Sustainable Energy Technology

Macroeconomic Analysis of Green Hydrogen Industry in India – An Input-output Model Study

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Macroeconomic Analysis of Green Hydrogen Industry in India – An Input-output Model Study

by

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Preface

This thesis is written as a graduation project for the Master in Sustainable Energy Technology. First I would like to thank Ruchi Gupta from whom this thesis has been inspired from. Second, I would like to express my gratitude to Enno Schroder for being my supervisor and guiding me throughout the thesis. He was always patient to listen to me and willing to help me out whenever I got stuck at a point. His valuable input and suggestions have uplifted the quality of this thesis. Third, I would like to thank Linda Kamp for joining my thesis committee and tracking my progress timely. Lastly, I would like to thank my friends and family who stood as my moral support since day one of my university.

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Abstract

Hydrogen is key to decarbonising hard-to-abate industries where electrification has a limited role to play. With a cleaner carbon footprint and versatility with existing industrial processes, hydrogen can be used as a fuel in these energy-intensive industries. As the hydrogen industry is still in its initial phases many researchers have estimated its economic impacts. Most of the current research is focused on the employment market. This study evaluates the economic impact of the emerging green hydrogen industry in India both in terms of employment creation and contribution to GDP growth. The study also quantifies the savings in imports caused by switching from fossil fuel to green hydrogen in different industries. The main objective of this study is to verify the projections of the National Green Hydrogen Mission(NGHM) of India which aims to produce 5 million metric tons (MMT) of hydrogen per annum by 2030. Leontief's input-output model is used to evaluate the economic impacts.

The study revealed that there would be an employment creation of 410570 FTE jobs and 4838 M USD contribution to GDP for every gigawatt(GW) scale hydrogen plant installed. Additionally, there would also be import savings of around 1 B USD per annum for a GW-scale plant. It is found that the amount of imports of machinery and equipment significantly affects the impact indicators. If half of the machinery and equipment is imported the contribution to GDP is reduced by 50% whereas the employment creation and GHG emissions are reduced by 30% when compared to the all the machinery is domestically manufactured scenario. The projections of India's NGHM are evaluated and found comparable with those of the government projections. Overall, the establishment of the green hydrogen industry in India is found to have a positive impact on the economy by significantly boosting the national GDP and employment creation.

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1 Introduction

The phenomenon of climate change, mostly caused by human activity, presents an existential threat to life as we know it, with effects expected to be felt by every individual in every nation on every continent. Rising sea levels, catastrophic weather patterns, and unstable ecosystems are just a few of the disastrous effects of climate change that are being brought on by the sharp increase in greenhouse gas emissions. If climate change is not addressed, it will not only reverse much of the recent gains in development but also lead to large-scale migrations, which will increase conflicts and instability. Global warming must be kept to 1.5°C over pre-industrial levels to prevent these disastrous consequences, which requires that emissions must be reduced by almost half by 2030—just six years from now. Unfortunately, we are far from reaching this crucial goal at this time, and immediate action is required to stop the impending climate disaster (United Nations, 2023).

1.1 Role of Hydrogen in Sustainable Future

Electrification has attracted considerable attention as a key strategy for mitigating climate change. Many believe that the adoption of electric vehicles, renewable energy sources, and electrified industrial processes are essential measures in the reduction of carbon emissions. Although electrification has shown promise in some areas, its application faces significant limits in hard-to-abate industries. These industries, such as heavy manufacturing and aviation, often require high-temperature heat sources or involve energy-intensive processes. The main challenge here is to find an alternative which reduces emissions without compromising productivity and competitiveness. This is where hydrogen comes into play, as it offers versatility and compatibility with existing industrial processes (Franco & Giovannini, 2023).

Furthermore, the intermittent nature of renewable energy sources like solar and wind presents a serious threat to grid stability. As we move toward a sustainable energy future, hydrogen's ability to store energy can play a crucial role in maintaining grid stability. Hydrogen can be produced from surplus power produced during times of strong renewable output. When renewable energy output is scarce, this hydrogen could be stored and then transformed back into electricity, assisting in maintaining a balance between supply and demand on the grid (Bennoua, Le Duigou, Quéméré, & Dautremont, 2015).

1.2 Ambitions of Different Countries for Hydrogen

Countries around the globe are investing heavily in hydrogen, seeing it as the future fuel. More than 30 countries have developed or started to prepare national hydrogen strategies. The adoption of hydrogen is being vigorously pursued by South Korea and Japan, with particular attention paid to fuel-cell vehicle deployment and decentralized small-scale power generation. Production and export of hydrogen is a top priority for Australia, a leading energy exporter, in addition to its domestic application in heavy-duty transportation. While the Netherlands investigates the development of hydrogen infrastructure, countries in Europe such as Germany and France want to decarbonize their industries by using clean hydrogen. While exploring local alternatives for hydrogen generation, Norway is cautious of the expenses associated with infrastructure. Portugal and Spain prioritize using renewable hydrogen domestically and exporting it. Chile wants to replace imported ammonia with environmentally friendly products made locally. Canada wants to transition away from exporting hydrocarbons and instead employ advanced hydrogen technologies for transportation and heating (World Energy Council, 2021).

1.3 Research Question

In India, the focus is majorly on the adaptation of hydrogen into heavy transport, shipping and steel production. As agriculture is majorly practised in the country, there is also a special focus on producing hydrogen from biomass. "National Green Hydrogen Mission" is one of the major initiatives in India, intending to produce 5 million metric tons(MMT) of green hydrogen per year by 2030. As per the Ministry of New and Renewable Energy (MNRE), the initial outlay for the mission will be Rs 19,744 crore (approx. 2 billion euros) (Ministry of New and Renewable Energy, 2023).

Currently, India is seeing the brightest economic future being one of the fastest-growing economies in the world with a growth rate of 7.2 % in FY 22-23 (The World Bank, 2023). It aims to become a USD 5 trillion economy by 2025. From this viewpoint, studying the economic impacts of the emerging green hydrogen industry is essential. Henceforth, the main research question of this study is

What are the economic impacts of the emerging green hydrogen industry in India?

The research question can be further divided into the following sub-questions

1. What would be the contribution of the green hydrogen industry to GDP growth and employment generation in India?
2. What would be the reduction in emissions and savings in imports by switching to green hydrogen in India?
3. What would be the most affected industries by the emerging green hydrogen industry in India?

The format of the report is as follows. At first, the significance of India's developing green hydrogen sector is explained in Chapter 2. In Chapter 3 different methodologies to study the implications of renewable energy investments are discussed. The methodology used in this study and the fundamental concepts of it are introduced in Chapter 4. The details of the data used in this study are discussed in Chapter 5. The results of this study are elaborated in chapter 6. In Chapter 7, the results are analysed and finally, the findings of this study are concluded in Chapter 8.

2 Background

This chapter aims to provide background knowledge of hydrogen and its alternatives. First, the history of hydrogen use is discussed followed by current production methods and challenges for widespread market diffusion. Second, the potential of hydrogen to decarbonise the hard-to-abate industries is described followed by a discussion on the transition to net zero emissions. Third, the landscape of the hydrogen industry in India is presented. Thus, the foundation for understanding the significance of India's developing green hydrogen sector is laid.

2.1 Hydrogen's Ups and Downs: A Journey through Time

The use of hydrogen as an energy source dates back to the early 1800s when it was used to light homes in the form of gaslighting. It is used in gas furnaces to provide heat for homes in the early 1900s. Due to the rise of fossil fuels in the mid-20th century, these applications were replaced by electricity derived from coal and natural gas respectively. Later, it is used in the space race as a rocket propellant limiting its application to the aerospace industry. In the earlier days, hydrogen production was often tied to fossil fuels, making it less economically competitive compared to conventional fuels(ATCO LTD., 2023).

Like a rollercoaster ride with multiple phases, interest in hydrogen has seen highs and lows. People were enthusiastic about hydrogen in the 1970s because it looked like a fantastic way to solve issues like pollution from burning fossil fuels and a lack of electricity. But as time went on, difficulties began to arise. The process of producing hydrogen was costly, and the infrastructure required to use it—such as fuel-efficient vehicles and storage facilities—was complex. Also, during that time oil prices dropped and the crises of the 1970s and 1980s seemed to be over. So the people did not feel the need for hydrogen then. Thus, by the 1980s and 1990s, interest in hydrogen had somewhat declined (Resilience, 2021).

One important event which backslashed the interest in hydrogen in the early days was "The Hindenburg disaster". Hydrogen being less dense and lighter than air has a great ability to lift things like balloons. Realising this, large airships using hydrogen as their lifting gas became a popular mode of air transportation by the early 1900s. On round-trip voyages between Germany and the US in 1936, the Hindenburg airship carried 1,002 passengers. Of the 97 passengers on board, 35 were killed when the Hindenburg exploded on May 6, 1937, while landing in Lakehurst, New Jersey. This explosion brought attention to the possible risks associated with utilizing hydrogen for transportation, especially in aircraft. In addition to causing a large number of fatalities, this disastrous event also damaged public confidence in hydrogen's safety and potential as an energy source(Lets talk Science, 2019).

But the interest bounced back again in the 2000s. This time, it was due to new ways of producing hydrogen from renewable energy sources like the sun and wind. Concerns about climate change and the desire for cleaner fuels were also prevalent. But once more, there were difficulties. Still, producing hydrogen wasn't inexpensive enough, and not everyone agreed it was the best course of action. Thus, interest fell again (Resilience, 2021).

However, interest is already increasing once more. People's perspectives about hydrogen are changing as a result of increased technological advancement and the pressing need to combat climate change. The production of hydrogen and its application in vehicles and power plants is receiving increased government and corporate investment. Therefore, although interest in hydrogen has fluctuated throughout time, it appears that we may be amid another surge.

2.2 Potential of Hydrogen

Hydrogen plays a key role in decarbonising hard-to-abate industries. A few of the potential applications of hydrogen are discussed in the following subsection. Figure 1 illustrates the range of hydrogen applications from uncompetitive meaning economically not viable to unavoidable meaning where hydrogen usage is inevitable.

2.2.1 Steel manufacturing

As a clean and versatile energy source, hydrogen is crucial in combating climate change. The steel industry contributes to around 7% of global greenhouse gas (GHG) emissions (Ritchie, 2020) because of its heavy use of coke and coal for the reduction of iron ore. An average of 1.85 tons of CO_2 are released into the environment while producing 1 ton of steel. Hydrogen can be used as a direct reducing agent here producing only water vapour as a bi-product and thus decarbonising the steel-making. A ton of steel would cost around one-third more at present prices if hydrogen were to replace coal. It is expected that this disparity will reduce in the upcoming years and may vanish by 2030. On the one hand, the price of carbon and carbon emissions may increase the cost of using coal. On the other hand, falling prices for renewable electricity, increased efficiency from producing hydrogen on a larger scale, and optimised processes for producing hydrogen-based steel will reduce the cost of this alternative (European Parliament, 2020).

2.2.2 Process Industry

Hydrogen is an ingredient of many different chemical products in the chemical industry. This industry has historically been linked to significant carbon emissions because it relied on fossil fuels for both energy and feedstock (Nigel Rambhujun & Aguey-Zinsou, 2020). From figure 11 in section A, we can see that ammonia and methanol contribute around 60% and 30% of global hydrogen demand in the process industry. Currently, natural gas is the main source of hydrogen in both of these industries. Almost 2 tonnes of CO_2 is emitted for every ton of ammonia produced (Iberdrola, 2023), which is also the same in the case of methanol (Methanol Institute, 2023). These emissions can be mitigated by replacing natural gas with hydrogen.

Based on a gas price range of USD 1–15/GJ, the estimated cost of producing green ammonia is three to four times greater than that of producing grey ammonia (Saygin et al., 2023). Similarly, the levelized cost of methanol(LCoM) using green hydrogen is estimated at 960 €/t which is over two times as much as the current price for methanol on the global market (450 €/t) (Sollai, Porcu, Tola, Ferrara, & Pettinau, 2023). However, the competitiveness of green ammonia and methanol production is expected to improve in the future by cost reductions in electrolyser and renewable electricity.

Hydrogen can also be burned to produce heat to achieve high temperatures in industrial processes such as cement kilns, chemical reactors, blast furnaces, and glass making. On an industrial scale, it can be used to generate mid-grade (100°C – 400°C) and high-grade heat (400°C+). Still, very little hydrogen is being used for this purpose at the moment. This is because it is a costly alternative to fossil fuels, even when CO_2 prices hit USD 100/tCO_2 (IEA, 2019a)

2.2.3 Transport

The transport sector which contributes to around 16% of global GHG emissions (Ritchie, 2020) can be decarbonised with the help of hydrogen and its derivative fuels. Fuel cell electric vehicles(FCEV) are preferred for long-haul trucks, buses and locomotives because of their longer driving ranges, faster refuelling times and ability to carry heavy payloads, which battery-electric vehicles(BEV) cant offer because of the low energy density and heavy weight of battery packs. The refuelling time for an FCEV long-haul vehicle is about 10 to 20 minutes, whereas BEVs take hours to charge. This distinction has implications for lowering downtime in a fleet's regular operations(Center on Global Energy Policy, 2021).

Hydrogen can also offer a variety of maritime fuel choices such as methanol and ammonia, which are both derived from hydrogen, as well as liquid or gaseous compressed hydrogen. Ammonia seems the most appropriate for the shift to a sustainable shipping industry. Though ammonia and methanol both have a high volumetric energy density, the ability to blend with existing fuels, and ease of storage as a liquid, ammonia is preferred because it contains no carbon and releases no carbon dioxide in use (Center on Global Energy Policy, 2021).

In aviation, it is anticipated that CO_2 and hydrogen might be mixed to produce synthetic low-carbon aviation fuels with high volume, gravimetric energy density. Adapting hydrogen-based liquid fuels would be easy as it requires no changes in design or refuelling infrastructure at airports(IEA, 2019a).

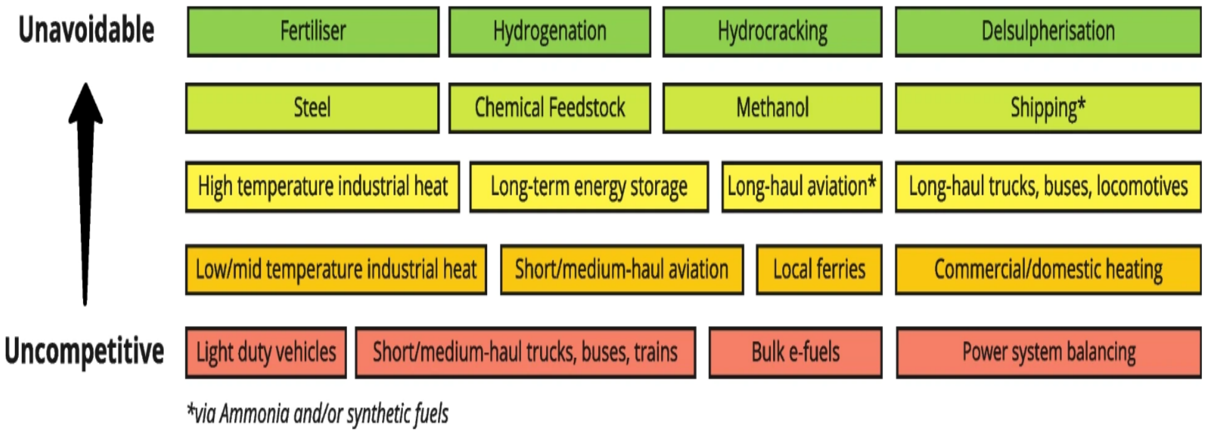


Figure 1: Spectrum of potential hydrogen applications spanning from unavoidable to uncompetitive

(Jake Whitehead & Lim, 2023)

2.3 Hydrogen Industry in India

Aiming at achieving energy independence by 2047 and net-zero emissions by 2070, India is moving rapidly towards clean energy. Green hydrogen is expected to play a crucial role in accomplishing these goals. Given its excellent potential for renewable electricity, markets for the consumption of hydrogen and its derivative products, and the availability of suitable sites that can be developed into green hydrogen hubs, India is well-positioned to emerge as a hub for the production of green hydrogen.

Compared to other parts of the world, India has the low cost of renewable electricity at USD 0.027/kWh for solar, USD 0.03/kWh for wind power and USD 0.044/ kWh for round-the-clock power with an annual capacity utilisation factor(CUF) of 80%. Furthermore, renewable energy potential is abundant with an estimated solar energy potential of about 750 GW and wind energy potential of 695 GW at hub height over 120 meters. The country already has installed generation capacities of 62 GW of solar and 42 GW of wind energy respectively (SAREP, 2023). Renewable electricity is a major cost component in the production of green hydrogen as discussed in section B.0.1, having cost-competitive renewable electricity would help scale up green hydrogen production in India.

Furthermore, India also has access to large geological storage capacity for bulk storage applications in the form of sedimentary basins, deep saline aquifers, and potential salt structures. According to recent research, significant sedimentary basins including the Krishna-Godavari, Rajasthan, Cauvery, and Cambay basins have capacities of over 7,100 TWh, however deep saline aquifers alone have an estimated potential of almost 22,600 TWh. Just the combined capacity of these two storage solutions makes up around 35% of all onshore and offshore storage capacity in Europe (Vishal, Verma, Sulekh, Singh, & Dutta, 2022).

The current demand for hydrogen primarily comes from the chemical and petrochemical industries in India. Potential demand would increase with increased usage of hydrogen in transportation, industry, and power. The demand for hydrogen is expected to rise from 6 Mt to 28 Mt by 2050, according to the Energy and Research Institute (TERI) of India, and the price of hydrogen produced from renewable sources would decrease by 50% by 2030. According to TERI, by 2050, roughly 80% of India's hydrogen would come from renewable sources(Sontakke & Jaju, 2021).

2.3.1 Key Drivers for Hydrogen

India has four main drivers guiding its hydrogen ambitions

- **Energy independence and security**
  India's dependency on imported fossil fuels has grown during the 2000s; imports now account for more than 25%, 75%, and 50% of the country's need for gas, oil, and coal, respectively(Delaval, Trevor Rapson, Will Hugh-Jones, & Max Temminghoff, 2022). India's import reliance would be lessened and export prospects would arise from the establishment of indigenous hydrogen manufacturing capability. Domestically produced green hydrogen can result in net energy import savings of 3–5 billion USD between 2020 and 2030 alone, or 246–358 billion USD cumulatively between 2020 and 2050. This is due to a decrease in the imports of natural gas as green hydrogen replaces grey hydrogen and oil as long-haul freight switches to vehicles equipped with hydrogen fuel cells(NITI Aayog & RMI, 2022).

- **Emission reductions and energy targets**
  India committed in 2021 to achieve the "five elixirs," or major reductions in carbon and energy-related benchmarks. India wants to reach net-zero emissions by 2070, reduce its total projected carbon dioxide equivalent (CO2-e) emissions by 1 billion tonnes, reduce the carbon intensity of its economy by less than 45%, raise its capacity to produce 500GW of non-fossil fuel energy by 2030 and meet 50% of its energy needs from renewable sources(Delaval et al., 2022). Figure 2 illustrates the possible reductions in emissions by using hydrogen in different applications. India may reduce its CO_2 emissions by 3.6 giga tons overall between 2020 and 2050 as compared to a scenario with limited deployment of hydrogen(NITI Aayog & RMI, 2022).

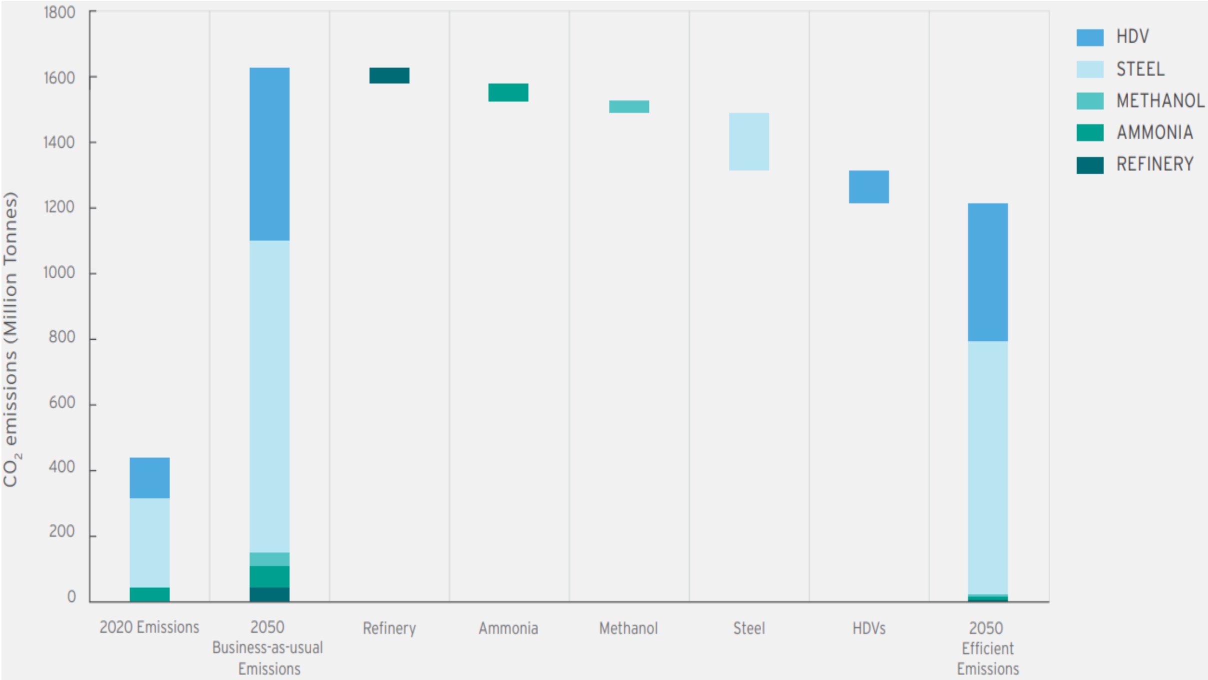


Figure 2: CO_2 emissions reductions due to green hydrogen uptake in end-use sectors (NITI Aayog & RMI, 2022)

- **Technology leadership**
  To become a worldwide hub for the production and export of renewable hydrogen, India aims to accelerate the innovation and R&D of renewable hydrogen technologies. This includes spearheading the development of associated technologies(Delaval et al., 2022).

- **Economic development**
  The development of hydrogen hubs, potential export markets for hydrogen, and R&D into renewable energy technologies are all viewed as key factors contributing to India's economic expansion. India's economic plan places a strong emphasis on the development of renewable energy technologies, particularly hydrogen technology. For India, this transition can be synergistic with the scale, ambition, and economic competitiveness of its renewable industry(Delaval et al., 2022).

2.3.2 Policies

Currently, there is relatively little value recognition for "green" hydrogen since the demand for hydrogen is mostly independent of its precise origin. Because of this, there is currently no market for "green" hydrogen and no assessment of the potential reduction in CO_2 emissions.This further restricts the product's demand and significantly hinders many of its potential downstream uses. Also, price parity is yet to be achieved to compete with conventional technologies available in the market. Figure 3 illustrates the required cost reduction to compete with conventional alternatives in the Indian market. Given these conditions and the fact that the generation of green hydrogen is still in its initial phase, government support policies are needed to create a growing supply chain, mitigate investor risks, facilitate innovation, and deploy necessary infrastructures.

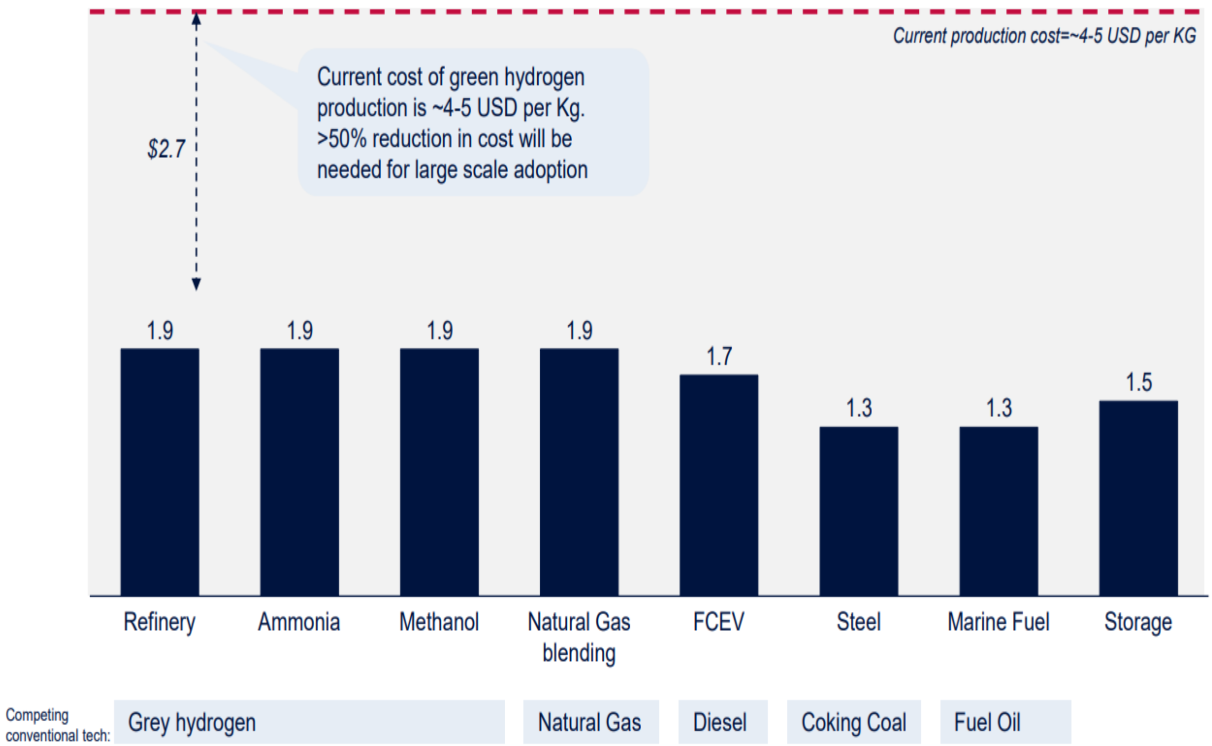


Figure 3: Required cost of hydrogen production for breakeven against conventional technologies in India (USD/kg)

(MEC Intelligence, 2022)

India still needs to establish legislative or regulatory frameworks tailored to the hydrogen industry to assist the expansion of a hydrogen economy. The commercialization, deployment, and adoption of hydrogen technologies are being aided by government-implemented hydrogen policies, RD&D programs, and schemes, in the lack of a specific regulatory framework. These policies include

- **National Green Hydrogen Mission(NGHM)**
  The NGHM aims to build capabilities to produce at least 5 Million Metric Tonne (MMT) of Green Hydrogen per annum by 2030, with the potential to reach 10 MMT per annum with the growth of export markets. The projected outcomes of NGHM are shown in figure 4.

Figure 4: National Green Hydrogen Mission Outcomes
(Ministry of New and Renewable Energy, 2023)

The NGHM will be implemented in two phases and include the following sub-components:

- **Strategic Interventions for Green Hydrogen Transition(SIGHT)**
  Two separate financial incentive mechanisms are proposed aiming at domestic manufacturing of electrolysers and production of Green Hydrogen with an outlay of 17,490 crore (approx. 2 billion euros) up to 2029-30
- **Pilot Projects**
  Supporting pilot projects in end-use sectors and production pathways such as low-carbon steel, mobility and shipping with an outlay of 1,466 crore. It also includes pilot projects of hydrogen production from biomass, hydrogen storage technologies etc.
- **R&D Projects**
  Facilitating SHIP (Strategic Hydrogen Innovation Partnership), a public-private partnership framework for R&D projects that are goal-oriented, time-bound, and suitably scaled up to develop globally competitive technologies.
- **Skill Development**
  Creating a coordinated skill development program to fulfil the mission capacity-building needs (Ministry of New and Renewable Energy, 2023)

• **Green Hydrogen Policy**
In February 2022, the Green hydrogen policy was announced. Under this policy, inter-state transmission charges for green hydrogen production plants commissioned up to June 2025 are waived off for 25 years. The policy also provides a

30-day banking facility and limits the applicable banking charges for the renewable energy used in the production of green hydrogen. It grants open access to renewable energy sourced within 15 days and land allocation in renewable energy parks will depend on the efforts from state governments towards proper adoption and enforcement(Ministry of Power, 2022).

- **Production-linked Incentive Scheme**
  India announced in September 2021 that it will start providing producers of electrolysers with subsidies to encourage the generation of hydrogen using solar and wind power. Even though they are not yet finalized, these subsidies might allow for up to 15 gigawatts of electrolysers (Delaval et al., 2022).

- **'Green Tariff' Policy**
  The Ministry of Power (MoP) of India proposed a set of "Draft Electricity Rules, 2021" in June 2021 to encourage the use of renewable energy sources across the country. These rules establish a "green tariff" policy, which would enable electricity distribution companies to provide green electricity at a more affordable price than that of electricity produced using conventional fuel sources (Delaval et al., 2022).

- **Perform, Achieve, and Trade (PAT) Scheme**
  The PAT is a regulatory tool designed by the National Mission for Enhanced Energy Efficiency to lower energy use in energy-intensive industries. It is based on the Cap-and-Trade system. Once hydrogen is used on a large basis, the program may be extended to include hydrogen (Delaval et al., 2022).

The government has also announced a target for the reduction of green hydrogen production costs – less than USD 2.5/kg by 2025 and USD 1/kg by 2030 (ETEnergyWorld, 2022)

2.3.3 Investments

Resonating to the NGHM active collaborations and investments are being made in the green hydrogen industry. Some major announcements are shown in figure 5. Public sector enterprises like National Thermal Power Corporation(NTPC) and Indian Oil Corporation Limited (IOCL) are collaborating with private sector companies such as L&T and ReNew Power to diversify their energy portfolios through joint ventures. The primary objective of these partnerships is to produce green hydrogen assets and electrolyzers. Together with TotalEnergies, Adani Group has committed 50 billion toward the development of green hydrogen, with a projected capacity of 1 MMT annually by 2030. Reliance Industries Limited plans to invest 10 billion in batteries, fuel cells, solar panels, hydrogen, and other sustainable energy infrastructure. Additionally, companies such as PTC India, L&T, Greenko, and Renew Power have partnered with foreign companies on projects involving the production and export of green hydrogen, the production of alkaline water electrolyzers, and the creation of "centres of excellence" for the facilitation of green hydrogen (The National Bureau of Asian Research, 2023).

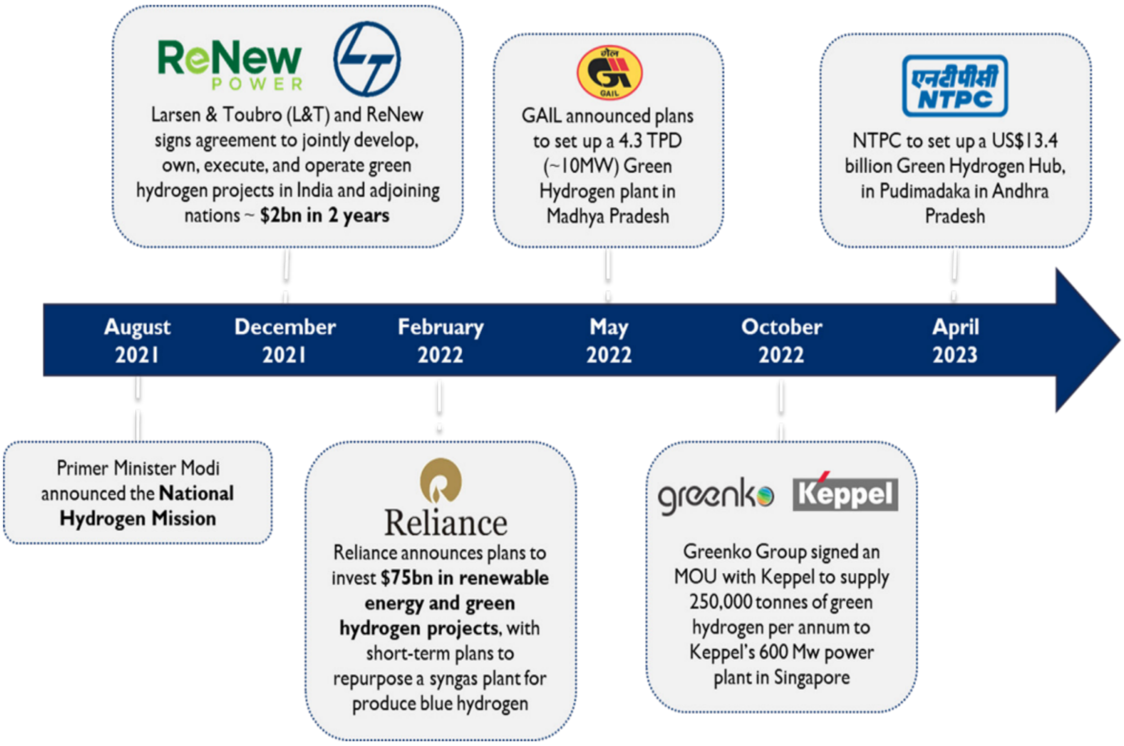


Figure 5: Some major announcements in the sector
(SAREP, 2023)

3 Literature Review

In this chapter, we discuss different studies analysing the economic impacts of investments in renewable energy using various economic models such as input-output (I-O) analysis, computable general equilibrium (CGE) models and Autoregressive Distributed Lag models(ARDL). This is followed by a review of studies on the hydrogen industry and its economic implications.

3.1 Economic Impacts of Investments in Renewable Energy

Investments in renewable energy have diverse economic impacts that are evaluated using a range of metrics. The primary economic benefits of investing in renewable energy are the creation of jobs, the boosting of regional economies, and the promotion of sustainable economic growth. These impacts are often quantified in terms of gross domestic product (GDP), employment, total output and investment.

In general, the macroeconomic effects of renewable energy investment comprise direct, indirect, and induced effects. Direct effects are seen as immediate impacts within the renewable energy sector, such as the generation of employment due to the development of solar parks or unemployment caused in the mining industry because of decreased demand for fossil fuels. Indirect effects ripple through related industries that support and complement the renewable energy sector, stimulating demand for goods and services like manufacturing components and construction materials. Induced effects extend further, as increased incomes from employment resulting from investment in the renewable energy sector spur additional spending in the broader economy, benefiting sectors ranging from retail to healthcare.

3.2 Analytical Approaches to Renewable Energy Investment Implications

There are mainly two approaches while analyzing the macroeconomic implications of investing in renewable energy: the top-down and bottom-up. The top-down approach includes methodologies such as Input-Output and Computable General Equilibrium (CGE) models. These models provide a broad perspective by examining the overall effects of renewable energy investments on the economy. On the other hand, the bottom-up approach includes methods such as the Employment Factor Approach (EFA) and Autoregressive Distributed Lag models (ARDL). These approaches focus on specific aspects, such as employment or energy consumption, to understand the impacts of renewable energy investments in detail. Additionally, hybrid approaches combine two or more of these methods to provide a more comprehensive analysis.

3.2.1 Input - Output (I-O) models

The Input-Output (I-O) model is an economic tool used to analyze the interdependencies between different economic sectors. It illustrates how changes in one sector impact others through direct and indirect links, quantifying the movement of commodities and services between sectors. The economy is shown as a matrix in an IO model, with rows and columns denoting the various sectors and each cell denoting the total value of transactions between them. The effects of different economic shocks or policy changes on output, employment, and income across multiple sectors can be evaluated by examining this matrix. I-O models can estimate all the effects i.e. direct, indirect and induced. The I-O models are best applicable for short and medium-term assessments.

Using the I-O model Markaki et al. (2013) has conducted a study to estimate the direct, indirect and induced macroeconomic effects of required green energy investments in Greece across industrial sectors to meet European energy and environmental targets. Their findings suggest a total investment of 47.9 billion euros over 2010-2020, leading to an average annual increase of 9.4 billion euros in national output and the creation of 108,000 full-time equivalent(FTE) jobs. This means that for every million euros spent, 2.25 FTE jobs are created.

Similarly, using the same method Yushchenko and Patel (2016) evaluated the impacts on GDP and employment of two energy efficiency programs operated by the local utility. The two programs they have analyzed are Eco-Sociales which targets social housing and Communs d'immeubles which focuses on common spaces in buildings. Their findings reveal that around 0.2 Swiss Franc (CHF) of additional GDP would be created for each CHF spent within the energy efficiency program. The net impacts (difference between the situation with and without programs) on employment are estimated to be around 0.7 and 1.6 FTE jobs for 1 million CHF of expenditure driven by Eco-sociales and Communs d'immeubles respectively.

Both studies have reported a positive impact on investing in renewable energy. However, there is a significant difference in employment generation per million spent. This is because Markaki et al. (2013) has not considered the induced effects of energy savings because of a lack of data. Whereas Yushchenko and Patel (2016) has considered it, avoiding overestimating the effects.

3.2.2 Computable General Equilibrium (CGE) models

In Computable General Equilibrium (CGE) models the entire economy is represented as a system of equations that capture the interactions between different economic agents, such as households, firms, and governments, within various markets for goods, services, and factors of production. CGE models consider how changes in one part of the economy, such as a policy change or external shock, affect all other parts of the economy through various channels, including changes in prices, quantities, and resource allocation. The CGE models are best performing for investigating medium and long-term impacts. CGE models can estimate Indirect and Induced effects.

Bulavskaya and Reynès (2018) have used the CGE model to analyse the economic impact of transitioning to a renewable electricity mix in the Netherlands by 2030. This study applied the ThreeME model, a neo-Keynesian CGE model allowing for situations where supply and demand are not instantly balanced (disequilibrium). This makes it more realistic, as prices and quantities adjust slowly in the real world. The analysis concludes that transitioning to 75% renewable electricity by 2030 would increase GDP by 0.85% and create around 48,500 new jobs compared to the baseline scenario(business-as-usual case).

However, the study done by Rivers (2013) for USA finds that a renewable electricity subsidy policy tends to increase unemployment. The mechanism is that the subsidy requires raising labour taxes to fund it, reducing real wages. It also reduces conventional electricity production, lowering tax revenues and requiring higher labour taxes, further depressing employment.

The contrasting results can be explained by the different policy scenarios analyzed (renewable transition vs subsidy). Also, the two studies have employed different versions of the CGE model. Bulavskaya and Reynès (2018) used a neo-Keynesian model that incorporates price effects and feedback loops, focusing on the Dutch context and the specific impacts of renewable energy on various economic sectors. Whereas Rivers (2013) used a three-sector model with specific conditions for when renewable policies might decrease unemployment, focusing on the elasticity of substitution and labour intensity.

3.2.3 Employment Factor Approach (EFA)

The Employment Factor Approach(EFA) is the simplest and fastest way to evaluate direct jobs from renewables. It measures the correlation between changes in GDP or output and employment levels to assess how economic activity affects jobs. Employment factors, which are usually determined from surveys, literature studies, or interviews with industry experts, indicate the number of jobs or job-years per unit of capacity (e.g., jobs/MW) for each activity in the life cycle(R&D, manufacturing, construction, installation and O&M). The total direct jobs are then calculated by multiplying these Employment Factors with the projected installed or manufacturing capacity for each activity. The EFA methods are applicable for short and medium-term assessments.

Adopting EFA method, Ram et al. (2022) estimated direct energy jobs worldwide in the power, heat, transportation, and desalination sectors, with a vision of achieving 100% renewable energy sources by 2050. The study has extended the EFA method by adding a dynamic component that considers global labour intensity variations and technology learning effects. The study's findings point to a significant rise in direct energy employment from around 57 million in 2020 to over 134 million by 2050, suggesting that a worldwide energy transition will benefit the stability and growth of economies everywhere.

Similarly, using the same method Wei et al. (2010) has made the job projections in the US power sector from 2009 to 2030. The study has also considered the job losses in the coal and natural gas industry to project net employment impacts, a step that captures wider economic effects. The results of this study indicate that compared to coal and natural gas, nonfossil fuel technologies such as low-carbon sources, energy efficiency, and renewable energy provide more employment per unit of energy. In particular, a 30% renewable portfolio standard (RPS) target by 2030 when combined with vigorous energy-saving efforts can provide more than 4 million full-time equivalent employment years.

The findings from both papers suggest that a shift towards renewable energy and energy efficiency not only addresses environmental concerns but also offers a viable path to economic growth. However, the EFA method primarily focuses on direct employment impacts, potentially underestimating the broader economic ripple effects captured by more complex input-output models.

3.2.4 Autoregressive Distributed Lag models (ARDL)

Autoregressive Distributed Lag (ARDL) models are a class of time series regression models that capture the relationship between a dependent variable and one or more independent variables over time. Lags of the independent variables (distributed lag component) and lags of the dependent variable (autoregressive component) are included in these models. This enables the models to take into consideration the possibility that it may take some time for changes in the independent variables to affect the dependent variable completely.

Busu (2020) has applied ARDL method to panel data from 28 European Union(EU) member states over the period 2004-2017 to quantify the impact of renewable energy sources(RES) on sustainable economic growth within the EU. The study explores the causality and long-term relationship between renewable energy consumption and economic growth, incorporating control variables such as labour force and R&D expenditures. According to the findings, RES—especially biomass—have a favourable impact on economic growth, supporting EU policies that promote RES investment.

Afonso et al. (2017) performed a study using the ARDL method on 28 countries over the period 1995-2013 examining the relationship between economic activity and both renewable and non-renewable energy consumption. The analysis reveals that non-renewable energy contributes positively to economic growth (GDP per capita) in the short run, while renewable energy sources have a negative impact in the long run.

The contrasting results can be attributed to the geographical focus of each study. The Busu (2020) study benefits from a homogeneous policy environment, as EU countries are subject to similar environmental and energy policies, which aim to increase the share of RES in their energy mix. On the other hand, the study done by Afonso et al. (2017) considers a more diverse set of countries, including both developed and developing nations. This introduces variability in terms of economic structures, energy policies, and stages of development, which could influence the relationship between energy consumption and economic growth.

3.2.5 Hybrid approaches

The hybrid approach allows for a combination of the strengths of different models and reduces their limitations. In both the micro and macroeconomic perspectives, they measure direct, indirect, and induced impacts. They are applicable for short, medium and long-term assessments.

Fragkos and Paroussos (2018) have employed a combination of EFA and CGE to investigate the net employment impacts from the projected transformation of the EU energy sector towards RES. Through the disaggregated estimation of direct employment impacts, the EFA gives a bottom-up study, whereas the CGE model offers a top-down analysis, assessing the total job impacts from RES development in the EU economy. The study reveals that low-carbon transition would lead to the net creation of 200,000 direct jobs in energy sectors by 2050, representing about 1% of the EU workforce. The CGE modelling further confirms the positive employment impacts of RES expansion, projecting a reallocation of 1.3% of the EU's workforce across sectors by 2050 due to the low-carbon transition

Dell'Anna (2021) have used a hybrid approach by combining EFA and I-O analysis to assess the potential of investments in the energy sector in Italy, focusing on wind, photovoltaic, hydroelectric, and geothermal infrastructures. The EFA was employed to evaluate labour intensity in the entire chain of activities related to RES and fossil fuels, focusing on the production phase. To overcome the limitations of EFA quantifying only direct job impacts I-O analysis has been applied to quantify the full range of employment impacts, including direct, indirect, and induced jobs. According to the study, investments in RES can have a strong positive impact on the Italian economy both directly and indirectly.

These few examples of earlier research demonstrate the variety of macroeconomic methodologies and related outcomes when examining the investment consequences of renewable energy and energy efficiency initiatives. Despite growing interest in the clean energy sector, green hydrogen has not been the main focus until now.

3.3 Economic impacts of green hydrogen industry

The studies on the economic impacts of the hydrogen industry are limited as the industry is new and emerging. Most of the researchers have used the I-O model to analyse the economic impacts(in terms of employment generation and GDP growth) of the hydrogen industry at a national or regional level for the European Union (Wietschel & Seydel, 2007), Japan (Hienuki, 2017), Korea (Chun et al., 2014), Switzerland(Gupta, Guibentif, Friedl, Parra, & Patel, 2023), US, China, Japan and India (Lee & Chiu, 2012). The assessment of economic impacts varies according to the focus of the research i.e. the production pathways and the demand side applications of hydrogen considered for the studies. Hienuki (2017) has focused on hydrogen production by naphtha reforming, a fossil fuel-based method and for the demand side he considered the hydrogen-powered fuel cell electric vehicles (FCEV). FCEV is also the major focus in the studies of Chun et al. (2014). Whereas Lee and Chiu (2012) have worked on impacts of biohydrogen i.e. hydrogen produced from biomass.

As the outcome of the research, few studies have focused on economic growth in terms of GDP and employment generation. Wietschel and Seydel (2007) has focused on determining potential employment effects and sectoral shifts resulting from the usage of hydrogen in the energy system for a few chosen European nations until 2030. The study highlights the need for timely workforce skill development in hydrogen technologies to capitalize on employment benefits without interfering with export/import flows. The macroeconomic effects of green hydrogen production in Switzerland have been examined by Gupta et al. (2023), including GDP growth, employment generation and GHG emissions, comparing green hydrogen with diesel as a transportation fuel under various scenarios. They found that, relative to the construction phase, the operational phase generates 6.0, 5.9, and 9.5 times higher GDP, employment, and greenhouse gas emissions per kilogram of green hydrogen generated (all values in gross terms).

In other study Lee and Chiu (2012) have predicted the development of the biohydrogen sector in the US, China, Japan and India, and its impact on the economic growth of these countries. According to their findings, China will have the biggest market for biohydrogen, followed by the US, Japan, and India in that order. While Japan has the largest potential to replace fossil fuels with biohydrogen, India will witness the most efficient investment in the biohydrogen industries.

Furthermore, few studies focused on environmental, socioeconomic and investment impacts in the hydrogen sector as the outcome of the research. Using I-O tables Hienuki (2017) have examined the environmental and socioeconomic impacts of the hydrogen energy system at every stage of its life cycle, from hydrogen production by naphtha reforming to refilling fuel cell cars. His findings showed that throughout the manufacturing and construction stages, 31%, 44%, and 9% of the effects on employment, production, and greenhouse gas (GHG) emissions, respectively, during the manufacturing and construction stages were temporary. These values were discovered to be 69%, 56%, and 91%, respectively, during continuous operation and maintenance stages.

Similarly, Chun et al. (2014) have used input-output analysis and an exogenous specification approach to examine the impact of investments in hydrogen energy technologies on the Korean economy for the period 2020–2040. The study used an exogenous specification approach to overcome the limitations of the standard demand-driven I-O model, which struggles to accurately assess the production-inducing effect of a specific sector on the entire economy and overestimates the effects. By considering the hydrogen sectors as external to the model and including them in the final demand group, the exogenous specification approach allowed the researchers to investigate how changes in the cost of the hydrogen sector may affect the production costs of other sectors. They concluded that the hydrogen sector can be characterized as intermediate primary production because of its significant impact on production costs in other sectors of the economy.

3.4 Estimating the structure of the hydrogen industry

I-O tables generally classify industries according to their economic significance; the hydrogen sector might not be mentioned separately because of its small size to other industries. Thus it is crucial to accurately represent the hydrogen industry within I-O tables for any research. This includes estimating the industry's intermediate inputs i.e. the goods and services required in the production process and its value-added components, which include taxes, operational surplus, and labour contributions. The sales distribution system, which specifies how the industry's products are distributed across various markets, also has to be established. A variety of approaches have been employed by researchers to estimate these elements for the hydrogen industry. Some researchers have interviewed technical and economic experts of different stakeholders of the industry to produce these estimates (Wietschel & Seydel, 2007; Chun et al., 2014). This approach has the advantage of incorporating nuanced insights that traditional data sources might miss. However, the expert comments may reflect personal preferences or experiences that are not necessarily reflective of the sector as a whole, making them subjective and sometimes biased.

Whereas, in another research, to create the biohydrogen demand chains for the US, China, Japan, and India, Lee and Chiu (2012) have taken the hydrogen demand chain found in Taiwan's economic IO tables (Lee & Lee, 2008). They justified this by asserting that the technological levels and hydrogen demand structure of mature, global chemistry-related industries are comparable. Although global trends, such as the standardization of technology, international regulations, and the activities of multinational corporations suggest a certain level of homogeneity, significant regional differences persist. The degree of economic growth, legal frameworks, the availability of natural resources, market dynamics, infrastructural investment, cultural preferences, and the rate of technological innovation are some of the elements that affect these differences.

For the case of Switzerland, Gupta et al. (2023) has separated the investments needed to establish a green hydrogen sector into two categories: (1) one-time infrastructure capital expenditures, or CAPEX, and (2) yearly operating and maintenance expenses, or OPEX. This separation makes it possible to distinguish more clearly the financial obligations related to the growth and maintenance of the green hydrogen sector. By allocating gathered expenditure data to the already existing sectors, they have estimated the input components of the green hydrogen industry. However, thorough verification and careful assessment of industry-specific details are essential to guarantee the accuracy of the predicted input components obtained from this allocation method.

3.5 Research Gap

The review of the literature highlights the following key points:

- Depending on the structure of the economy and the level and nature of local activity, the macroeconomic consequences of these investments may vary greatly from nation to nation or even from area to region.
- There is limited research focusing on quantifying the potential benefits of switching to green hydrogen
- The employment market implications are the main focus of research on the macroeconomic impact of the green hydrogen sector using I-O analysis; comparatively little research has been done on assessing the impact on GDP and production.

To this end, the objectives of the study are:

- To evaluate the contribution of green hydrogen industry to the Indian economy in terms of GDP
- To quantify the savings in imports and reduction in carbon emissions by switching to green hydrogen

Also, to the best knowledge of the author, as of now there have not been any studies analysing the economic impacts of the hydrogen industry explicitly for the case of India. This could be because of a lack of push for green hydrogen in the country until the government announced the National Green Hydrogen Mission in 2021, which created traction for investments in the industry. Though Lee and Chiu (2012) have included India in the analysis along with US, China and Japan; it underlays the fact that India, as a developing nation, lacks the advanced infrastructure present in these countries. Also Lee and Chiu (2012) have considered only biohydrogen in his studies. Though India is focusing on biohydrogen, it is majorly promoting domestic manufacturing of electrolysers. So, this thesis will consider the production of green hydrogen by electrolysis using renewable electricity.

The main aim of this thesis is to verify the projections of the National Green Hydrogen Mission of India mentioned in the background section by providing insights into the economic impacts of the emerging industry using I-O analysis. Such an analysis could be pivotal for policy measures to enhance positive macroeconomic impacts and increase the acceptance of green hydrogen.

4 Methodology

This chapter discusses the methodology applied in this study to examine the macroeconomic effects of India's emerging green hydrogen industry. The analysis uses the Input-Output (I-O) modelling framework because of three main factors. Firstly, the I-O models provide detailed implications of how a new industry affects different industries in the economy. This level of detail is crucial while assessing the impacts. Secondly, the I-O model can be extended to incorporate environmental factors such as emissions produced in the value chain. Thirdly, I-O models rely on national or regional input-output tables that capture the economic transactions between sectors. This data-driven approach makes the analysis grounded in empirical evidence.

In this chapter, the I-O analysis is explained first followed by an introduction of the underlying concepts required for this study.

4.1 Basic I-O Model

Professor Wassily Leontief developed the I-O model in the late 1930s. The model is essentially a system of linear equations that individually describe how a product of an industry is distributed across the economy. In this model, the whole economy is divided into different industries that produce and consume goods and services, and the flows of these goods and services are documented in an I-O table.

Figure 6 depicts a basic I-O table. The I-O table is divided into three parts which are the intermediate demand, the final demand and the value added. The exchange of goods and services between the industries is recorded in the intermediate demand. The shaded area in Figure 6 represents the intermediate demand. The rows of the table describe the distribution of the total output of an industry. The columns show the industries as the purchasers of intermediate inputs required to produce their output. The sales of an industry to their final markets such as personal consumption purchases, sales to the government and foreign trade etc are recorded in the final demand part. In the value-added part, all the other (non-industrial) inputs to production are recorded. These include labour, depreciation of capital, indirect business taxes, and imports. All the data in the I-O table is recorded in monetary terms.

The output from an industry is distributed between intermediate demand and final demand. The total output of an industry is then the sum of intermediate demand and final demand. This in turn must always be equal to the total inputs which is the sum of intermediate demand and the value added.

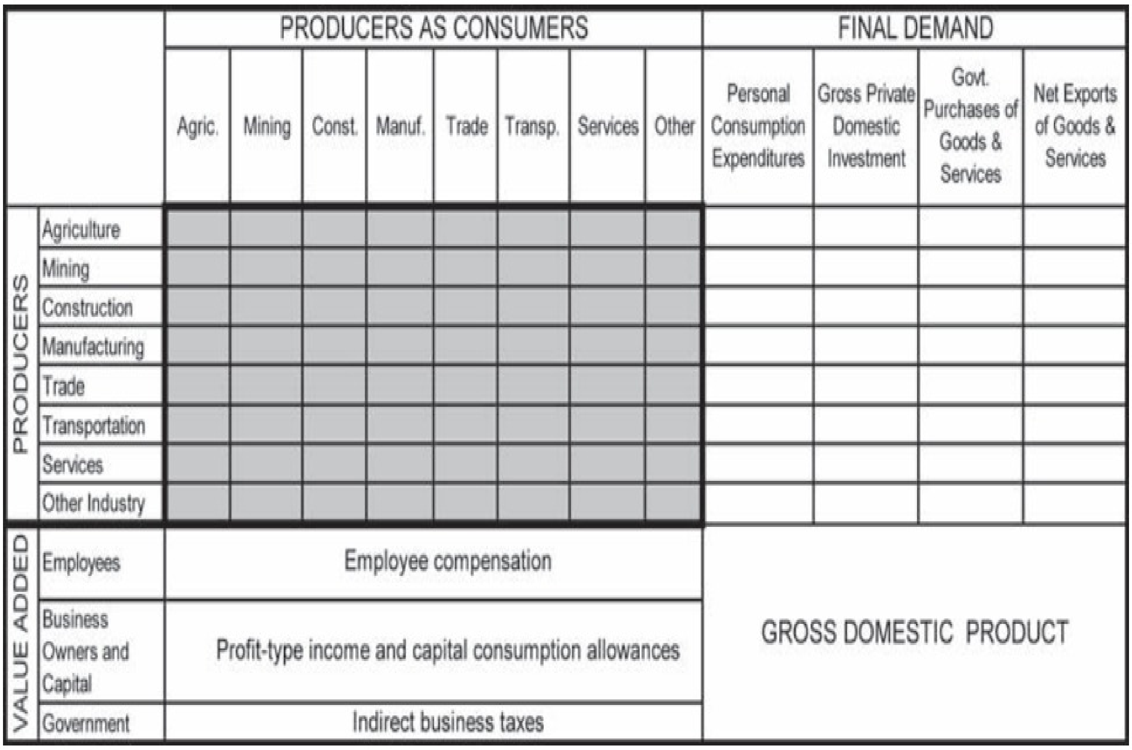


Figure 6: Basic Input Output table
(Miller & Blair, 1985)

Coming to the assumptions of the model, it assume that the amount of each input required to produce one unit of output is constant, regardless of the level of production. This is referred to as the assumption of constant returns to scale. Another critical assumption is the lack of supply constraints, where industries are always able to produce the required intermediate and final goods to meet any increase in demand. This assumption of no capacity constraints suggests that an increase in labour demand will lead to a corresponding rise in employment rather than just the reassignment of current employees. Lastly, the model assumes that economic adjustments resulting from changes in demand happen immediately, without considering the time required for these changes to occur. Because of this simplification, the model can only depict the economy as it is at a specific moment in time. But in the real world, the economic processes are dynamic.

Despite these limitations, the I-O model remains a powerful tool for determining the structural interdependencies of an economy and assessing the direct and indirect effects of changes in one industry on the rest of the economy. The model offers a systematic and quantitative framework for examining the ripple effects of economic shocks and identifying key industries that can drive economic development.

4.2 Demand Shock Analysis

Demand shock analysis examines how a change in final demand for a specific good or service flows through the production network and impacts the total output of all industries in an economy. Specifically, the model determines the new total output vector that would meet a greater final demand for an industry, taking into consideration the interdependencies across industries. This allows quantifying the direct and indirect effects of demand shocks as they spread across the economy via the input-output linkages. For instance, if the final demand for an industry in the economy increases, the model can determine how much each industry's output needs to rise to meet this higher demand.

Considering the total output as vector X, intermediate demand matrix as Z and final demand vector as F, the effects of demand shocks are calculated as follows

$$X = Z + F$$

rewriting the intermediate demand as a proportion of total output, we have

$$X = AX + F \tag{1}$$

Where A is the coefficient matrix, defined as $a_{ij} = \frac{z_{ij}}{x_j}$

The coefficient matrix represents the direct productive interdependence between sectors of an economy. The a_{ij} indicates the direct input requirement of the sector j from the sector i. It thus captures the direct effects and is also called as direct input coefficient matrix.

Assuming that I-O coefficients remained unchanged and the matrix (I-A) is nonsingular, we have the unique solution of total output as

$$X = (I - A)^{-1}F$$

Considering $L = (I - A)^{-1}$, we have

$$X = L.F \tag{2}$$

Where L is known as Leontief inverse matrix

The elements in the Leontief inverse matrix represent the total output required from sector i to produce one unit of final demand in sector j. This total output includes both direct and indirect requirements. It thus captures both direct and indirect effects and is also called as the total requirements matrix.

For calculating the change in output for a given change in final demand we have

$$\Delta X = L \cdot \Delta F \tag{3}$$

The Leontief I-O model always considers the change in final demand as exogenous. This means that the final demand vector F is viewed as an independent variable that is determined outside the model.

4.3 Impact Analysis

Impact analysis examines how the change in final demand reflects on different macroeconomic indicators. This study quantifies the impacts in terms of Gross Domestic Product (GDP), employment and emissions. The total worth of goods and services produced inside a nation's boundaries is measured by its GDP, representing overall economic activity and production. The GDP is a critical statistic for evaluating the state and performance of an economy as changes in GDP can signal changes in productivity, competitiveness, and economic growth.

On the other hand, employment indicates the number of accessible jobs in an economy and offers insights into the dynamics of the labour market. Also, employment directly affects social welfare and economic stability. Therefore, analyzing employment trends alongside GDP offers a broader understanding of economic growth and its social effects.

GHG emissions are a key indicator of environmental sustainability and climate change impact. As concerns over global warming are increasing, monitoring and reducing emissions has become very important. By integrating GHG emissions information into impact analysis, stakeholders and policymakers can evaluate how economic activities affect the environment and find ways to separate environmental degradation from economic growth.

For the impact analysis, at first, we define a technical coefficient γ_i for a given impact indicator.

$$\gamma_i = \frac{q_i}{x_i} \tag{4}$$

where q_i is the indicator's total value for industry i and x_i is the total output for industry i.

Then the diagonal matrix of technical coefficients ($\hat{\Gamma}$) is multiplied by the Leontief inverse matrix (L) to create the total requirement matrix (Γ) for a given impact indicator.

$$\Gamma = \hat{\Gamma} \cdot L \tag{5}$$

where $\hat{\Gamma}$ is represented by

$$\hat{\Gamma} = \begin{bmatrix} \gamma_1 & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & \gamma_n \end{bmatrix} \tag{6}$$

Finally, Γ is multiplied by the change in final demand ΔF to estimate the change in the quantity of a given impact indicator.

$$\Delta Q = \Gamma \cdot \Delta F \tag{7}$$

4.4 Multipliers

Multipliers measure the total effect on the economy due to a change in the final demand of a particular sector. It tells how much the total output will increase for every unit increase in final demand for a specific sector. Simple output multipliers are calculated by the column sums of the L matrix.

$$m(o) = i' \cdot L \tag{8}$$

where m(o) represents output multipliers and i' represents a row vector of 1's.

For the impact analysis, the multipliers are calculated as follows

$$m(\Gamma) = i' \cdot \Gamma \tag{9}$$

where m(Γ) represents impact indicator multipliers.

4.5 Inter-industry Linkage Effect

Inter-industry linkage effect examines how a given industry interacts with its upstream and downstream sectors within an economy. There are two different ways that a given industry's production affects other economic sectors in the I-O model. Backward linkages represent an industry's dependence on other industries for inputs it needs to produce its own goods and services. Conversely, forward linkages represent how an industry's output is used as inputs by other industries further down the value chain.

The backward and forward linkages are calculated as follows

$$BL_j = \frac{ni'L}{i'Li} \tag{10}$$

$$FL_i = \frac{nLi}{i'Li} \tag{11}$$

where n is the number of industries and i is a column vector of 1's.

The denominators of each equation are normalized for both measurements, resulting in an average backward and forward linkage effect of one across all industries. This makes it simpler to identify industries that are above and below average. Further, the backward and forward linkage results are categorised as shown in the below table

		Direct or Total Forward Linkage	
		Low (<1)	High (> 1)
Direct or Total Backward Linkage	Low (< 1)	(I) Generally independent	(II) Dependent on interindustry demand
	High (> 1)	(IV) Dependent on interindustry supply	(III) Generally dependent

Figure 7: Classification of Backward and Forward Linkage Results
(Miller & Blair, 1985)

Industries with low backward and forward linkages are generally independent indicating that they depend very less on both upstream industries and downstream industries. Industries that exhibit strong forward linkage but weak backward linkages are reliant on demand from other sectors, implying that their products are essential to the manufacturing processes of other industries. On the other hand, industries with strong backward linkage but weak forward linkages heavily rely on inputs from other sectors. Lastly, industries that exhibit strong forward and backward linkages are generally dependent, signifying their deep integration into the economy since they depend on other sectors for inputs.

5 Data and Analysis

This chapter discusses the system boundary and the data necessary to examine the impacts of the green hydrogen(GH) industry in India through the I-O model. Such data includes I-O tables of India and inputs to the GH industry.

5.1 I-O tables for India

Construction of an I-O table is a very complex process which includes the collection of data from different sources such as economic censuses, household income and expenditure surveys, and most importantly, the National Accounts. It is therefore done once every few years by the national statistical agencies to provide a reliable representation of the economic activities taking place inside an economy during a certain time frame, usually a year.

For India, the IO tables are last updated for the year 2007- 08 by the Ministry of Statistics & Programme Implementation (MoSPI). However, the data for the supply and use tables (SUTs) are made available for the year 2019 - 20. SUTs are a fundamental part of the I-O framework in national accounts. I attempted to balance the SUTs by using a software tool developed by IMF (IMF, 2022) to construct the I-O table for 2019-20. However, the resulting I-O table does not balance with total supply and total input.

Other sources for I-O tables are found to be the Asian Development Bank (ADB, 2024) and the Organisation for Economic Co-operation and Development (OECD, 2024a). The ADB has classified the economy into 35 industries whereas the OECD has classified it into 45 industries. The OECD I-O table is chosen for this study as it offers a more comprehensive and disaggregated view of the economy, making it possible to depict inter-industry linkages and dependencies more accurately. The analysis is done based on the 2018 OECD I-O table for India. The 2018 I-O table is chosen because the industry-wise emissions are updated till 2018 at the time of this study. Figure 8 represents the schematic view of the OECD I-O table.

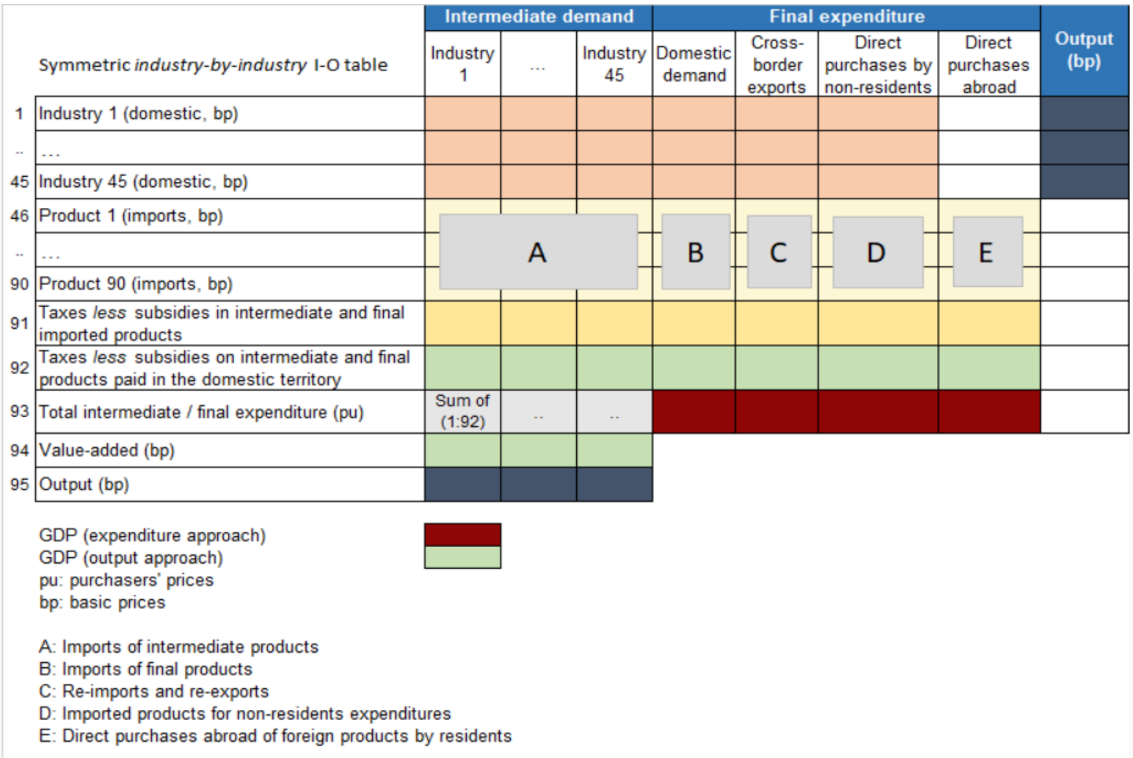


Figure 8: Schematic view of OECD I-O table
(OECD, 2024a)

5.2 System boundary of the green hydrogen industry considered

The system boundary reflects the scope of this study. It is essentially the components that have been considered in the supply chain of the GH industry. The GH industry generally comprises the production by electrolysis, transportation from production sites to end use and refuelling stations.

In this study, the GH industry is divided into the construction phase and the operational phase. Coming to the components considered, the construction phase includes one-time investments in infrastructure like building the production sites, electrolyser systems and other auxiliary equipment required for producing GH. The construction phase also includes the costs of hydrogen truck trailers needed for transporting GH to end users.

On the other hand, the operational phase includes recurring costs of operating the GH plant like electricity, water, maintenance of equipment and hydrogen truck trailers. Supporting activities that are needed for the operation of GH plants like IT, Financial and administrative services are also included in the operational phase. Breaking down the expenditures into construction and operational components helps to identify the major cost drivers in each phase. It also involves the sales of the green hydrogen industry to other sectors and final demand.

5.3 Hydrogen Industry Input Structure

The inputs for the GH industry are collected from different sources and are assigned to the already existing sectors in the OECD I-O table. In the construction phase inputs from different industries are taken to build the new GH industry. In the operational phase, the GH industry starts producing hydrogen and sells its output to other industries.

5.3.1 Construction Phase

The one-time investments in the construction phase which is the capital expenditure (CAPEX) for a hydrogen plant are generally expressed in cost per installed capacity. The capacity for this analysis is calculated based on the NGHM's target of producing 5 MMT of hydrogen which translates to around 60 GW electrolyser capacity. Please refer to the appendix for detailed calculations of electrolyser capacity. Also, the CAPEX varies according to the scale of the production capacity. For this analysis, a scale of 1 GW is chosen because it maximizes the benefits of economies of scale as discussed in section B.0.1. For the chosen scale this essentially means that to fulfil NGHM's target, 60 hydrogen plants with a capacity of 1 GW each would be established.

The expenditures for the construction phase are taken from the study of the GigaWatt Scale Electrolyser project done by Hydrohub (Hydrohub, 2020). The total installed capital costs for a 1 GW green hydrogen plant with alkaline electrolyser technology is estimated to cost 1400 €/kW in CAPEX. These estimates include the indirect costs and contingency to the components of the capex considered. It has also considered the owners cost which refers to costs for owner project management, site supervisory teams and operator training. The estimates are done at the 2020 cost level. The chosen I-O table is for the year 2018 and is in terms of USD. So the costs of the components from Hydrohub (Hydrohub, 2020) are deflated to the year 2018 assuming a deflation rate of 3% and then converted to USD. The CAPEX breakdown for the NGHM capacity is shown in table 1.

The breakdown CAPEX comprises the following cost components :

- **Construction and Engineering Services** This includes the cost of the buildings, foundations, and other infrastructure needed to house and sustain the plant's machinery.
- **Electrolyser System** This includes the cost of the actual electrolyser units, which are an essential component in the production of hydrogen.
- **Balance of plants** This includes the cost of auxiliary equipment required for overall plant operations like compressors, pumps, heat exchangers, and piping.
- **Utilities and Process Automation** This includes the cost of cooling, instrumentation, process control, and water treatment equipment.
- **Power Supply and Electronics** This includes the cost of rectifiers, transformers, and other electrical devices required to provide and regulate the electrolysers' power input.

- **Hydrogen Truck Trailor** This includes the cost of the hydrogen truck trailer which are used for transporting from production sites to end use.

S. No	Component	CAPEX(M USD)	Industry Name in OECD I-O Table
1	Construction and Engineering Services	9262.43	Construction
2	Electrolyser System	21700.56	Machinery and equipment, necessary
3	Balance of plants	24346.97	Machinery and equipment, necessary
4	Utilities and Process Automation	14290.61	Machinery and equipment, necessary
5	Power Supply and Electronics	23089.93	Electrical equipment
6	Hydrogen Truck Trailor	84.82	Motor vehicles, trailers and semi-trailers
Total		92775.33	

Table 1: Inputs from different industries in the construction phase for NGHM capacity

The Hydrohub expert teams prepared the cost estimates following standard practices, with over half of the equipment costs derived from supplier data or other sources. The accuracy of the data collected is stated to be in the range of -25% to +40%.

The investment required to establish the GH industry i.e. the data in the table 1 is taken as a change in final demand in the construction phase for both the demand shock and impact analysis.

For the impact analysis, the data for industry-wise employment (OECD, 2024b) and emissions (OECD, 2024b) are taken from the OECD statistics. The GDP is calculated by adding the value-added and taxes less subsidies on products (United Nations, 1999).

5.3.2 Operational Phase

The inputs in the operational phase include the following

- **Water** Water is the raw material for the production of hydrogen through the electrolysis process. Stoichiometrically 9 liters of water is required for producing 1 kg of hydrogen. However, electrolyser manufacturers report that water consumption is in the range of 15-20 litres per kg of hydrogen (Store&GO, 2018). Assuming the need for water to be 200% of the stoichiometric need 18 litres of water is needed to produce 1 kg of hydrogen.

In India, the industrial water rates vary significantly from state to state. It is as low as 15 INR per kiloliter in Rajasthan and Haryana to 90 INR per kiloliter in Delhi in the year 2018 (India Briefing, 2018). So an average of 50 INR per kiloliter is considered.

- **Electricity** Electricity is used to split the water into its constituent elements, hydrogen and oxygen in the electrolysis process. According to a survey of the major manufacturers 50 kWh of electricity is required for producing 1 kg of hydrogen(Carbon Commentary, 2021). The cost of renewable electricity in India is 0.063 USD per kWh in the year 2018 (IRENA, 2019).

- **Maintenance of Electrolysers and other equipment** This includes the costs of regular maintenance and the replacement of parts of the system that are affected by wear and tear over time. These costs are generally expressed in percentages of CAPEX. According to a report from IEA, it is 2% of CAPEX (IEA, 2019b).
- **Maintenance of hydrogen truck trailors** Hydrogen is transported in pressurized containers, regular maintenance is essential to uphold safety and prevent leakages. This costs around 12% CAPEX, according to a report from IEA (IEA, 2019b).
- **Land** According to a report from IRENA, a 1 GW plant could occupy about 0.17 square kilometres (km^2) of land (IRENA, 2020). The land for industrial activities is often taken on lease or rent. To estimate this the Gujarat policy of green hydrogen is used. This policy offers the land for hydrogen plants at the cost of 15000 INR annual rent (Lexology, 2023).

For incorporating essential business and operational support functions of the new GH industry, the Electricity, gas, steam and air conditioning supply (EGSA)sector in the OECD I-O table is used. This includes calculating the proportionality ratios which are input required for producing one dollar's worth of output. These ratios are then used to calculate the inputs for the new GH industry.

The EGSA sector is chosen because of its similar nature to the new GH industry. Both the GH and the EGSA sectors are highly energy-intensive. Further, considering their roles in energy generation, distribution, and consumption these sectors' economic transactions and inter-industry relationships are likely to be similar.

- **Information Technology(IT) Services** This includes the IT tools that assist in forecasting maintenance requirements and maximising efficiency by simulating and modelling the hydrogen production process.
- **Financial and Insurance Services** This includes the services that provide capital for financing the GH projects. It also includes the services that provide coverage for property damage, operational disruptions, liability issues, and environmental risks of a GH plant.

- **Administrative and Support Services** This includes essential services to run a GH plant efficiently, such as building management, business support services, and office administration.

S No	Component	OPEX (M USD)	Industry Name in the OECD I-O Table
1	Water	65.6	Water supply; sewerage, waste management and remediation activities
2	Electricity	15800	Electricity, gas, steam and air conditioning supply
3	Maintenance of Electrolysers and other equipment	1668.56	Manufacturing necessary; repair and installation of machinery and equipment
4	Maintenance of hydrogen truck trailers	10.18	Wholesale and retail trade; repair of motor vehicles
5	Land	0.19	Real estate activities
6	IT Services	7.17	IT and other information services
7	Financial and Insurance Services	556	Financial and Insurance Services
8	Administrative and Support Services	809	Administrative and Support Services
	Total	18916.7	

Table 2: Inputs from different industries in the operational phase for NGHM capacity

In the operational phase, the GH industry is included in the I-O table. FCEVs in India are projected to penetrate around 0.91% of on-road vehicles by 2030 in an optimistic scenario. To cater to FCEVs hydrogen demand is estimated to be around 0.4 MMT (WWF-India, 2024). This is converted to monetary terms using the hydrogen production cost and considered as a change in final demand for the operational phase.

For the impact analysis, the emissions from the GH industry are taken 0, as the production is based on renewable electricity using electrolysis. The employment for a 1 GW plant is estimated to be around 2000 FTE (Gupta et al., 2023) .

5.4 Distribution of Sales

Essential data on the distribution of the output of the GH industry among different economic sectors was taken from the "Investment Landscape of Green Hydrogen in India" report to integrate the GH industry into the I-O table for the operational phase. According to the report the output of the GH industry is distributed among the following sectors

- **Oil Refining** Processing over 250 million tons of crude oil annually, India's refinery industry ranks fourth in the world in terms of capacity. Presently, the refinery industry is responsible for over 3 million tonnes of hydrogen consumption, or 46%

of the nation's total hydrogen demand. Currently, on-site SMR plants produce the majority of this hydrogen. The total demand for hydrogen in India's oil refining industry is projected to reach around 6 million tons by 2030. The industry is expected to be among the first to switch to green hydrogen. It is because hydrogen only accounts for 2-4% of the total costs (SAREP, 2023).

- **Natural Gas Blending** In 2022, India has consumed around 63 billion cubic meters of natural gas. Also, India's natural gas consumption is expected to increase to 200.75 billion cubic meters by 2030. The government intends to blend portions of GH with natural gas in the city gas distribution(CGD) pipes that are now in place because of green hydrogen's cleaner footprint. Pilot projects are already being carried out to assess the technical considerations of such blending (SAREP, 2023).

- **Fertilizer** India is the second-largest consumer of fertilizers worldwide, consuming around 63.94 million metric tons in 2021. Ammonia is a raw material for around 75% of these fertilizers which are nitrate-based. Currently, India imports about 3 million tons of ammonia each year. The use of domestically produced GH to produce ammonia provides a potential solution to reduce this dependency on imported fertilizers. Also, the Indian government sets a goal in the NGHM to replace all nitrogenous fertilizer imports by 2035 with greener alternatives (SAREP, 2023).

- **Freight transport** Road freight accounts for 95% of freight-related CO2 emissions and 71% of freight movement, making it a crucial pillar of the whole freight transport industry. Fuel-cell electric vehicles(FCEV) can help in reducing these emissions. However, since there aren't any FCEVs available in India, there is currently not much demand for hydrogen in the transportation industry. Nonetheless, sales of FCEVs are projected to increase in 2026 and reach around 30% by 2050 (NITI Aayog & RMI, 2022).

- **Exports** As countries throughout the world step up their efforts to meet net-zero objectives, hydrogen is becoming a more and more significant part of the global energy transition. The development of India's GH sector is still in its early stages. To stabilize demand and promote the establishment of GH production facilities, exporting green hydrogen can play a crucial role. Based on their potential for imports, proximity to India, and purchasing power, Europe, Japan, Korea, and Singapore may serve as India's primary export hubs (SAREP, 2023).

The distribution of sales is shown in the table 3. The demand estimates are converted to monetary terms by using the production costs of GH. In 2018, the cost of producing green hydrogen in India ranged from 3.6 to 5.8 USD/kg depending on the renewable energy mix (CEEW, 2019). An average of 4.7 USD/kg is considered for the conversion.

S No	Industry	GH Demand (MMT)	Sale (M USD)
1	Oil Refining	1.8	8460
2	Natural Gas Blending	0.54	2538
3	Fertilizer	1.32	6204
4	Freight Transport	0.09	423
5	Exports	1.25	5875
Total		5	23500

Table 3: Sales of GH industry output

5.5 Addition of new GH industry and balancing the updated I-O table

After, accessing all the inputs required and the distribution of sales of the GH industry a new column and a new row are added to the OECD I-O table for the inclusion of the GH industry. The OECD I-O table is updated by the data collected. The updated I-O table needs to be rebalanced when the GH sector is added to the existing I-O table to ensure that the total input (addition of various columns) equals the total output (addition of all rows).

The Generalized RAS (GRAS) method is used to solve this problem. The GRAS method is used because it can balance the I-O table including both positive and negative elements. Also, the GRAS method is an iterative approach which can be easily applied in programming languages like MATLAB and R (Umed Temurshoev & Bouwmeester, 2013). MATLAB is used to apply the GRAS method in this study.

The notation used in the further explanation is only valid in this section. In the GRAS method, the initial matrix is considered as A with elements a_{ij}. X is the balanced matrix with elements x_{ij} such that the X has the correct row and column sums. A ratio of z_{ij} is defined such that $z_{ij} = x_{ij}/a_{ij}$. The ratio is set to unity when the $a_{ij} = 0$. The Z matrix essentially indicates how much the matrix A has to be scaled for the balanced matrix X. The objective function of the GRAS method is then defined as

$$\min_{z_{ij}} \sum_{i,j} |a_{ij}| \, z_{ij} \ln\left(\frac{z_{ij}}{e}\right) \tag{12}$$

$$\text{subject to:} \sum_{j} a_{ij} z_{ij} = u_i \text{ for all } i \qquad \sum_{i} a_{ij} z_{ij} = v_j \text{ for all } j$$

where u_i and v_j are the given row and column totals respectively

The initial matrix A is decomposed as $A = P - N$, where P contains the positive elements of A, and N contains the absolute values of the negative elements of A. The equivalent element-wise decomposition is $a_{ij} = p_{ij} - n_{ij}$.

The objective function essentially minimizes the changes from the original estimate A by adjusting the elements of a matrix X to meet specified row and column sums. Now this translates to a non-linear optimization problem with two equality constraints. This can be solved by using the Lagrangian function.

$$\begin{aligned}\mathcal{L}(\mathbf{Z}, \lambda, \tau) = &\sum_{(i,j)\in P} a_{ij} z_{ij} \ln(z_{ij}/e) - \sum_{(i,j)\in N} a_{ij} z_{ij} \ln(z_{ij}/e) \\ &+ \sum_{i} \lambda_i \left[u_i - \sum_{j} a_{ij} z_{ij}\right] + \sum_{i} \tau_j \left[v_j - \sum_{i} a_{ij} z_{ij}\right]\end{aligned} \tag{13}$$

Where λ and τ are the lagrangian multipliers.

Using the optimality conditions we have,

$$\frac{\partial L}{\partial z_{ij}} = |a_{ij}| \left(\ln \left(\frac{z_{ij}}{e} \right) + 1 \right) - \lambda_i a_{ij} - \tau_j a_{ij} = 0 \tag{14}$$

Simplifying this equation, we get:

$$z_{ij} = e^{\lambda_i + \tau_j} \tag{15}$$

Let r_i and s_j be the row and column scaling factors, respectively. Then z_{ij} can be written as $z_{ij} = r_i \; s_j$. From the optimality condition $z_{ij} = e^{\lambda_i + \tau_j}$ we get $r_i = e^{\lambda_i}$ and $s_j = e^{\tau_j}$. The balanced matrix is then

$$\begin{aligned} x_{ij} &= r_i a_{ij} s_j \quad \text{for } a_{ij} \geq 0 \\ x_{ij} &= r_i^{-1} a_{ij} s_j^{-1} \quad \text{for } a_{ij} < 0 \end{aligned} \tag{16}$$

Substituting $z_{ij} = r_i \; s_j$ in the constrains of row and column sums we have

$$r_i = \frac{u_i}{\sum_j a_{ij} s_j} \tag{17}$$

For an iteration process, this is

$$r_i^{(k+1)} = \frac{u_i}{\sum_j a_{ij} s_j^{(k)}} \tag{18}$$

Similarly for the column sums we have,

$$s_j^{(k+1)} = \frac{v_j}{\sum_i a_{ij} r_i^{(k+1)}} \tag{19}$$

where k is the iteration number

Iteration process

1. **Initialize :** Start with an initial guess for s_j, mostly with $s_j^{(0)} = 1$ for all j.
2. **Update Row Scaling Factors :** Now calculate the new row scaling factors $r_i^{(k+1)}$ using equation 18 based on the current column scaling factors $s_j^{(k)}$.
3. **Update Column Scaling Factors :** Now calculate the new column scaling factors $s_j^{(k+1)}$ based on the updated row scaling factors $r_i^{(k+1)}$.
4. **Repeat :** Till the row and column scaling factors converge, that is, the difference between iterations is less than a predetermined threshold, the process is repeated.

The iterations in the GRAS method are essential to guarantee that the balanced matrix precisely satisfies the given row and column sums. Through the iterations, the GRAS approach gradually improves the scaling factors from an initial guess. The row and column scaling factors are adjusted in every iteration to reduce the discrepancy between the current adjusted matrix and the target sums. The iteration process is necessary because the initial guess may not satisfy the constraints, and direct adjustment is typically insufficient due to the interdependent nature of row and column sums.

5.6 Import Savings and Emission Reduction

Among the industries that are considered to purchase the output of GH industry, oil refining and fertilizer use natural gas as a source of hydrogen currently. Also, both of these industries use on-site SMR process to derive hydrogen from natural gas (thyssenkrupp, 2023). India's natural gas demand is growing rapidly particularly in the industrial sector outpacing its domestic production capacity. This led to a heavy import dependency on natural gas of around 46.3% in 2022 (Press Information Bureau, 2023).

Assuming 70% efficiency for the SMR process and 85% of methane content in natural gas, to produce 1 kg of hydrogen around 3.364 kg of natural gas is required. This means that for every kg of hydrogen purchased by oil refining and fertilizer industries from the GH industry, there would be a reduction of 3.364 kg of natural gas in imports. Also, 1.64 kg of carbon dioxide is emitted per kg of natural gas used in the SMR process

For natural gas blending, considering energy content is appropriate for estimating how much natural gas would be replaced by hydrogen for a given blending ratio. Because in energy applications the amount of useful energy that can be extracted from a fuel is more crucial. Blending is typically done on a volumetric basis and the volumetric energy density of hydrogen is 1/3 compared to the natural gas. In an optimistic scenario, it is estimated that in India 15% of green hydrogen will be blended with natural gas in CGD pipes by 2030 (SAREP, 2023). This means that for every kg of blended gas, 0.05 (15% * 1/3) kg of natural gas would be reduced in imports in terms of energy content. The natural gas distributed through CGD pipes is combusted at the end use for domestic and industrial purposes. Combustion of natural gas releases 2.33 kg of carbon dioxide. The natural gas price in Asia was 5.25 USD/kg in 2018 (CEDIGAZ, 2023). The savings on imports and reduction in emissions are thus calculated based on replacing imported natural gas with domestically produced green hydrogen.

6 Results

This chapter presents the GH industry's economic impacts in India, focusing on the construction and operational phases. The impacts are quantified by three indicators: GDP contribution, employment creation and GHG emissions. At first, a broad overview is given by identifying the top five industries contributing to each indicator in both phases. Please refer to the appendix for the detailed results. It is followed by a sensitivity analysis evaluating the influence of imports on economic impacts. Then the inter-industry linkage effect of the GH industry is presented. Finally, the import savings and emission reduction because of using domestic green hydrogen in place of imported natural gas are presented.

6.1 Contribution to GDP

The leading industries contributing to GDP growth in the construction and operational phase are shown in table 4 and table 5 respectively. During the construction phase, the machinery and equipment necessary and electrical equipment industries are leading as they include the manufacturing of electrolysers, compressors and electrical devices which are prime inputs to the GH industry. The basic metals industry is also seen as a significant contributor as it indirectly benefits from the machinery and equipment industry by supplying raw materials and components. In the operational phase, the EGSA industry is leading followed by the GH industry. This is because electricity is the prime input in the operational phase.

S. No	**Industry**	**Change in GDP (M USD)**	**% contribution**
1	Machinery and equipment, necessary	21936	31
2	Electrical equipment	6580	9
3	Wholesale and retail trade; repair of motor vehicles	6567	9
4	Construction	5379	8
5	Basic Metals	5328	8
6	Other industries	25014	35
Total		70805	100

Table 4: Top industries contributing to additional GDP in the construction phase

S. No	**Industry**	**Change in GDP (M USD)**	**% contribution**
1	Electricity, gas, steam and air conditioning supply	598	39
2	Green Hydrogen	376	25
3	Administrative and support services	92	6
4	Financial and insurance activities	84	5
5	Wholesale and retail trade; repair of motor vehicles	56	4
6	Other industries	321	21
Total		1529	100

Table 5: Top industries contributing to additional GDP in the operational phase

6.2 Employment Creation

Table 6 and table 7 represent the major industries that contribute to the increase in employment in the construction and operational phase respectively. The wholesale and retail trade; repair of motor vehicles industry and construction industry are leading in the construction phase. These industries include setting up major infrastructure for the GH industry such as vehicles for hydrogen transport and buildings for housing the equipment and machinery. The manufacturing necessary; repair and installation of machinery and equipment industry is leading in the operational phase as it includes the maintenance of electrolysers and other machinery. The Agriculture, hunting, and forestry industry is seen as a significant contributor to the employment creation in both phases. This is because almost 40% of all the employment in 2018 is from this industry which makes it very sensitive to any change in final demand.

S. No	**Industry**	**Change in Employment (FTE)**	**% contribution**
1	Wholesale and retail trade; repair of motor vehicles	945417	15
2	Construction	933093	15
3	Agriculture, hunting, forestry	893768	14
4	Machinery and equipment, necessary	695904	11
5	Administrative and support services	521130	9
6	Other industries	2212821	36
Total		6202134	100

Table 6: Top industries contributing to additional employment in the construction phase

S. No	Industry	Change in Employment (FTE)	% contribution
1	Manufacturing necessary; repair and installation of machinery and equipment	22133	21
2	Agriculture, hunting, forestry	14319	13
3	Administrative and support services	13817	13
4	Electricity, gas, steam and air conditioning supply	13778	13
5	Green Hydrogen	9760	9
6	Other industries	33048	31
Total		106856	100

Table 7: Top industries contributing to additional employment in the operational phase

6.3 GHG Emissions

While the GH industry is assumed to be having zero GHG emissions, indirect emissions are observed throughout its supply chain. Top industries contributing to additional emissions in the construction and operational phase are shown in table 8 and table 9 respectively. It can be seen that a significant amount of emissions are being released from the Basic metals industry and EGSA industry in both phases. This is because the basic metals industry is included in supplying the metals to manufacture the electrolysers and other infrastructure required for the GH industry. Also because of heavy dependency on fossil fuels for electricity the EGSA industry is observed to be emitting most of the emissions.

S. No	Industry	Change in Emissions (Mt Co2 eq)	% contribution
1	Basic Metals	62	47
2	Electricity, gas, steam and air conditioning supply	49	37
3	Machinery and equipment, necessary	4	3
4	Rubber and plastics products	3	2
5	Other non-metallic mineral products	3	2
6	Other industries	11	9
Total		133	100

Table 8: Top industries contributing to additional emissions in the construction phase

S. No	Industry	Change in Emissions (Mt Co2 eq)	% contribution
1	Electricity, gas, steam and air conditioning supply	9	93
2	Basic Metals	0.3	3
3	Manufacturing necessary; repair and installation of machinery and equipment	0.2	2
4	Coke and refined petroleum products	0.04	0.4
5	Administrative and support services	0.03	0.3
6	Other industries	0.12	1.2
Total		9.5	100

Table 9: Top industries contributing to additional emissions in the operational phase

6.4 Sensitivity Analysis

The GH industry is still in the initial phase of development on a global scale. India being a developing country, the machinery and equipment required may not be readily available domestically, necessitating imports. So a sensitivity analysis is conducted to examine the influence of varying machinery and equipment import levels on the impacts. Three scenarios are created for this analysis: All of the machinery is domestically manufactured (0% imports), half of the machinery is imported (50% imports) and all of the machinery is imported (100% imports).

Table 10 represents the influence of the imports on the impacts. From the table, it can be seen that higher import levels significantly affect economic outcomes. It is observed, that the more the imports, the lesser the growth in GDP, employment creation and emissions produced. This highlights the significance of enhancing domestic manufacturing capabilities to maximize the economic benefits of the GH industry in India.

Scenario	GDP (M USD)	Employment (FTE)	Emissions (Mt CO2 eq)
All of the machinery is domestically manufactured	70804.82	6202134	132.60
Half of the machinery is imported	36272.14	4488163.97	90.42
All of the machinery is imported	24462.55	2774194.42	48.22

Table 10: Influence of imports on impacts

6.5 Inter-industry Linkage Effect

The GH industry falls under the category IV in the classification of linkage results. This depicts that the GH industry is dependent on interindustry supply. The backward linkage of the GH industry is found to be greater than 1. This means that it significantly affects the industries from which it purchases its inputs. This implies that the GH industry can boost these providing sector's growth and expansion. The forward linkage of the GH industry is found to be less than 1. This suggests that its impact on industries that use its outputs as inputs is relatively limited. Please refer to the appendix for the detailed linkage results.

6.6 Import Savings and Emission Reduction

The savings on natural gas imports and reduction in emissions are shown in the table below. It can be seen that there are significant import savings and emission reductions in the oil refining and fertilizer industry. The total savings are found to be around 55 B USD. Reduction in emissions is found to be around 17 MMT. This highlights the role of the GH industry in making India self-reliant and decreasing its carbon footprint.

S No	**Industry**	**Savings (B USD)**	**Emission Reduction (MMT)**
1	Oil Refining	31.8	9.93
2	Fertilizer	23.34	7.28
3	Natural Gas Blending	0.14	0.06
Total		55.28	17.3

Table 11: Import savings and reduction in emissions

7 Discussion

This chapter discusses the results and the recommendations for further research are presented.

7.1 Time scale of the impacts

This study divides the hydrogen industry into construction and operation phases. The demand shock and impact analysis is done for both phases separately. However, one must assess the time frame during which these impacts are generated to interpret them correctly. Considering the time frame of the construction phase as 1 year and the operation phase as 15 years, figure 9 depicts the impacts generated by the GH Industry in both phases. It can be seen that the construction phase contributes around 80% of the total additional GDP and employment created. This is because the construction phase involves building the infrastructure for the GH industry which is labour-intensive, requiring a large workforce for tasks such as site preparation, installation of equipment, and construction of facilities. As a result, it creates a greater amount of economic activity and potential for employment than the operational phase, which is primarily concerned with operation and maintenance and requires comparatively less labour. Also, the significant capital expenditure in the construction phase directly contributes to GDP growth.

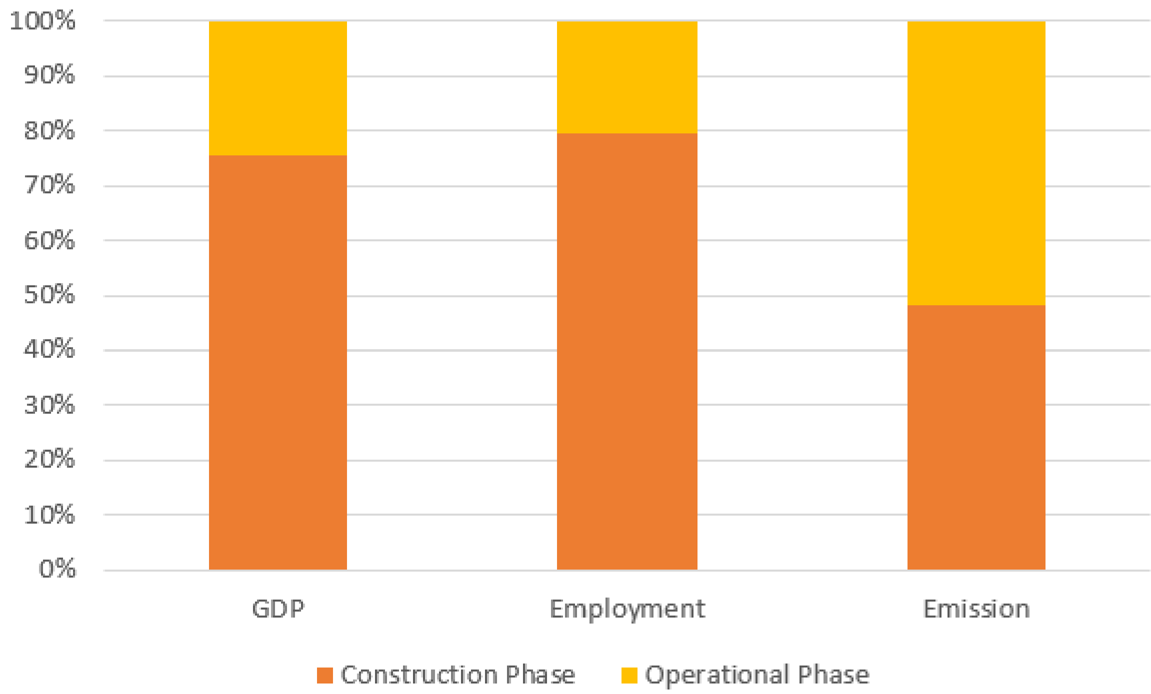


Figure 9: Impacts due to construction and operational phase of GH Industry

7.2 Limitations of the study

Depending on how well the input structure and distribution of sales considered in this study reflect the actual scenario, the accuracy of the results is determined. Also because of inherent assumptions in the I-O model, there is a possibility of overestimation of the results. Firstly, due to fixed technical coefficients and constant returns to scale assumptions, the GDP growth rate can be overestimated. Secondly, as the I-O model assumes a linear relationship between output and labour, it can lead to the overestimation of employment created. Thirdly, because of the fixed technology assumption, there can be an overestimation in the emissions released.

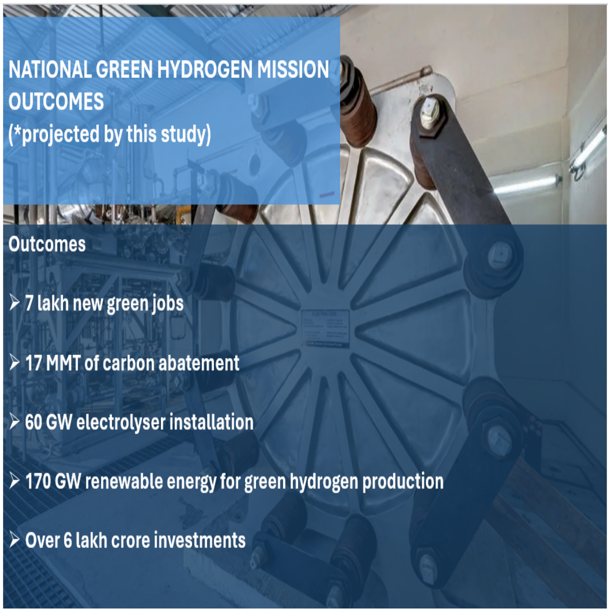
These variables and their relationships would be dynamic rather than static in a more complicated model. Computable general equilibrium (CGE) models, for example, may support variable input-output relations, allowing industries to modify their input mix in response to shifts in policy, technology, or pricing. As industries scale up or down, they may encounter cost benefits or drawbacks that would be taken into consideration by accounting for different returns to scale. Improved models would also consider technology advancements, allowing production functions to change to reflect enhanced productivity. These modifications would give a more realistic and accurate assessment of the economy, possibly resulting in lower and more nuanced estimates of the economic impacts.

Also, this study has been done using the 2018 I-O table of India due to the lack of availability of the latest data. The results could have significantly differed if the latest data had been used because of the change in industrial linkages, technological advancements and economic structure over time. The latest data would reflect the increased integration of renewable energy sources within the economy, changes in the composition of inputs, and the evolution of industries. As industries become more capital-intensive, technological advancements in production processes can result in different input coefficients, potentially lowering the overall input requirements and increasing efficiency. This could lower the GDP contribution and employment creation per unit of green hydrogen capacity. Furthermore, the mix of energy sources in India has been shifting from more conventional to renewable sources. As a result, there can be a lower GHG emission during construction and operational phases.

7.3 Analysis of India's NGHM mission

However, the results of this study are comparable with the projections of NGHM of India. Figure 10 shows the comparison. Over 6 lakh (1 lakh is equivalent to 0.1 million) new green jobs are projected by the NGHM because of the emerging GH industry. But the term green jobs is not well-defined by the NGHM. In this study, the jobs created in the Machinery and equipment industry can be considered green jobs as they involve the supply of electrolysers which is a crucial input to the GH industry. From the table 6 it can be seen that this is around 7 lakh. Further, the NGHM has estimated around 8 lakh crore INR (around 116 B USD) investment to establish the GH industry. From the table 1 we can see the estimation of investment required for the GH industry by this study is 92 B USD which after conversion comes around to 6 lakh crore. The difference can be explained as the investment required depends on the components considered in the evaluation. This study has considered the most essential components required for the establishment of the GH industry. Further detailing in the components included can lead to a more accurate estimation. Lastly, 50 MMT of carbon abatement is estimated by NGHM. From the table 11 it can be seen that this study estimates it to be around 17 MMT. The difference can be explained as it depends on the intensity and number of industries switching from fossil fuels to green hydrogen. In this study, Oil refining, Fertilizers and natural gas blending industries are considered in evaluating the carbon abatement.

(a) NGHM outcomes projected by government



(b) NGHM outcomes projected by this study

Figure 10: Comparision of NGHM outcomes

7.4 Comparision with Swiss study

A similar study has been done by Gupta et al. (2023) for Switzerland. The study has been done at a smaller scale of 1 MW size. The scale of this study has been determined by India's NGHM target of producing 5 MMT of hydrogen per annum by 2030. This translates to establishing a GH industry of 60 GW size. So in terms of scale, the nominal capacity considered for this study is around 6000 times larger when compared to Switzerland.

Both studies have used the I-O model for the analysis. However, the Swiss study has assumed that all of the hydrogen produced is consumed by passenger vehicles. Whereas in this study there is a diversification of sales of the GH industry as seen in table 3 based on the available projections. But while evaluating the impacts only the freight transport industry is considered for the change in final demand. Because of this in this study, the aggregated operational phase impacts are lesser than that of the construction phase which is in contrast with the Swiss study.

Table 12 and table 13 represent the results of the Swiss study and this study per installed capacity of the GH industry. In both countries the contribution of GH industry to additional GDP, employment and GHG emissions are different. This is because India and Switzerland have different economic structures, labour costs, and industrial infrastructure. India being a developing country with a low per capita GDP where labour costs are low shows higher employment potential during the construction phase compared to

Switzerland.

The difference in energy infrastructure, industrial efficiency, and environmental regulations is reflected in the GHG emissions released. India has significantly higher emissions in both phases compared to Switzerland. In 2018, India largely relied on fossil fuels, especially coal, for its energy mix, which raises the carbon intensity of the electrical power needed for GH industry development and operation (Ministry of New and Renewable Energy, 2018). Switzerland, on the other hand, has a far cleaner energy mix and lower corresponding greenhouse gas emissions due to its heavy dependence on nuclear and hydropower (IEA, 2022).

Impact Indicator	**Construction Phase**	**Operational Phase**
Contribution to GDP	2.40 M USD/MW	0.95 M USD/MW/year
Employment Creation	15.08 FTE/MW	5.96 FTE/MW
GHG Emissions	84.18 tCO2 eq/MW	53.15 tCO2eq/MW

Table 12: Results of Swiss study per installed capacity
(Gupta et al., 2023)

Impact Indicator	**Construction Phase**	**Operational Phase**
Contribution to GDP	1.19 M USD/MW	0.026 M USD/MW/year
Employment Creation	104 FTE/MW	1.8 FTE/MW
GHG Emissions	2220 tCO2 eq/MW	160 tCO2eq/MW

Table 13: Results of this study per installed capacity

7.5 Recommendations on Future Research

For further investigation on the topic of this thesis, several recommendations can be made. First, the sector-specific impacts of the GH industry can be explored within the Indian context. While the current study gives a broad overview, further research can focus on the unique benefits and challenges that the adoption of green hydrogen could present for various industries such as steel manufacturing and heavy transport. This would facilitate the development of strategies that optimize economic gains while reducing disruptions within these industries.

Second, narrowing down the geographic scope from a national level to a regional level can be beneficial. India is a land of states with different labour markets, resource availability, and industrial development all of which may have an impact on the GH industry's success and outcomes. Future research could focus on local case studies to determine the best regions for the growth of the GH industry and the potential localized economic effects.

Third, advanced economic modelling and scenario analysis can be done to see how the GH industry may evolve in different scenarios. One can use CGE models to simulate scenarios with varying levels of technological advancement, changes in policy support, and fluctuations in market demand. Policymakers can foresee possible trade-offs between environmental sustainability, job creation, and economic growth with the use of this kind of research, which would help them create more effective policies.

Another important area for future research is the long-term effects of the GH industry on sustainability and the environment. Although the current study addresses emissions during the construction and operational phases, a more thorough life-cycle assessment (LCA) can be carried out. This would include the effects on the environment by extracting raw materials, production, transportation, and disposing of or recycling GH infrastructure when it has reached the end of its useful life. A more comprehensive understanding of the true environmental costs and advantages of green hydrogen as a clean energy source can be obtained from such a study.

8 Conclusion

The main objective of this study is to evaluate the economic impacts of the emerging green hydrogen industry in India. This is done by analysing the National Green Hydrogen Mission of India, which aims to produce 5 MMT of hydrogen per annum by 2030. This translates to a 60 GW green hydrogen production capacity. The main research question of this study is

What are the economic impacts of the emerging green hydrogen industry in India?

This is further divided into sub-questions which will be answered in the following paragraphs.

What would be the contribution of the green hydrogen industry to GDP growth and employment generation in India?

From the impact analysis, it was found that in the construction phase of a 60 GW green hydrogen industry, there would be a contribution of around 70805 M USD to the GDP and around 6 million jobs would be created. While in the operational phase, the GDP contribution is around 1530 M USD/year and the employment generation is around 0.1 million jobs per year.

What would be the reduction in emissions and savings in imports by switching to green hydrogen in India?

Oil refining, Fertilizer and Natural gas blending industries are considered to switch from natural gas to green hydrogen. Because of this the reduction in emissions is found to be around 17 MMT and the import savings are around 55 B USD.

What would be the most affected industries by the emerging green hydrogen industry in India?

The industries that are required to increase their output to a large extent to support the establishment of the GH industry are considered the most affected industries. From the linkage results it is found that the GH industry will significantly affect its supplying industries. Further from the demand shock analysis, it is observed that Machinery and Equipment, Basic Metals and Electrical equipment industries will be the most affected in the construction phase. While in the operational phase, the EGSA, Administrative and support services and FIS are found to be the most affected.

In conclusion, the main research question is addressed by combining the answers to the sub-research questions

What are the economic impacts of the emerging green hydrogen industry in India?

The economic impacts of the emerging green hydrogen industry can be seen in three-folds. For every GW scale of green hydrogen plant installed, there would be an addition of around 1575 M USD to the GDP and an addition of around 131135 FTE jobs including both the construction and operational phases. Additionally in the operational phase, for a GW-scale plant, there would be import savings of around 1 B USD per year because of industries switching from fossil fuels to green hydrogen.

India has just announced the NGHM in January 2021. To the best knowledge of the author, this study is the first to scientifically evaluate the economic implications of an emerging green hydrogen industry in India. The outcomes of the NGHM are estimated in this study which mostly aligns with the government projections. The findings of this study can be used by policymakers to develop appropriate frameworks and regulations that would define the terms of their hydrogen strategy. For example, understanding the GDP contribution facilitates the decision-making process when it comes to investments and subsidies, and knowledge of employment generation aids in workforce planning and social policies. Furthermore, the emissions analysis reveals the environmental trade-offs and advantages, which directs the development of rules and guidelines to reduce the carbon footprint of the GH industry. Also, the detailed description of the input data and methodology used in evaluating the economic impacts in this study can be seen as a potential scientific contribution.

Overall a positive economic impact is estimated by the establishment of the green hydrogen industry in India. But from the viewpoint of decarbonisation, one has to observe that there are indirect emissions along the value chain of the green hydrogen industry as shown in this study. Therefore decarbonisation of such industries as machinery and equipment in the construction phase is important to have the footprint of the whole green hydrogen ecosystem cleaner. Finally, this study provides an important policy message for the decision-makers who are designing hydrogen strategies: The establishment of the green hydrogen industry not only reduces emissions but also boosts the national economy by significantly contributing to GDP growth and employment generation.

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A Appendix - Production of hydrogen

The global demand for hydrogen in 2021 can be seen in Figure 11. From the figure, it is clear that the demand is majorly driven by the use of hydrogen in ammonia synthesis and Petroleum refineries. Almost 80 % of global hydrogen produced is consumed by these two industries. In ammonia synthesis, hydrogen is a key component that reacts with nitrogen to form ammonia through the Haber-Bosch process. Additionally, hydrogen is also used in hydrocracking, hydrotreating, and desulfurization, among other critical activities, which are essential to the refining process. These refining processes are necessary to fulfil strict environmental standards and transform crude oil into valuable petroleum products like jet fuel, diesel, and gasoline.

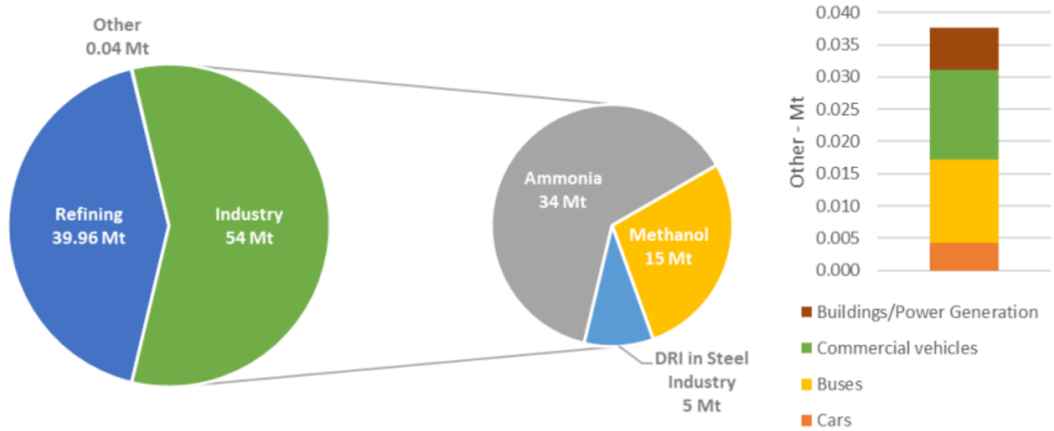

Figure 11: Global hydrogen demand in 2021, million metric tons (Mt)
(EFI Foundation, 2024)

The use of different sources for hydrogen production in 2021 at a global scale can be seen in Figure 12. From the figure, we can observe that almost 99% of hydrogen produced globally comes from fossil fuel sources mainly from natural gas and coal(ARC Advisory Group, 2021). Steam methane reforming(SMR) and coal gasification are the most prominent methods used for the industrial production of hydrogen. In SMR methane and steam are reacted at high pressures and temperatures (usually 700–1100°C) to create hydrogen and carbon monoxide. Whereas, coal gasification involves converting coal through a high-temperature reaction with steam and oxygen to synthesis gas (syngas), a combination of hydrogen, carbon monoxide, and other gases. The SMR method is mostly used because of its high energy efficiency(70–85%) compared to coal gasification (60–75%) (Ji & Wang, 2021).

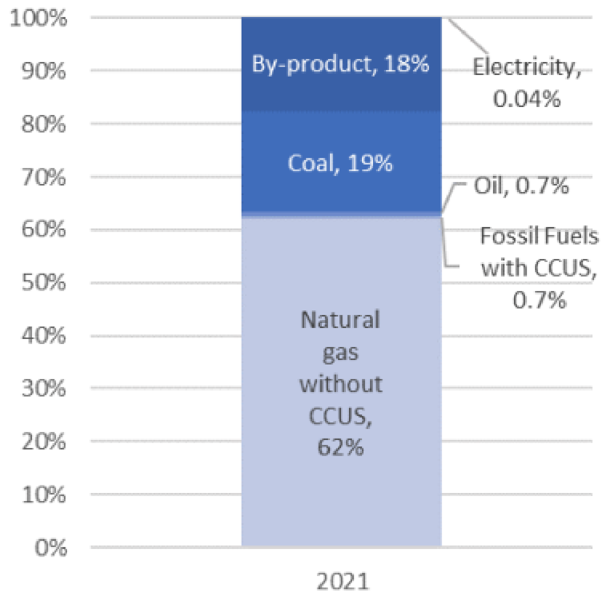

Figure 12: Global hydrogen production mix in 2021, percentage (EFI Foundation, 2024)

Although the cost of producing hydrogen from fossil fuels is still competitive, there are environmental issues because of its significant carbon footprint. Carbon capturing is integrated with fossil fuel-based production processes to reduce emissions. Using Carbon capture, utilization, and storage(CCUS) technology, CO_2 is caught and stored underground in geological formations for long-term sequestration. It may also be used for a variety of purposes, including increased oil recovery and the synthesis of chemicals and minerals. The amount of CO_2 released for every kg of hydrogen produced from different production methods can be seen in Figure 13. Hydrogen derived from natural gas coupled with CCUS has the lowest CO_2 intensity after hydrogen produced from renewable or nuclear power. Also generating electricity by coal and natural gas for electrolysis has a high CO_2 intensity (Tymofiiv, Al-Rabeei, Hovanec, & Korba, 2022). The analysis done by DNV GL shows that to produce hydrogen using water electrolysis with less CO2 emissions than fossil fuels with CCUS, the energy mix's carbon intensity would need to be less than 75g CO_2/kWh. Compared to the global average of 500 gCO_2/kWh, this is substantially lower (Coal Age, 2021).

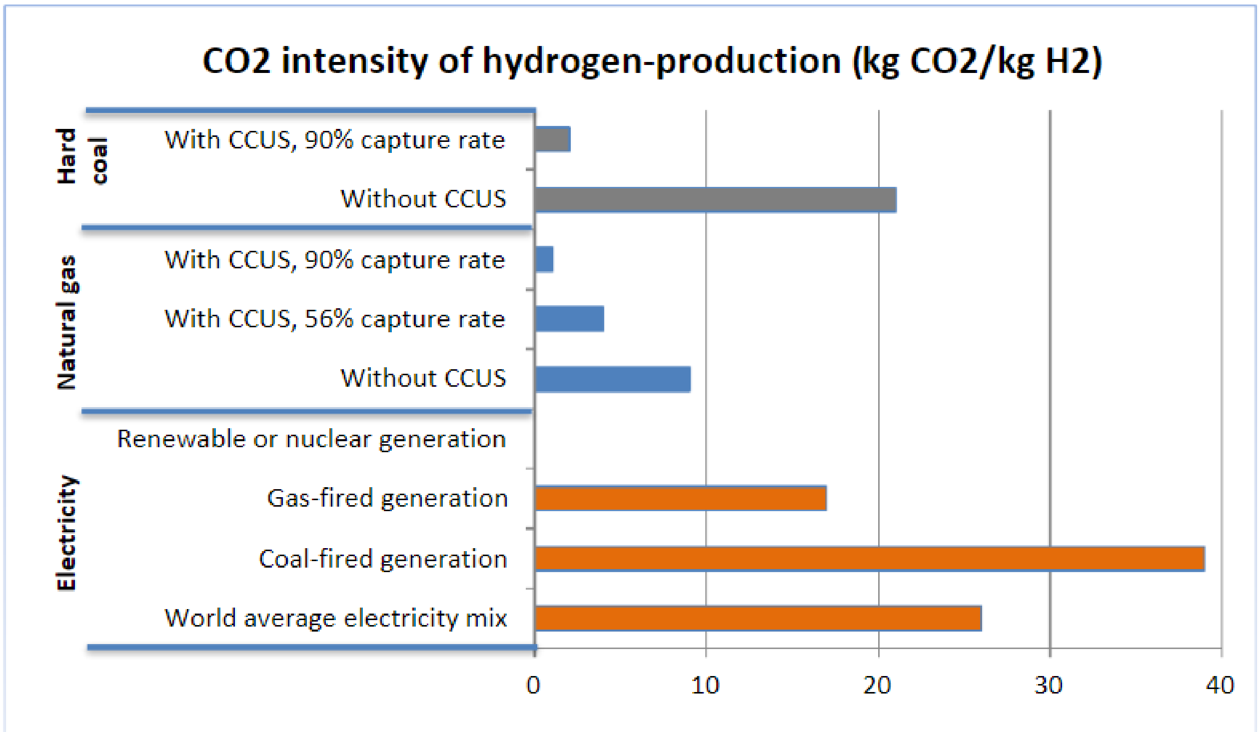

Figure 13: CO_2 intensity of hydrogen-production (kg CO_2/kg H2) (Tymofiiv et al., 2022)

Lately, there has also been growing interest in hydrogen production from biomass. This is mostly driven by its renewable and carbon-neutral nature, offering opportunities to reduce greenhouse gas emissions and repurposing organic waste simultaneously. The energy efficiency of biomass to hydrogen is around 70 % using gasification. However, the production costs are higher for biomass pathways than for fossil fuel and water electrolysis pathways. Mostly, biomass pathways can not compete with fossil fuel pathways without any economic policy support (ETIP Bioenergy, 2021).

Based on the raw material for production, hydrogen is labelled with different colours. Every colour denotes a varying degree of sustainability and environmental impact. The hydrogen produced from a fossil fuel source is termed "grey hydrogen". When 80–90% of the CO_2 emitted during the production of grey hydrogen is captured and stored, then it is referred to as "blue hydrogen" or "low carbon hydrogen". Green hydrogen, also referred to as "renewable hydrogen," is hydrogen produced using renewable energy sources. Electrolysis of water is the most used method in the production of green hydrogen which includes splitting of water using renewable electricity.

B Appendix - Challenges of green hydrogen

B.0.1 High production costs

Hydrogen from electrolysis accounts for only 0.04% of global hydrogen generation, as shown in figure 12. This is mainly due to the higher production costs associated with green hydrogen. The average levelised cost of hydrogen produced from fossil sources is about 1-3 USD/kg, whereas it is about 3-8 USD/kg from renewable sources (IEA, 2020). However, according to a forecast drawn up by McKinsey & Company, the production costs of green hydrogen are expected to reduce by 50 % by 2030 (McKinsey & Company, 2022).

The electricity prices in the operational expenditure (OPEX) and the cost of electrolysers in the capital expenditure(CAPEX) are the two key cost components for the high production costs of green hydrogen. The electricity prices account for about 50-70% of the total production costs (Eh et al., 2022). Coming to the electrolyser system, the stacks account for around 50% of the entire system. The rest includes the balance of plant (BoP) and power electronics costs (Store&GO, 2018).

Also, the scale of production of electrolysers is slow. As of now, most of the electrolysers are in the range of megawatts (MW). By scaling up the plant from 1 MW to 20 MW, it is estimated to have significant cost reductions which would be about one-third of the original expenses (Patonia & Poudineh, 2022). However, it is at the 1 GW/year level where the greatest benefits for economies of scale in electrolyser production seem to be obtained. A cost reduction of about 60%-70% in the stack is estimated at this scale compared to a MW-scale (IRENA, 2020). Figure 14 shows the potential possibilities of cost reductions to achieve 1 USD/ kgH_2 in future. It can be seen that through cost reductions in electrolysers and electricity, along with technological advancements i.e. by increasing the efficiency and the lifetime of electrolysers the green hydrogen can become competitive in future.

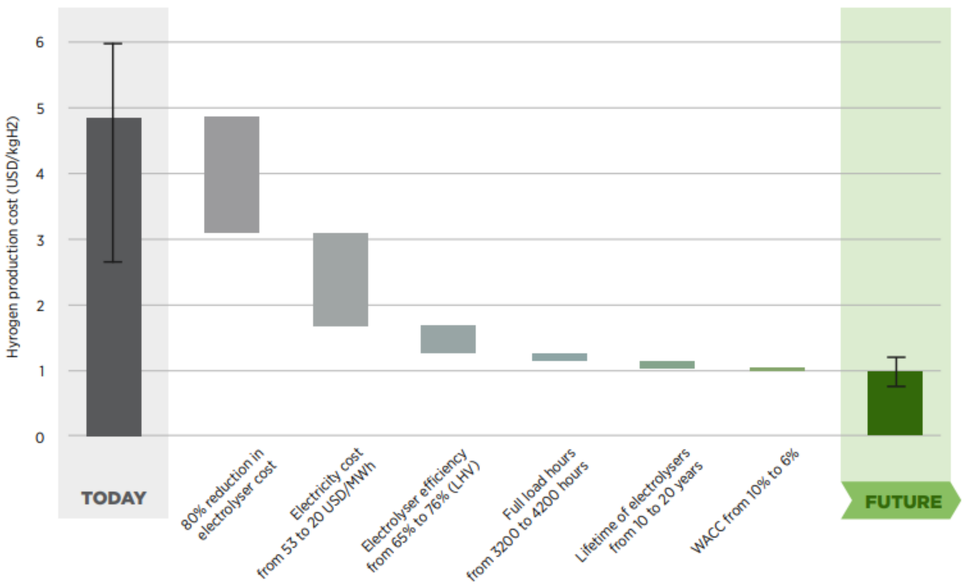

Figure 14: Step changes for achieving green hydrogen competitiveness (IRENA, 2020)

B.0.2 Distribution and Storage

Distribution and storage of hydrogen are two issues that need to be resolved to speed up the commercialization of hydrogen and fuel cell technologies, as the hydrogen infrastructure is still not developed enough to allow for the decentralized use of hydrogen fuel cell systems (Eh et al., 2022). The main difficulty with hydrogen transportation and storage stems from its poor volumetric energy density and significantly lower boiling point. Because of this, hydrogen must be stored at high pressures or low temperatures to reach useful levels of energy storage.

Transport expenses are determined by the energy carrier, the distance travelled, and the volume transmitted as shown in figure 15. Truck transportation of compressed hydrogen is viable for small amounts and short distances (up to a few hundred kilometres). Hydrogen is often carried in liquid form over longer distances. Hydrogen must be cooled to –253°C or below to be liquefied. In one truck, up to 3,500 kg of liquid hydrogen can be delivered. Trucks are a less practical alternative as volume and distance rise. Compressed hydrogen pipes might be utilized as an alternative. They could be able to transport thousands of tons every day. Transporting hydrogen via pipeline can be as cheap as a tenth of the price of transferring the same amount of energy as electricity (IRENA, 2021).

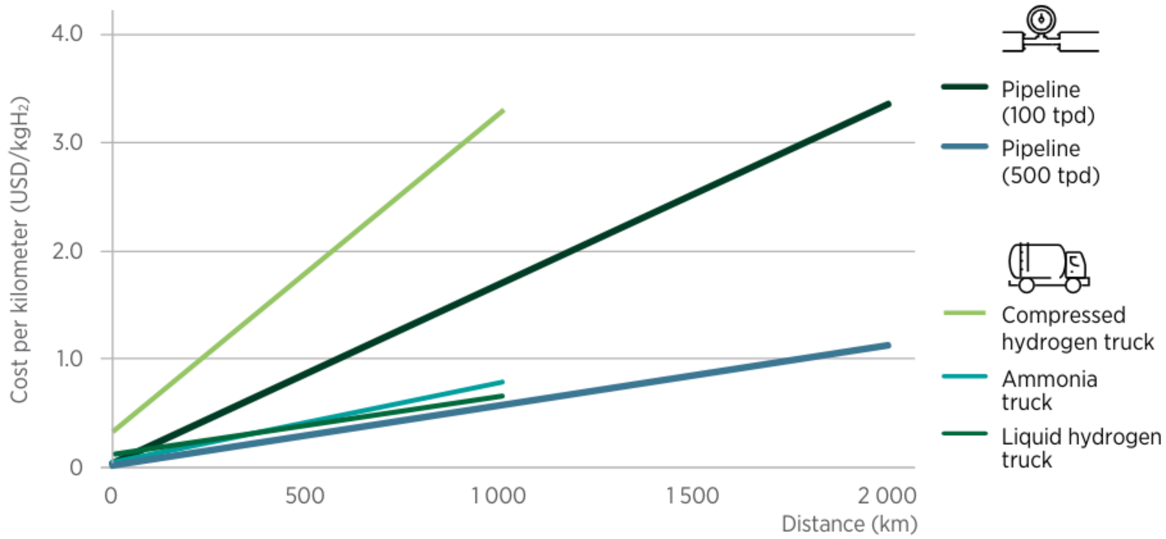

Figure 15: Costs of hydrogen transport by different modes
(IRENA, 2021)

Coming to the storage, the cycle or frequency of usage of the storage facility determines the levelized cost of storage. Figure 16 demonstrates the different hydrogen storage options. Regarding storing hydrogen, cycling is essentially the number of times a year when the facility is filled and emptied. The additional cost of the storage per given unit of hydrogen will decrease with increased usage. Because of this, technologies that require a lot of capital investment but have small volumes (like pressurized tanks or liquefied hydrogen tanks) must cycle frequently to lower their total delivered cost per unit, whereas low capital investment solutions (like salt caverns) are best suited for a few cycles annually (like seasonal storage) (IRENA, 2021). From the figure 16 we can see that, Salt cavern and high-pressure tank storages have lower levelized cost of storage

(LCOS) because they are mature technologies, while the other options are, for the most part, at the lab scale.

	Gaseous state				Liquid state			Solid state
	Salt caverns	Depleted gas fields	Rock caverns	Pressurized containers	Liquid hydrogen	Ammonia	LOHCs	Metal hydrides
Main usage (volume and cycling)	Large volumes, months-weeks	Large volumes, seasonal	Medium volumes, months-weeks	Small volumes, daily	Small - medium volumes, days-weeks	Large volumes, months-weeks	Large volumes, months-weeks	Small volumes, days-weeks
Benchmark LCOS ($/kg)[1]	$0.23	$1.90	$0.71	$0.19	$4.57	$2.83	$4.50	Not evaluated
Possible future LCOS[1]	$0.11	$1.07	$0.23	$0.17	$0.95	$0.87	$1.86	Not evaluated
Geographical availability	Limited	Limited	Limited	Not limited	Not limited	Not limited	Not limited	Not limited

Source: BloombergNEF. Note: [1] Benchmark levelized cost of storage (LCOS) at the highest reasonable cycling rate (see detailed research for details). LOHC – liquid organic hydrogen carrier.

Figure 16: Hydrogen storage options
(BloombergNEF, 2020)

B.0.3 Safety

There are also concerns about safety while using hydrogen as an energy carrier. One of the primary concerns is hydrogen's flammability and explosive potential, particularly when combined with air in specific amounts. Hydrogen is extremely flammable in a wide range of concentrations, from 4% to 74%, and it also creates highly flammable mixes with air. Even at low concentrations, hydrogen is especially prone to ignite due to its broad range. While hydrogen has no taste, smell, or colour, the flames created by a hydrogen fire are almost invisible, which further poses security and detection challenges (The National Hydrogen Association, 2018).

The other concern is hydrogen leakage into the atmosphere. Being a tiny molecule, hydrogen is challenging to confine. Throughout the value chain, it is known to leak into the atmosphere with ease. The likelihood of leakage increases with the distance between production and final usage. Though hydrogen is not directly a greenhouse gas, it does influence the quantities of methane, ozone, and stratospheric water vapour in addition to aerosols through chemical reactions. A recent study has found the global warming potential of hydrogen to be 11.6, which is significant (Sand, Skeie, Sandstad, et al., 2023). In a high leakage scenario, the warming effects of hydrogen emissions could be nearly twice as much in the first five years after replacing fossil fuels. However, in the same time frame, hydrogen might result in an 80% reduction in warming if leak rates are low (Environmental Defense Fund, 2023).

Despite these challenges, research on advanced safety methods and technology to reduce hazards and guarantee hydrogen's safe use in various industrial and energy applications is still driven by hydrogen's potential as a clean, efficient energy source.

C Appendix - Transitioning to Net Zero Emissions

To reach net zero emissions, fossil fuels must be replaced in every sector by renewables both as primary energy sources and energy carriers. While zero-carbon electricity is expected to play a crucial role – both as a primary energy source and direct energy carrier, other energy carriers, such as hydrogen and biofuels, also have critical roles to play. Also, energy efficiency needs to be improved which is not often discussed in the debate about a sustainable future (Jake Whitehead & Lim, 2023).

Electrification is preferred wherever it is possible because of its high energy efficiency. The efficiency gains of electrification can reduce energy demand by up to 40% (Eyre, 2021). According to a recent study done by the Energy Transitions Commission(ETC), it was forecasted that electricity would be around 67-72% of the global final energy share by 2050 to reach net zero emissions. This includes powering the majority of transport, heating, and agriculture. Strong efficiency gains from the increasing proportion of electricity in the energy mix are also anticipated to lower final energy consumption (Energy Transitions Commission, 2020).

Where electrification is not possible, hydrogen and its derivative fuels are expected to play a major role at 18-20% of the global final energy share in 2050 – under a net zero emissions scenario by ETC. Emission reduction potential, costs and efficiency would be the main criteria for choosing alternatives in the hard-to-abate industries. Figure 17 illustrates the emissions reduction potential of hydrogen compared with direct electrification. The figure shows that hydrogen can play a significant role in hard-to-abate industries while opting for direct electrification where it is possible is beneficial as it accounts for a higher emissions reduction potential compared with hydrogen.

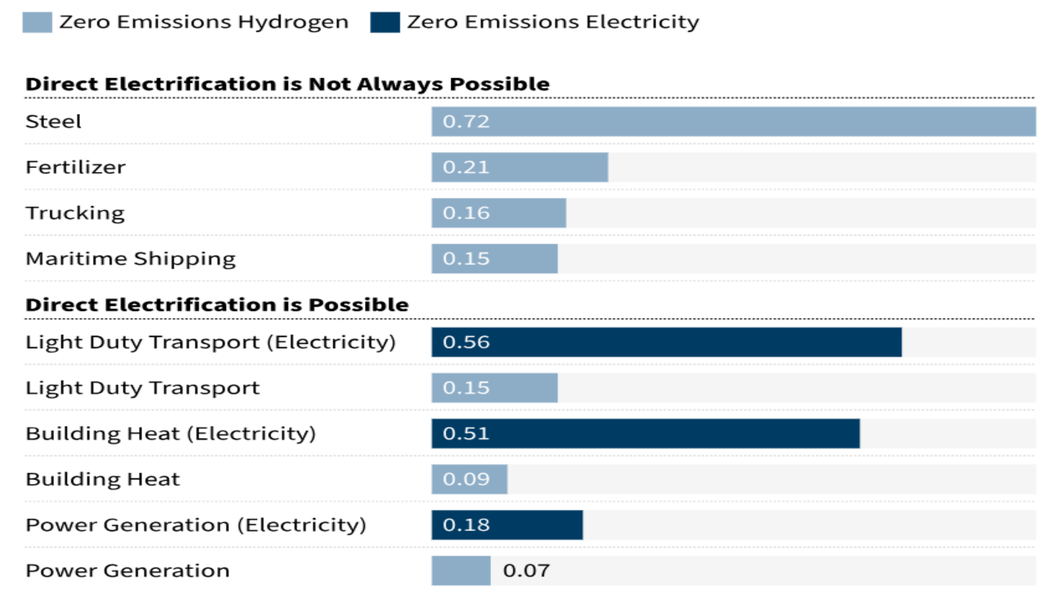

Figure 17: Emissions Reduction Potential: Hydrogen Vs Direct Electrification (KgCO_2 e/Kwh)

(RMI, 2022)

The end use of renewable hydrogen, and hydrogen-derived fuels, is energy-intensive, consuming two to fourteen times more electricity than direct electrification. So, going for more hydrogen would lead to investing even more in producing electricity worldwide, adding to the already high demand for electrification. Thus, a balance must be achieved with the strategic use of hydrogen directed towards those harder-to-electrify applications (Jake Whitehead & Lim, 2023).

Bioenergy is expected to play a minor role in heating, heavy industry, shipping, aviation, and agriculture – at around 4% of the global final energy share in 2050 as per ETC. The possibility of competition for land and water resources, particularly with the growing global population, is a major source of concern about the ability to "sustainably" supply feedstock for bioenergy. One possible counterargument to the benefits of adopting bioenergy to replace fossil fuels in the fight against climate change is the loss of soil carbon during the planting of energy crops or residue clearance (George & Cowie, 2011). In these aspects, algae are gaining much interest as they can be grown on non-arable lands, using saltwater or brackish water. Also, algae are said to have the potential to yield at least 30 times more energy than land-based crops currently used to produce biofuels. However, this technology is in the initial stages and needs to scale commercially to contribute significantly to emissions reduction (Biotechnology Innovation Organization, 2020).

According to the ETC, fossil fuels will still account for 7–10% of the total energy share in 2050, but they will be used in combination with carbon capture and storage (CCS) technology. CCS is mostly seen as a false solution to climate change as it enables industries to keep operating and polluting while claiming to be part of the climate solution (Earthjustice, 2023). CCS was at the heart of negotiations at the COP28 climate summit, held in Dubai. There's a heated debate going on over whether or not fossil fuels should be "phased down" or "phased out," and how much the usage of "abatement" technologies like CCS should allow for the ongoing use of fossil fuels (Energy Monitor, 2023). Some say CCS has a critical role to play, but only as a last resort given the potential costs and risks to investors concerning stranded assets. For example, further investment in fossil fuel extraction today, based on the promise of CCS becoming economically viable, is not only a risky proposition but also diverts much-needed capital away from emission-reduction technologies, such as renewable energy generation, batteries, and electric vehicles (Jake Whitehead & Lim, 2023).

Overall, hydrogen is positioned to decarbonise hard-to-abate sectors, where other options are less mature or more costly in the journey of achieving net zero emissions. The alternatives for such a specific role can be biofuels and CCS. While biofuels face the challenge of competition for land and water resources, the development of algae-based biofuels can be a potential competitor to hydrogen. Coming to CCS, it can offer a short-term solution to abate emissions until fossil fuels are replaced by renewable energy sources. In the long run, hydrogen has the potential to contribute 10-12% of the mitigation required to keep global warming to 1.5°C (IRENA, 2023).

D Appendix - Electrolyser Capacity Calculations

NGHM is aiming to produce 5 MMT of hydrogen annually by 2030
Lower Heating Value(LHV) of hydrogen = 33.33 Kwh/Kg
Assuming
Electrolyser efficiency = 0.7
Operational hours = 4000

$$\text{Electrolyser capacity required for 5 MMT} = \frac{\text{Amount of hydrogen} \cdot LHV}{\text{Efficiency} \cdot \text{opeartional hours}} \tag{20}$$

Electrolyser capacity required for 5 MMT = 59.52 GW
Assuming
capacity factor = 0.35

$$\text{Renewable energy required} = \frac{\text{Eletrolyser Capacity}}{\text{Capacity factor}} \tag{21}$$

Renewable energy required = 170 GW

E Appendix - Construction Phase

E.1 Demand Shock Analysis

S No	Industry Name	Change in output (M USD)
1	Agriculture, hunting, forestry	2082.184
2	Fishing and aquaculture	34.5283
3	Mining and quarrying, energy producing products	2252.578
4	Mining and quarrying, non-energy producing products	2305.789
5	Mining support service activities	972.8706
6	Food products, beverages and tobacco	825.7724
7	Textiles, textile products, leather and footwear	1339.928
8	Wood and products of wood and cork	375.5083
9	Paper products and printing	810.8717
10	Coke and refined petroleum products	5894.627
11	Chemical and chemical products	4162.758
12	Pharmaceuticals, medicinal chemical and botanical products	473.9302
13	Rubber and plastics products	2532.435
14	Other non-metallic mineral products	2414.183
15	Basic metals	27833.56
16	Fabricated metal products	3838.555
17	Computer, electronic and optical equipment	879.73
18	Electrical equipment	25407.43
19	Machinery and equipment, necessary	62824.18
20	Motor vehicles, trailers and semi-trailers	529.801
21	Other transport equipment	272.2403
22	Manufacturing necessary ; repair and installation of machinery and equipment	1483.287
23	Electricity, gas, steam and air conditioning supply	6501.968
24	Water supply; sewerage, waste management and remediation activities	472.6346
25	Construction	13008.75
26	Wholesale and retail trade; repair of motor vehicles	8391.375
27	Land transport and transport via pipelines	3800.366
28	Water transport	118.2952
29	Air transport	344.3372
30	Warehousing and support activities for transportation	1038.737

31	Postal and courier activities	161.618
32	Accommodation and food service activities	410.6591
33	Publishing, audiovisual and broadcasting activities	62.40614
34	Telecommunications	596.0098
35	IT and other information services	35.52411
36	Financial and insurance activities	3383.525
37	Real estate activities	349.9579
38	Professional, scientific and technical activities	154.3999
39	Administrative and support services	5177.543
40	Public administration and defence; compulsory social security	0.471432
41	Education	89.9363
42	Human health and social work activities	0.9765
43	Arts, entertainment and recreation	4.288823
44	Other service activities	17.72004
45	Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use	0
Total		193668.2

Table 14: Demand Shock Analysis for construction phase

E.2 Impact Analysis

S No	Industry Name	Change in GDP (M USD)	Change in Employment (FTE)	Change in Emissions (tco2 eq)
1	Agriculture, hunting, forestry	1690.615	893768.5	188224.1
2	Fishing and aquaculture	29.9202	1965.151	98.18884
3	Mining and quarrying, energy producing products	1521.572	26686.72	1166802
4	Mining and quarrying, non-energy producing products	1148.567	186619.7	481301.2
5	Mining support service activities	740.9161	1880.602	112733.6
6	Food products, beverages and tobacco	147.6371	21427.71	9962.756
7	Textiles, textile products, leather and footwear	406.1895	97717.26	52878.53
8	Wood and products of wood and cork	146.3864	53790.07	2060.764
9	Paper products and printing	256.5385	28020.48	83300.48
10	Coke and refined petroleum products	789.4771	6848.723	1945218
11	Chemical and chemical products	1184.355	31618.17	409870.8
12	Pharmaceuticals, medicinal chemical and botanical products	220.4433	4187.955	64520.31

13	Rubber and plastics products	706.0319	27500.43	2805490
14	Other non-metallic mineral products	925.147	109883.3	2762293
15	Basic metals	5328.243	230527.3	62130614
16	Fabricated metal products	1298.702	200334.4	60829.5
17	Computer, electronic and optical equipment	243.776	3527.802	12865.8
18	Electrical equipment	6579.85	284659.2	376284.4
19	Machinery and equipment, necessary	21936.37	695904.2	4179833
20	Motor vehicles, trailers and semi-trailers	166.159	3334.498	3929.617
21	Other transport equipment	124.1191	1710.334	1418.188
22	Manufacturing necessary ; repair and installation of machinery and equipment	382.3756	205989.2	1735149
23	Electricity, gas, steam and air conditioning supply	3019.983	76087.26	49128852
24	Water supply; sewerage, waste management and remediation activities	229.4971	25089.24	56051.2
25	Construction	5379.086	933092.7	346162.7
26	Wholesale and retail trade; repair of motor vehicles	6567.279	945417.1	575801
27	Land transport and transport via pipelines	2114.675	345380.6	1470360
28	Water transport	50.63576	4130.825	152622.9
29	Air transport	74.735	3829.111	511745.2
30	Warehousing and support activities for transportation	498.9291	62650.93	177666.4
31	Postal and courier activities	97.43917	13697.97	28394.77
32	Accommodation and food service activities	140.9981	29991.92	8838.862
33	Publishing, audiovisual and broadcasting activities	27.38323	964.7431	2001.08
34	Telecommunications	221.717	5291.722	101465.2
35	IT and other information services	26.31603	489.7558	894.4451
36	Financial and insurance activities	2432.335	67017.41	94221.15
37	Real estate activities	295.9613	718.7375	18119.43
38	Professional, scientific and technical activities	99.11067	24614.29	20758.26
39	Administrative and support services	3465.111	521130.2	1325936
40	Public administration and defence; compulsory social security	0.373375	32.2223	8.457036
41	Education	73.31231	13139.8	2098.339
42	Human health and social work activities	0.641607	131.4944	18.40005
43	Arts, entertainment and recreation	2.520658	1233.317	126.7411
44	Other service activities	13.38499	10100.51	1964.381
45	Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use	0	0	0
46	Total	70804.82	6202134	1.33E+08

Table 15: Impact Analysis of Construction Phase

F Appendix - Operational Phase

F.1 Demand Shock Analysis

S No	Industry Name	Change in output (M USD)
1	Green Hydrogen	1911.447
2	Agriculture, hunting, forestry	33.35791
3	Fishing and aquaculture	0.321476
4	Mining and quarrying, energy producing products	63.32312
5	Mining and quarrying, non-energy producing products	11.00357
6	Mining support service activities	16.50395
7	Food products, beverages and tobacco	6.586969
8	Textiles, textile products, leather and footwear	14.28062
9	Wood and products of wood and cork	10.25372
10	Paper products and printing	23.78384
11	Coke and refined petroleum products	112.9449
12	Chemical and chemical products	29.96043
13	Pharmaceuticals, medicinal chemical and botanical products	3.775803
14	Rubber and plastics products	9.664988
15	Other non-metallic mineral products	11.71255
16	Basic metals	129.7884
17	Fabricated metal products	18.97202
18	Computer, electronic and optical equipment	3.74737
19	Electrical equipment	6.824723
20	Machinery and equipment, necessary	5.18407
21	Motor vehicles, trailers and semi-trailers	1.81937
22	Other transport equipment	1.792779
23	Manufacturing necessary ; repair and installation of machinery and equipment	163.3051
24	Electricity, gas, steam and air conditioning supply	1316.07
25	Water supply; sewerage, waste management and remediation activities	47.74189
26	Construction	63.39334
27	Wholesale and retail trade; repair of motor vehicles	71.51676
28	Land transport and transport via pipelines	36.27415
29	Water transport	1.7391
30	Air transport	5.07357

31	Warehousing and support activities for transportation	9.754711
32	Postal and courier activities	9.822247
33	Accommodation and food service activities	14.87096
34	Publishing, audiovisual and broadcasting activities	1.420988
35	Telecommunications	30.91251
36	IT and other information services	1.55565
37	Financial and insurance activities	117.2519
38	Real estate activities	2.771277
39	Professional, scientific and technical activities	1.709907
40	Administrative and support services	138.1717
41	Public administration and defence; compulsory social security	0.008027
42	Education	2.374497
43	Human health and social work activities	0.027161
44	Arts, entertainment and recreation	0.199559
45	Other service activities	0.37428
46	Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use	0
Total		4463.389

Table 16: Demand Shock Analysis for Operational phase

F.2 Impact Analysis

S No	Industry Name	Change in GDP (M USD)	Change in Employment (FTE)	Change in Emissions (tco2 .eq)
1	Green Hydrogen	376.2365	9760.582	0
2	Agriculture, hunting, forestry	27.06039	14318.74	3015.47
3	Fishing and aquaculture	0.278377	18.29655	0.914187
4	Mining and quarrying, energy producing products	42.69723	750.201	32800.43
5	Mining and quarrying, non-energy producing products	5.461822	890.577	2296.841
6	Mining support service activities	12.54639	31.90286	1912.433
7	Food products, beverages and tobacco	1.172606	170.9232	79.47028
8	Textiles, textile products, leather and footwear	4.309441	1041.446	563.5663
9	Wood and products of wood and cork	3.986579	1468.804	56.2717
10	Paper products and printing	7.503645	821.8743	2443.303
11	Coke and refined petroleum products	14.317	131.2259	37271.64

12	Chemical and chemical products	8.098999	227.564	2949.945
13	Pharmaceuticals, medicinal chemical and botanical products	1.749611	33.36544	514.0334
14	Rubber and plastics products	2.681047	104.9548	10707.1
15	Other non-metallic mineral products	4.469875	533.1056	13401.43
16	Basic metals	24.74931	1074.953	289716.2
17	Fabricated metal products	6.406293	990.1505	300.6492
18	Computer, electronic and optical equipment	1.035418	15.02732	54.80422
19	Electrical equipment	1.762955	76.46267	101.0742
20	Machinery and equipment, necessary	1.806094	57.424	344.9077
21	Motor vehicles, trailers and semi-trailers	0.568947	11.45088	13.49455
22	Other transport equipment	0.815339	11.26304	9.339167
23	Manufacturing necessary ; repair and installation of machinery and equipment	41.92198	22132.59	186433.8
24	Electricity, gas, steam and air conditioning supply	598.2973	13778.52	8896668
25	Water supply; sewerage, waste management and remediation activities	23.13412	2527.978	5647.688
26	Construction	26.15213	4547.084	1686.896
27	Wholesale and retail trade; repair of motor vehicles	55.92658	8057.235	4907.214
28	Land transport and transport via pipelines	20.16132	3296.627	14034.46
29	Water transport	0.742286	60.72872	2243.763
30	Air transport	1.099861	56.4193	7540.211
31	Warehousing and support activities for transportation	4.681996	588.3506	1668.453
32	Postal and courier activities	5.917129	832.4867	1725.677
33	Accommodation and food service activities	5.089282	1086.08	320.0767
34	Publishing, audiovisual and broadcasting activities	0.622605	21.9672	45.56459
35	Telecommunications	11.48121	274.4593	5262.572
36	IT and other information services	1.152046	21.44606	39.16712
37	Financial and insurance activities	84.24161	2315.77	3255.789
38	Real estate activities	2.342586	5.691596	143.4856
39	Professional, scientific and technical activities	1.096673	272.5917	229.888
40	Administrative and support services	92.40606	13817.52	35156.56
41	Public administration and defence; compulsory social security	0.006352	0.548633	0.143994
42	Education	1.93472	346.9168	55.40032
43	Human health and social work activities	0.017807	3.657416	0.511783
44	Arts, entertainment and recreation	0.117238	57.38615	5.897251
45	Other service activities	0.282486	213.3416	41.4914
46	Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use	0	0	0

Total		1528.539	106855.7	9565666

Table 17: Impact Analysis for Operational Phase

F.3 Inter-Industry Linkage Effect

S No	Industry Name	Backward Linkage	Forward Linkage	Category
1	Green Hydrogen	1.366853	0.771914	IV
2	Agriculture, hunting, forestry	0.733226	2.05062	II
3	Fishing and aquaculture	0.681843	0.640489	I
4	Mining and quarrying, energy producing products	0.844912	1.053429	II
5	Mining and quarrying, non-energy producing products	1.017137	0.83119	IV
6	Mining support service activities	0.754763	0.860202	I
7	Food products, beverages and tobacco	1.222333	0.899369	IV
8	Textiles, textile products, leather and footwear	1.203293	1.03785	III
9	Wood and products of wood and cork	1.085605	0.781588	IV
10	Paper products and printing	1.194203	1.092773	III
11	Coke and refined petroleum products	0.90822	1.818162	II
12	Chemical and chemical products	1.225042	1.685648	III
13	Pharmaceuticals, medicinal chemical and botanical products	1.051004	0.887231	IV
14	Rubber and plastics products	1.206035	0.999003	IV
15	Other non-metallic mineral products	1.078248	0.894373	IV
16	Basic metals	1.283071	2.481831	III
17	Fabricated metal products	1.227421	0.945513	IV
18	Computer, electronic and optical equipment	1.173724	0.689631	IV
19	Electrical equipment	1.306444	0.758116	IV
20	Machinery and equipment, necessary	1.181911	0.769386	IV
21	Motor vehicles, trailers and semi-trailers	1.247154	0.64506	IV
22	Other transport equipment	1.088076	0.846008	IV
23	Manufacturing necessary ; repair and installation of machinery and equipment	1.146601	0.974105	IV
24	Electricity, gas, steam and air conditioning supply	0.982444	2.078635	II

25	Water supply; sewerage, waste management and remediation activities	0.971564	0.824712	I
26	Construction	1.130604	1.292321	III
27	Wholesale and retail trade; repair of motor vehicles	0.754668	2.161132	II
28	Land transport and transport via pipelines	0.950444	1.229019	II
29	Water transport	1.032278	0.596325	IV
30	Air transport	1.216815	0.635683	IV
31	Warehousing and support activities for transportation	1.016791	0.78532	IV
32	Postal and courier activities	0.901848	0.696405	I
33	Accommodation and food service activities	1.079505	0.740927	IV
34	Publishing, audiovisual and broadcasting activities	1.043079	0.612352	IV
35	Telecommunications	1.108313	0.906768	IV
36	IT and other information services	0.773054	0.596401	I
37	Financial and insurance activities	0.79963	1.846228	II
38	Real estate activities	0.72211	0.65893	I
39	Professional, scientific and technical activities	0.853167	0.604911	I
40	Administrative and support services	0.834541	1.782575	II
41	Public administration and defence; compulsory social security	0.74174	0.576143	I
42	Education	0.707577	0.645803	I
43	Human health and social work activities	0.896649	0.577124	I
44	Arts, entertainment and recreation	0.889162	0.581635	I
45	Other service activities	0.791171	0.581437	I

Table 18: Inter-Industry Linkage Effect