

FACTORS AFFECTING GREEN HYDROGEN BUNKERING AT THE INDIAN COAST

Project report submitted to the School of Maritime Management, Indian Maritime University in
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In

INTERNATIONAL TRANSPORTATION AND LOGISTICS MANAGEMENT

Submitted by

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DECLARATION

I, **JEYASURIYA J**, Reg. No.2303305018 student of School of Maritime Management, Indian Maritime University, pursuing MBA in International Transportation and Logistics Management hereby declare that this submission of this project report titled **FACTORS AFFECTING GREEN HYDROGEN BUNKERING AT THE INDIAN COAST** has been prepared by me towards the partial fulfilment of the Master of Business Administration in International Transportation and Logistics Management under the supervision of **Dr. Totakura Bangar Raju** Professor and Dean SMM, Indian Maritime University, Chennai Campus. I also declare that this project report is my original work and has not been copied from any other report previously submitted for the award of any degree, fellowship or other in the similar title.

Place: Chennai

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CERTIFICATE

This is to certify that the project report titled **Factors affecting green hydrogen bunkering at the Indian coast submitted** to School of Maritime Management, Indian Maritime University, Chennai Campus, in partial fulfillment for the award of the degree of Master of Business Administration (MBA) in International Transportation and Logistics Management, is a record work carried out entirely by **Jeyasuriya J (Reg.No.2303305018)**

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ABSTRACT

The rising global action to decarbonize shipping, green hydrogen has been identified as a potential alternative fuel, especially for coastal economies such as India. This study investigates the determinants of the potential for green hydrogen bunkering along the Indian coast. An eight set of frameworks was constructed to assess the preparedness and strategic feasibility of such facilities. To minimize complexity and uncover underlying patterns, Principal Component Analysis (PCA) was used in IBM SPSS. This aided in the discovery of a subset of latent constructs that aggregate corresponding sub-factors into higher-order thematic components and provide insight into how different components interact to produce feasibility. Supplementary statistical tests supported the data as being sufficient for such dimension reduction. The findings offer a better sense of how cost, technical, social acceptability, policy-oriented, infrastructural, and market-based factors intersect in this new space. These findings are meant to guide stakeholders ranging from policymakers and port authorities to industry investors on where interventions can be most effective. Although the research is exploratory and subject to some methodological and contextual limitations, it provides a starting point toward strategic planning for green hydrogen uptake in India's maritime sector.

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1.0 INTRODUCTION

In a time of energy crisis and constant pressure exerted by the global community to change the fuels used from fossil to zero-emission ones, the maritime sector is also directly involved in this progressing transition and faces many challenges associated with it. The adoption of new, low or zero-carbon marine fuels, although enforced by various regulations and public pressure, presents shipping with an enormous challenge in terms of policies, propulsion technology, shipboard fuel management, ship design, and maritime supply chains. Regardless of their intrinsic complexities, those issues appear easier to resolve than the need to construct a whole new fuel supply chain and bunkering facilities (Kołakowski et al., 2024) There is growing pressure to reduce greenhouse gas (GHG)emissions from maritime transportation. One of the most effective strategies for reducing GHG emissions is to switch from conventional fuels such as heavy fuel oil to alternative fuels. Green hydrogen is a promising alternative for the shipping industry.(Notteboom & Haralambides, 2023)

Maritime bunkering, the act of refueling ships, is a vital link in the international shipping supply chain that allows vessels to run continuously on international waters. This specialized logistics activity involves not just the physical delivery of fuel but also a sophisticated network of suppliers, traders, port authorities, and regulatory systems that enable the international transfer of some 300 million tonnes of marine fuel every year. The bunkering process requires careful planning, execution, and documentation to guarantee safety, compliance, and precise fuel delivery. Different bunkering techniques—such as Pipe-to-Ship (PTS), Ship-to-Ship (STS), and Truck-to-Ship (TTS)—are utilized depending on port facilities, ship size, and operational needs. The business model of bunkering is centered on fuel procurement, storage, blending, quality assurance, delivery logistics, and financing, with profit margins usually tied to volume throughput and operational effectiveness. The value chain for the industry reaches from bunker suppliers, traders, and brokers to storage facilities and refineries, and finally to shipowners and operators who end up using the fuel. With stricter environmental regulations and the decarbonization of the industry on the horizon, the bunkering industry has to change by creating new business models, expertise, and infrastructure to support alternative fuels, bringing both challenges and opportunities to players in the industry.

The energy transition from fossil fuels to renewables is widely considered as a key action field in decarbonizing the global economy, thus preventing the disastrous, irreversible, consequences of climate change, too well known to all.(Notteboom & Haralambides, 2023) To reduce the greenhouse gases (GHGs) emissions and the dependence of the energy market on fossil fuels, most countries in the world are focusing on the development of renewable energy sources (RESs) to drive the energy transition and to reduce their dependence on external supplies (Squadrito et al., 2023)

As India speeds up its progress toward decarbonization and ocean sustainability, green hydrogen stands out as a crucial substitute fuel with the power to revolutionize port life and shipping supply chains. Green hydrogen bunkering facilities at the Indian coast are not only technologically daunting but also strategically challenging, subject to an array of interdependent factors from policy frameworks to societal perception. Green hydrogen generated by the electrolysis of water with renewable energy — has become a key energy vector in the transition to low-carbon economies globally. Maritime shipping, responsible for approximately 3% of global greenhouse gas (GHG) emissions, is facing mounting pressure to decarbonize in line with the International Maritime Organization (IMO)'s net-zero emission targets by or around 2050 (IMO, 2023).Bunkering ship refueling using green hydrogen or its by-products like ammonia or methanol is a viable solution. India, with its extensive 7,500 km coastline and favorable geographical position along the major international shipping routes, can emerge as a world-class green hydrogen bunkering hub (TERI, 2023).The government of India has already initiated the National Green Hydrogen Mission (NGHM)with a goal to produce 5 million metric tonnes per year of green hydrogen by 2030, complemented by port infrastructure development and export incentives (Ministry of New and Renewable Energy, 2023).

The focus on green hydrogen bunkering along India's coastline is especially timely and relevant, as India has a strategic geographical location astride prominent international shipping routes and ambitious renewable energy goals. With a 7,500-kilometer coastline, 12 major ports, and 200 minor ports, India has tremendous potential to become a central player in the green maritime fuel sector. India's National Green Hydrogen Mission, announced in January 2023 with an initial investment of ₹19,744 crore (\$2.4 billion), seeks to make the country a leading global centre for green hydrogen production, use, and export. The Mission focuses on 5 million tonnes of green

hydrogen production per annum by 2030, establishment of 10 GW of indigenous manufacturing capacity for electrolyzers, and generation of more than 600,000 jobs. The incorporation of green hydrogen bunkering into this national strategy would have several advantages: it would diversify India's shipping service provision, decrease the reliance of the nation on imported fossil fuels, make use of its rich renewable energy resources, and generate new economic opportunities along its coastlines. In addition, setting up green hydrogen bunkering facilities would enhance India's stature in international shipping and trade circles, possibly drawing ships looking to meet stricter global environmental regulations as well as generate foreign exchange for the country.

The possible effects of building green hydrogen bunkering facilities along the Indian coast have wider implications that transcend the direct maritime industry to involve wider economic, environmental, and strategic factors. Economically, it has the potential to create significant investment in renewable energy ventures, hydrogen manufacturing plants, high-tech storage and handling units, and upgrading port facilities, which will create employment across industries and skill levels. Creation of a green hydrogen economy would encourage innovation and technology transfer, which could place India at the forefront of technology in this new sector. On the environmental side, substitution of traditional marine fuels with green hydrogen would lead to a drastic reduction in sulfur oxides, nitrogen oxides, particulate matter, and greenhouse gas emissions in port cities and coastal regions, enhancing air quality and public health conditions for millions of people living there. Strategically, early entry into green hydrogen bunkering services would make India more energy secure, less exposed to oil price volatility, and more geopolitically strong in the Indian Ocean region. Moreover, it would be consistent with India's Paris Agreement climate commitments and show leadership in tackling global environmental issues, which could enhance the nation's global position and clout in international climate talks and marine management forums.

An in-depth appreciation of the variables influencing green hydrogen bunkering is necessary to meaningfully enable India's National Green Hydrogen Mission and make the most of this transformation. These variables range across technological, economic, regulatory, and infrastructural spaces, each with distinct challenges and opportunities that need to be purposefully addressed. Technologically, overcoming hydrogen storage issues, establishing proper handling protocols, and identifying proper production technologies for the Indian context are all important

considerations. Economic considerations encompass production costs, investment in infrastructure, market development strategies, and funding models capable of rendering green hydrogen cost-competitive with traditional fuels. The regulatory environment includes safety norms, government facilitative policies, global harmonization initiatives, and certification regimes to ensure conformity and generate confidence in the new fuel. Infrastructure factors include port preparedness audits, supply chain creation, location planning, and integration with the existing infrastructure to achieve maximum utilization of resources. Through structured examination of these drivers, stakeholders are able to determine intervention priority areas, resource distribution effectively, and construct specific strategies for bridging barriers to adoption. Policymakers, port authorities, shipping liners, and investors will all be informed by the research and empowered to align effort between the public and private sector, speeding up India's journey to sustainable maritime transportation.

National Green Hydrogen Mission reflects India's ambition to make a leadership contribution towards the hydrogen economy with lofty ambitions for its domestic production, export, and indigenous use of green hydrogen. Investigating what drives green hydrogen bunkering in particular serves to enhance this mission directly by isolating key enablers and determinants for deployment, helping shape strategic choice, and prioritizing areas to require policy intervention or investment attention. The results can contribute to streamlining the Mission strategy towards hydrogen marine applications so that production capacity investment is complemented with the buildup of corresponding distribution and utilization infrastructure. In addition, this research can assist in the Mission aim to decrease import dependence on fossil fuels by evaluating the potential to displace traditional marine fuels based on domestic production of green hydrogen. By realizing synergies among renewable power deployment, electrolyzer production, and bunkering infrastructure development, the research can drive the integrated approach that generates maximum economic value and lowest costs of implementation. International best practices and future standards analysis can inform the regulation and certification schemes shaped according to international norms with due regard for the unique needs of India. Further, by analyzing the likely economic effects along the value chain, the study can aid the Mission's job creation goals by emphasizing skill development needs and fresh employment generation possibilities in the coastal areas.

The shift to green hydrogen in the shipping industry is not just an incremental step but a paradigm shift in energy systems that needs to be addressed through concerted action across multiple sectors. This research study addresses this complexity by analyzing the interlinkages between technological innovation, economic incentives, regulatory regimes, and infrastructure development in the particular context of India's coastal environment. The traditionally conservative mindset of the maritime industry's fuel transition strategy highlights the need for thorough planning and risk mitigation strategies to surmount change resistance and gain confidence among stakeholders. Through the determination of critical success factors and likely implementation routes, this research hopes to speed up the uptake of green hydrogen bunkering along India's coastlines in support of global decarbonization and Indian sustainable development aspirations. As the globe transitions to a low-carbon world, knowing the complex factors driving the adoption of green hydrogen in maritime uses will be key to successfully managing this transformation. This research project presents a valuable and timely input into this new area of research, with implications for policymaking, investment strategy, and strategic planning in the maritime and energy industries in India and more widely. With thorough analysis and evidence-based advice, it aims to shed light on the way forward for sustainable shipping in Indian waters and assist India in realizing its vision of emerging as a green hydrogen economy world leader.

Here, the current study seeks to identify and assess the latent constructs that regulate the feasibility, implementation, and stakeholder alignment required for the effective deployment of green hydrogen bunkering infrastructure in India. Employing Principal Component Analysis (PCA) as a multivariate statistical approach, the research distills a broad range of 16 thoughtfully chosen sub-factors—cutting across Regulatory and Policy, Infrastructure and Technical, Economic and Financial, Geographic and Environmental, Technological, Supply Chain, Market and Demand, and Social and Human categories—into a simplified framework of underlying factors.

1.1 Objectives of the Study

1. To identify and evaluate the key sub-factors influencing the feasibility and development of green hydrogen bunkering on the Indian coast.
2. To apply Principal Component Analysis (PCA) to reduce the dimensionality of the dataset and uncover latent components that group related sub-factors.
3. To determine the interrelationships and clustering among factors and dimensions.
4. To generate empirical evidence and insights that can guide strategic planning, policy formulation, and investment decisions for green hydrogen bunkering infrastructure at Indian ports.

1.2 Rationale of the study

This paper aims to identify and describe several factors that influence the adoption of green hydrogen bunkering in the Indian maritime industry. It aims to identify the major and minor drivers, challenges and impacts in the Indian maritime industry. To achieve these factors literature review and expert opinion is considered within the bunkering (Oil and petroleum) and management discipline, where the research papers are identified using the keywords where the keywords like LNG, LPG, green hydrogen, ammonia, barriers in bunkering and etc, after which PCA is used to evaluate the proposed factors . The following part will provide a literature review, where previous research on green packaging and related topic will be discussed. After that, the methodology section will describe the approach and method used to analyse the factors affecting the adoption of green hydrogen bunkering at the Indian coast. The results and discussion section will present the findings, and results, showing their relevance to the industry and sustainability practices.

2.0. LITERATURE REVIEW

(Lucon et al., 2004) aims to present the case of LPG in Brazil and to make recommendations in order to preserve the benefits obtained from the utilization of this fuel: cleaner environments through an affordable energy source. The paper analyses the LNG supply, demand and the penetration of LPG in rural and urban areas, it reviews about various policies for LPG in Brazil, the paper concludes that usage of LPG is far better than deforestation and it act as a portable energy and recommends the coordinated energy policy.

(Acosta et al., 2011) provides an exploratory analysis from the perspective of the port operators of the factors that determine the competitiveness of fuel supply at the ports of the Gibraltar Strait, the methodology is based on interviews and questionnaires focused on public and private institutions involved in the port services. The results reveal that fuel prices and geographical advantage are the two main factors seen by Gibraltar Strait port operators as influencing shipping company choice of bunkering port. In order of importance, other identified factors related to the cost and quality of services, including port tariffs, supply waiting time, service rates, simplicity of crew changing, presence of restrictive environmental regulations and customs strictness.

(Ahmad, 2014) has briefly discussed why is there is a need of green shipping and what are the steps to be taken in coastal shipping by adopting LNG and addressing coastal shipping problems such as poor infrastructure, constant dredging, government policies, and so on and briefly explained about hoe LNG can be an alternative fuel oil.

(Wang & Notteboom, 2015) analyses the role of port authorities in the development of LNG bunkering facilities and to investigate why and how port authorities promote this new application. A multiple-case study approach is adopted to examine the performance of eight North European port authorities in their LNG bunkering projects. The paper provides a deeper understanding of the current port practices in developing LNG bunkering facilities in North Europe and identifies the important role of the evolving port function beyond the tradition model in promoting innovations. The paper also proposes a set of port implementation policies on the facilitation and promotion of the use of LNG as a ship fuel.

(Calderón et al., 2016) has pictured in detail about the LNG terminals at European ports as context and briefly analysed based on 3 sets of information such as: 1) safety standards and regulations, 2) logistics infrastructure, 3) financing approaches implemented by selected ports, The research is carried out by analysing secondary data from international databases.

(Han et al., 2016) aims at presenting bunkering educational programs for LNG fueled ship taking into consideration existing similar education programs and safety systems at the international level in order to enhance both seafarers' and vessels' safety. In order to prepare for installation and operation of LNG fueled propulsion ship on board, with a view to providing equipment and system of LNG bunkering. Hence, this paper reviews and proposes professional educational programs of LNG bunkering in consideration of technical aspects of the safety system of LNG bunkering based on the types of bunkering systems.

(Aronietis et al., 2017) develops a generic forecasting method at port level. This method is then applied to the port of Antwerp. The research deals with the bunker market and wants to increase the insight into the strategy of the shipping companies in the current bunker market. It is the aim of this research to determine which criteria are the most important in determining the bunker strategy: the price per tonne, the quality of the fuel, or another criterion a two-stage methodology of both qualitative research through interviews and a discrete choice experiment was chosen.

(Ranjan et al., 2018) has analysed the volatility and the leverage effect in the bunker prices in IFO 380 and IFO 180 grades. The research investigated the causal relationships between IFO 380 and IFO 180 grades of bunkers. Serial correlations were found through using Lagrange multiplier (LM test) and heteroskedastic tests in the bunker price data. The research revolves around two categories of marine fuels such as: 'distillates' and 'residuals' The data collection is from 'Bunker specifications from January 2000 to October 2016.' The methods used to carry out this research are E-GARCH, ADF, Bivariate analysis, Lagrange multiplier test and Heteroskedasticity tests.

(Ghasemzadeh et al., 2018) The paper focuses on the development of an artificial neural network (ANN) model to investigate the performance of a silica membrane reactor (MR) during the methanol steam reforming (MSR) reaction, The results suggest that using a silica membrane reactor can enhance hydrogen production efficiency and reduce CO selectivity

compared to traditional reactors. This literature is an experimental study where experiments like silica membrane reactor design, catalyst preparation and gas composition analysis were done.

(Park et al., 2018) has examined the characteristics of leaked-gas dispersion in ship-to-ship liquefied natural gas (LNG) bunkering, thereby providing an insight such as: various operational and environmental conditions, with varying geometry of the ships, gas leak rate, wind speed and wind direction towards determining the appropriate level of safety zones. This study applies computational fluid dynamics (CFD) simulations.

(MacHiels et al., 2020) discussed about the complexity and uncertainty are related and inherent elements of the planning, design and decision-making (DM) process of mega projects The social cost–benefit analysis (SCBA) and the environmental impact assessment (EIA) are two important instruments that support DM in megaprojects The paper attempted to provide a first step to better understand and illustrate the complexity of DM under uncertainty in megaprojects, enlarging the research scope to the interaction between both the SCBA and EIA, as well as the project’s DM process.

(Van Hoecke et al., 2021) has discussed a theoretical introduction to different hydrogen storage methods precedes an analysis of the energy-efficiency and practical storage density of the carriers. In the final section the major challenges and hurdles for the development of hydrogen storage for the maritime industry are discussed. The most likely challenges will be the development of a new bunkering infrastructure and suitable monitoring of the safety to ensure safe operation of these hydrogen carriers on board the ship. Key processes in the use of hydrogen are discussed, starting with the production of hydrogen from fossil and renewable sources. The focus of this review is different storage methods, and in this work.

(De et al., 2021) investigates the problem of bunker fuel management for liner shipping networks under different fuel pricing scenarios and taking into consideration different fuel bunkering policies. The authors of this literature developed a mixed integer non-linear programming model to minimize the total expected cost consisting of inventory cost related to container transportation, operating cost associated with ship hiring, as well as bunkering cost and fuel consumption cost at the port.

(Sánchez et al., 2021.) is an attempt to make ammonia rises as one of the fuels with the highest potential in a scenario targeting decarbonization. The work represents a process scale analysis for the ammonia-to-power transformation. Ammonia could be key in the future energy system as a carbon-free technology to store energy and, also, as an energy carrier.

(Atilhan et al., 2021) provides a critical assessment of the potential usage of green hydrogen in the shipping industry with an evaluation of production routes, techno-economic performance, storage, and safety. a comparison is made for the safety and health issues of hydrogen compared to conventional and emerging maritime shipping fuels.

(Shrivastava, 2021) is an M.Sc. Thesis from the discipline of Maritime affairs from World Maritime University, Sweden. The dissertation provides the feasible solutions and strategies which, if implemented, could reduce the menace of supplying lesser quantity and/or poor quality of bunker fuel oil. A bunker buyer's preventive measures to minimize the possibility of receiving short delivery and poor-quality bunker have also been identified. Data is collected through Questionnaires, journals and articles, in a nutshell, the study is an attempt to make the bunker market transparent in order to prevent any menace.

(Kazi et al., 2021) via green hydrogen economy. The problem was formulated as a mixed integer linear programming (MILP) and solved in GAMS/ IBM ILOG CPLEX 30.3.0 solver the multi-purpose model can accomplish detailed techno-economic-environmental analysis for variable scenarios based on net present value.

(Agarwala, 2022) provides two verticals: one that focuses on the environment, through the Green Ports Initiative; and the other focuses on clean India, through the Swachh Bharat Abhiyaan, the aim is to include digitization, renewable energy development and distribution, environment consciousness, cleanliness drive, infrastructure development, and time, cost, and efficiency enhancement. And briefly discussed about the efforts of major ports towards the Project Green ports.

(Gerbec & Aneziris, 2022) has done a survey of failure rate data used for bunkering interface equipment (arms, hoses) in terms of Per hour per hose (arm) per hour per year per operation per transshipment basis, Quantitative Risk Assessment studies have been carried out in this study.

(Agaton et al., 2022) aims to review the prospects and challenges for the potential use of green hydrogen in several production and utilization pathways in the Philippines. This study proposes a roadmap for a green hydrogen economy in the country by 2050, divided into three phases: I green hydrogen as industrial feedstock, II green hydrogen as fuel cell technology, and III commercialization of green hydrogen. the analysis identified several challenges, including technical, economic, and social aspects, as well as the corresponding policy implications for the realization of a green hydrogen economy that can be applied in the Philippines and other developing countries.

(Wappler et al., 2022) has carried out a meta-analysis on green hydrogen demand and electrolyzer manufacturing companies globally and it lays the roadmap of countries to aware of the demand and equipment manufacturing companies, meta- analysis has been carried out, this research is funded by The Germany Federal Ministry of Education and Research.

(Bachras, 2022.) is an M.sc Thesis from the discipline of Hydraulic Engineering from Delft university, Rotterdam. has been briefly discussed about the a) favourable environmental policies on hydrogen projects, b) The terminal Planning and area requirements for the hydrogen projects, c) terminals operators, investors and policy makers will need to make decisions on the preferred hydrogen carrier and location for various hydrogen projects that may developed in the near future, the thesis revolves around the research question “How can hydrogen (or a hydrogen carrier) be integrated as a new service in an operational port environment, and next to an existing liquid bulk terminal?”, Multi-criteria analysis method is used in this thesis.

(Gupta & Singh, 2022) helps to analyze how bunkering operations can be identified through AIS data by taking examples that can give any insight on the quality of bunker operations and how it can help to make operations without delay and interruptions in different bunkering operations with variable types of data.

(Sinha & Roy Chowdhury, 2022) has aimed to measure the environmental and operational performance of the Indian major ports which is an attempt to make a multicriteria optimization model to develop Port sustainable Index Causal method such as System Dynamics and the paper aims to develop the zero defects and sustainable operations in major Indian ports,

multiple problems addressing the multiple problems such as: operational inefficiencies, sustainability gaps, lack of ICT's and infrastructure limitations.

(Schinas & Oulolidis, 2022) studied about a competitive analysis of bunkering spots that suggests the optimal location for bunkering is of interest. The paper uses a combination of primary and secondary research, both from operators' and suppliers' side, to identify the key performance factors (KPFs) affecting the decision-making process of a bunkering port selection process. Answers were then combined by using a fuzzy TOPSIS analytical approach to quantify the competitive position of each port in the Amsterdam-Rotterdam-Antwerp (ARA) region.

(Rathod et al., 2023) focuses on how Singapore can manage the possible health hazards if the fuels is transitioning is happening from HFO to ammonia by 2050, it also focuses on the Atmospheric modeling for secondary PM_{2.5}, and Impacts on both health hazard to humans and environment. And the potential ammonia emissions from storage and bunkering operations for shipping in Singapore.

(Pfeifer et al., 2023) was concerned with the energy efficiency of three different ammonia terminal concepts dealing with both pressure liquefied and cold-liquefied ammonia, The different terminal concepts were analyzed by numerical methods. A model has been formulated in Modelica to investigate the system behavior on a component scale. The system performance during long-term storage operation, import and export operation has been investigated. and the study is limited to steady analysis.

(Notteboom & Haralambides, 2023) has explored critical challenges and opportunities green hydrogen can bring to the economics and governance of seaports in Europe, discussed the fast-growing public and private interest in green hydrogen as part of the energy transition trajectory, the study uses secondary data such as world energy outlook 2022, APS and so on...

(Ng et al., 2023) has highlighted several behaviors of ammonia dispersion over land and sea surfaces when it is released accidentally under different operational parameters settings. It provides information needed to formulate future technical references for ammonia bunkering in Singapore. (Five operational parameters (a) storage condition, (b) release duration, (c) transfer flow rate, (d) release height, and (e) release direction)

(Klopott et al., 2023) has done a research on the basis of threefold : (1) to provide an overview of some of the emerging alternative fuel technologies that are being used or tested for further use in maritime transport, (2) to analyse the bunkering infrastructure in seaports, and (3) to assess the level of advancement of Polish ports in relation to the bunkering of alternative fuels by ships and to explore the ports' plans, to achieve these goals, several research methods were applied: a critical literature review, desk-study research, critical and comparative analyses, and semi-structured interviews with representatives of three major Polish seaports

(Duong et al., 2023) has made an attempt to the latest advancements and potential developments related to the safety of ammonia as a marine fuel. In this paper, the main challenges and recommendations for the implementation of ammonia bunkering and further development of ammonia as a marine fuel are proposed.

(Squadrito et al., 2023) has discussed briefly about the peculiar advantages and shortcomings of different green hydrogen technologies (biomass pyrolysis and gasification, water electrolysis, etc.) have been analysed and compared, with a focus on the electrolysis process as the most promising method for large scale and distributed generation of hydrogen.

(Saborit et al., 2023) discuss about the current state of the art of hydrogen pipelines and subsea cables, as well as the storage and bunkering system that is needed on shore to deliver hydrogen and derivatives The analysis extends the scope of most of the previous works that consider port-to-port transport, while we report offshore to port, A parametric analysis of both alternatives, focused on cost estimates of each infrastructure (cable/pipeline) and shipping has been carried out versus the total amount of energy to transport and distance to shore.

(Mohamed & Ismail, 2023) is an M.Sc. Thesis from the discipline of Maritime affairs from World Maritime University, Sweden. The dissertation aims to identify barriers and challenges that ports encounter in becoming part of green shipping corridors by conducting interviews with various stakeholders involved in green shipping corridors to get a holistic view of these port challenges. the study explores ports' drivers and challenges, such as outdated infrastructure, complex regulations, financial concerns, alternative fuel limitations, stakeholder involvement and technological limitations. this research emphasizes the significance of addressing port challenges in the context of green shipping corridors. As global efforts to make shipping more environmentally friendly, this study also guides ports, policymakers, and

industry players by offering a roadmap to help ports overcome these challenges and become active participants in sustainable shipping corridors, ultimately contributing to a greener maritime industry.

(Sarkar et al., 2023) aims to analyze various port logistics barriers and their associated risks in the context of Industry 4.0 for Indian Major Ports, the study develops a framework by integrating the fuzzy set theory, the evidential reasoning approach and the expected utility theorem for identifying the severity value of port logistics barriers under the Industry 4.0, the study also reveals that poor infrastructure, non-supportive policy ecosystem, and lack of research and development are the top barriers that need immediate attention.

(Fini et al., 2024) aims to enhance maritime a) fuel supply's efficiency, b) safety, and c) Sustainability by advocating for the standardization of bunkering systems in ports, the methods used in this research paper are: MCDM (Multi-Criteria Decision Making) & AHP (Analytical Hierarchy Process). The criteria for evaluation encompass safety, economic factors, operational efficiency, technical considerations and other relevant aspects were evaluated.

(Osman et al., 2024) is an M.Sc. Thesis from the discipline of International Management from Alpen-Adria-Universität, Klagenfurt. made a study about transition to green hydrogen in the logistics transportation industry presents both challenges and opportunities. While the path to widespread adoption is fraught with obstacles, the potential benefits for climate mitigation and energy sustainability are significant. Continued research, investment, and policy support will be essential to realize the full potential of green hydrogen as a transformative energy source in the transportation sector.

(Kołakowski et al., 2024) discusses about the perspectives of all potential stakeholders and the factors they find relevant for deciding on the location of bunkering infrastructure, Multi-Criteria Decision-Making methods were used to carry out the research, specific polish ports are taken as the consideration for data analysis and finally the paper suggests three marine alternative fuels distribution network planning with regard to factors relevant to the location of their bunkering station.

3.0 METHODOLOGY

The main goal of this paper is to explore the adoption of green hydrogen bunkering in the Indian maritime industry and to identify the key factors that influence its adoption. To achieve this, a methodological framework was adopted that is Principal Component Analysis (PCA). Initially, a detailed literature review was conducted to identify major factors and sub-factors which impact the adoption of green hydrogen bunkering, then these were categorized under eight broad themes: Regulatory, Infrastructure, Economic, Geographic, Technological, Supply-chain, Market and Social factors. The identified factors are presented in Table 1.

To Evaluate the importance of these factors a survey was Conducted among 100 decision makers representing various stakeholders in the Maritime industry that participants included individuals from Port Authority, Companies related to renewable energy, Maritime researchers, Maritime management and Nautical Science students. Each participant had relevant experience in their respective field and has contributed valuable insights to the research the survivors conducted in April 2025 using a Google form. Asked the importance of the identified factor using the Principal Component Analysis.

3.1 Data collection

Data was collected with a questionnaire on April 2025 via Google Forms, targeting stakeholders who are actively in the field of maritime industry. In fact, the study surveyed 100 respondents. All respondents provided adequate responses to all questions concerning about the factors that are influencing the green hydrogen bunkering specifically to the Indian coasts.

3.2 Questionnaire Structure

The text has been developed into two sections, with twenty separate questions in a questionnaire intended to light upon the factors that comprise regulatory, infrastructure, economic, geographic, technological, supply-chain, market and social factors. These questions were extracted considering the various writings bearing relevance to factors affects green hydrogen bunkering adoption. 5-point Likert scale scoring was used. A 20-item questionnaire was developed that focuses in on the factors like regulatory, infrastructure, economic, geographic, technological, supply-chain, market and social factors These have been extracted from the insights drawn from literature related to

Alternative fuels adoption, Bunkering sector of the maritime industry. Each item was scored by the respondents through a 5-point Likert scale:

• 1 = Strongly Disagree • 2 = Disagree • 3 = Neutral • 4 = Agree • 5 = Strongly Agree

This format was chosen to allow quantifying the level of agreement on each behavioral statement, as well as allowing for statistical analysis wherein Principal Component Analysis (PCA) was used to arrive at identifying the underlying dimensions affecting green hydrogen bunkering in the Indian Maritime Industry.

3.3 Sampling technique

The study employed purposive sampling; a non-probability technique that targets respondents based on their relevance to the research topic. stakeholders in port and logistics operations, maritime researchers, companies related to renewable energy, management and nautical science students were intentionally selected to ensure contextual richness and insight.

Factors	Description	Abbreviations
Regulatory and Policy Factor	Maritime regulatory frameworks for alternative fuels	RPF 1
	Carbon taxation and incentive frameworks	RPF 2
Infrastructure and Technical Factors	Availability of renewable energy sources near ports	ITF 1
	Electrolyzer capacity and scalability	ITF 2
Economic and Financial Factors	Levelized cost of green hydrogen production	EFF 1
	Capital expenditure requirements for infrastructure	EFF 2
Geographic and Environmental Factors	Proximity to shipping lanes and major maritime routes	GEF 1
	Cyclone vulnerability of coastal facilities	GEF 2
Technological Factors	Hydrogen storage technology maturity	TFH 1

	Leak detection and safety systems advancement	TFH 2
Supply Chain Factors	Skilled labor availability for specialized operations	SCF 1
	Supply reliability during seasonal variations	SCF 2
Market and Demand Factors	Shipping industry adoption rates of hydrogen propulsion	MDF 1
	Green shipping corridor development plans	MDF 2
Social and Human Factors	Public perception and acceptance of hydrogen facilities	SHF 1
	Local employment generation potential	SHF 2

Table 3.1. Factor with abbreviation

3.4 Data Analysis Procedures

Data collected through the questionnaire was analyzed in IBM SPSS. The following steps were taken:

3.4.1 Data Cleaning and Preparation

The survey responses were first saved as .csv files. Data was then checked for inconsistency, missing values, outliers and reversed scores were normalized to normal scores for consistency using Excel. and imported into IBM SPSS and evaluated for the analysis, only completed responses were retained for the analysis to ensure reliability and accuracy.

3.4.2 Descriptive Statistics (mean scores, frequency distributions)

Likert-scale data (1-5) can be standardized, and while all of the response's options are flat, a level of equality contribution of the variables in Principal Component Analysis (PCA). PCA, or Principal Component Analysis was chosen as a method of dimensionality reduction and retained important dimensional information. IBM SPSS for Principal Component Analysis of the collected data, Principal Component Analysis is a multivariate statistical tool for transformation of dense datasets into lower components, while allowing stakeholders to interpret the real structure

governing the related influencing factors which were included in the core component. This improved the interpretation of factors that really affecting the adoption of green hydrogen bunkering at the Indian coast. These metrics allow you to judge the **reliability, consistency, and interpretability** of each sub-factor. Variables with **extreme skewness or kurtosis** may need **data transformation** or closer examination. Factors with **low variability (SD)** and **normal skew/kurtosis** are often more **statistically stable** and reliable for inclusion in further analysis like PCA.

3.4.3 Kaiser-Meyer-Olkin (KMO) Test for Sampling Adequacy

Before running PCA, Kaiser-Meyer-Olkin (KMO) test and Bartlett's Test of Sphericity were run to ensure the data would be suitable for factor analysis. Retain factors having eigenvalues greater than 1, and apply varimax rotation for better interpretability of the extracted component. KMO Value 0.8 and Bartlett's test of significance is less than 0.005: therefore, acceptable adequacy for factor analysis. Based on the PCA results, different influential drivers could be described under different central themes (e.g., regulatory, infrastructure, economic, geographic, technological, supply-chain, market and social factors) which contributed further to identifying the significant factors that underpin consumer influential in Indian bunkering sector. Determining number of Components: To decide how many Components to retain in interpreting the final components, a Scree Plot and Parallel Analysis were used, as there may be an optimal number of components to retain in the PC's and final evaluation. Components with eigenvalues greater than 1 thus formed the final selection for interpretation.

3.4.4 Visualization and Interpretation

The visuals were created for the purpose of interpreting the PCA results: Scree Plot: To see the proportion of variance each of the components represents, also to decide the number of significant components. Correlation Plot: For understanding the relationships and patterns of clustering between influential variables. Component scores were finally extracted and saved for likely further analysis or subsequent regression modelling if required for deepening the understanding of the dimensions influencing green hydrogen adoption

4.0 RESULT AND DISCUSSION

4.1 Introduction

This chapter explains the statistical findings from the principal component analysis (PCA) and allied exploratory methods directed towards identifying the underlying pattern among the important driving factors of green hydrogen bunkering in the Indian coastal setting. The process is initiated by Kaiser-Meyer-Olkin (KMO) and Bartlett's Test of Sphericity, which ascertain the dataset to be appropriate for factor analysis. Communalities indicate the amount of variance in each variable explained by the retained factors. Scree Plot and Total Variance Explained outputs are the rationale for retaining factors, determining the most influential dimensions. Rotated Component Matrix continues to make clearer the classification of sub-factors into latent components, and Component Transformation Matrix and correlation heatmap assist interpretation and theory alignment. These results confirm not only the relevance of the initial conceptual structure but also empirically inform about the latent dimensions that influence green hydrogen bunkering system feasibility and scalability. This discussion interprets these findings based on factors and provides an informed view of policy and implementation trajectory.

4.2 Data Preparation

The preprocessing steps were the ones taken before carrying out Principal Component Analysis. The raw data obtained from the questionnaire were cleaned, filtered, and formatted for analysis in IBM SPSS. The present research study utilized a developed questionnaire as an instrument and was constructed using the Google Forms platform. The overall survey examined influencing factors that affects green hydrogen bunkering at the Indian coast. The respondents' ratings of 16 influential statements were solicited via a 5-point Likert scale (whether the respondent Strongly Disagreed or Strongly Agreed with a respective statement). One hundred complete responses were received, and there is no partial or questionable records from the dataset, to maintain the integrity of the data. Demographic variables were excluded so that pure influential could be measured through PCA analysis. The 16 survey items were organized by influential types: Regulatory, Infrastructure, Economic, Geographic, Technological, Supply-chain, Market and Social factors.

This grouped set (20 items) was kept in the Excel dataset from column five to column twenty in the data sheet. This data block was extracted for further analysis and processing in IBM SPSS.

4.3 Descriptive Statistics and Distribution

This method evaluates how reasonably data are good for PCA as well as tests assumptions, such as linearity and, to a lesser extent, normality. But before applying PCA, such basic statistical techniques as KMO and Bartlett's test of sphericity normality tests were first conducted to check for factors among the 16 factors being analyzed. This methodology tests how well the data fit for use in PCA and whether key assumptions such as linearity and approximate normality have been reasonably fulfilled. The table below displays Mean, Standard deviation, skewness and kurtosis.

Sub-Factor	Mean	Std Deviation.	Min	Max	Skewness	Kurtosis
RPF1	0.48	0.28	0	0.98	-0.131	-0.637
RPF2	0.59	0.302	0.05	0.96	0.026	-0.877
ITF1	0.55	0.293	0.05	1	-0.215	-1.169
ITF2	0.52	0.279	0.04	0.99	0.181	-1.436
EFF1	0.43	0.311	0.02	1	-0.255	-1.189
EFF2	0.43	0.264	0.01	1	0.292	-1.175
GEF1	0.41	0.279	0.03	0.98	0.163	-0.77
GEF2	0.57	0.287	0.02	1	-0.181	-0.862
TFH1	0.52	0.296	0.01	0.95	-0.297	-0.613
TFH2	0.54	0.329	0.03	0.96	0.189	-1.028
SCF1	0.4	0.27	0	0.95	0.124	-1.38
SCF2	0.59	0.301	0.05	0.97	0.137	-0.787
MDF1	0.57	0.309	0.01	0.97	0.163	-0.739
MDF2	0.44	0.255	0.03	0.96	-0.256	-0.939
SHF1	0.44	0.311	0.02	0.99	-0.085	-0.729
SHF2	0.44	0.267	0.03	0.97	-0.23	-1.006

(Table.4.1. Mean, standard deviation, kurtosis and skewness for each factor)

4.4 Sampling adequacy

The suitability of the dataset for deriving factor could be shown through the Kaiser-Meyer-Olkin test of sampling adequacy which was done prior to double principal component conversion. A high KMO value indicates that the variables share common variance enough to be able to enter into PCA. Beneath the application of factor extraction, the adequacy of a dataset has to be checked out. This was done by using the Kaiser-Meyer-Olkin (KMO) test, which measures sampling adequacy, where a high value of KMO implies that the variables have common variance sufficient for PCA.

KMO and Bartlett's Test		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		0.819
Bartlett's Test of Sphericity	Approx. Chi-Square	691.133
	df	120
	Significance	0.000

(Table.4.2. KMO and Bartlett's Test)

The overall KMO score was 0.819, which falls into the "meritorious" category. This indicates a fair amount of shared variance between the different variables and strong factorability for the whole data set. The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy was calculated to determine the appropriateness of the dataset for Principal Component Analysis. In addition, the KMO individual values for all the 16 variables across the eight main domains exceeded the acceptable threshold 0.5, Bartlett's Test of Sphericity was significant at $p < 0.001$ ($\chi^2 = 691.133$, $df = 120$), suggesting strong correlations among variables. further confirming the appropriateness of the data set for PCA. Hence, the data is suitable for dimension reduction and extraction of underlying factors.

4.5 Communalities

Communalities		
Factors	Initial	Extraction
RPF1	1.000	0.624
RPF2	1.000	0.554
ITF1	1.000	0.676

ITF2	1.000	0.699
EFF1	1.000	0.706
EFF2	1.000	0.629
GEF1	1.000	0.538
GEF2	1.000	0.642
TFH1	1.000	0.527
TFH2	1.000	0.591
SCF1	1.000	0.681
SCF2	1.000	0.661
MDF1	1.000	0.541
MDF2	1.000	0.693
SHF1	1.000	0.690
SHF2	1.000	0.724
<i>Extraction Method: Principal Component Analysis.</i>		

(Table.4.3. Communalities table)

Communalities—indicating how much of each sub-factor's variance is explained by the extracted components—ranged from **0.527 to 0.724**. This demonstrates that a substantial portion of each variable's variance is captured by the factor solution. For example:

1. Local employment generation potential (SHF2): 0.724
2. Leak detection and safety systems advancement (TFH2): 0.591
3. Carbon taxation and incentive frameworks (RPF2): 0.554

All sub-factors met or exceeded the 0.5 threshold, confirming their relevance in the final factor structure.

4.6 Total Variance, Component Retention and Justification

Total Variance Explained			
Component	Initial Eigenvalues	Extraction Sums of Squared Loadings	Rotation Sums of Squared Loadings

	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	6.189	38.682	38.682	6.189	38.682	38.682	3.316	20.728	20.728
2	1.609	10.059	48.741	1.609	10.059	48.741	3.059	19.121	39.849
3	1.308	8.175	56.916	1.308	8.175	56.916	2.332	14.572	54.421
4	1.072	6.698	63.613	1.072	6.698	63.613	1.471	9.192	63.613
5	0.939	5.868	69.482						
6	0.774	4.840	74.322						
7	0.721	4.503	78.825						
8	0.595	3.721	82.546						
9	0.522	3.261	85.807						
10	0.464	2.900	88.707						
11	0.427	2.670	91.377						
12	0.354	2.210	93.587						
13	0.328	2.047	95.634						
14	0.305	1.907	97.541						
15	0.241	1.508	99.049						
16	0.152	0.951	100.000						

Extraction Method: Principal Component Analysis.

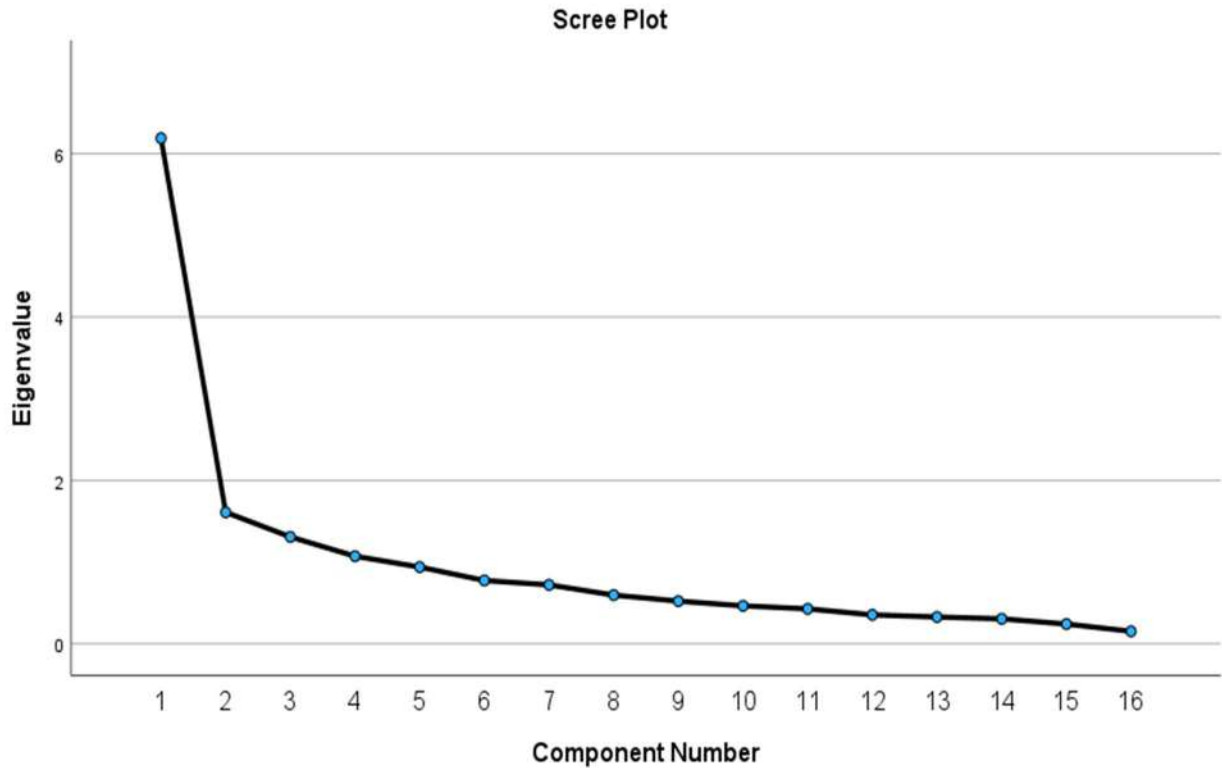
(Table.4.4. Total Variance explained table)

The number of components to retain for analysis was determined by the following three well established criteria: eigenvalue-greater-than-weighting rule, and scree plot elbow method, and the eigenvalue summary from PCA showed that the first four components had The **Eigenvalue criterion (>1.0)**, and thus together accounted for a total of 60.613% of the total variance:

1. **Component 1:** 20.728%
2. **Component 2:** 19.121%
3. **Component 3:** 14.572%
4. **Component 4:** 9.192%

4.7 Screen plot analysis

The Screen Plot, a visual means of determining the appropriate number of principal components to keep in the context of a principal component analysis, displays the eigenvalues for all components so as to illustrate the point at which taking more components adds little explanatory value—known as the elbow criterion. As can be seen in Figure 4., a clear elbow is observed after PC2, where the line representing the eigenvalues had a steep decrease in slope. The conclusion we can draw is that the first two components explain most of the variance and that there will be very little explained variance by other components. Therefore, with respect to the observations we made and 50.52% of cumulative variance, retaining two components to continue with our further analyses is statistically and interpretively meaningful.



(Fig.4.1. Scree plot of components)

4.8 Rotated Component Matrix Interpretation

Using **Varimax rotation**, in IBM SPSS, a clear clustering of sub-factors emerged across four interpretable components:

Component 1: Operational Infrastructure and Strategic Planning

1. Skilled labor availability for specialized operations (SCF1): 0.742
2. Green shipping corridor development plans (MDF2): 0.742
3. Shipping industry adoption rates of hydrogen propulsion (MDF1): 0.718
4. Leak detection and safety systems advancement (TFH2): 0.652

This component reflects readiness and commitment from maritime industry stakeholders in terms of both workforce capacity and strategic planning for green hydrogen implementation.

Component 2: Techno-Financial Readiness

1. Electrolyzer capacity and scalability (ITF2): 0.780
2. Levelized cost of green hydrogen production (EFF1): 0.780
3. Capital expenditure requirements for infrastructure (EFF2): 0.648
4. Supply reliability during seasonal variations (SCF2): 0.623

This construct captures the economic and technical viability of hydrogen bunkering, highlighting the importance of cost, capacity, and resilience.

Component 3: Regulatory and Technological Enablers

1. Availability of renewable energy sources near ports (ITF1): 0.782
2. Maritime regulatory frameworks for alternative fuels (RPF1): 0.709

This cluster ties regulatory clarity and energy access to the feasibility of green hydrogen adoption.

Component 4: Socio-Environmental Integration

1. Local employment generation potential (SHF2): 0.772

Although this component comprises a single strong loading, it emphasizes the social acceptability and developmental benefits of hydrogen facilities.

4.9 Outlier Sub-Factors with Low Loadings

Few sub-factors which include:

- Public perception and acceptance of hydrogen facilities (SHF1)
- Proximity to shipping lanes and major maritime routes (GEF1)
- Cyclone vulnerability of coastal facilities (GEF2)
- Carbon taxation and incentive frameworks (RPF2)
- Hydrogen storage technology maturity (TFH1)

Have not load strongly on any single factor (i.e., loadings < 0.5), suggesting either cross-loading tendencies or weak alignment with latent components. These may require further exploratory analysis or qualitative contextualization in future research.

4.10 Component Transformation Matrix

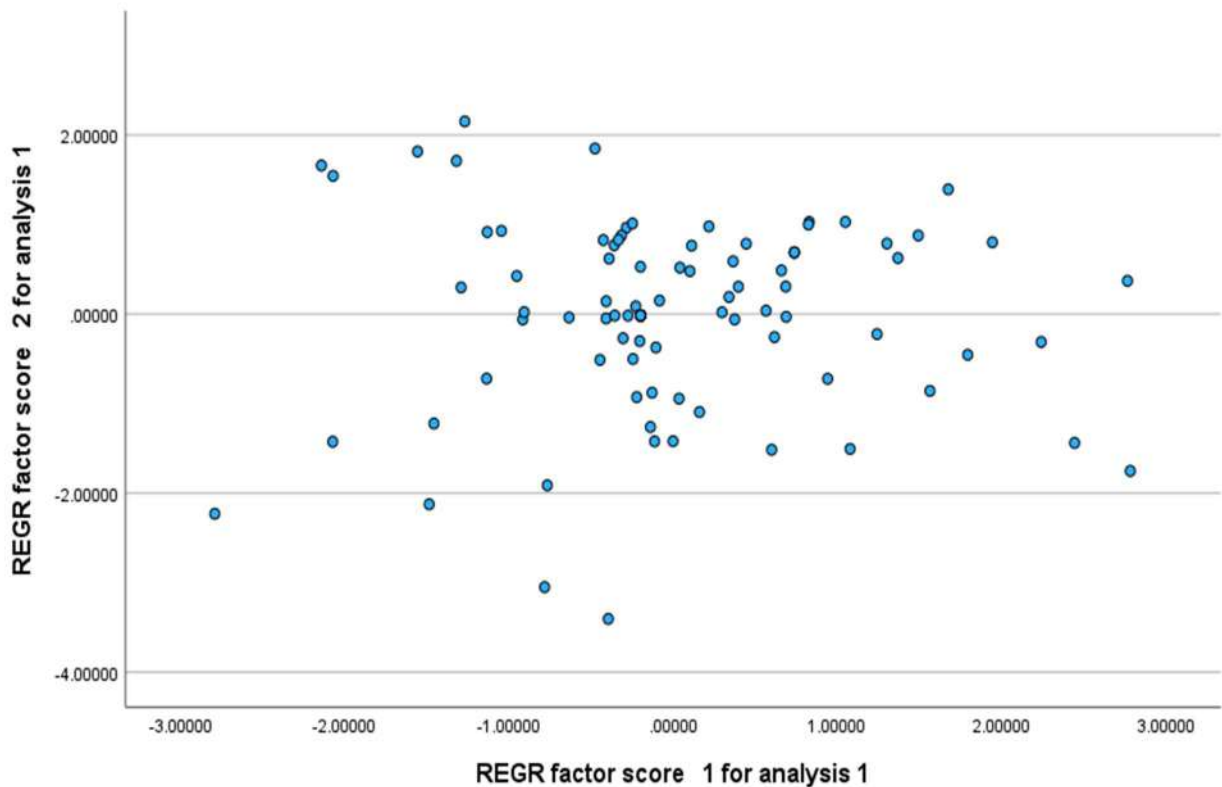
The **Component Transformation Matrix** indicated that the rotated solution successfully minimized correlations among the extracted factors. Values in the matrix show the linear combinations used to transform the unrotated component axes into the rotated solution, supporting clearer interpretability as shown in Table.4.5:

Component Matrix				
Factors	Component			
	1	2	3	4
SCF1	0.745			
EFF2	0.736			
SHF1	0.708			
TFH2	0.698			
GEF1	0.691			
EFF1	0.673			
TFH1	0.661			
MDF2	0.651			
RPF2	0.636			
SCF2	0.632			
ITF2	0.618			
RPF1				
MDF1				
ITF1		-0.647		
SHF2				0.627
GEF2				
<i>Extraction Method: Principal Component Analysis.</i>				
<i>4 components extracted.</i>				

(Table.4.5. Component matrix table)

4.11 Scatterplot analysis

This is a scatter plot indicating a relationship between two regression (REGR) factor scores. The x-axis is REGR factor score 1 for analysis 1 while the y-axis is REGR factor score 2 for analysis 1. The graph shows a set of data points (blue circles) spread out over the coordinate plane. These points seem to be spread out in about a circular fashion about the origin, with most data points within the range of -2 to +2 on both the x and y axes. this kind of visualization is often employed in factor analysis or principal component analysis to illustrate how observations distribute themselves among two factors that have been extracted. Each point presumably indicates a single case or observation in the dataset. the fact that there is no distinct linear pattern indicates that these two factor scores are not highly correlated with one another, which is typically desirable in factor analysis because it means that the factors are measuring different aspects of variance in the data. the relatively uniform distribution of the points over all four quadrants shows that the sample includes a variety of cases with different combinations of high and low scores on the two factors, without any visible grouping.



(Fig.4.2. Scatter plot analysis for first 2 Principal components)

4.12 Correlation Plots and Loadings

To show the relationships between the original influential variables and the extracted principal components, correlation plots were created. In this way, insights arise on how strongly and in what direction each variable influences the underlying components. This plot facilitates the understanding of component loadings and demonstrates clusters of related influentials

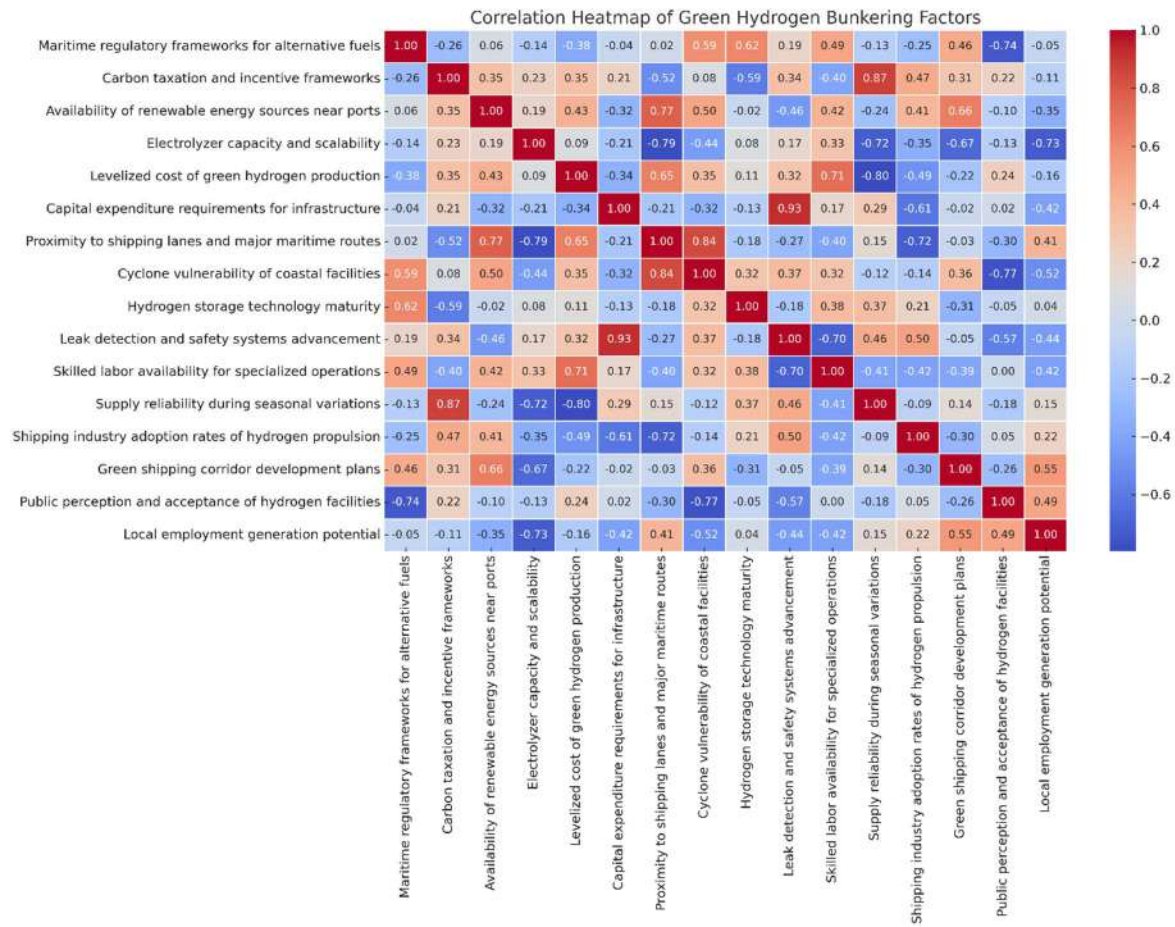
(Table.4.6. Pearsons's Correlation table)

	RPF1	RPF2	ITF1	ITF2	EFF1	EFF2	GEF1	GEF2	TFH1	TFH2	SCF1	SCF2	MDF 1	MDF 2	SHF1	SH F2
RPF1	1.															
RPF2	0.47* *	1.														
ITF1	0.51* *	0.35* *	1.													
ITF2	0.32* *	0.45* *	0.28* *	1.												
EFF1	0.35* *	0.51* *	0.26* *	0.60* *	1.											
EFF2	0.40* *	0.48* *	0.24* *	0.56* *	0.50* *	1.										
GEF1	0.51* *	0.44* *	0.32* *	0.29* *	0.44* *	0.47* *	1.									
GEF2	- 0.26* *	-0.26* *	-0.25* *	-0.23* *	-0.06 *	-0.23* *	-0.22* *	1.								
TFH1	0.35* *	0.24* *	.17 *	0.30* *	0.33* *	0.55* *	0.44* *	-0.21* *	1.							
TFH2	0.30* *	0.37* *	.1 *	0.36* *	0.43* *	0.37* *	0.42* *	-0.23* *	0.60* *	1.						
SCF1	0.35* *	0.41* *	.11 *	0.30* *	0.39* *	0.44* *	0.50* *	- 0.30* *	0.52* *	0.64* *	1.					
SCF2	0.20* *	0.26* *	.04 *	0.46* *	0.46* *	0.46* *	0.30* *	-0.03 *	0.39* *	0.42* *	0.42* *	1.				
MDF 1	.16 *	0.30* *	.12 *	0.22* *	0.22* *	0.36* *	0.21* *	-0.18 *	0.27* *	0.41* *	0.46* *	0.36* *	1.			
MDF 2	0.25* *	0.24* *	.16 *	0.25* *	0.24* *	0.35* *	0.42* *	-0.24* *	0.39* *	0.36* *	0.55* *	0.42* *	0.64* *	1.		

SHF1	0.34*	0.29*	.14	0.37*	0.44*	0.50*	0.45*	-.07	0.42*	0.46*	0.42*	0.54*	0.34*	0.57*	1.	
	*	*		*	*	*	*		*	*	*	*	*	*		
SHF2	.19	0.24*	0.29*	.05	0.25*	.19	0.31*	-.15	.16	0.23*	0.37*	0.25*	.18	0.31*	0.41*	1.
		*	*		*		*			*	*	*		*	*	

** . Correlation is significant at the 0.01 level (2-tailed).

* . Correlation is significant at the 0.05 level (2-tailed).



(fig.4.3. Correlation heatmap for green hydrogen bunkering factors)

5.0 FINDINGS AND CONCLUSION

5.1 Key Findings

In-depth understanding of Factors affecting green hydrogen bunkering at the Indian coast, was the basis of this study, which applied Principal Component Analysis (PCA). The study distilled influential factors into four components from primary data collected through a structured questionnaire and analyzed using IBM SPSS. The PCA identified four broad components that were responsible for the influential dimension of Bunkering.

The components reflect from in Bunkering, offering actionable strategies for such platforms, The Principal Component Analysis (PCA) identified four strong latent constructs of the green hydrogen bunkering system on the Indian coast, explaining a total of 63.6% variance in data. The analysis was statistically valid, as evidenced by a meritorious value of KMO as 0.819 and significant Bartlett's Test (691.133, $p < 0.001$). High communality values (most of which were above 0.5) confirmed that the sub-factors were suitably represented in the extracted components. The four specific elements revealed were: **Market & Supply-Oriented Factors (20.73% variance)**, with an emphasis on planning and logistics abilities; **Cost & Technical Efficiency Factors (19.12% variance)**, as techno-economic feasibility factors; **Regulatory & Strategic Access (14.57% variance)**, with a focus on policy support and proximity to infrastructure; and **Social Acceptability & Job Creation (9.19% variance)**, as a focus on community outreach and public support. These results present a holistic framework to comprehend the green hydrogen implementation opportunities and challenges with a multidimensional perspective in coastal India, presenting useful insights to inform strategic decision-making in port development, policy-making, and stakeholder involvement for effective green hydrogen deployment initiatives.

5.2 Recommendations

As per the Principal Component Analysis (PCA) results, which yielded four dominant latent constructs accounting for 63.6% of variance in data, the following strategic recommendations are made to ensure successful implementation of green hydrogen bunkering along the Indian coastline:

5.2.1 Market & Supply-Based Factors

To tackle market and supply issues, India needs to focus on ramping up green hydrogen (GH₂) output and optimizing logistics. This can be done by promoting local GH₂ production by offering tax incentives, subsidies, and low-interest finance for coastal electrolyzers, especially in industrial cluster proximity (e.g., refineries, ammonia plants) to serve as an anchor of near-term demand. Ports such as V. O. Chidambaranar Port Authority, Kandla (Deenadayal Port Authority) and Paradip Port Authority should be redeveloped into specialist GH₂ bunkering terminals with built-in storage, pipelines, and rehabilitated jetties. Partnerships with international logistics companies can support GH₂ export supply chains, while aggregation measures to meet demand—requiring a 5% GH₂ mix in ocean-going fuels by 2030 and granting priority berthing to ships running on GH₂ will balance market take-off. Public sector adoption, in the form of using GH₂-fueled Indian warships, can also secure demand base and convey market assurance.

5.2.2 Cost & Technical Efficiency Factors

Government subsidy for R&D of indigenous electrolyzers, cryogenic storage, and fuel cells should reduce capital costs, aided by a special "GH₂ Innovation Fund" for pilot schemes such as ship retrofitting and intelligent bunkering systems. Parallely, implementation of ISO/TC 197 safety standards for GH₂ handling and storage will provide technical dependability, reinforced by training facilities for port personnel. Utilizing current LNG infrastructure for bunkering GH₂ can save retrofitting expenses, and a phased upgrade roadmap with priority to renewable energy integration will maximize long-term efficiency.

5.2.3 Regulatory & Strategic Access

Making regulations simpler is paramount. Single-window digital platform must integrate approvals for GH₂ projects (safety, land, environmental) to speed up timelines, and "GH₂ Special Zones" close to ports with pre-approved lands and grid connectivity can enable investors to step

in. Strategic strategies, such as long-term GH₂ offtake contracts and GST waivers, will de-risk investment, with export diplomacy able to make India a world GH₂ supplier through selective trade alliances.

5.2.4 Social Acceptability & Job Creation

Social uptake needs focused incentives and local outreach. Subsidies on vehicles (e.g., 30% for hydrogen ferries/trucks) and pilot projects in coastal towns can hasten the transition from fossil fuel, while public information campaigns touting GH₂'s environmental advantages (cleaner air, protection of coastal regions) will help generate public confidence. Development of skills is also crucial: setting up GH₂ institutes in proximity to ports can certify engineers and technicians, tying employment to "Make in India" drives in local manufacturing of electrolyzers and storage systems. Social acceptability is promoted through awareness-building initiatives, subsidies, and reserve local jobs, to make the community see GH₂ as both economic and environmental opportunity. Retention of 20% of GH₂ project employment for coastal societies and encouragement of community-based solar farms to produce GH₂ will provide for inclusive growth and acceptance at the grass roots level. **Government Strategies for Encouraging Futuristic Fuels** Governments tend to encourage futuristic fuels such as GH₂ by a carrot-and-stick regulatory policy, interposing mandates (e.g., quotas for GH₂ blending) with incentives (tax incentives, subsidies) in order to compel industry compliance. Market and supply drivers are met by anchoring demand via public-sector uptake and export-led diplomacy, and cost savings by leveraging R&D investment and repurposing infrastructure.

Through the implementation of these recommendations sequentially, India will be able to establish a feasible roadmap for the implementation of green hydrogen bunkering along its coast. The multi-dimensional strategy involving operational, technical, regulatory, and societal dimensions will position India as the leader in maritime decarbonization while making coastal areas sustainable economic enclaves.

These suggestions should be adopted through a phased implementation process with continuous evaluation and realignment of strategies with regard to technological advancements, market feedback, and regulatory changes. Public-private sector cooperation and international collaborations will be crucial for effective implementation.

5.3 Limitation of the study

While the findings of this study offer valuable insights, there are several limitations that should be acknowledged. One limitation is the relatively small sample size of 100 respondents. While this sample was representative to sustainable green hydrogen bunkering, it may not fully capture the diversity of perspectives from all stakeholders in the industry. Additionally, the study was geographically limited, as data was only collected from respondents in specific regions. This limits the generalized ability of the findings to other regions or countries, where the adoption of green hydrogen bunkering due to various other conditions.

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