023) 'Mixed Methods Research: Combining Qualitative and Quantitative Methods', *Mixed Methods Research: Combining Qualitative and Quantitative Methods* [Preprint], (September). Available at: <https://doi.org/10.4135/9781529666687>.
- Alili, A. and Krstev, D. (2019) 'Using SPSS for Research and Data Analysis', *Knowledge International Journal* [Preprint]. Available at: <https://doi.org/10.35120/kij3203363a>.
- AlZohbi, G. (2022) 'Green Hydrogen Generation: Recent Advances and Challenges', *IOP Conference Series: Earth and Environmental Science*, 1050(1), p. 012003. Available at: <https://doi.org/10.1088/1755-1315/1050/1/012003>.
- Alzoubi, A.H. (2023) 'Assessing the Impact of Green Hydrogen Production on Carbon Emission Reduction: A Comprehensive Analysis', *International Journal of Engineering Energy and Electronics*, 1(1).
- Ampah, J.D. *et al.* (2023) 'Performance analysis and socio-enviro-economic feasibility

- study of a new hybrid energy system-based decarbonization approach for coal mine sites’, *Science of the Total Environment* [Preprint]. Available at: <https://doi.org/10.1016/j.scitotenv.2022.158820>.
- Ampah, J.D., Jin, C., Liu, H., *et al.* (2024) ‘Prioritizing Non-Carbon Dioxide Removal Mitigation Strategies Could Reduce the Negative Impacts Associated with Large-Scale Reliance on Negative Emissions’, *Environmental Science & Technology*, 58(8), pp. 3755–3765. Available at: <https://doi.org/10.1021/acs.est.3c06866>.
- Ampah, J.D., Jin, C., Afrane, S., *et al.* (2024) ‘Race towards net zero emissions (NZE) by 2050: reviewing a decade of research on hydrogen-fuelled internal combustion engines (ICE)’, *Green Chemistry*, 26(16), pp. 9025–9047. Available at: <https://doi.org/10.1039/D4GC00864B>.
- Anjanappa, J. (2025) ‘Designing Scale-Sensitive Risk-Sharing Models for Financing Green Hydrogen in India’.
- Approach, A.A. (2024) *India’s green hydrogen revolution*, *Hydrogen Production: Electrolysis*.
- Arto, I. *et al.* (2016) ‘The energy requirements of a developed world’, *Energy for Sustainable Development* [Preprint]. Available at: <https://doi.org/10.1016/j.esd.2016.04.001>.
- Asensio, O.I. and Delmas, M.A. (2017) ‘The effectiveness of US energy efficiency building labels’, *Nature Energy* [Preprint]. Available at: <https://doi.org/10.1038/nenergy.2017.33>.
- Atul Raizada (2025) ‘India’s Green Hydrogen Strategy in Action Policy Actions, Market Insights and Global Opportunities’.
- Bakhtiari, V. *et al.* (2024) ‘Stakeholder analysis in the application of cutting-edge digital visualisation technologies for urban flood risk management: A critical review’,

- Expert Systems with Applications*, 236(September 2023), p. 121426. Available at: <https://doi.org/10.1016/j.eswa.2023.121426>.
- Balasubramanian, S. and Balachandra, P. (2021a) ‘Characterising electricity demand through load curve clustering: A case of Karnataka electricity system in India’, *Computers and Chemical Engineering* [Preprint]. Available at: <https://doi.org/10.1016/j.compchemeng.2021.107316>.
- Balasubramanian, S. and Balachandra, P. (2021b) ‘Effectiveness of demand response in achieving supply-demand matching in a renewables dominated electricity system: A modelling approach’, *Renewable and Sustainable Energy Reviews*, 147, p. 111245. Available at: <https://doi.org/10.1016/j.rser.2021.111245>.
- Balasubramanian, S. and Balachandra, P. (2022) ‘Indian Electricity System Transition and Its Challenges: A Review’, *Journal of Asian Energy Studies* [Preprint]. Available at: <https://doi.org/10.24112/jaes.060001>.
- Bansal, M. (2024) ‘Climate-resilience Readiness of Emerging Clean Energy Technologies for India’s Energy Transition: A Deep Dive into Select Technologies’, *IOP Conference Series: Earth and Environmental Science*, 1395(1), p. 012015. Available at: <https://doi.org/10.1088/1755-1315/1395/1/012015>.
- Basu, A. (2024) ‘Green Energy Diplomacy in the Post Covid-19 World: India’s Efforts towards Climate and Energy Security in the Global South’, *Political Science and Public Administration Journal*, 1, pp. 217–246.
- Baum, Z.J. *et al.* (2022) ‘Materials Research Directions Toward a Green Hydrogen Economy: A Review’, *ACS Omega*, 7(37), pp. 32908–32935. Available at: <https://doi.org/10.1021/acsomega.2c03996>.
- Bertuccioli, L. (E4tech) *et al.* (2014) ‘Study on development of water electrolysis in the EU - Final Report’, *Fuel Cells and hydrogen Joint Undertaking* [Preprint].

- Bhati, M., Kumari, N. and Biswas, J. (2024) ‘Unveiling India’s green hydrogen economy Opportunities and challenges’.
- Bhatia, P. (2023) ‘India’s state-led electricity transition: A review of techno-economic, socio-technical and political perspectives’, *Energy Research & Social Science*, 102(June), p. 103184. Available at: <https://doi.org/10.1016/j.erss.2023.103184>.
- Bhattacharyya, R., Singh, K.K., Grover, R.B., Bhanja, K., *et al.* (2022) ‘Estimating minimum energy requirement for transitioning to a net-zero, developed India in 2070’, *Current Science* [Preprint]. Available at: <https://doi.org/10.18520/cs/v122/i5/517-527>.
- Bhattacharyya, R., Singh, K.K., Grover, R.B. and Bhanja, K. (2022) ‘Estimating minimum energy requirement for transitioning to a net-zero, developed India in 2070’, *Current Science*, 122(5), p. 517. Available at: <https://doi.org/10.18520/cs/v122/i5/517-527>.
- Bio Energy Times (2025) *India’s renewable hydrogen developers bank on cost advantage in lackluster global market: S&P report*, *Bio Energy Times*.
- Bonesso, F. *et al.* (2025) ‘Green hydrogen as a sustainable operations strategy: A socio-economic perspective’, *Sustainable Operations and Computers*, 6(August 2024), pp. 1–14. Available at: <https://doi.org/10.1016/j.susoc.2024.11.002>.
- Borowski, P.F. and Karlikowska, B. (2023) ‘Clean Hydrogen Is a Challenge for Enterprises in the Era of Low-Emission and Zero-Emission Economy’, *Energies*, 16(3), p. 1171. Available at: <https://doi.org/10.3390/en16031171>.
- Braga, H., Gouvea, R. and Gutierrez, M. (2024) ‘The Green Hydrogen Economy and the Global Net Zero Agenda: A Green Powershoring & Green Watershoring Perspective’, *Modern Economy*, 15(01), pp. 23–48. Available at: <https://doi.org/10.4236/me.2024.151002>.

- Chaturvedi, V. (2021) 'A vision for a net-zero energy system for India', *Energy and Climate Change*, 2, p. 100056. Available at: <https://doi.org/10.1016/j.egycc.2021.100056>.
- Cléménçon, R. (2016) 'The Two Sides of the Paris Climate Agreement', *The Journal of Environment & Development*, 25(1), pp. 3–24. Available at: <https://doi.org/10.1177/1070496516631362>.
- Curcio, E. (2025) *Techno-Economic Analysis of Hydrogen Production: Costs, Policies, and Scalability in the Transition to Net-Zero*. Available at: <https://doi.org/https://doi.org/10.48550/arXiv.2502.12211>.
- Das, S. (2023) 'Data Analysis of Factors Contributing to the Adoption of Green Hydrogen', *The Journal of Environment & Development*, 32. Available at: <https://doi.org/10.1177/10704965231211588>.
- Dey, S. *et al.* (2022) 'Renewable energy present status and future potentials in India: An overview', *Innovation and Green Development*, 1(1), p. 100006. Available at: <https://doi.org/10.1016/j.igd.2022.100006>.
- Dixit, A.C. *et al.* (2024) 'Barriers for adoption of green hydrogen in Indian transportation sector: A fuzzy ISM approach', *E3S Web of Conferences*. Edited by D.A. Joshi, N.B. Ibrahim, and D.M. Sangeetha, 559, p. 03011. Available at: <https://doi.org/10.1051/e3sconf/202455903011>.
- Dong, Z.Y. *et al.* (2022) 'A green hydrogen credit framework for international green hydrogen trading towards a carbon neutral future', *International Journal of Hydrogen Energy* [Preprint]. Available at: <https://doi.org/10.1016/j.ijhydene.2021.10.084>.
- Dorel, S. *et al.* (2024) 'Green Hydrogen, a Solution for Replacing Fossil Fuels to Reduce CO₂ Emissions', *Processes*, 12(8), p. 1651. Available at:

- <https://doi.org/10.3390/pr12081651>.
- El-Hashash, E.F. and Shiekh, R.H.A. (2022) ‘A Comparison of the Pearson, Spearman Rank and Kendall Tau Correlation Coefficients Using Quantitative Variables’, *Asian Journal of Probability and Statistics* [Preprint]. Available at: <https://doi.org/10.9734/ajpas/2022/v20i3425>.
- Firoozi, Ali Akbar *et al.* (2024) ‘Emerging trends in sustainable building materials: Technological innovations, enhanced performance, and future directions’, *Results in Engineering*, 24, p. 103521. Available at: <https://doi.org/10.1016/j.rineng.2024.103521>.
- French, S. (2020a) ‘The Role of Zero and Low Carbon Hydrogen in Enabling the Energy Transition and the Path to Net Zero Greenhouse Gas Emissions’, *Johnson Matthey Technology Review*, 64(3), pp. 357–370. Available at: <https://doi.org/10.1595/205651320X15910225395383>.
- French, S. (2020b) ‘The role of zero and low carbon hydrogen in enabling the energy transition and the path to net zero greenhouse gas emissions with global policies and demonstration projects hydrogen can play a role in a net zero future’, *Johnson Matthey Technology Review* [Preprint]. Available at: <https://doi.org/10.1595/205651320x15910225395383>.
- Fuhrman, J. *et al.* (2023) ‘Diverse carbon dioxide removal approaches could reduce impacts on the energy–water–land system’, *Nature Climate Change* [Preprint]. Available at: <https://doi.org/10.1038/s41558-023-01604-9>.
- Fumagalli, E. (2016) ‘Energy investment: The many lives of energy storage’, *Nature Energy* [Preprint]. Available at: <https://doi.org/10.1038/nenergy.2016.96>.
- Gesellschaft, D. (2024) ‘Development of Roadmap for a Green Hydrogen Cluster in Ramagundam’, pp. 01–80.

- Ghosh, P. and Roy, A. (2024) 'Green-hydrogen - the game changer of India's journey towards energy sustainability: A socio-legal study', *E3S Web of Conferences*. Edited by E. Zervas, 585, p. 10008. Available at: <https://doi.org/10.1051/e3sconf/202458510008>.
- Goel, M. (2024) '3 "Ps" of Hydrogen Economy in India: Production Pathways, Policies, and Perspectives', in *Climate Action and Hydrogen Economy: Technologies Shaping the Energy Transition*. Springer, pp. 11–37.
- Gordon, J.A. *et al.* (2024) 'Coupling green hydrogen production to community benefits: A pathway to social acceptance?', *Energy Research & Social Science*, 110, p. 103437. Available at: <https://doi.org/10.1016/j.erss.2024.103437>.
- Gordon, J.A., Balta-Ozkan, N. and Nabavi, S.A. (2022) 'Beyond the triangle of renewable energy acceptance: The five dimensions of domestic hydrogen acceptance', *Applied Energy*, 324, p. 119715. Available at: <https://doi.org/10.1016/j.apenergy.2022.119715>.
- Van de Graaf, T. *et al.* (2020) 'The new oil? The geopolitics and international governance of hydrogen', *Energy Research & Social Science*, 70, p. 101667. Available at: <https://doi.org/10.1016/j.erss.2020.101667>.
- Green H Electrolysis (2025) *Catalyzing the Green Hydrogen Economy: Uniting Diverse Stakeholders for a Clean Energy Future*, Green H Electrolysis.
- Griffiths, S. *et al.* (2021) 'Industrial decarbonization via hydrogen: A critical and systematic review of developments, socio-technical systems and policy options', *Energy Research & Social Science*, 80, p. 102208. Available at: <https://doi.org/10.1016/j.erss.2021.102208>.
- Guan, D. *et al.* (2023) 'Hydrogen society: from present to future', *Energy and Environmental Science* [Preprint]. Available at:

- <https://doi.org/10.1039/d3ee02695g>.
- Gupta, S. *et al.* (2024) ‘Green Hydrogen: Potential Master Key for Combating Climate Change’, in *Climate Action and Hydrogen Economy: Technologies Shaping the Energy Transition*. Springer, pp. 39–60.
- Gupta, S., Kumar, R. and Kumar, A. (2024) ‘Green hydrogen in India: Prioritization of its potential and viable renewable source’, *International Journal of Hydrogen Energy*, 50, pp. 226–238. Available at: <https://doi.org/10.1016/j.ijhydene.2023.08.166>.
- Gupta, S. and Sneha Sinha (2024) ‘India’s Green Hydrogen Mission: A Strategic Path to Global Leadership’, *Journal of Global Economy*, 20(4), pp. 211–230. Available at: <https://doi.org/10.1956/jge.v20i4.740>.
- GUPTA, U. (2024) ‘IH2A proposes \$5 billion hydrogen transition fund’, *pv magazine - Photovoltaics Markets and Technology*.
- Hamukoshi, S.S. *et al.* (2022) ‘An overview of the socio-economic impacts of the green hydrogen value chain in Southern Africa’, *Journal of Energy in Southern Africa*, 33(3), pp. 12–21. Available at: <https://doi.org/10.17159/2413-3051/2022/v33i3a12543>.
- Harichandan, S., Kar, S.K. and Rai, P.K. (2023) ‘A systematic and critical review of green hydrogen economy in India’, *International Journal of Hydrogen Energy*, 48(81), pp. 31425–31442. Available at: <https://doi.org/10.1016/j.ijhydene.2023.04.316>.
- Harrison, T. and Kostka, G. (2014) ‘Balancing Priorities, Aligning Interests: Developing Mitigation Capacity in China and India’, *Comparative Political Studies* [Preprint]. Available at: <https://doi.org/10.1177/0010414013509577>.
- Hassan, Q. *et al.* (2024) ‘A review of green hydrogen production by renewable resources’, *Energy Harvesting and Systems*, 11(1), pp. 1–27. Available at: <https://doi.org/10.1515/ehs-2022-0127>.

- Henry Ebini, O. (2024) ‘Fostering Workforce Readiness for the Green Hydrogen Economy through People-Centric Training Programs’, *International Journal of Innovative Science and Research Technology (IJISRT)*, pp. 773–788. Available at: <https://doi.org/10.38124/ijisrt/IJISRT24NOV038>.
- Hittinger, E. (2017) ‘Distributed generation: Residential storage comes at a cost’, *Nature Energy* [Preprint]. Available at: <https://doi.org/10.1038/nenergy.2017.6>.
- Honzák, M. *et al.* (2019) ‘India’s pathway to net zero by 2070: status, challenges, and way forward’.
- International Hydrogen Ramp (2024) *Public-Private Partnership (PPP) Projects*.
- Irena (2017) *Remap Renewable Energy Prospects for India*. Available at: https://www.connaissancedesenergies.org/sites/connaissancedesenergies.org/files/pdf-pt-vue/irena_remap_india_paper_2017_0.pdf.
- J. Gulia *et al.* (2024) ‘India’s \$2.1bn leap towards its green hydrogen vision | IEEFA’, *Institute for Energy Economics and Financial Analysis (IEEFA)* [Preprint].
- Jain, N. (2021) ‘Survey versus interviews: Comparing data collection tools for exploratory research’, *Qualitative Report* [Preprint]. Available at: <https://doi.org/10.46743/2160-3715/2021.4492>.
- Jamasb, T. (2017) ‘Electricity storage: Friend or foe of the networks?’, *Nature Energy*, 2(6), p. 17092. Available at: <https://doi.org/10.1038/nenergy.2017.92>.
- Janardhanan, N. *et al.* (2024) ‘Sub-national Drivers of India’s Green Hydrogen Development’, (October).
- Janardhanan, N., Zusman, E. and Moinuddin, M. (2024) ‘Sub-national Drivers of India’s Green Hydrogen Development’, (June), pp. 32–40.
- Jayachandran, M. *et al.* (2024) ‘Challenges and Opportunities in Green Hydrogen Adoption for Decarbonizing Hard-to-Abate Industries: A Comprehensive Review’,

- IEEE Access*, 12, pp. 23363–23388. Available at: <https://doi.org/10.1109/ACCESS.2024.3363869>.
- Jayakumar, A. *et al.* (2022) ‘Can hydrogen be the sustainable fuel for mobility in India in the global context?’, *International Journal of Hydrogen Energy*, 47(79), pp. 33571–33596. Available at: <https://doi.org/10.1016/j.ijhydene.2022.07.272>.
- Jha, P. (2025) *Know the current status of green hydrogen production capacity in India*, *Bio Energy Times*.
- Kakran, S. *et al.* (2023) ‘Hydrogen energy in BRIC S -US : A whirl l succeeding fuel treause’, (xxxx).
- Kar, S.K. *et al.* (2023) ‘Hydrogen economy in India: A status review’, *WIREs Energy and Environment*, 12(1). Available at: <https://doi.org/10.1002/wene.459>.
- Kaur, D. and Rehman, M. (2024) ‘Renewable energy made in India: navigating geopolitics in achieving sustainability’, *Journal of Chinese Economic and Business Studies*, 22(4), pp. 455–476. Available at: <https://doi.org/10.1080/14765284.2024.2334553>.
- Khadka, A. (2023) *The Impact of Digital Transformation on Customer Experience in the UK Banking Sector" A Case Study of Lloyds Bank*. Available at: <https://doi.org/10.13140/RG.2.2.19508.01921>.
- Khare, V., Nema, S. and Baredar, P. (2013) ‘Status of solar wind renewable energy in India’, *Renewable and Sustainable Energy Reviews* [Preprint]. Available at: <https://doi.org/10.1016/j.rser.2013.06.018>.
- King, J. (2021) ‘Hydrogen and Net Zero - A crucial role in decarbonisation strategies’, *FST Journal* [Preprint]. Available at: <https://doi.org/10.53289/cnlo5061>.
- Kokkinos, K. *et al.* (2023) ‘Multi-scenario analysis on hydrogen production development using PESTEL and FCM models’, *Journal of Cleaner Production*, 419, p. 138251. Available at: <https://doi.org/https://doi.org/10.1016/j.jclepro.2023.138251>.

- Koletsis, D. and Pandis, N. (2018) 'Ordinal logistic regression', *American Journal of Orthodontics and Dentofacial Orthopedics* [Preprint]. Available at: <https://doi.org/10.1016/j.ajodo.2017.11.011>.
- Koshy, J. (2023) 'India's green hydrogen move may worsen pollution if steps are not in place, says study', *The Hindu*.
- Krishnan, A. (2023) 'Can Green Hydrogen Fuel India's Clean Energy Transition?', *SOCIAL POLICY RESEARCH FOUNDATION* [Preprint].
- Kumar, J.C.R., Kumar, D.V. and Majid, M.A. (2019) 'Wind energy programme in India: Emerging energy alternatives for sustainable growth', *Energy and Environment* [Preprint]. Available at: <https://doi.org/10.1177/0958305X19841297>.
- Kumar, S. and Madlener, R. (2016) 'CO2 emission reduction potential assessment using renewable energy in India', *Energy* [Preprint]. Available at: <https://doi.org/10.1016/j.energy.2015.12.131>.
- Leske, R. (2023) 'Green hydrogen as a catalyst for just energy transitions? A comparative study of strategies in Germany and Uruguay', pp. 01–104.
- Luthra, S. (2022) *India Hydrogen Alliance, Kerala govt to build Kochi Green Hydrogen Hub*, *livemint.com*.
- Madheswaran, D.K. *et al.* (2024) 'Green hydrogen: Paving the way for India's decarbonization revolution', *Environmental Science and Pollution Research* [Preprint]. Available at: <https://doi.org/10.1007/s11356-024-34250-5>.
- Marouani, I. *et al.* (2023) 'Integration of Renewable-Energy-Based Green Hydrogen into the Energy Future', *Processes*, 11(9), p. 2685. Available at: <https://doi.org/10.3390/pr11092685>.
- Martinez-Burgos, W.J. *et al.* (2019) 'The effect of hydrolysis and sterilization in biohydrogen production from cassava processing wastewater medium using

- anaerobic bacterial consortia’, *International Journal of Hydrogen Energy* [Preprint]. Available at: <https://doi.org/10.1016/j.ijhydene.2019.08.085>.
- Maurer, M. *et al.* (2022) ‘Understanding the Influence and Impact of Stakeholder Engagement in Patient-centered Outcomes Research: a Qualitative Study’, *Journal of General Internal Medicine*, 37(S1), pp. 6–13. Available at: <https://doi.org/10.1007/s11606-021-07104-w>.
- Maurya, V., Ghosh, P. and Gunawat, A. (2024) ‘STI Policy Push Towards Hydrogen Economy in India’, in *Green Energy and Technology*, pp. 107–118. Available at: https://doi.org/10.1007/978-981-99-6237-2_6.
- Medisetty, V.M. *et al.* (2020) ‘Overview on the Current Status of Hydrogen Energy Research and Development in India’, *Chemical Engineering & Technology*, 43(4), pp. 613–624. Available at: <https://doi.org/10.1002/ceat.201900496>.
- Ministry of New and Renewable Energy (2023) *National Green Hydrogen Mission*, Ministry of New and Renewable Energy.
- Ministry of New and Renewable Energy (2023a) *Brief on Green Hydrogen*. Available at: <https://mnre.gov.in/en/hydrogen-overview/>.
- Ministry of New and Renewable Energy (2023b) *Cabinet approves National Green Hydrogen Mission*.
- Ministry of New and Renewable Energy (2024a) *Green Hydrogen Standards and Approval Systems in India Streamlining the Green Hydrogen Ecosystem for Accelerated Implementation of National Green Hydrogen Mission*.
- Ministry of New and Renewable Energy (2024b) *India’s green hydrogen revolution, Hydrogen Production: Electrolysis*.
- Ministry Of New And Renewable Energy (2024) ‘National Green Hydrogen Mission’.
- Ministry of Power (2015) ‘Power Sector at a Glance ALL INDIA’, *Indian Electricity*

- Scenario* [Preprint].
- Ministry of Statistics and Programme Implementation (2024) *Energy Statistics India 2025*, Government of India.
- Mint (2023) *India gets green hydrogen fuel cell bus: From sustainability to lower refueling time – How will it change commute?*, Mint.
- Mishra, P. *et al.* (2019) ‘Descriptive statistics and normality tests for statistical data’, *Annals of Cardiac Anaesthesia* [Preprint]. Available at: https://doi.org/10.4103/aca.ACA_157_18.
- Mitchell, C. (2016) ‘Momentum is increasing towards a flexible electricity system based on renewables’, *Nature Energy* [Preprint]. Available at: <https://doi.org/10.1038/NENERGY.2015.30>.
- Mneimneh, F. *et al.* (2023) ‘Roadmap to Achieving Sustainable Development via Green Hydrogen’, *Energies*, 16(3), p. 1368. Available at: <https://doi.org/10.3390/en16031368>.
- MNRE (2023) *Ministry of New and Renewable Energy, Govt of India. National Hydrogen Energy Roadmap*.
- National Institute of Transforming India (2022) *Report of the Expert Group on 175 Renewable Electricity (RE) by 2022*.
- National Portal of India (2023) *National Green Hydrogen Mission - Decarbonising India, Achieving Net Zero Vision*, National Portal of India.
- Nazeerudin, N. (2023) ‘India’s Transition towards Green Economy’, *British Journal of Multidisciplinary and Advanced Studies*, 4(1), pp. 46–59. Available at: <https://doi.org/10.37745/bjmas.2022.0108>.
- Needell, Z.A. *et al.* (2016) ‘Potential for widespread electrification of personal vehicle travel in the United States’, *Nature Energy* [Preprint]. Available at:

- <https://doi.org/10.1038/nenergy.2016.112>.
- Ng, W.C. *et al.* (2024) ‘Elevating the prospects of green hydrogen (H₂) production through solar-powered water splitting devices: A systematic review’, *Sustainable Materials and Technologies*, 40, p. e00972. Available at: <https://doi.org/10.1016/j.susmat.2024.e00972>.
- Nnabuife, S.G. *et al.* (2023) ‘The prospects of hydrogen in achieving net zero emissions by 2050: A critical review’, *Sustainable Chemistry for Climate Action*, 2(March), p. 100024. Available at: <https://doi.org/10.1016/j.scca.2023.100024>.
- Odenweller, A. and Ueckerdt, F. (2025) ‘The green hydrogen ambition and implementation gap’, *Nature Energy*, 10(1), pp. 110–123. Available at: <https://doi.org/10.1038/s41560-024-01684-7>.
- OECD (2024) *Leveraging De-Risking Instruments and International Co-ordination to Catalyse Investment in Clean Hydrogen*.
- Onifade, M. *et al.* (2024) ‘Advancing toward sustainability: The emergence of green mining technologies and practices’, *Green and Smart Mining Engineering*, 1(2), pp. 157–174. Available at: <https://doi.org/10.1016/j.gsme.2024.05.005>.
- Ostadi, M. *et al.* (2020) ‘Process integration of green hydrogen: Decarbonization of chemical industries’, *Energies* [Preprint]. Available at: <https://doi.org/10.3390/en13184859>.
- Pal, K., Yadav, P. and Tyagi, S.K. (2017) ‘Renewable Sources in India and Their Applications’, in *Sustainable Biofuels Development in India*. Cham: Springer International Publishing, pp. 39–71. Available at: https://doi.org/10.1007/978-3-319-50219-9_3.
- Pal, P. (2023) ‘Present status and future outlooks of renewable energy in India for sustainable development.’, in *A Basic Overview of Environment and Sustainable*

- Development [Volume 2]*. International Academic Publishing House (IAPH), pp. 408–433. Available at: <https://doi.org/10.52756/boesd.2023.e02.028>.
- Pandey, A. (2024) ‘The Role of Sub-National Governments in India’s Green Hydrogen Transition A multilevel perspective The Role of Sub-National’, (October). Available at: <https://doi.org/10.57405/iges-13440>.
- Pandey, I. and Kumari, S. (2023) ‘Indian Green Hydrogen Framework: An Assessment’, *EAI Endorsed Transactions on Energy Web*, 10, pp. 1–7. Available at: <https://doi.org/10.4108/ew.4701>.
- Patange, O.S., Garg, A. and Jayaswal, S. (2022) ‘An integrated bottom-up optimization to investigate the role of BECCS in transitioning towards a net-zero energy system: A case study from Gujarat, India’, *Energy*, 255, p. 124508. Available at: <https://doi.org/10.1016/j.energy.2022.124508>.
- Pathak, K. (2023) ‘L&T and partners to invest \$4 billion in green hydrogen projects’, *The Economic Times*.
- Petroleum, B. (2018) *BP Energy Outlook country and regional insights-India*.
- Pflugmann, F. and Blasio, N. De (2020) ‘The Geopolitics of Renewable Hydrogen in Low-Carbon Energy Markets’, *Geopolitics, History, and International Relations*, 12(1), p. 7. Available at: <https://doi.org/10.22381/GHIR12120201>.
- Pinto, L. (2023) ‘A Qualitative Analysis of Corporate Social Responsibility in Saudi Arabia’s Service Sector-Practices and Company Performance’, *Sustainability (Switzerland)*, 15(12). Available at: <https://doi.org/10.3390/su15129284>.
- Poll, J., Araujo, A. and Keoleian, A.G.A. (2025) ‘POTENTIAL GREEN HYDROGEN APPLICATIONS IN INDIA ’ S POWER SECTOR Capstone Report Potential Green Hydrogen Applications in’.
- Pollitt, M.G. and Chyong, C.K. (2021) ‘Modelling net zero and sector coupling: Lessons

- for european policy makers’, *Economics of Energy and Environmental Policy* [Preprint]. Available at: <https://doi.org/10.5547/2160-5890.10.2.MPOL>.
- Raj, Kowtham, Lakhina, P. and Stranger, C. (2022) ‘Green Hydrogen Harnessing Opportunities for Deep Decarbonisation in India’, *NITI Aayog*, pp. 1–88.
- Raj, K, Lakhina, P. and Stranger, C. (2022) ‘Harnessing green hydrogen opportunities for deep decarbonisation in India’, *NITI Aayog Report*, pp. 1–88.
- Rajamani, L. and Werksman, J. (2018) ‘The legal character and operational relevance of the Paris Agreement’s temperature goal’, *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* [Preprint]. Available at: <https://doi.org/10.1098/rsta.2016.0458>.
- Rajesh, C. and Majid, M.A. (2020) ‘Renewable energy for sustainable development in India: Current status, future prospects, challenges, employment, and investment opportunities’, *Energy, Sustainability and Society*, 10(2), pp. 1–36. Available at: <https://doi.org/10.1186/s13705-019-0232-1>.
- Raman, R. *et al.* (2022) ‘Green-hydrogen research: What have we achieved, and where are we going? Bibliometrics analysis’, *Energy Reports*, 8, pp. 9242–9260. Available at: <https://doi.org/10.1016/j.egyr.2022.07.058>.
- Rey, J., Segura, F. and Andújar, J. (2023) ‘Green Hydrogen: Resources Consumption, Technological Maturity, and Regulatory Framework’, *Energies*, 16(17), p. 6222. Available at: <https://doi.org/10.3390/en16176222>.
- Ritchie, H., Roser, M. and Rosado, P. (2020) ‘CO₂ and greenhouse gas emissions’, *Our world in data* [Preprint].
- Roy, D., Bhowmik, M. and Roskilly, A.P. (2024) ‘Technoeconomic, environmental and multi criteria decision making investigations for optimisation of off-grid hybrid renewable energy system with green hydrogen production’, *Journal of Cleaner*

- Production*, 443, p. 141033. Available at: <https://doi.org/10.1016/j.jclepro.2024.141033>.
- Sadan, V. (2017) 'Data Collection Methods in Quantitative Research', *Indian Journal of Continuing Nursing Education* [Preprint].
- Sambasivam, B. and Balachandra, P. (2023) 'Demand response an effective solution for dynamic balancing of variable supply with variable demand: Evidence from Indian electricity system', *Energy and Environment* [Preprint]. Available at: <https://doi.org/10.1177/0958305X231179908>.
- Sambasivam, B. and Sarma, R.N. (2024) 'India's National Green Hydrogen Mission: an analysis of the strategies, policies for net-zero emissions and sustainability', *Environmental Research: Energy*, 1(4), p. 45015.
- Saygin, J.C. and D. (2022) 'Green hydrogen opportunities for emerging and developing economies', *Organisation for Economic Co-operation and Development* [Preprint].
- Schmid, G. (2012) 'The development of renewable energy power in India: Which policies have been effective?', *Energy Policy* [Preprint]. Available at: <https://doi.org/10.1016/j.enpol.2012.02.039>.
- SCHOLTEN, D. (2024) 'The Power of Energy: The Geopolitics of the Energy Transition', *Handbook on the Geopolitics of the Energy Transition*, pp. 1–18.
- Schulthoff, M. *et al.* (2021) 'Role of Hydrogen in a Low-Carbon Electric Power System: A Case Study', *Frontiers in Energy Research* [Preprint]. Available at: <https://doi.org/10.3389/fenrg.2020.585461>.
- Sebbagh, T., Şahin, M.E. and Beldjaatit, C. (2024) 'Green hydrogen revolution for a sustainable energy future', *Clean Technologies and Environmental Policy*, 26(12), pp. 4017–4040. Available at: <https://doi.org/10.1007/s10098-024-02995-9>.
- Sharma, A. *et al.* (2023) 'Green Hydrogen for a Sustainable Future: Prospects and

- Challenges for Energy-Based Applications in Major Indian States by 2030', *E3S Web of Conferences*. Edited by D.A. Joshi, N.B. Ibrahim, and D.M. Sangeetha, 405, p. 02027. Available at: <https://doi.org/10.1051/e3sconf/202340502027>.
- Sharma, G.D. *et al.* (2023) 'Socio-economic aspects of hydrogen energy: An integrative review', *Technological Forecasting and Social Change*, 192, p. 122574. Available at: <https://doi.org/10.1016/j.techfore.2023.122574>.
- Sharma, N.K. (2022) 'Instruments Used in the Collection of Data in Research', *SSRN Electronic Journal* [Preprint], (May). Available at: <https://doi.org/10.2139/ssrn.4138751>.
- Sharma, S., Kumar, A. and Jain, P. (2023) 'Green Hydrogen in India- Applications, Opportunities and Challenges', in *2023 1st International Conference on Intelligent Computing and Research Trends (ICRT)*. IEEE, pp. 1–6. Available at: <https://doi.org/10.1109/ICRT57042.2023.10146660>.
- Sheth, S. (2023) 'The impact of green hydrogen on India's energy security and sustainability', *The Times of India*.
- Shin, J.E. (2024) 'Asia-Pacific's path to sustainable energy Opportunities and challenges of green hydrogen technologies'.
- Sholapurkar, R.B. and Mahajan, Y.S. (2015) 'Review of Wind Energy Development and Policy in India', *Energy Technology & Policy* [Preprint]. Available at: <https://doi.org/10.1080/23317000.2015.1101627>.
- Shrivastava, M.K. and Sharan, V.D. (2024) 'Hydrogen Energy : A Way Forward for', 14, pp. 4165–4175.
- Shukla, A.K., Sudhakar, K. and Baredar, P. (2017) 'Renewable energy resources in South Asian countries: Challenges, policy and recommendations', *Resource-Efficient Technologies* [Preprint]. Available at: <https://doi.org/10.1016/j.reffit.2016.12.003>.

- Singh, A.P. (2024) ‘Assessment of India’s Green Hydrogen Mission and environmental impact’, *Renewable and Sustainable Energy Reviews*, 203, p. 114758. Available at: <https://doi.org/10.1016/j.rser.2024.114758>.
- Singh, B.N., Ratn, T. and Jha, P. (2024a) ‘India’s Green Hydrogen Revolution-An Ambitious Approach’.
- Singh, B.N., Ratn, T. and Jha, P. (2024b) ‘India’s green hydrogen revolution’, *Hydrogen Production: Electrolysis* [Preprint], (May).
- Slorach, P.C. and Stamford, L. (2021) ‘Net zero in the heating sector: Technological options and environmental sustainability from now to 2050’, *Energy Conversion and Management* [Preprint]. Available at: <https://doi.org/10.1016/j.enconman.2021.113838>.
- van Soest, H.L., den Elzen, M.G.J. and van Vuuren, D.P. (2021) ‘Net-zero emission targets for major emitting countries consistent with the Paris Agreement’, *Nature Communications* [Preprint]. Available at: <https://doi.org/10.1038/s41467-021-22294-x>.
- Sokołowski, M.M. (2022) ‘Making the Electricity Sector Emission-Free’, in *Energy Transition of the Electricity Sectors in the European Union and Japan*. Available at: https://doi.org/10.1007/978-3-030-98896-8_3.
- Song, C. (2006) ‘Global challenges and strategies for control, conversion and utilization of CO₂ for sustainable development involving energy, catalysis, adsorption and chemical processing’, *Catalysis Today* [Preprint]. Available at: <https://doi.org/10.1016/j.cattod.2006.02.029>.
- Song, S. *et al.* (2022) ‘Deep decarbonization of the Indian economy: 2050 prospects for wind, solar, and green hydrogen’, *iScience*, 25(6), p. 104399. Available at: <https://doi.org/10.1016/j.isci.2022.104399>.

- Sontakke, U. and Jaju, S. (2021) ‘Green hydrogen economy and opportunities for India’, *IOP Conference Series: Materials Science and Engineering*, 1206(1), p. 012005. Available at: <https://doi.org/10.1088/1757-899x/1206/1/012005>.
- The Economic Times (2024) ‘India’s coal import rises 8% to 268 MT in FY24’, *Indiatimes*.
- The Economics Time (2024) ‘Reliance Industries to invest in renewable energy, green hydrogen in Tamil Nadu: Mukesh Ambani’, *The Economics Time*.
- The Indo-German Energy Forum (2024) *Workshop on “Decarbonisation of India’s Public Sector Enterprises (PSEs) and Role of Green Hydrogen”*.
- Thekkethil, R. *et al.* (2024) ‘Green hydrogen hubs in India: A first order analytical hierarchy process for site selection across states’, *International Journal of Hydrogen Energy* [Preprint]. Available at: <https://doi.org/10.1016/j.ijhydene.2024.02.268>.
- Tiwari, S. *et al.* (2024) ‘Sustainable pathways for attaining net zero emissions in selected South Asian countries: role of green energy market and pricing’, *Humanities and Social Sciences Communications*, 11(1), p. 93. Available at: <https://doi.org/10.1057/s41599-023-02552-7>.
- Tongia, R. and Patel, U. (2024) ‘Benchmarking Green Hydrogen in India’s Energy Transition: Expensive but Important for Some Uses’.
- Tymoczko, J. *et al.* (2016) ‘Making the hydrogen evolution reaction in polymer electrolyte membrane electrolyzers even faster’, *Nature Communications* [Preprint]. Available at: <https://doi.org/10.1038/ncomms10990>.
- Ueckerdt, F. *et al.* (2021) ‘Potential and risks of hydrogen-based e-fuels in climate change mitigation’, *Nature Climate Change* [Preprint]. Available at: <https://doi.org/10.1038/s41558-021-01032-7>.
- Valente, A. *et al.* (2021) ‘The role of hydrogen in heavy transport to operate within

- planetary boundaries’, *Sustainable Energy & Fuels*, 5(18), pp. 4637–4649. Available at: <https://doi.org/10.1039/D1SE00790D>.
- Vallejos-Romero, A. *et al.* (2023) ‘Green Hydrogen and Social Sciences: Issues, Problems, and Future Challenges’, *Sustainability (Switzerland)*, 15(1). Available at: <https://doi.org/10.3390/su15010303>.
- Verma, P., Sharma, B. and Mehta, P. (2024) ‘Green Hydrogen Production: Impacts on Environmental Sustainability Scale’, in *Green Hydrogen Economy for Environmental Sustainability. Volume 1: Fundamentals and Feedstocks, Part 2 - Green Hydrogen Production: Impacts on Environmental Sustainability Scale*. American Chemical Society, pp. 29–48. Available at: <https://doi.org/10.1021/bk-2024-1473.ch002>.
- WEF (2024) ‘Green Hydrogen: Enabling Measures Roadmap for Adoption in India’, *World Economic Forum*, (January), pp. 1–44.
- Whitehead, Jake *et al.* (2023) ‘Striking the right balance: understanding the strategic applications of hydrogen in transitioning to a net zero emissions economy’, *Sustainable Earth Reviews*, 6(1). Available at: <https://doi.org/10.1186/s42055-022-00049-w>.
- World Energy Council (2013) *World Energy Scenarios: Composing energy futures to 2050*, WEC.
- Wu, X., Tian, Z. and Guo, J. (2022) ‘A review of the theoretical research and practical progress of carbon neutrality’, *Sustainable Operations and Computers* [Preprint]. Available at: <https://doi.org/10.1016/j.susoc.2021.10.001>.
- Yan, Y. *et al.* (2020) ‘Techno-economic analysis of low-carbon hydrogen production by sorption enhanced steam methane reforming (SE-SMR) processes’, *Energy Conversion and Management*, 226(October), p. 113530. Available at:

<https://doi.org/10.1016/j.enconman.2020.113530>.

Yesodharan, V. *et al.* (2024) ‘Role of Green Hydrogen in Decarbonizing Heavy Industries in India’, in, pp. 99–116. Available at: <https://doi.org/10.1021/bk-2024-1474.ch005>.

Yu, M., Wang, K. and Vredenburg, H. (2021) ‘Insights into low-carbon hydrogen production methods: Green, blue and aqua hydrogen’, *International Journal of Hydrogen Energy*, 46(41), pp. 21261–21273. Available at: <https://doi.org/10.1016/j.ijhydene.2021.04.016>.

Zabeltitz, C. Von (1994) ‘Effective use of renewable energies for greenhouse heating’, *Renewable Energy*, 5(1–4), pp. 479–485. Available at: [https://doi.org/10.1016/0960-1481\(94\)90419-7](https://doi.org/10.1016/0960-1481(94)90419-7).

APPENDIX: DATASET

Survey Dataset

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1	What is your age	What is your gender	What is your highest education level	Which sector do you work in	What is your citizenship	How many years have you been in the country	Does your organization have a formal policy on diversity and inclusion	What is your role in the organization	Government position	Existing government position	The current regulatory environment	The regulatory environment	The government's role in the economy	Subsidies and incentives	Bureaucratic procedures	The existing political system	There is strong support for diversity and inclusion
2	5	1	7	4	1	5	1	7	5	4	3	4	3	4	3	3	4
3	4	1	5	4	2	5	1	7	5	4	3	3	2	3	3	3	3
4	5	1	4	7	1	5	2	9	3	3	3	2	3	2	2	2	2
5	5	1	4	4	1	5	2	7	2	2	2	2	2	2	2	4	3
6	5	1	5	4	1	5	2	9	3	3	3	3	3	3	3	4	3
7	5	1	5	5	5	5	2	7	5	4	4	4	4	4	4	2	4
8	5	1	5	4	5	5	2	7	4	4	4	4	4	4	4	2	5
9	5	1	5	4	5	5	2	9	4	4	3	3	2	3	4	4	3
10	5	1	7	4	5	5	1	7	3	3	4	2	2	3	2	2	3
11	5	1	5	4	5	5	2	7	5	4	4	4	5	3	5	3	3
12	5	1	5	1	1	5	2	9	3	3	3	3	3	3	3	3	3
13	4	1	5	1	1	5	2	7	5	4	3	3	3	3	3	3	3
14	3	1	5	4	2	4	2	9	3	3	3	3	3	3	3	3	3
15	2	2	5	1	3	1	1	1	3	2	2	3	2	2	4	4	3
16	3	1	5	1	2	4	2	9	4	3	3	3	3	3	3	3	3
17	5	1	3	1	2	5	1	7	4	4	4	4	3	3	4	3	3
18	4	1	4	2	5	2	2	7	5	5	5	5	5	4	3	1	4
19	4	1	7	4	4	5	2	7	3	3	3	3	3	2	3	3	2
20	2	1	6	4	5	3	2	7	4	3	5	2	1	3	1	1	3
21	2	2	4	4	2	2	1	7	3	4	4	3	3	3	4	3	4
22	2	2	4	1	3	2	1	5	5	5	5	5	5	5	5	5	5
23	2	2	6	1	2	2	2	1	5	2	2	1	2	2	5	5	2
24	2	1	5	4	2	3	2	9	3	4	1	2	2	2	4	4	4
25	2	2	4	1	2	3	2	7	2	2	2	2	2	2	2	2	3
26	2	2	4	5	2	2	2	9	4	5	5	5	5	5	5	5	5
27	2	1	5	1	5	2	1	7	5	5	3	3	4	4	4	2	3
28	2	2	5	4	5	1	2	9	4	4	3	3	4	3	2	4	2
29	2	2	5	4	5	1	2	9	4	4	3	3	4	3	2	4	2
30	4	1	3	4	2	5	1	7	5	5	4	4	4	3	5	5	5
31	4	1	3	4	2	5	1	7	5	5	4	4	4	3	5	5	5
32	4	1	3	4	2	5	2	1	4	2	2	3	2	2	2	4	4
33	5	1	7	3	5	5	2	1	5	4	4	3	4	3	2	3	3
34	2	2	6	2	1	3	2	2	7	2	3	3	4	3	2	3	2
35	2	1	6	2	1	3	2	2	5	4	3	3	4	3	2	3	2
36	4	1	5	6	1	5	1	2	4	4	3	4	3	3	4	4	5
37	5	1	6	3	1	5	2	6	5	4	4	2	2	3	3	5	3
38	5	1	4	3	1	5	2	6	5	4	4	2	2	3	3	5	3
39	3	1	7	5	3	5	2	3	3	3	3	3	3	3	3	3	3
40	3	1	5	2	3	5	2	2	2	3	3	3	3	3	3	3	3
41	3	2	5	2	2	4	1	4	3	5	4	4	4	3	5	3	4
42	4	1	5	2	1	5	1	4	4	2	4	4	3	3	3	4	4
43	4	1	5	2	1	5	1	4	4	2	4	4	3	3	3	4	4
44	3	1	5	2	2	4	1	4	4	3	3	3	3	3	4	3	3
45	3	1	4	2	2	4	1	5	4	3	3	3	3	3	2	4	2
46	3	1	7	2	1	5	2	6	5	3	3	3	3	3	3	3	3
47	3	1	6	2	1	5	2	6	5	3	3	3	3	3	3	3	3
48	4	1	6	2	1	5	1	2	3	3	3	2	1	2	2	2	2
49	3	2	5	2	4	1	2	9	3	3	3	3	3	3	3	3	3
50	2	2	5	6	2	3	1	2	4	4	4	2	2	1	1	6	4
51	2	1	5	2	2	2	1	4	3	2	3	2	2	1	1	4	3
52	2	1	5	2	2	2	4	1	2	3	3	2	2	1	2	3	2

	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH
1	Private sector companies in the country	There is sufficient investment in the country	Investors are willing to invest in the country	There is sufficient investment in the country	The organization has a formal policy on diversity and inclusion	Adequate training and development opportunities are available	There is a strong commitment to diversity and inclusion	There is a clear, measurable goal for diversity and inclusion	There is strong support for diversity and inclusion	Partnerships are established with government and academia	The current regulatory environment is supportive of diversity and inclusion	The existing government policies are supportive of diversity and inclusion	There are concrete plans for diversity and inclusion	Government action is taken to support diversity and inclusion	Private equity is invested in the country	Government action is taken to support diversity and inclusion	
2	4	1	1	2	1	5	1	3	1	2	2	1	1	1	1	1	5
3	3	1	1	3	3	1	1	3	2	3	1	1	1	2	3	2	5
4	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2
5	1	1	1	2	2	2	2	1	1	3	2	1	1	1	2	2	1
6	3	1	1	3	2	1	1	1	1	1	1	2	2	2	2	2	2
7	4	3	2	4	3	1	3	3	2	3	4	3	3	3	2	2	4
8	4	3	3	4	3	3	2	4	4	4	4	5	2	3	5	4	5
9	3	1	2	2	1	1	1	1	1	2	2	1	1	1	1	1	3
10	2	4	3	4	4	4	3	4	4	3	2	3	3	3	3	3	2
11	4	3	1	4	2	2	2	4	2	2	3	2	1	2	2	1	4
12	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2
13	3	1	1	4	3	1	1	5	2	4	5	1	1	1	3	3	5
14	3	2	3	3	2	2	3	3	3	3	3	3	3	3	3	2	4
15	2	2	3	2	3	4	2	3	2	2	4	2	2	4	3	3	3
16	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
17	2	3	3	3	2	3	3	5	5	3	3	3	3	3	3	3	4
18	5	3	3	3	4	3	4	3	3	3	4	3	2	3	5	2	4
19	3	1	3	3	2	1	1	2	2	2	2	2	3	2	2	2	3
20	4	1	1	1	1	1	1	2	1	1	1	1	1	1	3	3	3
21	3	2	2	4	2	2	2	4	2	2	4	2	2	2	2	3	4
22	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
23	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	3
24	2	3	3	4	4	4	2	3	2	3	4	3	3	3	3	3	4
25	2	1	1	3	3	1	2	4	3	3	3	1	2	1	2	3	3
26	2	3	3	3	3	3	1	3	4	3	3	4	2	3	3	3	5
27	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
28	3	2	3	3	2	2	3	3	3	3	4	2	3	3	3	4	4
29	4	4	4	4	4	4	4	4	4	4	4	5	3	3	4	4	4
30	4	4	4	4	4	4	4	4	4	4	4	5	3	3	4	4	4
31	3	4	3	4	2	2	2	4	2	2	4	2	2	3	3	4	5
32	3	3	2	2	2	1	2	3	3	3	3	2	1	2	2	2	3
33	3	3	3	2	3	2	3	3	3	3	3	3	2	3	4	3	3
34	3	3	3	2	3	2	3	3	3	3	3	3	2	3	4	3	3
35	3	1	1	3	1	1	1	3	3	3	2	1	1	3	2	3	5
36	3	4	3	3	3	2	2	4	3	3	3	3	3	3	4	3	5
37	3	3	2	2	2	2	2	2	2	2	3	2	3	3	3	3	5
38	3	3	3	3	3	2	2	3	3	3	3	3	3	3	3	3	5
39	3	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2
40	3	2	5	3	3	3	2	3	2	3	3	3	3	3	4	3	3
41	3	3	1	2	1	4	3	3	2	3	4	2	1	3	3	2	3
42	3	3	2	3	2	3	4	3	2	3	3	3	2	3	4	3	3
43	3	2	3	3	3	2	3	3	2	3	3	3	2	3	4	3	3
44	2	3	2	2	2	2	2	3	3	2	4	3	2	3	3	3	2
45	2	3	2	2	2	2	2	2	2	2	4	3	2	3	3	3	2
46	2	4	4	3	3	3	2	2	2	2	3	2	3	2	2	2	3
47	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
48	3	2	1	2	2	2	1	2	2	2	4	1	1	2	2	2	3
49	3	2	2	2	2	4	2	4	2	2	4	2	2	4	4	4	5
50	2	4	1	4	3	3	2	1	2	2	4	1	1	1	3	3	5
51	2	4	1	4	3	3	2	1	2	2	4	1	1	1	3	3	5
52	2	2	1	3	2	1	1	2	1	2	1	2	2	2	4	2	5

	AI	AJ	AK	AL	AM	AN	AO	AP	AQ	AR	AS	AT	AU	AV	AW	AX	AY
1	Investors perc	Market uncer	High initia cap	Land acquisi	The current st	There is an urg	Organization o	More investm	Transporting O	The developm	The demand fo	Policy and indu	Government / P	Public-private p	Organizations c	Existing safety	Well-defined en
2	5	5	5	5	5	1	5	1	5	5	1	3	5	5	3	4	2
3	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	1
4	1	1	3	3	2	5	2	5	5	3	2	2	5	3	1	2	1
5	1	1	1	3	1	5	3	5	5	2	3	3	5	3	3	1	1
6	2	2	2	2	5	5	5	5	5	1	2	3	5	5	1	1	1
7	3	3	4	3	2	5	3	5	1	1	2	5	5	3	3	4	1
8	5	5	5	5	1	5	3	5	5	2	3	5	5	5	5	2	3
9	5	4	4	4	1	4	1	4	5	1	3	2	4	3	4	1	1
10	2	2	3	2	3	2	2	2	3	4	2	2	3	4	3	3	3
11	3	4	4	3	3	5	2	5	4	2	1	3	5	2	5	4	2
12	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
13	5	4	5	5	1	5	1	5	5	1	4	5	5	5	3	4	3
14	4	4	4	4	3	4	3	4	3	3	3	3	5	5	3	3	3
15	5	4	5	4	3	4	3	4	4	2	4	4	5	4	3	2	2
16	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
17	4	4	4	4	4	5	3	5	4	3	2	3	5	4	3	3	3
18	1	5	5	3	1	5	4	4	2	2	4	4	5	4	4	3	4
19	2	2	2	2	2	1	4	1	3	3	2	3	3	3	1	1	1
20	4	5	5	5	5	3	1	5	5	2	1	1	5	4	1	1	1
21	3	3	4	4	2	4	2	4	4	3	4	4	4	4	3	3	2
22	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
23	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
24	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
25	2	3	4	3	1	4	2	4	3	1	4	2	3	3	4	2	1
26	4	5	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3
27	4	5	4	4	3	4	4	4	3	4	3	4	4	4	4	4	4
28	5	5	4	4	2	4	3	5	4	2	4	4	5	5	5	5	5
29	4	3	3	4	1	5	3	4	3	4	3	3	4	4	4	4	4
30	4	3	3	4	1	5	3	4	3	4	3	3	4	4	4	4	4
31	4	3	3	4	1	5	3	4	3	4	3	3	4	4	4	4	4
32	5	5	5	4	2	4	3	5	5	1	3	4	5	5	3	2	3
33	4	4	4	4	2	2	2	4	4	3	3	4	4	3	3	3	3
34	4	4	4	4	2	2	2	4	4	3	3	4	4	3	3	3	3
35	4	1	5	2	1	4	2	4	4	5	2	5	4	4	3	2	2
36	4	1	5	2	1	4	2	4	4	5	2	5	4	4	3	2	2
37	4	2	4	4	3	4	2	4	4	3	3	2	4	3	3	3	3
38	3	2	4	4	3	4	2	4	4	3	3	2	4	3	3	3	3
39	3	2	4	4	3	4	2	4	4	3	3	2	4	3	3	3	3
40	2	2	4	4	2	4	2	4	4	3	3	2	4	3	3	3	3
41	2	2	4	4	2	4	2	4	4	3	3	2	4	3	3	3	3
42	5	1	3	4	1	3	3	4	5	2	3	4	5	3	4	4	3
43	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
44	5	3	5	5	1	5	3	5	5	2	3	4	5	4	3	3	2
45	2	3	5	5	2	1	2	2	5	2	2	2	2	2	2	2	2
46	3	3	3	3	3	1	3	3	3	3	3	3	3	3	3	3	3
47	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
48	1	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
49	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
50	2	4	4	5	2	4	2	4	4	3	4	5	5	4	4	5	4
51	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
52	4	2	3	4	2	2	2	2	5	3	3	2	3	3	3	3	2

	AZ	BA	BB	BC	BD	BE	BF
1	Green Hydroge	Investments in	Infrastructure is	Green Hydroge	There is a need	Green Hydroge	More stringent c
2		3		2	1	5	5
3		1	1	1	1	5	5
4		2	2	1	5	2	5
5		1	2	1	2	5	5
6		1	1	1	1	1	1
7		1	3	1	1	5	5
8		5	5	5	5	3	5
9		3	2	1	2	4	5
10		2	2	2	4	2	4
11		4	3	3	3	5	5
12		3	3	3	3	3	3
13		5	5	3	4	5	4
14		3	3	3	5	5	5
15		4	4	2	3	4	4
16		3	3	3	3	3	3
17		4	5	3	4	5	5
18		3	3	3	3	4	5
19		1	1	1	3	3	5
20		1	1	1	1	5	4
21		2	3	2	2	4	4
22		5	5	5	5	5	5
23		2	2	2	3	5	5
24		3	3	3	3	4	3
25		2	1	1	1	4	4
26		3	3	3	3	3	3
27		4	4	4	3	5	5
28		3	4	3	4	5	5
29		4	4	4	3	3	4
30		3	3	3	4	4	3
31		3	4	4	4	5	4
32		1	1	1	4	5	5
33		3	3	3	4	4	4
34		3	4	4	4	4	4
35		2	2	2	3	5	5
36		2	3	2	5	5	4
37		3	4	3	3	3	4
38		3	4	3	5	3	5
39		1	2	2	5	3	5
40		3	4	4	4	4	3
41		2	3	2	4	2	4
42		4	4	4	5	5	4
43		2	3	2	3	4	2
44		2	2	2	5	3	5
45		3	3	3	3	3	3
46		2	2	2	5	2	5
47		3	3	3	3	3	3
48		1	1	1	1	2	1
49		3	3	3	2	5	3
50		2	3	3	4	4	5
51		5	5	5	5	5	5
52		5	3	2	4	5	5

Interview 1

	A	B	C	D	E	F	G	H	I
1	Questions	Respondent 1	Respondent 2						
2	Name	PAPAN/USH D.	Siddhey Shinde						
3	Designation	JR. CONSULTANT	Assistant Manager						
4	Industry Sector	GOVT. DEPT.	GreenTech						
5	Years of Expertise	4	6						
6	Country/Region	INDIA	India						
7	How effective do you think the Green Hydrogen Mission is as a step in the right direction, but driving adoption is a long term activity and its effectiveness remains to be seen.	10-May	Moderately effective.	The Green Hydrogen Mission is a step in the right direction, but driving adoption is a long term activity and its effectiveness remains to be seen.					
8	What are the key challenges in the Green Hydrogen ecosystem? There need to be fiscal incentives and tax incentives for projects promoting Green Hydrogen adoption.	SUPPLY - DEMAND	Financing for climate change. There need to be fiscal incentives and tax incentives for projects promoting Green Hydrogen adoption.						
9	What steps has the Government taken to promote Green Hydrogen adoption?	SCHEMES	It has started manufacturing equipment to protect and to use Green Hydrogen.						
10	How do you see the Green Hydrogen ecosystem in the next 5-10 years? Domestic industry collaboration is somewhat low, but international collaborations are high. Improvements can be realised with an increase in climate conscious projects and corporate environmental responsibility measures.	GOOOD STAKE	Domestic industry collaboration is somewhat low, but international collaborations are high. Improvements can be realised with an increase in climate conscious projects and corporate environmental responsibility measures.						
11	What are the main barriers to Green Hydrogen adoption? It is difficult to say where the main 'gaps' are since the entire ecosystem is still nascent. That is to say that each portion of the Green Hydrogen value chain is only coming up now, and therefore will need time to mature before 'gaps' can be assessed.	RAW MATERIAL	It is difficult to say where the main 'gaps' are since the entire ecosystem is still nascent. That is to say that each portion of the Green Hydrogen value chain is only coming up now, and therefore will need time to mature before 'gaps' can be assessed.						
12	How do financial incentives or tax breaks help in the adoption of Green Hydrogen? They are excited by the potential of Green Hydrogen but they find the higher operating cost to be a deterrent to long term adoption.	LACK OF CRIE	They are excited by the potential of Green Hydrogen but they find the higher operating cost to be a deterrent to long term adoption.						
13	What strategies does the Government have to bring down the manufacturing cost of equipment to produce and use Green Hydrogen, it is working hard to lower the entry barrier to the Green Hydrogen ecosystem and effectively benefitting the entire ecosystem.	DEMAND AGG	By bringing down the manufacturing cost of equipment to produce and use Green Hydrogen, it is working hard to lower the entry barrier to the Green Hydrogen ecosystem and effectively benefitting the entire ecosystem.						
14	How do you see the role of the Government in the Green Hydrogen ecosystem? The Government must play the role of an enabler for large projects and create soft power influence to drive increase in adoption of Green Hydrogen. The Private sector on the other hand must be flag-bearers of this transition and increase adoption by pushing the adoption.	FACILITATOR	The Government must play the role of an enabler for large projects and create soft power influence to drive increase in adoption of Green Hydrogen. The Private sector on the other hand must be flag-bearers of this transition and increase adoption by pushing the adoption.						
15	What safety protocols does the Government / Public Sector Undertakings follow to prevent Green Hydrogen leaks and explosions? Are there any areas that need improvement?	ALL INTERNA	The organization adheres to the highest levels of safety standards, pledging to make safety its topmost priority in all stages of the Green Hydrogen value chain.						

Interview 2

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB
1	Name	Designation	Industry	Years of Experience	Country/Region	How effective do you think the Green Hydrogen Mission is as a step in the right direction, but driving adoption is a long term activity and its effectiveness remains to be seen.	What are the key challenges in the Green Hydrogen ecosystem? There need to be fiscal incentives and tax incentives for projects promoting Green Hydrogen adoption.	What steps has the Government taken to promote Green Hydrogen adoption?	How do you see the Green Hydrogen ecosystem in the next 5-10 years? Domestic industry collaboration is somewhat low, but international collaborations are high. Improvements can be realised with an increase in climate conscious projects and corporate environmental responsibility measures.	What are the main barriers to Green Hydrogen adoption? It is difficult to say where the main 'gaps' are since the entire ecosystem is still nascent. That is to say that each portion of the Green Hydrogen value chain is only coming up now, and therefore will need time to mature before 'gaps' can be assessed.	How do financial incentives or tax breaks help in the adoption of Green Hydrogen? They are excited by the potential of Green Hydrogen but they find the higher operating cost to be a deterrent to long term adoption.	What strategies does the Government have to bring down the manufacturing cost of equipment to produce and use Green Hydrogen, it is working hard to lower the entry barrier to the Green Hydrogen ecosystem and effectively benefitting the entire ecosystem.	How do you see the role of the Government in the Green Hydrogen ecosystem? The Government must play the role of an enabler for large projects and create soft power influence to drive increase in adoption of Green Hydrogen. The Private sector on the other hand must be flag-bearers of this transition and increase adoption by pushing the adoption.	What safety protocols does the Government / Public Sector Undertakings follow to prevent Green Hydrogen leaks and explosions? Are there any areas that need improvement?														
2	Shalish Ch	Chairman Consulting		50	India	Just begin	Safety, By Defined	Nascent	Land and capacity: Global installed capacity reached just 1.484 GW by the end of 2023, with a forecast of "5.84 GW by end of 2024" far behind the "5204 GW announced for 2030, of which only 484 GW is expected to be operational by 2023." Infrastructure: NGHM targets 584 T per annum production by 2030, backed by 8,19,744 sq. crore investment of 2.484 billion) funding through Phase 4 (2023-26) to build electrolyser and storage facilities, and The public	India has built a solid foundation using existing safety laws and PESO oversight with rigorous equipment approvals and emergency protocols. To match																		
3	Rushikesh	Associate	Renewable	12	India	Yes	Key regul	The gover	Public-pr	has	Investors	and																

Company Data

	A	B	C	D	E
1	JSW Energy				
2	Indicator	2024	2023	2022	2021
3	Annual investment in green hydrogen projects	Estimated ₹200 Cr	Estimated ₹150 Cr	Initial feasibility & infra	Not applicable
4	Share of total energy from renewables (%)	~65%	~61%	~55%	~30%
5	Capital Expenditure (₹ Cr)	₹6,130 Cr	₹4,835 Cr	₹3,270 Cr	₹2,140 Cr
6	Debt-to-Equity Ratio	0.5	0.51	0.59	0.65
7	Return on Equity (ROE)	10.40%	10.80%	10.20%	9.60%
8	Operating Profit Margin	38.70%	39.50%	37.40%	36.10%
9	Earnings Per Share (EPS)	₹12.9	₹12.2	₹11.1	₹10.0
10	Return on Capital Employed (ROCE)	12.10%	11.50%	10.90%	10.30%
11	Return on Assets (ROA)	5.10%	4.80%	4.20%	3.90%
12	Total Assets (₹ Cr)	₹42,320 Cr	₹39,770 Cr	₹35,650 Cr	₹31,980 Cr
13	Reliance New Energy				
14	Indicator	2024	2023	2022	2021
15	Annual investment in green hydrogen projects	Part of ₹1,31,769 Cr capex (not separately given)	Giga Complex investment underway	\$10 Bn announced (₹75,000 Cr over 3 yrs)	Initial planning phase
16	Share of total energy from renewables (%)	~1.35% (6.85M GJ out of 506.18M GJ)	~0.83% (4.1M GJ out of 496M GJ)	~0.67% (3.3M GJ out of 492M GJ)	Minimal (not explicitly stated)
17	Capital Expenditure	₹1,31,769 Cr	₹1,16,961 Cr	₹99,472 Cr	₹76,400 Cr
18	Debt-to-Equity Ratio	0.44	0.44	0.34	0.36
19	Return on Equity (ROE)	8.8% approx. (based on Net Profit / Net	~11.0%	~10.5%	12.50%
20	Operating Profit Margin	15.6% (EBITDA: ₹1,53,920 Cr / Revenue: ₹9,86,000 Cr	15.8% (₹1,53,920 Cr / ₹9,74,864 Cr)	~15.9% (₹1,25,687 Cr / ₹7,92,756 Cr)	11.90%
21	EPS	₹103.9	₹98.0	₹92.0	₹76.4 (page 7)
22	ROCE	~9.4%	~11.0% (approximate)	~10.2% (approximate)	~9.5%
23	ROA	~4.6%	~4.7% (approx.)	~4.6% (approx.)	~3.4%
24	Total Asset	₹16,00,000 Cr approx. (₹16 Lakh Cr)	₹15,77,093 Cr	₹14,48,323 Cr	₹13,15,998 Cr

27	Adani Energy				
28	Indicator	2024	2023	2022	2021
29	Annual investment in green hydrogen projects	₹100 billion (group-level pledge)	₹100 billion (pledged)	Not specifically mentioned	Not specifically mentioned
30	Share of total energy from renewables (%)	100% (renewable co.)	1	1	1
31	Capital Expenditure	₹20,124 Cr (Capex)	₹15,769 Cr approx	₹10,987 Cr approx	₹8,735 Cr approx
32	Debt-to-Equity Ratio	4.0x (Net Debt/EBITDA)	5.4x	~5.6x (approx from report)	~6.0x
33	Return on Equity (ROE)	0.174	0.131	0.125	0.109
34	Operating Profit Margin	92% (EBITDA margin)	0.9	0.89	0.85
35	EPS	₹11.4 approx	₹9.1 approx	₹7.3 approx	₹5.8 approx
36	ROCE	0.129	0.103	0.094	0.076
37	ROA	0.052	0.043	0.037	0.031
38	Total Asset	₹1,42,193 Cr	₹1,09,312 Cr	₹91,202 Cr	₹72,450 Cr
39					
40	Greenko				
41	Indicator	2024	2023	2022	2021
42	Annual investment in green hydrogen projects	\$20 B planned (3–5 yrs)	Part of long-term energy transition	\$8.1 B cumulative till date	Not explicitly mentioned
43	Share of total energy from renewables (%)	100% (entire portfolio)	1	1	1
44	Capital Expenditure	\$694.54 Mn (₹5,778 Cr)	\$687.18 Mn (₹5,528 Cr)	\$622.34 Mn (₹5,000 Cr approx)	₹4,286 Cr approx
45	Debt-to-Equity Ratio	3.9x (Net Debt/Equity)	4.1x approx	4.2x approx	4.5x approx
46	Return on Equity (ROE)	0.102	0.093	0.081	0.078
47	Operating Profit Margin	84.6% (EBITDA Margin)	0.837	0.829	0.812
48	EPS	₹7.3 approx	₹6.8 approx	₹6.3 approx	₹5.5 approx
49	ROCE	0.089	0.081	0.076	0.068
50	ROA	0.039	0.036	0.032	0.029
51	Total Asset	₹94,752 Cr	₹84,231 Cr	₹76,540 Cr	₹68,120 Cr
53	Hero Future Energies				
54	Indicator	2024	2023	2022	2021
55	Annual investment in green hydrogen projects	Pilot project in progress (Hydrogen)	MoUs and pilot strategy initiated	R&D phase only	Not reported
56	Share of total energy from renewables (%)	~100% (entire portfolio is renewable)	~100%	~100%	~100%
57	Capital Expenditure	₹298.99 Mn	₹62.16 Mn	450 Mn	176 Mn
58	Debt-to-Equity Ratio	2.33	3.61	3.45 (est.)	0.8
59	Return on Equity (ROE)	5%	-30%	-116.18%	
60	Operating Profit Margin	22.50%	21%		-40.80%
61	EPS	₹0.43	₹0.06		
62	ROCE	2%	4%	-37.13%	3.34%
63	ROA				
64	Total Asset	₹1,08,874 Mn	₹1,24,426 Mn	₹1,36,080 Mn	₹1,12,500 Mn