Advanced Green Fuels for Maritime Application-Road Map for India (Part A)

National Centre of Excellence in Green Port and Shipping (NCoEGPS)

NCoEGPS

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Message from the Director General of Shipping

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एवं अपर सचिव, भारत सरकार

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Director General of Shipping &
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MINISTRY OF PORTS, SHIPPING AND WATERWAYS
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Directorate General of Shipping

MESSAGE

from

THE DIRECTOR GENERAL OF SHIPPING

GREEN FUELS ROADMAP REPORT BY DR. PIYALI DAS

It is a privilege to present the *NCoEGPS Green Fuel Roadmap – Part A*, which represents an important analytical milestone in India's transition towards a low-carbon and future-ready maritime sector. Developed under the National Centre of Excellence for Green Port and Shipping (NCoEGPS), this report reflects a structured and collaborative effort to assess viable green fuel pathways for Indian maritime applications, with active engagement from the Directorate General of Shipping and other key technical stakeholders.

India's maritime sector is at a critical juncture, where decarbonisation imperatives must be pursued in a manner that is technically robust, operationally safe and economically viable. In this context, the present study provides a comprehensive and evidence-based assessment of a spectrum of low-carbon and alternative fuel pathways relevant to Indian maritime operations, examined through lifecycle and Greenhouse Gas Fuel Intensity (GFI)-based analytical parameters.

The report adopts a systematic and data-driven framework and goes beyond conceptual discussions by analysing demand - supply dynamics, fuel mix scenarios, retrofitting and engine replacement pathways, as well as blend-fuel options that can be implemented without major engine modifications. Such granular assessment is essential for enabling a phased and realistic transition of the Indian fleet, while remaining aligned with evolving international regulatory developments and compliance trajectories.

The Directorate General of Shipping has reviewed this study and considers it appropriate to recognise this report as Phase I / Part A of the *Advanced Green Fuel Roadmap for the Indian Maritime Sector*. The findings and recommendations presented herein provide a strong technical foundation for the next stage of work, which must focus on translating analytical outcomes into clear, time-bound and implementable actions.

The immediate priority going forward is the development of Phase II, encompassing a comprehensive implementation plan with defined short-, medium- and long-term action points for coastal vessels and foreign-going vessels. This phase will require close coordination among the Directorate General of Shipping, the NCoEGPS Green Fuel team and relevant technical and classification institutions, with due consideration of vessel typologies, size categories, fuel standards, certification frameworks and data-driven compliance mechanisms.

I place on record my appreciation for the efforts of TERI and the NCoEGPS team in undertaking this comprehensive study and for their continued engagement with regulatory authorities during the review process. I am confident that this roadmap will serve as a valuable reference for policymakers, industry stakeholders and technical experts as India advances towards a structured, safe and sustainable transition to green fuels in maritime transport.

(Shyam Jagannathan)

Mumbai
Date: 12.01.2026

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Foreward

As the Director General of The Energy and Resources Institute (TERI) I am delighted to present this Report which includes the key findings of the NCoEGPS Project entitled" **Advanced Green fuels for Maritime Application (Mono Fuel, Dual Fuel/Hybrid, Multi-Fuel Blending) Road Map for India"**. This project was undertaken by NCoEGPS with financial support from Cochin Shipyard Ltd. (CSL), V. O. Chidambaranar Port, Paradip Port, and Deendayal Port under overarching guidance and vision of Ministry of Port, Shipping and Waterways (MoPSW), Government of India.

The proposed adoption of the IMO Net-Zero Framework at the 83rd meeting of the Marine Environment Protection Committee (MEPC 83) marks a decisive step towards decarbonizing international shipping through mandatory, Greenhouse Gas Fuel Intensity (GFI) based emission targets. By shifting the focus from Tank-to-Wake to Well-to-Wake emissions and introducing market-based mechanisms, such as, Surplus and Remedial Units, the framework provides both regulatory certainty and economic signals for accelerating the uptake of low-carbon and zero or near-zero (ZNZ) fuels.

In this context, NCoEGPS has conducted a comprehensive study to make an overall ranking of all possible alternate fuels including E-fuels and Biofuels with a special emphasis on Hydrogen and its derivatives (e.g. green Hydrogen, Methanol and Ammonia) for Indian maritime applications especially for Coastal and Ocean-Going Vessels (OGVs). In addition to the analysis of Global alternative fuel adoption trend, in this study the overall demand supply gap of alternative fuels, blend-fuel options for Indian OGVs are quantified for GFI compliance for vessels > 5000 GT. Additionally, alternative fuel demand is also estimated for Coastal vessels < 5000GT. This report also covers alternative fuel marine engines development trajectory, Global Fuel Cells and Onboard Carbon Capture projects highlighting the prospect for Indian maritime sector.

In the next phase of Advanced Green Fuel Roadmap for Maritime Application-Part B study, the DG Shipping and NCoEGPS Green Fuel team are committed to work together with other collaborating partners in developing the **Fuel Transition Roadmap Implementation Plan** for Indian vessels based on their types and size categories.

TERI believes that evidence-based research, pilot demonstrations, and enabling standards will play a crucial role in supporting India's transition to sustainable maritime fuels. Equally important is enhanced international cooperation, including the provision of climate finance and technology support by developed countries, to ensure that global decarbonization efforts are fair, inclusive, and effective. I believe this report will serve as a valuable resource for policymakers, industries, researchers, and investors as India charts its course towards a resilient, low-emission maritime sector.

Dr. Vibha Dhawan
Director General
The Energy and Resources Institute (TERI)

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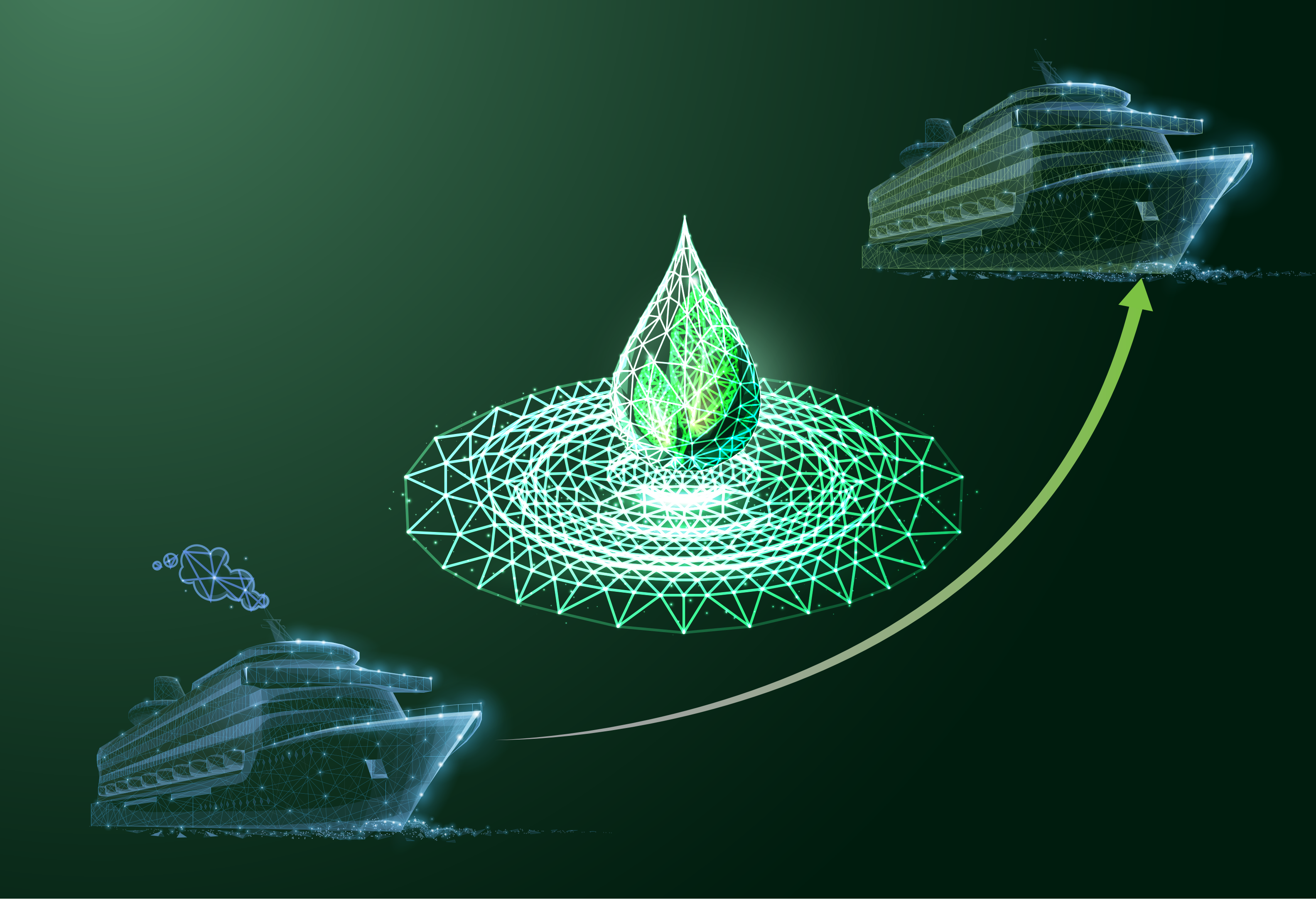
Abbreviations	Definitions
AFC	Alkaline Fuel Cell
AFIR	Alternative Fuels Infrastructure Regulation
AMU	Auxiliary Power Units
ASTM	American Society for Testing and Materials
BD	Biodiesel
BE	Battery Electric
BTL	Biomass to Liquid
Bxx/BDxx	where xx = Biodiesel Blend % (by volume)
C	Carbon
CBG	Compressed Biogas
CFPP	Cold Filter Plugging Point
CH_4	Methane
CHP	Combined Heat &Power
CI	Compression ignition
CO_2	Carbon Dioxide
CO2eq	Carbon Dioxide Equivalent
CP	Cloud Point
CRL	Commercial readiness level
D	Diesel oil/ Conventional fuel
DAC	Direct Air Capture
DME	Dimethyl Ether
DMFC	Direct Methanol Fuel Cell
DNV	Det Norske Veritas
DO	Diesel Oil
DWT	Deadweight Tonnage
EEDI	Energy Efficiency Design Index
EGR	Exhaust Gas Recirculation
eKW	kilowatt-electric
ekW	kilowatts
eLCC	Environmental Life Cycle Costing
EOL	End-of-Life
ETD	Energy Taxation Directive
EU	European Union
EU ETS	European Union Emissions Trading System

Abbreviations	Definitions
FAME	Fatty Acid Methyl Ester
FBIV	Fuel Booster Injection Valve
FC	Fuel Cells
FEED	Front-End Engineering Design
FID	Final Investment Decision
FT	Fischer–Tropsch
GCMD	Global Center for Maritime Decarbonization
GFI	Greenhouse Gas Fuel Intensity
GFOP	Green Fuels Optionality Project
GHG	Greenhouse Gas
GT	Gross Tonnage
GTL	Gas to Liquid
GWP	Global Warming Potential
HFO	Heavy Fuel Oil
HPDF	Dual Fuel High Pressure
HPDI	High Pressure direct injection
HTL	Hydro-Thermal Liquefaction
HVO	Hydrotreated Vegetable Oil
ICAO	International Civil Aviation Organization
ICE	Internal Combustion Engine
IEA	International Energy Agency
IEC	International Electrochemical Commission
IFO	Intermediate Fuel Oil
IMO	International Maritime Organisation
IPCC	Intergovernmental Panel on Climate Change
IRL	Investment Readiness Level
ISO	International Organization for Standardization
ISWG-GHG	Intersessional Working Group on Reduction of GHG Emissions
IWT	Inland Waterways Transport
LCA	Life Cycle Analysis
LFO	Light Fuel Oil
LGIM	Liquid Gas Injection Methanol
LH2	Liquefied Hydrogen
LHV	Lower Heating Value
LLCF	Low Life Cycle Fuels
LNG	Liquified Natural Gas

Abbreviations	Definitions
LOA	Length Overall
LPDF	Dual Fuel Low Pressure
LPG	Liquified Petroleum Gas
LTMFC	Low Temperature Methanol Fuel Cell
M	Methanol
MARPOL	International Convention for the Prevention of Pollution from Ships
MCFC	Molten Carbonate Fuel Cell
MDO	Marine Diesel Oil
MEPC	Marine Environment Protection Committee
MGO	Marine Gas Oil
MJ	Megajoules
MMMCZCS	Mærsk McKinney Møller Centre for Zero Carbon Shipping
MSW	Municipal solid wastes
MWh	Megawatt-hour
N_2O	Nitrous Oxide
NFPA	National Fire Protection Association
NG	Natural Gas
NO	Nitrous Oxide
NOx	Nitrogen Oxides
NPV	Net Present Value
NZE	Net Zero Emissions
OCCS	Onboard Carbon Capture
OCCUS	On board Carbon Capture Storage and Utilisation
OGV	Ocean Going Vessels
PAFC	Phosphoric Acid Fuel Cell
PEMFC	Polymer Electrolyte Membrane Fuel Cell
Plca	Prospective Life Cycle Assessment
PM	Particular Matter
PSV	Passenger Vessels
RCCI	Reactivity-Controlled Compression
RE	Renewable Energy
RED	Renewable Energy Directive
RO-RO	Roll-on/Roll-off
RU	Remedial Units
SCR	Selective Catalytic Reduction
SI	Spark Ignition

Abbreviations	Definitions
SIDS	Small Island Developing States
SMR	Steam Methane Reforming
SNCR	Selective Non-Catalytic Reduction
SO_2	Sulphur Dioxide
SOFC	Solid Oxide Fuel Cells
SOLAS	Safety of Life at Sea
STASHH	Standard Sized FC Module for Heavy Duty Applications
STS	Ship-to-Ship
SU	Surplus Units
SVO	Straight Vegetable Oil
TCO	Total Cost of Ownership
TEU	Twenty-foot Equivalent Unit
THC	Low Total Hydrocarbon
TRL	Technological Readiness Level
TTS	Truck-to-Ship operations
TTW	Tank to Wake
ULS	Ultra Low Sulfur
USD	United States Dollars
USD/t	United States Dollars/Ton
v/v	Volume%/Volume %
VLS	Very Low Sulfur
WTW	Well To Wake
YSZ	Yttria-stabilized Zirconia
ZNZ	Zero & Near Zero Emission Fuels



Executive Summary

In April 2025, during 83rd meeting of Marine Environment Protection Committee (MEPC 83), IMO has introduced Net Zero Framework setting mandatory GHG Fuel Intensity (GFI) based target for emission reduction from all global ships above 5000 GT. The GFI of a fuel sets a threshold on the annual well to wake GHG emission expressed per unit of energy used (gCO_2eq/MJ) and it is extremely critical for accurate assessment of the true environmental benefits and overall climate performance of the alternative marine fuels. Under new framework, ships achieving emission targets are eligible to earn Surplus Units (SUs) which can be traded, saved, or cancelled. Tier-1 (Direct compliance) shortfalls need to purchase Remedial Units (RUs) at $100/$tCO_2$ whereas, Tier-2 (Base compliance) shortfalls need to either pay $380/$tCO_2$ or use Surplus Units (SUs). Interestingly, use of Zero or Near-Zero (ZNZ) fuels would now-on qualify for rewards from the IMO Net-Zero Fund. It implies that ships that use zero or near-zero (ZNZ) fuels having GFI below 19 g CO_2e/MJ before 2035 and 14 g CO_2e/MJ after 2035 are eligible for financial rewards. This will be reviewed every five years, and the corresponding compensation amounts will be updated based on future IMO guidelines.

In this report a comprehensive overview of alterative shipping fuel adoption and global transition trend is presented based on analysis of over 0.12 million vessel data procured from Clarckson's Research database. This study develops the ranking of alternative low Carbon and ZNZ alternative fuels for maritime application in India based on 8 sustainability parameters such as i. Well to Wake (WtW) GFI of fuel ii. LCA based GHG reduction potential iii. Fuel supply readiness, iv. Storage tank capacity and bunkering infrastructure v. Global bunkering infrastructure readiness in ports, vi. Engine and Fuel Cell ecosystem vii. Cost of fuels with and without IMO proposed GHG emission tax and viii. Standard policy and regulatory gaps. In the absence of clearly defined classification of ZNZ fuels, in this study bio and e fuels with GFI value below the IMO's year wise threshold mark is considered as ZNZ fuels.

This report presents the estimates of the alternative and ZNZ fuel demand supply gap for India till 2035. Subsequently, the green Hydrogen and Renewable Energy (RE) based power to produce the alternative fuel is quantified. To align with GFI based trajectory large investment is needed both for ZNZ fuel production scale up and ZNZ fuel capable vessel manufacturing including alternative-fuel engines. To attract investment. sustained demand of these fuels and sound economical parameters is crucial. While the universal definition of ZNZ fuels and the clarity on reward distribution is still awaited from IMO, to comply with the IMO's GFI based emission target generating Surplus Units (SU) and ensuing qualification for receiving financial rewards the short-, medium- and long-term strategies are developed. The role of alternative fuel engines, scope for Onboard Carbon Capture (OCC) and Fuel Cell integration too is critically analysed and assessed for adoption by Indian ships towards long term decarbonization. Finally, policy gaps are identified towards effective green fuel transition in Indian maritime sector.

Towards meeting short to medium term GFI based emission targets at least up to 2035, blend fuel (dual -fuel and multifuel) strategy offers the most practical and economically viable pathway to India. It is found that, under the IMO proposed GFI regime, use of B30 (30% Biodiesel blend in Diesel) can meet direct compliance target only till 2031 where as B40 is needed to remain compliant until 2033. B50 covers direct compliance target till 2035. Although B40 and B50 are sufficient enough to meet Direct compliance emission targets till 2033 and 2035 respectively, multi-fuel blends such as Bio/E

Alcohol (Methanol/2GEthanol 10 v/v %)-Biodiesel- Diesel blends can fetch much higher degree of Surplus Unit and Rewards thus making the transition economically attractive. The advantage of blend fuel is continued use of existing engines without investing to alternate fuel engines. Additionally, although Coastal Vessels <5000GT are not presently subjected to IMO compliance, however, emission guidelines for vessels between 400-5000 GT range is under consideration by IMO. Hence, in the present study the fuel-blend Scenarios are also built for Indian Coastal vessels.

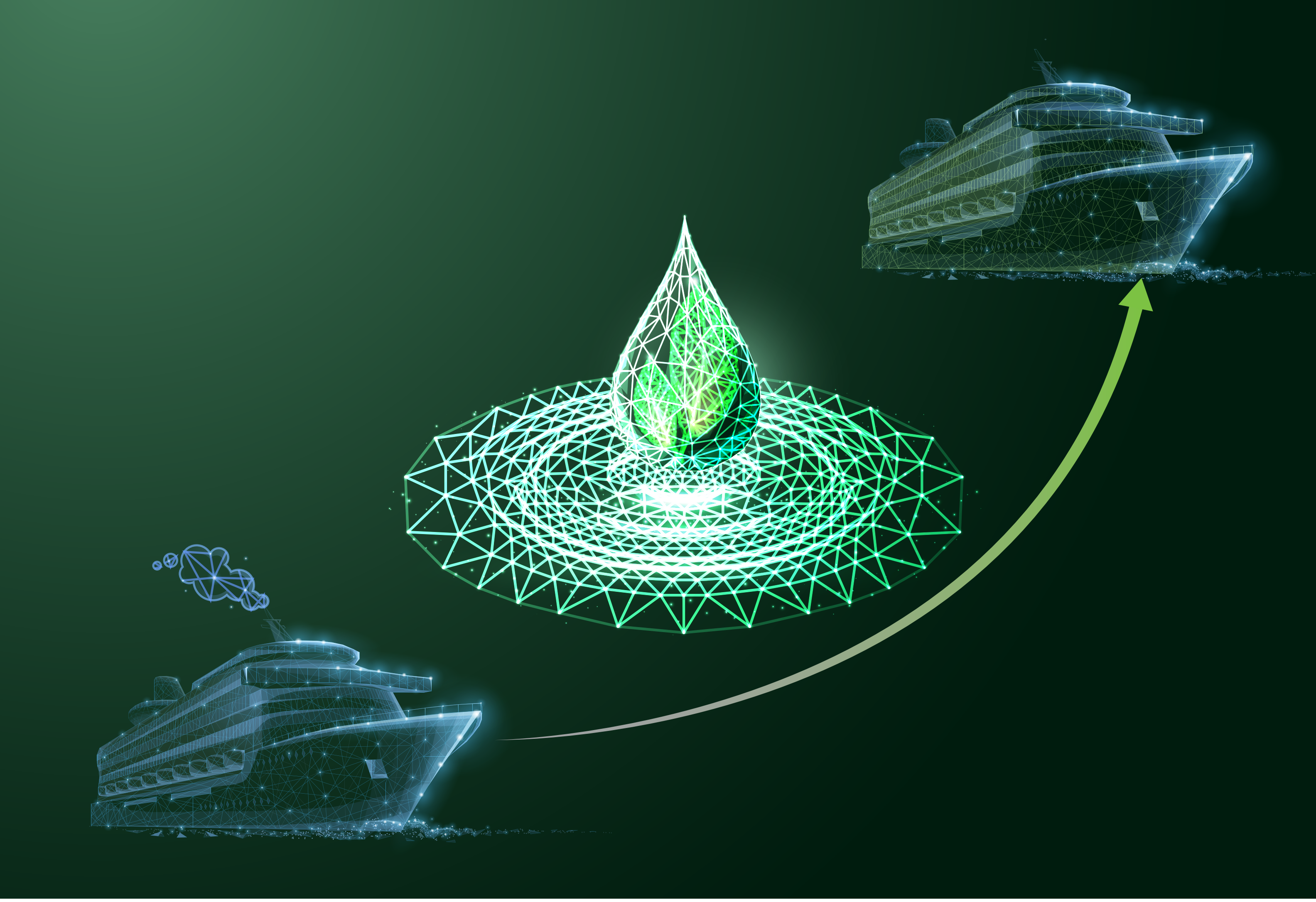
As a long term decarbonization strategy, adoption of dual-fuel engines for fuels only E/Bio (in the order Methanol> LBG/LNG> Ammonia) appears most preferred based on 8 sustainability parameters. However, considering two critical aspects i.e. supply readiness and cost of alternative engines, dual fuel engines are highly recommended for adoption only by new builds or vessels <5-7 years of age.

Fuel Cell should be considered as promising option for Inland water and shortsea/coastal shipping. Direct Methanol Fuel Cell (DMFC) could be worth investing for India in very small vessel <100eKW (Inland water) category. India should also develop small to mid-sized (100-500ekW) LTMFC Fuel Cell ships (PSV, Ferries, RO-RO & Cargo) till storage and safety challenges of compressed or liquified hydrogen (LH2) as fuel persist. In long term once LH2 overcome the become viable technological and safety challenges, larger inland water ships can be integrated too. SOFC technology should leverage its high fuel flexibility especially Ammonia & Methanol. For cruise, and long-haul vessels, pilot projects need to be initiated with SOFC –Battery hybrid (immediate) and SOFC/ICE hybrid with alternative fuel options like Methanol and Ammonia (medium to long term) especially for auxiliary power units (AMUs).

There is a heightened need to increasingly implement CO2 capture on-board and switching over to bio/ synthetic e-fuels from HFO with the advancement of alternate fuel engines. Immediate implementation strategy needs to be developed to pilot dual-fuel and multifuel blend in existing engines with OCC in few pilots for generating data to assess energy and economic viability. Domestic green corridor can be set up for with pilot demonstration. There is an urgent need of larger number of pilot demonstration of CCUS projects through valorisation of adsorbed CO2 especially for India with lack of geological CO2 storage sites along with innovation in sustainable CO2 adsorption material production.

In order to facilitate early transition to ZNZ fuels, India urgently needs to develop standards for Hydrogen derived fuels Bio & E (Methanol, Ammonia, Methane) along with blend fuels, such as, dual-fuel (Alcohol-Diesel, Diesel-Biodiesel B30, B40 & B50) and mixed-fuels for Alcohol (Methanol/ Ethanol), Diesel and Biodiesel for maritime application through BIS

Finally, this study highlights that along with ramping up domestic production of E& Bio Methanol, Ammonia and E LNG, India need to calibrate and undertake dynamic assessment of international shipping demand and target to create refueling/bunkering facilities in part of major ports along the coastal lines



Introduction and Objectives of Study

Presently there are stringent environmental standards and regulatory focus on maritime decarbonization. IMO, the governing body of international shipping, has set an overall goal of net zero GHG emissions from international shipping by or around 2050, relative to 2008 levels and is pursuing efforts to phase out the emissions. Earlier in 2020, IMO also placed regulations limiting marine fuel sulfur content to 0.5% by weight and issued a carriage ban on all non-compliant fuel. Fuel sulfur regulations are further restricted to 0.1% sulfur by weight (S) especially for vessel movement in emissions control areas. These regulations are pushing maritime sector to diversify their fuel portfolio and increasingly seek low-sulfur, low-carbon and also zero carbon alternatives. It is perceived that future use of maritime fuel will have multi fuel mix owing to present uncertainty about which alternative fuel option will be able to support a future-proof asset and operation.

Among global initiatives on GHG reduction from maritime ports and vessels; Getting to Zero Coalition, International Collaboration on Ship Emissions Reductions Initiative, World Ports Climate Action Program, Zero Emission Energy Distribution at Sea, Poseidon Principles, Sea Cargo Charter, Maersk Mc-Kinney Moller Center for Zero Carbon Shipping, and Northwest Ports Clean Air Strategy are mentioned worthy. Many carbon reduction measures are being tested in order to achieve IMO GHG emissions targets **[1, 2].** These includes adoption of alternative fuels, improvements in hull design along with exploring alternate power and propulsion systems, exercising operational measures like speed and voyage optimization, and market-based mechanisms **[3]**. IMO has also introduced technical measures for achieving long-term GHG reduction targets, including the Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management. However, the EEDI is grossly perceived as narrowly focused, considering only gate-to-gate vessel emissions. It is being argued to adopt well to wake life cycle perspective of alternative fuels which can effectively capture environmental externalities beyond the purview of traditional metrics (such as EEDI) and thus support mitigating unintended environmental consequences of marine fuel consumption, such as shifting environmental burdens across segments of the supply chain or across pollutant categories (e.g., emissions to land, water, and air) Additionally, it is also advocated that IMO consider a full life cycle perspective when accounting for the emissions from shipping and suggests exploiting the framework established by the International Civil Aviation Organization (ICAO) on Sustainable Aviation Fuels also in the maritime sector **[1].**

India has recently set an ambitious target to be a leading hub for green tugs including coastal vessels and ferries. A 3-phase transition is envisioned with Interim phase (50% green tugs between 2023-2030), 1st Phase (75% transition to green tugs between 2030-2035), and 2nd Phase (100 % transition to green tugs between 2035-2040). This implies that 50 % of all new tugs that would be constructed in the interim period are expected to run on sustainable green/future fuel. To achieve the target, accelerated innovation, setting up the supply chain for green fuels, developing technology at scale, establishing mono and blend fuel standards, storage and safety protocols are extremely crucial in the time towards 2030.

There is a great need to compare all possible green/sustainable alternative fuel options for India including (Methanol/ Hydrogen/Ammonia/LNG/Ethanol/Methanol-Diesel blends/DME/ /Bio-Diesel/ Green-Diesel etc.) and their roles in decarbonizing India's Maritime transport. Overall activities require alignment with global developments. Towards this, it is of paramount importance to understand progress in fuel and engine development, policy, economics and regulations, and global perspectives.

With this as a background, the major objective of this study was initially set to outline the green fuel roadmap (especially the Hydrogen derived fuels like Hydrogen, Methanol and Ammonia with fossil fuels as reference) ensuring IMO Compliance in Indian maritime sector.

However, with the evolving regulatory guidelines from IMO's Marine environment Protection Committee (MEPC) to implement mid- and long-term measures, the study has also incorporated the prospects for alternative fuel, fuel-mix/and blend-fuel for Indian Coastal and Overseas going Vessels (OGVs) to comply with IMO's latest guidelines.

Additionally, in order to see the effct of MEPC-83 GFI-based guidelines on Indian Vessels, the cost and compliance calculator is used for quantitative evaluation of possible revenue or penalty for one representative Indian OGV Vessel named Kashi. The vessel details are obtained from Clarkson's Research data bank.

In the present study the alternative green fuel options for shipping are compared on eight major sustainability aspects, such as,

» WtW GFI of fuel

» LCA based GHG reduction potential

» Fuel supply readiness

» Storage tank capacity and bunkering infrastructure w.r.to fossil counterpart

» Global bunkering infrastructure readiness at ports

» Alternative engine and Fuel Cell ecosystem readiness

» Cost of fuel with and without IMO's GHG emission price

» Standard policy and regulatory gaps

In order to make comparative assessment of alternative green fuel options for Indian maritime sector the following activities are performed.

» Statistics of Indian and global vessels and fuel consumption and analysis - **Chapter 1**

» Understanding global alternative green fuel transition trend w.r.to vessels, country ownership, engine and Fuel Cell developers and shipbuilders - **Chapter 2**

» Alternative fuel based marine engine development-global status -**Chapter 3**

» Estimation of alternative green fuel (low carbon/zero & near zero emission fuels i.e ZNZ) demand for Indian maritime sector (both Costal and OGVs) (Inland water not included in this study)- **Chapter 4**

Two Scenarios are built where the

Scenario-1 estimates fuel/fuel-mix demand for meeting **GFI based emission targets by year 2030 and 2035 as per MEPC 83 amended guidelines. Under this Scenario, except for use of drop in fuels, existing engines retrofitting or replacement to alternative engines (dual-fuel or mono fuel) is a necessity.**

Scenarios-2 is built on **blend-fuel approach which considers dual or multi-fuel blending of possible low carbon/ZNZ fuels** (such as, Diesel-Biodiesel, E/Bio Alcohol (Methanol/Ethanol)-Diesel & E/Bio Alcohol (Methanol/Ethanol)- Biodiesel -Diesel blends). **In the blend-fuel strategy, the major advantage is the use of existing engines without the need of expensive retrofitting or replacement in short to mid-terms i.e. up until 2035.**

» Assessment on alternative fuel demand supply gap, requirement of Renewable electricity (RE) and Green Hydrogen for making alternative fuel under all 2 Scenarios- **Chapter 4**

» Comparison of Alternative fuels w.r.to their properties, cost, LCA performance, ship design

» Implications-**Chapter 4**

» Ranking of alternative fuels based on 8 sustainability parameters- **Chapter 4**

» Assessment of feasibility of establishing supply chain logistics for alternative green fuels in India for marine ports/nearby areas comparative analysis amoung green fuel options -**Chapter 4**

» Understanding bunkering and storage options & global and Indian port infrastructure readiness level for alternative green fuels -**Chapter 4**

» Assessment of technical feasibility of establishing alternative green fuel storage, bunkering facilities at 3 selected major ports in India's east and west coast - **Chapter 4**

» Assessment of alternative fuel-based Fuel Cell and hybrid systems for ship- global status **-Chapter 5**

» Onboard Carbon Capture Technologies-global status & comparative assessment-**Chapter 6**

» Assessment of the global policy landscape related to fuel storage, transport, handling, bunkering & safety protocols for alternative green fuel adoption in India-**Chapter 7**

» Conclusions

» Recommendations

Latest Amendments in IMO's Regulations related to GHG Reduction and Fuel Standards-MEPC 83 & MEPC 2nd Extraordinary Session (MEPC-ES.2)

IMO's Marine Environment Protection Committee (MEPC 83) meeting held in April 2025 has established binding measures to reduce the well-to-wake (WTW) greenhouse gas fuel intensity (GFI) of International ships over 5,000 gross tonnage. To facilitate the transition to alternative fuels and accordingly achieve emission reductions in the maritime sector, carbon pricing is gaining unprecedented momentum as one of the most important measures.

As in the recently concluded MEPC 83, IMO has given green signal to Net-Zero Framework, setting mandatory GHG Fuel Intensity (GFI) Targets for all global ships > 5,000 GT. The new rules include a two-tiered compliance system, which not only imposes penalties on CO2eq emissions, but also provide rewards based on emission compliance of the ship as seen in Figure 1 below. The attained GFI, expressed in terms of gCO2eq/MJ, will be calculated based on Well-to-Wake (WtW) GHG emissions for each marine fuel/fuel-mix/blend-fuel options as per the following Equation-1,

$$GFI_{attained} = \frac{\sum_{j=1}^{J} EI_j \times Energy_j}{Energy_{total}}$$

Where, **EI**$_j$ represents **GHG Emission Intensity of each fuel/energy source** used by the ship, **Energy**$_j$ represents **Energy Value/Lower Heating Value of each fuel/energy source** used and Energy$_{total}$ is the **Total Energy consumed** by the ship. A lower GFI value indicates more environmentally friendly energy usage, contributing to reduced overall GHG emissions. IMO's LCA based methodological guidance is provided in Annexure I.

GFI targets for emissions from ships are set to be progressively stricter over the years. For instance, the **Base Targets** and **Direct Targets** for the years between 2028 to 2035 are given in **Table 1** below.

Table 1: IMO's proposed Emission Reduction Targets from International Water Ships > 5000GT

Year	Base Targets (GHG emission reduction % with 2008 as Reference)	Direct Targets (GHG emission reduction % with 2008 as Reference)
2028	4.0	17.0
2029	6.0	19.0
2030	8.0	21.0
2031	12.4	25.4
2032	16.8	29.8
2033	21.2	34.2
2034	25.6	38.6
2035	30.0	43.0

Setting of the Base and Direct Target for the years between 2036 to 2040 are scheduled at 1 January 2032 although the **Base Target for 2040 is tentatively set as 65%** GHG emission reduction against 2008 reference value. The **Well-to-Wake (WtW) fuel GFI** Target for the period until **2034**, is set as **19.0 gCO2e/MJ**, and from **2025 onward**, **14.0 gCO2e/MJ**.

Under new framework, ships achieving emission targets are eligible to earn Surplus Units (SUs) which can be traded, saved, or cancelled. Tier-1 (Direct compliance) shortfalls need to purchase Remedial Units (RUs) at \$100/tCO_2 whereas, Tier-2 (Base compliance) shortfalls need to either pay \$380/tCO_2 or use Surplus Units (SUs). Interestingly, use of Zero or Near-Zero (ZNZ) fuels would now-on qualify for rewards from the IMO Net-Zero Fund. It implies that ships that use zero or near-zero (ZNZ) fuels having GFI below 19 g CO_2e/MJ before 2035 and 14 g CO_2e/MJ after 2035 are eligible for financial rewards. This will be reviewed every five years, and the corresponding compensation amounts will be updated based on future IMO guidelines.

As per MEPC 83 framework all emission tracking were supposed to be performed using new IMO GHG Fuel Intensity (GFI) Registry. This was to be formally adopted by October 2025 with enforcement starting on 2028. Thus, ships need to start collecting the necessary GFI data from 1 January 2028 and report the same for the verification by the administration in early 2029. It is observed that under new regulations, Base as well as Direct Target trajectories are highly ambitious. Also, it is worth highlighting that MEPC 83 trajectories still fall short of reaching net zero target by or near 2050 which needs future readjustment of trajectories between 2035-2040 to reach near zero in 2050.

The disbursement of generated revenue is proposed to be utilized for the following activities

» To provide incentives for alternative-fuel ships and developing Infrastructure

» To support GHG-vulnerable countries, such as small island developing states (SIDS)

» To cover administrative expenses related to the implementation and management of the schemes

However, **MEPC 2nd Extraordinary Session (MEPC-ES.2)** held in October 2025, which was originally set to adopt **MEPC 83 framework, is adjourned till October 2026.** This implies that the enforcement of the framework as well as the GFI Data collection verification will eventually be delayed by a year.

In Addition, Intersessional working on Reduction GHG emissions from ships (ISWG-GHG 20) meeting held on 20-24th October 2025 discussed next steps for revising implementation guidelines IMO Net Zero Framework. **Especially on Fuel Certification, ZNZ Fuels, Technologies and Reward Mechanisms, use of IMO Net-Zero Fund, GHG Fuel Intensity (GFI) Calculation, Compliance, and Registry & Consolidation of overlapping draft guidelines by member states. Delegates are also invited to submit further proposals on refinement of LCA Framework**. **Draft TOR is prepared 5th IMO GHG study to cover Inventory of International shipping GHG emissions, estimates of GHG fuel intensity (GFI) & emission projections**. Next MEPC 84 is scheduled for April 2026

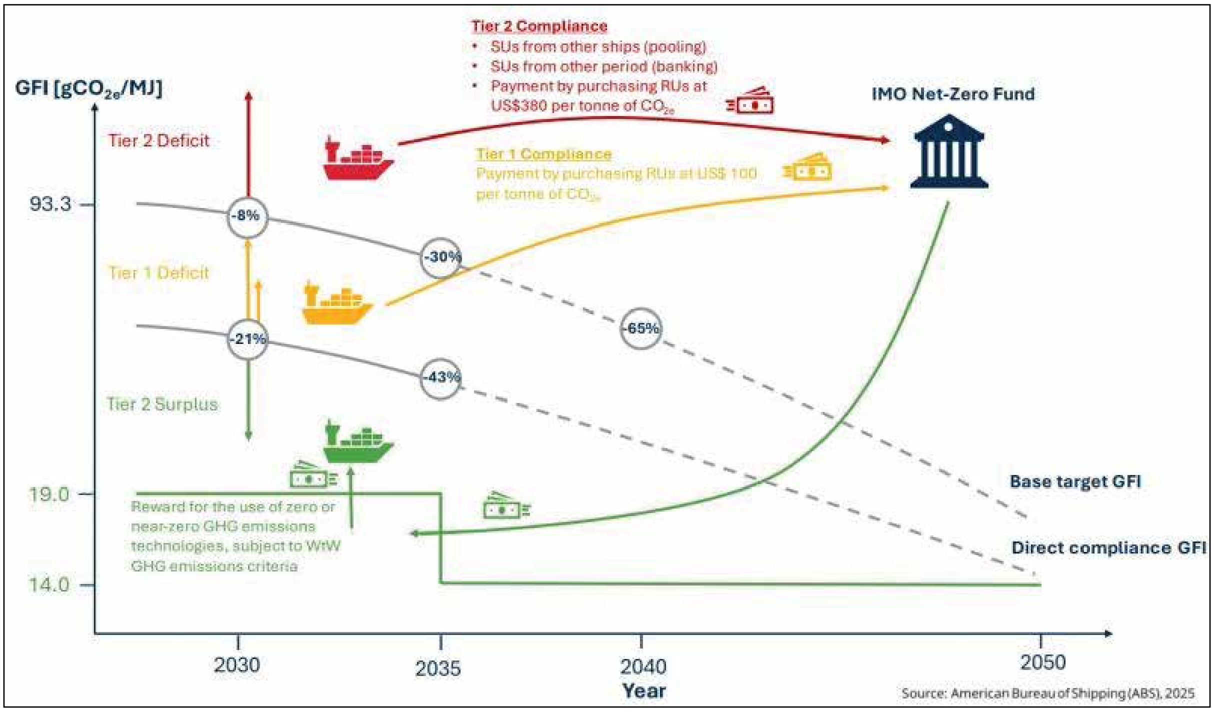


Figure 1: MEPC 83 New Amendments in Emission Targets

When carbon pricing is reinforced, it is expected to account for a large portion of fuel costs. Also, several financial institutions are signing onto the Poseidon Principles, established in 2019 in order to assess the climate alignment of ship finance portfolios. This is expected to expedite the process of shipping companies ensuring alignment with the IMO's GHG emission reduction targets.

The following **Table** illustrates the key outcome of MEPC 83.

Table 2: Key Outcome of MEPC 83

Topic	Description	Key Outcomes / Developments
Mid-Sterm GHG Reduction Measures	Amendment of MARPOL Annex VI for lifecycle-based GHG emissions regulation.	Approved for circulation and adoption by October 2025. Entering into force 1 March 2027. Applies to ships ≥5,000 GT.
GHG Fuel Intensity (GFI)	Annual ship-level GHG intensity metric based on energy source emissions.	Ships must calculate and report GFI; compliance determined by Base and Direct Compliance targets. Surplus units can be traded or banked.
Incentives for Zero/ Near-Zero GHG Fuels & Technologies (ZNZ)	Mechanism to financially reward adoption of ultra-low GHG fuels or technologies.	Fuels below 19 gCO2eq/MJ (until 2034, then 14 gCO2eq/MJ) eligible. Rewards framework under development.

Table 2: Key Outcome of MEPC 83

Topic	Description	Key Outcomes / Developments
Fuel Certification & Recognition Guidelines	Sets out requirements for certifying sustainable marine fuels via IMO-recognized schemes.	IMO will define certification standards and procedures for recognition of schemes. To be adopted in supporting guidelines.
Further Development of Life Cycle GHG Intensity Guidelines	Updates to LCA Guidelines for default values, fuel pathway codes, and emission boundaries.	Default emissions factors submitted for review (e.g., Methanol, Ammonia, Biodiesel, LNG). New fuel pathways under discussion.
Fifth IMO GHG Study	Comprehensive GHG inventory and carbon intensity trend analysis (2008–2025).	IMO will include WtW emissions, modeling to 2050. Final report due by MEPC 87 (2028). Scope includes CH4, N2O, and other pollutants.
Fuel Oil Consumption Data Reporting & Access	Increased transparency via amendments to DCS regulations under MARPOL Annex VI.	Data to be shared with recognized organizations, anonymized data accessible publicly. Amendments in force from March 2027.
Non-CO_2 GHG Measurement & Monitoring	Guidelines for CH_4 and N_2O emissions measurement from marine engines.	Approved MEPC.402(83); covers test-bed/onboard verification of CH_4 and N_2O emissions.
Onboard Carbon Capture (OCCS)	Development of a regulatory framework for CO_2 capture onboard ships.	Work to be completed by 2028. Focus on emission traceability, environmental safety, and reception facility access.
Fuel Standards and Certification Pathways	Verification of fuels under LCA framework using default or actual emissions factors.	Includes Excel-based templates, submission procedures, and sustainability criteria (e.g., land/water use, labor rights).

Key Findings of the Study

Chapter 1: Vessel Ownership

Analysis of global distribution of vessel ownership shows a clear dominance by Asian countries, followed by Europe and North America and India's significant contribution with 2,179 vessels.

Among top 25 countries, China P.R. leads significantly with 13,864 vessels, followed by Indonesia with 11,994 vessels and Japan with 8,731 vessels. Greece, the United States, and an unspecified category labeled "Unknown" also have substantial fleets, with 5,978, 4,890, and 4,066 vessels respectively. Mid-tier countries include Singapore with 3,623 vessels, South Korea with 3,061 vessels, and Turkey with 2,986 vessels. European countries such as Russia, Norway, and Germany have significant number of vessels counting to 2,948, 2,773, and 2,643 respectively. The U.A.E. stands out in the middle east with 2,608 vessels. Other notable countries are the Philippines with 2,212 vessels and Vietnam 2,151 vessels. Italy, Malaysia, the Netherlands, and Hong Kong contribute further with vessel counts ranging from 1,651 to 2,143.

Chapter 2: Global Alternative Fuel Transition in Marine Vessels

In maritime decarbonization, global focus is rapidly shifting on low GFI based Zero and Near Zero (ZNZ) fuels produced through Bio- and E pathways. Major alternative fuels presently being considered are fossil based Liquified Natural Gas (LNG), Biodiesel (FAME), SVO based Green Diesel, Methanol, Ammonia & Hydrogen.

TERI-NCoEGPS's analysis of Clarckson's [4] global vessel data shows that presently ~98% of ships operate on conventional fuels, and only ~2% are on alternative fuels/propulsion systems. This 2% in turn comprises of the number of propulsions using different alternative fuels such as, 1105 LNG, 125 Liquified Petroleum Gas (LPG), 123 Biofuel (primarily Biodiesel), 37 Methanol, 24 Ethane, 20 Hydrogen, 3 Ammonia and 10 nuclear vessels. **In addition, there are around 743 Battery/Hybrid based vessels sailing globally.**

Among in-service vessels, only looking through the prism of green/sustainable (Bio & E-fuel) alternative fuel options, Biofuel (mainly Biodiesel) based vessels dominate, with Methanol, Hydrogen, and Ammonia ranked next in descending order. Surprisingly, in the order-book data, Methanol is visibly emerging as the front-runner with 251 vessels followed by Biofuel with 24 vessels, Hydrogen with 23 vessels and Ammonia 22 vessels.

Comparative Assessment w.r.to Gross Tonnages (GT) Distribution of in-service vessels shows LNG is adopted highly in larger vessels particularly > 100K GT range. Whereas, from green alternative fuel perspective, Biofuel (Biodiesel) is adopted largely in 10-50K GT range, Methanol in 10K-50K GT range along with 20-50 GT, Hydrogen <500 GT and Ammonia adopted only for 3 vessels one each in <500, 10-30k and 5-10 K GT range. **Orderbook data reveals LNG domination with 991 vessels primarily >50K GT range among bulk carriers and container ships. With respect to alternative green fuel adoption, Methanol vessels leading in >50K GT range with significant presence in mid and smaller range too.**

Ammonia is still in nascent stages with 22 vessels, equally distributed in 10-50K GT range and > 50 K GT range. **Table 3 and 4** provide snapshot of alternative fuel adoption in OGVs w.r.to fuel types and GT distribution respectively.

Orderbook data reveals the following country wise lead in Green/E-fuel adoption

- **Methanol** comprised of the highest in all the category spread its adoption across different countries led by Denmark, China P.R, France, Germany, Japan, Taiwan, Singapore and many more, suggesting diverse strategies and regulatory frameworks.
- Among 24 **Biodiesel** vessels ordered, Singapore and Norway lead by 9 and 4 vessels respectively.
- The China P.R, Belgium, USA and UK stand out in **Hydrogen**-powered vessels.
- **Ammonia** powered 11 vessels will be owned by Belgium and 4 by Netherlands.

For other alternative fuel option

- Japan, Switzerland & Greece demonstrate substantial adoption of **LNG**
- Notably, Russia's exclusive involvement in **Nuclear**-powered vessels
- China P. R emerges as a frontrunner in **Ethane**-powered vessels with 28, Followed by Germany, Japan, Norway, Singapore and UAE

Table 3: Overall Alternative Fuel Vessels Statistics: Comparative Assessment (w.r.to Fuel Types)

In service				Orderbook			
All Alternative Fuels		**Hydrogen Derived Fuels**		**All Alternative Fuels**		Hydrogen Derived fuel	
Fuels	Total Number & % among all Alternative Fuels	Fuels	Total Number & % among Hydrogen Derived Fuel	Fuels	Total Number & % among Alternative Fuels	Fuels	Total Number & % among Hydrogen Derived Fuel
LNG	**1105(76 %)**	Methanol	37 (62%)	**LNG**	**991 (67 %)**	Methanol	251 (85%)
LPG	125 (9 %)	Hydrogen	20 (33%)	Methanol	251 (17%)	Hydrogen	23 (8%)
Biofuel*	123 (8%)	Ammonia	3 (<1%)	LPG	114 (8%)	Ammonia	22(7%)
Methanol	37 (3%)			Ethane	45 (3%)		
Ethane	24 (2%)			Biofuel*	24 (2%)		
Hydrogen	20 (1%)			Hydrogen	23(2%)		
Nuclear	10 (<1%)			Ammonia	22(1%)		
Ammonia	3 (<1%)			Nuclear	7(<1%)		

**Majorly Biodiesel or Biodiesel blends along with few other biofuels like Green Diesel, Biobutanol, Bioethanol etc. This excludes Methanol*

Table 4: Alternative Fuel Vessels Statistics: Comparative Assessment (w.r.to GT Distribution)

	Alternative fuel Vessels (In Service)							**Alternative fuel Vessels (Orderbook)**								
GT Range	LNG	LPG	*Biofuel	Methanol	Ethane	Hydrogen	Nuclear	Ammonia	LNG	Methanol	LPG	Ethane	*:Biofuel	Hydrogen	Ammonia	Nuclear
	Number of vessels								Number of vessels							
0-500	14	-	17	3	-	6	-	1	2	6			1	4	1	
500-1K	12	-	5	-	-	1	-		16							
1K-3K	33	-	23	-	-	4	-	1	1	2						
3K-5K	36	-	7	1	-	2	-		16	9			17	1		
5K-10K	83	6	4	-	-	-	-	1	20	17	2		1	8		
10K-50K	150	69	39	28	4	2	10		95	69	64	8	5		10	4
>50K	777	50	28	4	20	1	-	-	841	140	48	37		8	11	3
Unknown	14		17	1	-	4	-	-		8				2	1	

**Majorly Biodiesel or Biodiesel blends along with few other biofuels like Green Diesel, Biobutanol, Bioethanol etc. This excludes Methanol*

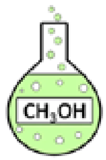
Ammonia **Hydrogen** **Methanol** **Ethane** **Biofuel**

Chapter 3: Alternative Fuel Powered Marine Engines (ICE)-Global Status

Alternative fuel propulsion is critically Important for long-term green shipping transition. Present global market is dominated by International engine manufacturers (**MAN** B&W leads with 79% for Methanol, 42.9% for Hydrogen, and varying shares with 49.1% LNG, 100% LPG, and Ethane; **Wartsila** follows with significant 57% shares in LNG, 33% in Hydrogen , 33.3% in Ammonia ; **WinGD** focuses on Methanol 9% share and Ammonia 80% share ; **Yanmar** leads with biofuel share by 64.3%.

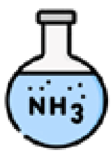
Dual-fuel combustion systems as retro fitment strategy for young vessels of age <7 years and also its adoption for new-build vessels are of absolute necessity towards achieving decarbonization in shipping without the risk of investment in stranded assets. It is also worth mentioning that in case of dual-fuel engines, for Methanol the modifications are needed only in the injectors, cylinder heads, and the fuel delivery system and not inside the engine, while for Ammonia readiness the engines internals /combustion system itself need replacement. This makes Methanol engines more cost effective against Ammonia engines presently. Although commercial Hydrogen engines are presently being developed it still awaits few critical technical challenges to be fully overcome as mentioned later in this chapter. India needs to initiate alternative fuel IC Engine manufacturing and alternatively developing strong strategic partnership with Global key players in ICE development.

Ammonia transition is projected between 2035 onwards due to ammonia-ICE development trajectory being in infancy. Although **Hydrogen** is promising, nevertheless owing to high liquefaction cost, safety challenges and absence of present large scale global distribution infrastructure, its adoption using Fuel Cell and Fuel Cell hybrid propulsions rather than ICE would be most suitable for India's inland waterways or domestic green corridors towards 2030 over deep sea/ocean going vessels. **Methanol s**hows the highest adoption potential in ICE owing to large scale commercial development, ease of storing and bunkering being liquid at room temperature and more cost-effective w.r.to retro fitment in comparison to its other contenders like Hydrogen and Ammonia. **DME** should also be looked into as a high cetane Diesel replacing renewable fuel which can easily be produced from Methanol through catalytic dehydration. **Methane slips** concerns make LNG and e-LNG still unattractive in medium to long run although it has the easy retro fitment and bunkering aspects. Overall analysis of global Methanol, Ammonia and Hydrogen combustion engines development trajectory is summarized in the following **Figure 2** whereas, for other alternative fuel-based combustion engines it is shown in **Figure 3.**



Methanol

- **Engines Makers:** MAN dominates 86.1% market share (in-service) and 79% (order-book)
- **Country Lead in ICE-Vessels Ownership:** China, France, Denmark, Japan, Singapore, Norway (order-book)
- **Country Lead in Ship Building:**
  - China (124), S Korea (58), Japan (26), Hong Kong (22) (in-service)
  - S.Korea (20) , China (8), Japan (3), Czech Republic (1), Turkey (14)(order-book)



Ammonia

- **Engines Makers:** Cummins, Wartsila & Nigata equal share of 33.3%(in-service) and WinGD 80% with
- MAN, J-Eng and CRRC Dalian at distant 6.7% share each (order book)
- **Country Lead in ICE-Vessels Ownership:** Belgium, Netherland, China, Malaysia, Japan (order-book)
- **Country Lead in Ship Building:**
  - Singapore (1), Japan (1), Norway (1) (in-service)
  - China P.R(14), S. Korea (6), Japan (2) (order-book)

Hydrogen

- **Engines Makers:** Wartsila 33.3% share followed by Sania and Cater Pillar each 16.7% (in-service),
- MAN 42.9 % closely followed by ABC-MAN 35.7% and Warsila 14.3% (order book)
- **Country ICE-Vessel Ownership:** Belgium, China, Norway, Netherland, USA (order-book)
- **Country Lead in Ship Building:**
  - Netherland(4), Germany(4),Spain (2),Italy (2) (in-service)
  - Italy (8), China P.R (5), Vietnam (5), India (3) (order-book)

Figure 2: Hydrogen derived Alternative Fuel based Marine Engine Development Status

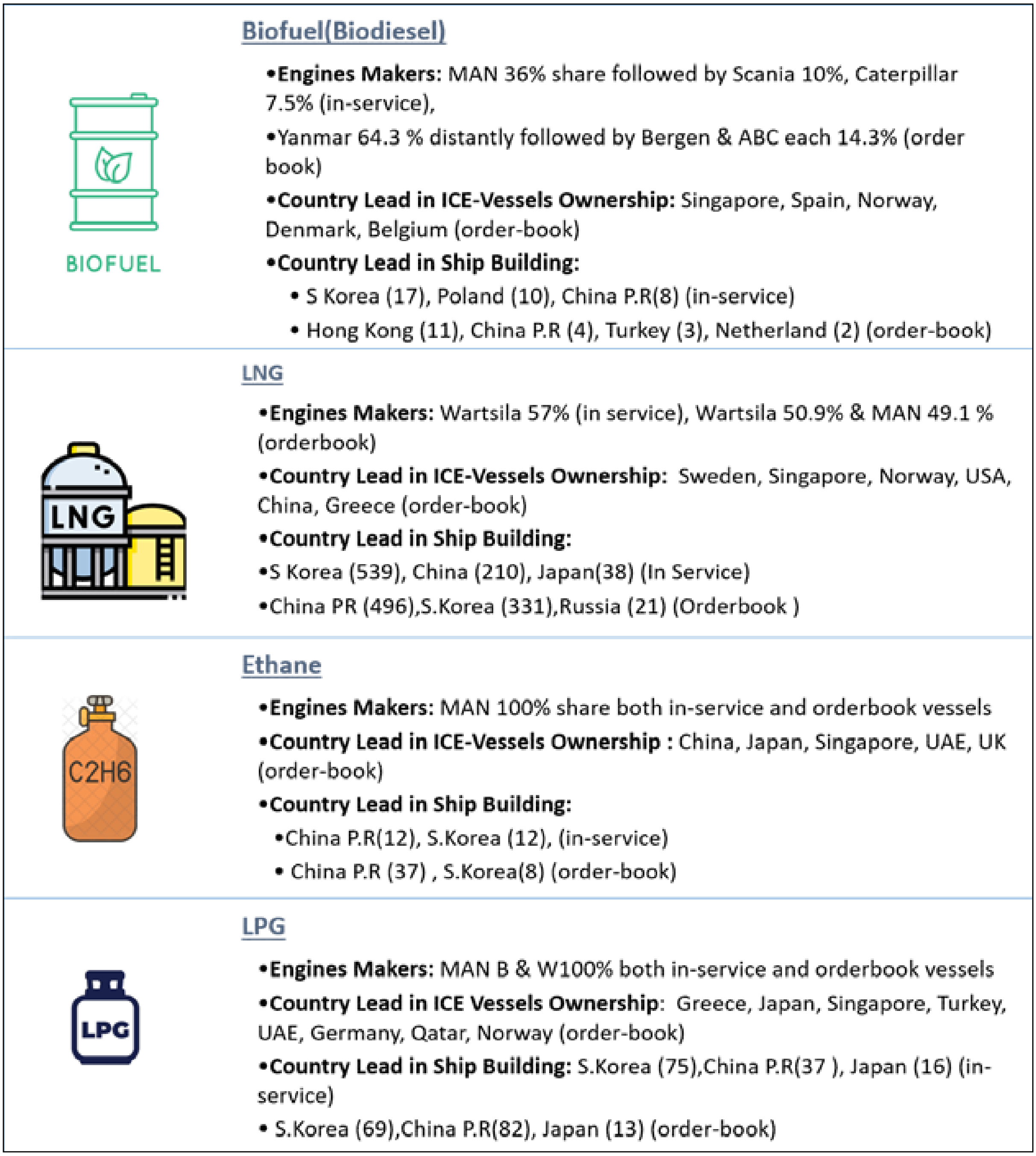


Figure 3: Alternative-Fuel (excluding Hydrogen derived) Marine Engine Development Status

Chapter 4: Comparative Assessment of Alternative Fuels

NCoEGPS's analysis shows that only the following alternative fuels have the potential to meet the IMO target of reducing the total GHG emissions which are Bio based and E-based fuels such as Bio Methanol, Green/E-Ammonia, E-Methanol, Green Hydrogen, where Bio Diesel, E-LNG and CCS combined Natural Gas (NG)-based Ammonia can be useful for short term compliance.

A recent exhaustive LCA study by IFP Energies Nouvelles, commissioned by CMA CGM has compared bio-, e- and blue fuel of both Methanol and Ammonia against VLSFO and provided critical insights. The saliant nature of this assessment is that for the first time (as far as the PI's knowledge is concerned) the geographic variation in alternative fuel production considered across 17 region including India, China, Australia, Indonesia and South Africa estimating the GHG emission of the fuels for 2035 and 2050.

It is also perceived and subsequently proposed to IMO that a functional unit shift from WtW (gCO2eq/MJ) to transport emission unit (gCO2eq/TEU.Km) is critical for accurate evaluation for the GHG reduction potential of the alternative marine fuels in different parts of the world. Although it is found that Ammonia GHG emission reduction expressed in gCO2eq/MJ is greater than that of Methanol, however, it is interesting to note that Methanol achieves higher overall decarbonization as per gCO2eq/TEU.Km unit. This is attributed to Methanol's much higher engine efficiency, lower pilot fuel consumption and absence of Nitrous Oxide (NO) emission compared to Ammonia.

From ship design perspective, another insight is significant. Ships tend to operate with more fuel, especially HFO storage onboard than is required for a single voyage. This study has shown that reducing storage levels to closer to the expected output for single trip can reduce mass and volume requirements and hence make alternative fuels significantly more viable. In other words, till the alternative fuels become largely available in a cost-effective manner, it could be an argument for large design ranges (akin to those seen now). **However once alternative fuel availability is more universal and price differential low then bunkering more frequently may be more viable and lower design ranges would be preferable.**

To comply with MEPC 83 proposed Base Scenario, minimum 8% GHG Emission reduction is required while for Direct compliance 21% is the cut off. However, use of alternative fuels in ships necessitates dual fuel ICE of Fuel Cell system integration in the ship. There is a huge demand supply gap both for ICE and Fuel cell to cater the global need. Moreover, Hydrogen and Ammonia engines are still not fully market ready for large commercial application. All these alternative fuel engine and Fuel Cell system integration through retrofit mentor new build also need large investment. The present study shows that blend fuel strategy could be extremely beneficial for India till it can have a significant dominance w.r.to ICE and Fuel cell manufacturing at least till 2035.

India can achieve the Base and Direct Compliance targets with dual-fuel and multi-fuel blends which don't need change of existing engine and hence would be cost effective option for existing vessels till 2035. The new built should be focused more on dual-fuel engine adoption.

Key highlights from the analysis of the blend-fuel Scenario 2 as observed from the following Figures 4,5&6 (These Figures are presented as Figures 4.37, 4.38, 4.39 and respectively in Chapter 4). Some representative Methanol- Biodiesel-Diesel blend options which could support in achieving either Base or Direct compliance in 2030 and 2035 are mentioned below.

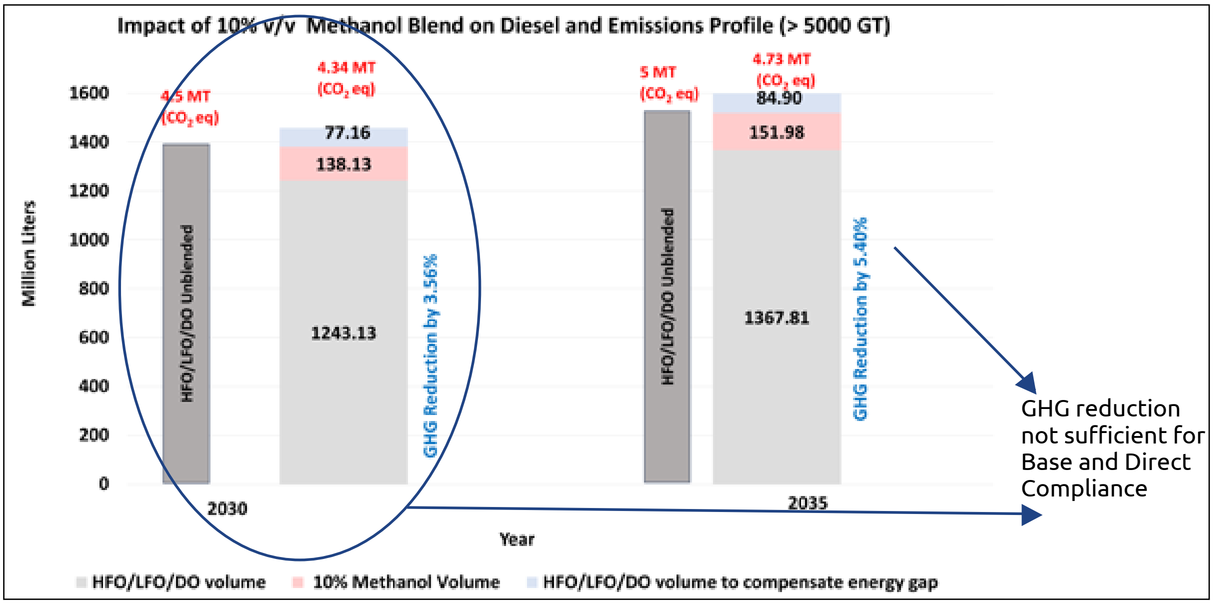


Figure 4: Dual Fuel Blend Scenarios (HFO/LFO/DO& Methanol 10 %v/v) with GHG Emission Reduction Profile (2030) for Indian OGVs (Figure 4.37 in Chapter 4)

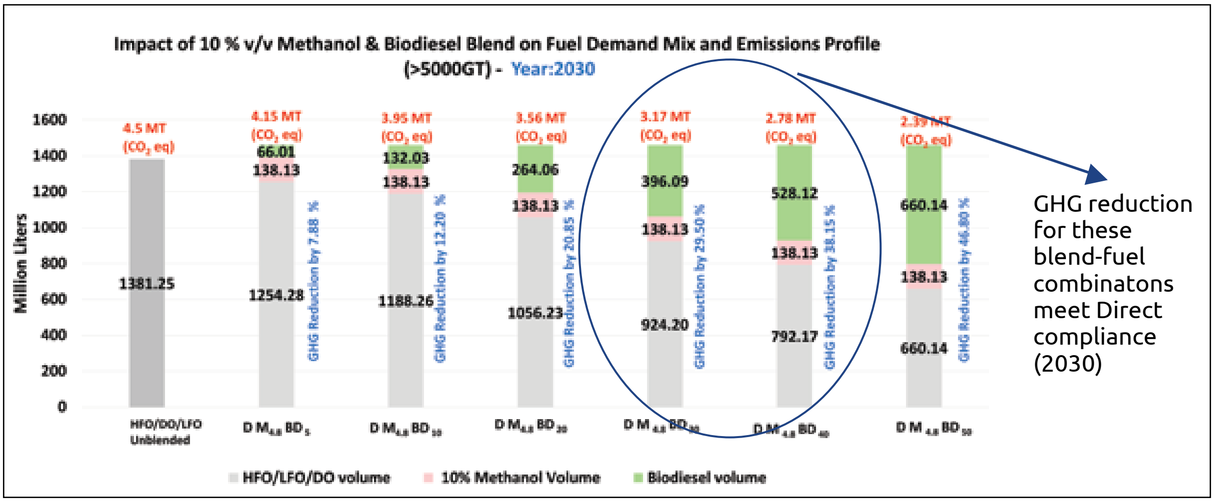


Figure 5: Multifuel Blend Scenarios (HFO/LFO/DO, Methanol 10 v/v %) & Biodiesel Blend (5%, 10%,20%, 30%, 40% & 50% v/v%) with GHG Emission Reduction Profile (2030) for Indian OGVs (Figure 4.38 in Chapter 4)

Additionally, although Coastal Vessels <5000GT are not presently subjected to IMO compliance, however, emission guidelines for vessels between 400-5000 GT range is under consideration by IMO. Hence, in the present study the fuel-blend Scenarios are also built for Indian Coastal vessels. Figures 7,8&9 (Figures 4.42,4.43 and 4.44 respectively in Chapter 4) presents the blend fuels options for Coastal Vessels.

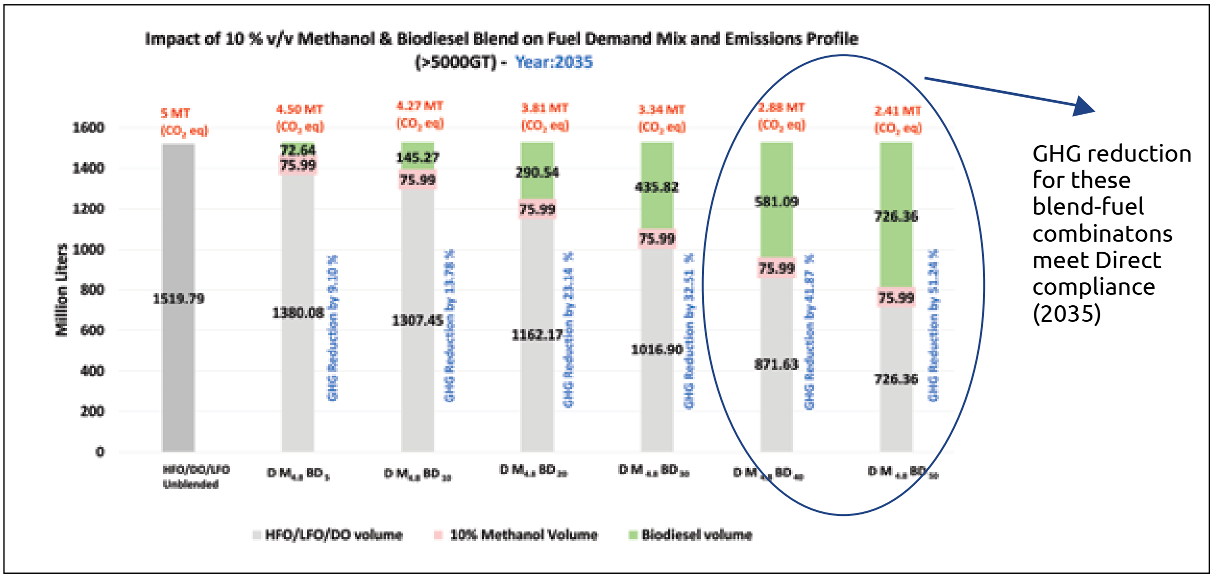


Figure 6: Multifuel Blend Scenarios (HFO/LFO/DO, Methanol 10 v/v %) & Biodiesel Blend (5%, 10%,20%, 30%, 40% & 50% v/v%) with GHG Emission Reduction Profile (2035) for Indian OGVs (Figure 4.39 in Chapter 4)

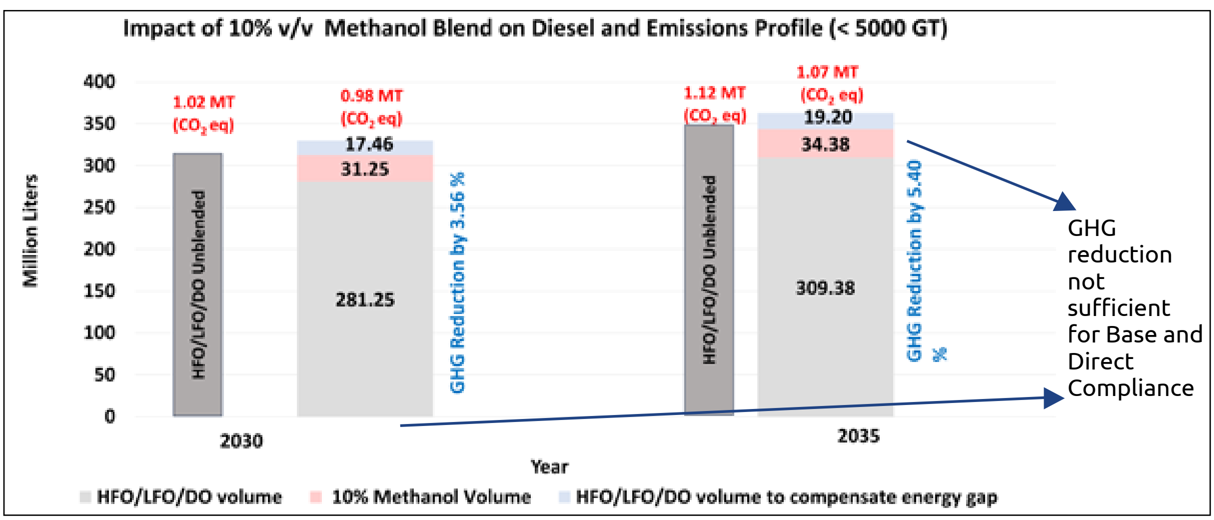


Figure 7: Dual Fuel Blend Scenarios (HFO/LFO/DO & Methanol 10 %v/v) with GHG Emission Reduction Profile (2030) for Indian Coastal Vessels(Figure 4.40 in Chapter 4)

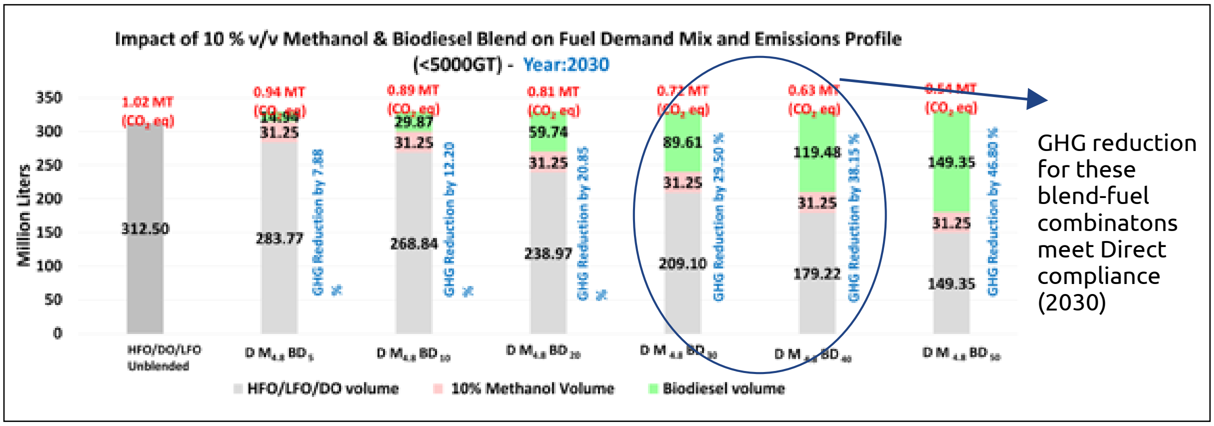


Figure 8: Multifuel Blend Scenarios (HFO/LFO/DO, Methanol 10 v/v %) & Biodiesel Blend (5%, 10%,20%, 30%, 40% & 50% v/v%) with GHG Emission Reduction Profile (2030) for Indian Coastal Vessels (Figure 4.41 in Chapter 4)

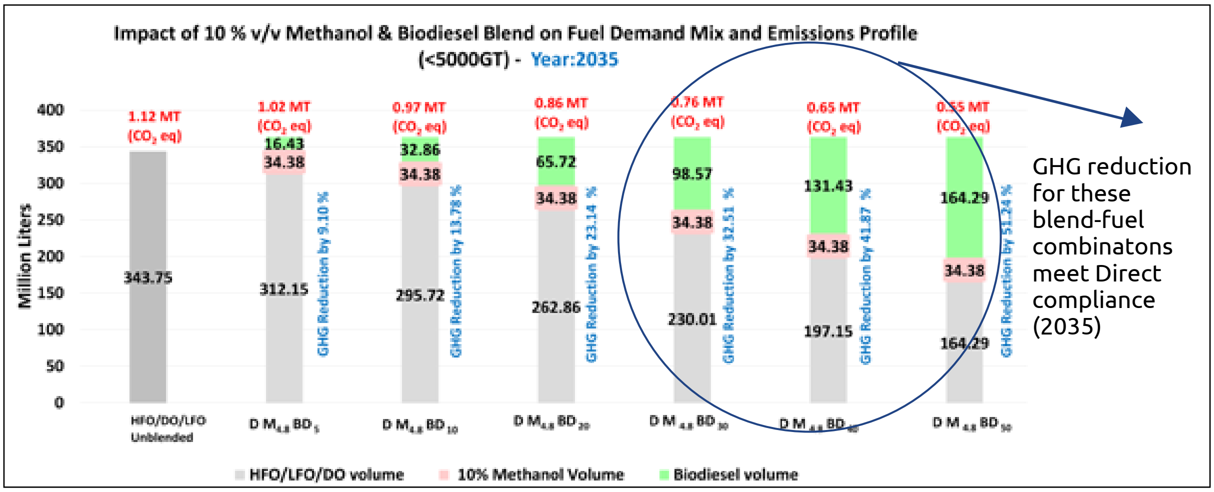


Figure 9: Multifuel Blend Scenarios (HFO/LFO/DO, Methanol 10 v/v %) & Biodiesel Blend (5%, 10%,20%, 30%, 40% & 50% v/v%) with GHG Emission Reduction Profile (2035) for Indian Coastal Vessels (Figure 4.42 in Chapter 4)

4.1 Alternative Fuel (un-blended and blended) Cost Comparison with and without IMO Proposed Carbon (GHG equivalent) Emissions Pricing

With respect to present cost of alternative fuels, the reported study shows Bio Methanol is having lowest Total Cost of Ownership (TCO) across 4 ship categories, viz., Large Ferries, General Cargo, Bulk Carrier Ships and Container Ships under all degrees of utilization. Among E-Fuel category, especially for ship types Bulk Carrier and large Ferries, e Methanol has close proximity to e DME and e Ammonia. **[5,6]**

The most cost-competitive option from a life cycle perspective is blended oil. Although as on today none of the fuel blend cases are more cost-competitive than LNG from a life cycle perspective, nevertheless, it is important to note that LNG cannot meet the CO2-eq emission limit.

It is crucial to not only implement carbon prices but also reinvest the revenue from carbon pricing as subsidies which in turn could be used for stimulating the alternative fuel technology and infrastructure development efforts. This will ultimately contribute to reducing the alternative fuel cost

The shift towards low-carbon and zero-emission fuels in the maritime industry needs a closer look into the cost dynamics of alternative fuels. The impact of GFI compliance on alternative fuel cost is estimated with GHG emission pricing (based on IMO's MEPC 83 framework) between 2028 to 2035. It's worth mentioning that many of the fuel prices referred here are projected or indicative figures derived from feasibility studies, pilot projects, and market forecasts. Some of these fuels are still in early stages of commercialization, their costs are subject to variation over time and across regions owing to factors like production scale, regional supply chains, policy support, and advancements in technology. Key data sources used in this estimation include reports from IEA, DNV, Clarkson's Research, and other scientific publications. The IMOs Net Zero Framework are expected to play a crucial role in bridging the cost gap between traditional, low-carbon and ZNZ fuels. Therefore, the prices presented reflect a scenario where carbon taxes (or similar pricing instruments) are applied to fossil fuels that exceed the GFI targets set by the IMO.

4.1.1 Impact of GFI Compliance on Alternative Fuel Cost with Carbon (GHG equivalent) Emissions Pricing (Non-Blended Fuels)

Table 5 presents the present cost of conventional and alternative fuels used or proposed for maritime applications in India. The Figures reflect a combination of reported prices from market forecast (e.g., DNV, IEA, and commercial price trackers) and projected estimates based on infrastructure readiness, production costs, and anticipated policy impacts. **Table 6 and Figure 10 represent estimated/projected cost per tonne of conventional and alternative fuels used or proposed for maritime applications in India with IMO's (MEPC 83) proposed GHG emission price.**

Table 5: Cost of Conventional & Alternative fuels Considered in USD/Ton

Fuel	Present Cost in 2025 (USD/Ton)	Reference
HFO	555	7
DO	469	8
LFO	768	8
Fossil LNG	589	9
Fossil Methanol	420	10
Fossil Ammonia	690	11
Blue Ammonia	508	-
E Ammonia	675	12
Bio Methanol	1400	13,14
E Methanol	1400	13
Biodiesel	1332	15
Blue Hydrogen	4780	16
Green Hydrogen liquid	4600	17
Green Hydrogen compressed	4600	17
Ethanol	855	18

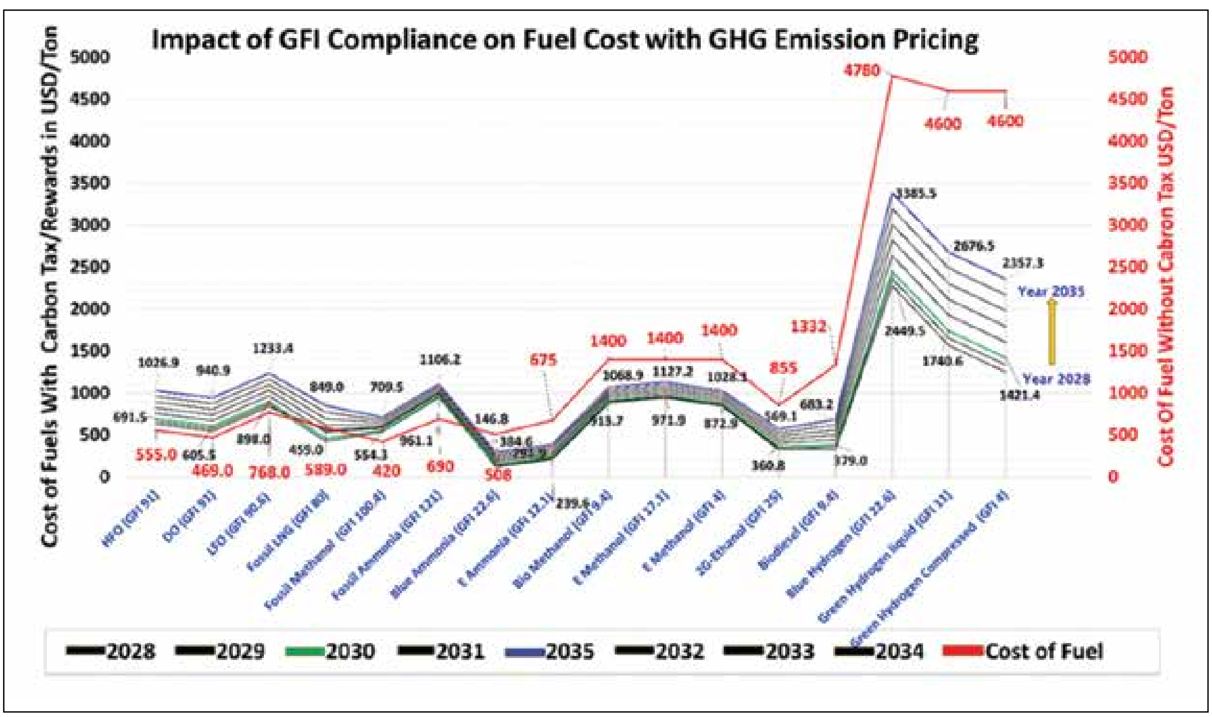


Figure 10: Impact of GFI Compliance on Fuel Cost with GHG Emission Pricing between Year 2028 to 2035.

Table 6: Fuel Cost with GHG Emission Pricing between Year 2028 to 2035

Fuel Type		Year-wise Total Cost in USD/ Ton							
	2025	2028	2029	2030	2031	2032	2033	2034	2035
HFO (GFI 91)	555	630.6	661.0	691.5	758.6	825.7	892.8	959.9	1026.9
DO (GFI 91)	469	544.6	575.0	605.5	672.6	739.7	806.8	873.9	940.9
LFO (GFI 90.6)	768	837.0	867.5	898.0	965.1	1032.1	1099.2	1166.3	1233.4
Fossil LNG (GFI 80)	589	557.9	423.5	459.0	537.0	615.0	693.0	771.0	849.0
Fossil Methanol (GFI 100.4)	420	593.6	540.2	554.3	585.3	616.4	647.4	678.4	709.5
Fossil Ammonia (GFI 121)	690	997.9	947.9	961.1	990.1	1019.1	1048.1	1077.2	1106.2
Blue Ammonia (GFI 22.6)	508	120.4	133.6	146.8	175.8	204.8	233.8	262.8	291.9
E Ammonia (GFI 12.1)	675	213.2	226.4	239.6	268.6	297.6	326.6	355.6	384.6
Bio Methanol (GFI 9.4)	1400	885.5	899.6	913.7	944.8	975.8	1006.8	1037.9	1068.9
E-Methanol (GFI 17.1)	1400	943.7	957.8	971.9	1003.0	1034.0	1065.1	1096.1	1127.2
E-Methanol (GFI 4)	1400	844.7	858.8	872.9	903.9	935.0	966.0	997.1	1028.1
2G Ethanol (GFI 25)	855	323.0	341.9	360.8	402.5	444.1	485.8	527.4	569.1
Biodiesel	1332	323.7	351.3	379.0	439.8	500.6	561.5	622.3	683.2
Blue Hydrogen	4780	2279.3	2364.4	2449.5	2636.7	2823.9	3011.1	3198.3	3385.5
Green Hydrogen liquid	4600	1570.4	1655.5	1740.6	1927.7	2114.9	2302.2	2489.4	2676.5
Green Hydrogen Compressed	4600	1251.2	1336.3	1421.4	1608.5	1795.7	1983.0	2170.2	2357.3

It is seen that from 2028 to 2035, the **total cost of marine fuels** varies significantly depending on their carbon intensity (GHG Equivalent), shaped by the **IMO's GHG emission pricing scheme**. Under this mechanism, fuels are subjected to carbon taxes or rewarded for carbon savings, based on their **greenhouse gas footprint (GFI)**. It is assumed a **surplus unit (SU) trading price of \$380/t CO_2 eq.**, **Tier 1 Removal Units (RUs)** are priced at **\$100/t CO_2**, and **Tier 2 RUs** continue at **\$380/t CO_2**. These financial instruments either penalize high-GHG fuels or incentivize low- or zero-carbon alternatives. The cost of fossil fuels such as HFO, DO, LFO, LNG, fossil Methanol, and fossil Ammonia show a significant upward trend due to the application of GHG emission pricing.

Among fossil fuels, there is a clear upward trajectory in cost due to GHG emission pricing. Heavy Fuel Oil (HFO) increases from \$630.6/ton in 2028 to \$1,026.9 in 2035, a 63% rise. Diesel Oil (DO) follows a similar pattern, jumping 72%, from \$544.6 to \$940.9. Light Fuel Oil (LFO) moves from \$837.0 to \$1,233.4, a 47% increase, reflecting its cleaner profile but still fossil-based origin.

Conversely, low- and zero-carbon fuels are expected to benefit substantially from reward mechanisms. E-Ammonia, despite a high base cost of $675 /ton, effectively falls to $213.2 in 2028, remaining within the $226.4-384.6 range through 2035. Similarly, Bio Methanol drops from $1,400 to $885.5 in 2028, then gradually increases to $1,068.9 in 2035. E-Methanol, with a base cost of $1,400, declines to $943.7 in 2028 and ends at $1127.1 in 2035. An ultra-low GFI version (GFI 4) sees even steeper reductions, from $1400 to 844.7-1028.1 over the period of 2028 to 2035. Ethanol (GFI 25) and Biodiesel also benefit significantly. Ethanol begins at $323.0 in 2028 and rises to $569.1—still well below the $855 base cost. Biodiesel drops from $1,332 to $323.7 in 2028, then increases to $683.2 by 2035, remaining far below its Base Price. These fuels are rewarded for their moderate to low GFIs.

Blue Hydrogen and Green Hydrogen (liquid and compressed), although high-cost fuels, see notable cost offsets. Blue Hydrogen drops from $4,780 to $2,279.3 in 2028 and increases to $3,385.5 by 2035, still significantly below its initial cost. Green Hydrogen (liquid) declines from $4,600 to $1,570.4 in 2028 and rises to $2,676.5, while Green Hydrogen (compressed) sees a similar drop from $4,600 to $1,251.2, then reaches $2,357.3. These reductions are primarily driven by their near-zero carbon intensity, attracting the highest rewards under the IMO system.

4.1.2 Impact of GFI Compliance on Alternative Blended Fuels Cost with GHG Emission Pricing

Table 7 presents the estimated present cost per tonne of blended alternative fuels used or proposed for maritime applications in Indi. Blended fuel costs are derived by applying the respective blend percentages to these baseline prices. **Figure 11 and Table 8** represent estimated/projected cost per tonne of blended alternative fuel used or proposed for maritime application for India with and without IMO's proposed GHG Emission Pricing.

Table 7: Cost of Alternative Fuel Blends Considered in USD/Ton

S. No	Fuel	Cost (USD/Ton)
1	Biodiesel 30%(Attained GFI 68.44)	727.9
2	Biodiesel 40% (Attained GFI 60.91)	814.2
3	Biodiesel 50% (Attained GFI 51.86)	900.5
4	*$DM_{9.47}BD_{25}$ (Attained GFI 69.39)	901
5	*$DM_{9.47}BD_{30}$ (Attained GFI 65.63)	944
6	*$DM_{9.47}BD_{40}$ (Attained GFI 57.69) (Bio Methanol GFI 9.4)	907.3
7	*$DM_{9.47}BD_{40}$ (Attained GFI 58.07) (E- Methanol GFI 17.1)	1030.5
8	*$DM_{9.47}BD_{40}$ (Attained GFI 57.45) (E Methanol GFI 4)	1030.5
9	*$DM_{9.47}BD_{50}$ (Attained GFI 50.29) (E- Methanol GFI 17.1)	1116.6
10	*$DM_{9.47}BD_{50}$ (Attained GFI49.91) (Bio Methanol GFI 9.4)	933.6
11	*$DE_{9.47}BD_{40}$ (Attained GFI 58.40) (2G- Ethanol GFI 25)	852.9
12	*$DE_{9.47}BD_{40}$ (Attained GFI 58.07) (2G- Ethanol GFI 17.73)	852.9

**D represents HFO/LFO/DO*

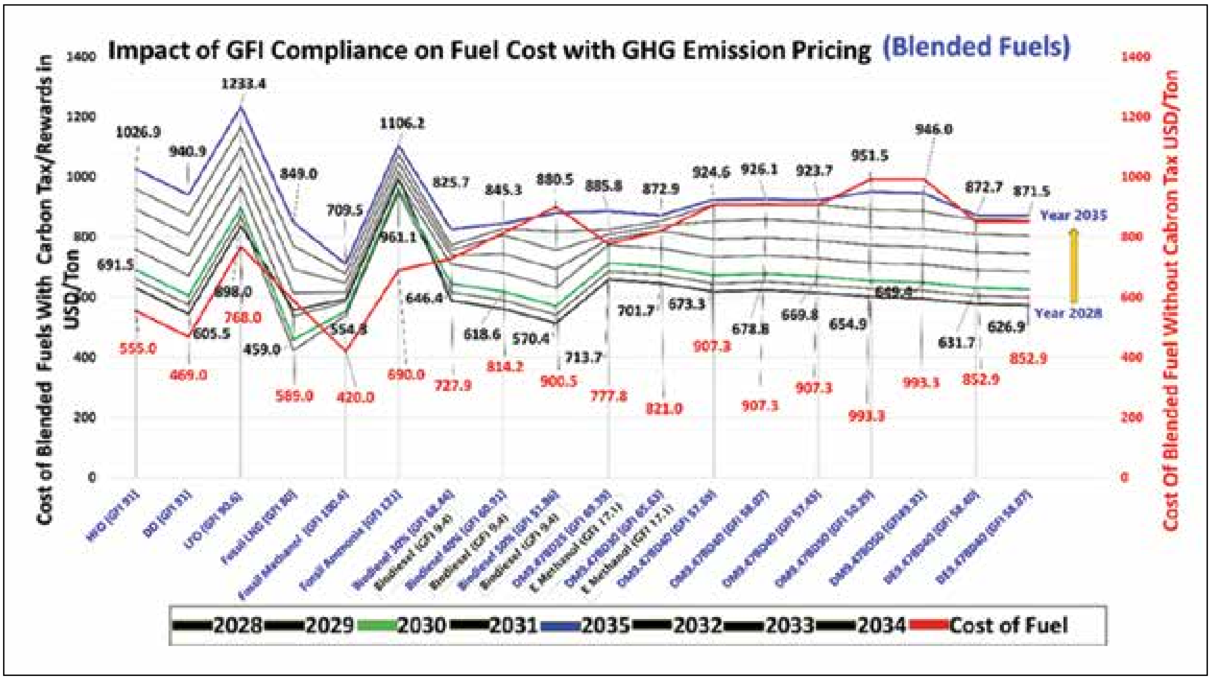


Figure 11: Impact of GFI Compliance on Blended Fuel Cost with GHG Emission Pricing from 2028 to 2035

Table 8: Fuel Cost with GHG Emission Pricing between Year 2028 to 2035

Blended Fuel Type	Cost of Fuel	Year-wise Total Cost in USD/ Ton							
	2025	2028	2029	2030	2031	2032	2033	2034	2035
HFO (GFI 91)	555	630.6	661.0	691.5	758.6	825.7	892.8	959.9	1026.9
DO (GFI 91)	469	544.6	575.0	605.5	672.6	739.7	806.8	873.9	940.9
LFO (GFI 90.6)	768	837.0	867.5	898.0	965.1	1032.1	1099.2	1166.3	1233.4
Fossil LNG (GFI 80)	589	557.9	423.5	459.0	537.0	615.0	693.0	771.0	849.0
Fossil Methanol (GFI 100.4)	420	593.6	540.2	554.3	585.3	616.4	647.4	678.4	709.5
Fossil Ammonia (GFI 121)	690	997.9	947.9	961.1	990.1	1019.1	1048.1	1077.2	1106.2
Biodiesel 30% (GFI 68.44)	727.9	588.62	617.50	646.38	709.92	739.89	756.61	773.33	825.75
Biodiesel 40% (GFI 60.91)	814.2	561.51	590.04	618.57	681.32	744.08	806.85	828.78	845.29
Biodiesel 50% (GFI 51.86)	900.5	514.03	542.23	570.42	632.44	694.46	756.50	818.52	880.54
*DM9.47BD25 (GFI 69.39)	777.8	777.8	658.3	686.0	713.7	774.7	793.0	809.1	825.1

Table 8: Fuel Cost with GHG Emission Pricing between Year 2028 to 2035

Blended Fuel Type	Cost of Fuel	Year-wise Total Cost in USD/ Ton							
	2025	2028	2029	2030	2031	2032	2033	2034	2035
*DM9.47BD30 (GFI 65.63)	821	821.0	646.6	674.1	701.7	762.3	821.5	837.5	853.4
*DM9.47BD40 (GFI 57.69)	907.3	907.3	618.7	646.0	673.3	733.3	793.2	853.2	908.9
*DM9.47BD40 (GFI 58.07)	907.3	907.3	624.3	651.6	678.8	738.8	798.8	858.8	910.3
*DM9.47BD40 (GFI 57.45)	907.3	907.3	615.2	642.5	669.8	729.7	789.7	849.7	907.9
*DM9.47BD50 (GFI 50.29)	993.3	724.26	751.23	778.19	837.51	896.84	956.18	1015.50	1074.82
*DM9.47BD50 (GFI49.91)	993.6	455.07	482.03	509.00	568.32	627.65	686.98	746.31	805.63

**D represents HFO/LFO/DO*

For D(HFO/LFO/DO)-Biodiesel Blends like BD30 (base cost: 727.9 USD/t), the price drops to 617.5 USD/t in 2030, which is a 15% reduction due to IMO carbon reward mechanism. However, by 2035 the cost rises to 825.8 USD/t, about 13% higher than the base, showing that there is no long-term advantage. **Blend BD 40% (base 814.2 USD/t) performs better initially, falling to 618.57 USD/t in 2030 (a 24% reduction), but by 2035 it increases to 845.3 USD/t, about 4% higher than base, again reflecting the shrinking impact of carbon credits. BD 50% (900.5 USD/t) offers the strongest short-term benefit, falling sharply to 570.42 USD/t in 2030 (a 36.6% reduction), although by 2035 the cost recovers to 880.5 USD/t, only 2.2% below base.**

The D(HFO/LFO/DO)-Biodiesel–Methanol blends show similar behavior. **DM9.47BD30** (base 944 USD/t) declines to 793.6 USD/t in 2030, a 15.9% reduction, but by 2035 the cost increases to 992.3 USD/t, which is 5% higher than base, eliminating the initial gain. DM9.47BD40 (base 907.3 USD/t) falls to 646.0 USD/t in 2030 (a 28.8% saving), but by 2035 it rises slightly above base to 924.6 USD/t, a 1.9% increase. **D(HFO/LFO/DO)-M9.47BD50 (base 993.6 USD/t) drops to 509 USD/t in 2030, giving a 38.8% reduction, and even by 2035 it retains a small benefit with a cost of 805.63 USD/t, about 18.9% lower than base.**

In summary, higher biodiesel shares (40–50%) consistently achieve deeper cost reductions by 2030 because of stronger carbon credit advantages linked to their lower GFI. However, by 2035 these benefits are mostly offset by the general rise in base fuel costs, with some lower blend (BD30) even becoming more expensive than their base price. This clearly indicates that high-biodiesel blends, especially BD50 and D(HFO/LFO/DO)-M9.47BD50, are better positioned to stay competitive under Tier-1 and Tier-2 carbon tax/reward regimes, though the margin of advantage declines over time.

4.2 Alternative Fuel Demand Scenarios vs Supply Readiness (India)

The demand supply gap or fuel supply readiness level for all the alternative fuels (including ZNZ fuels are estimated towards 2030 both for India's coastal vessels and OGVs. **Figure 12 & Figure 13** shows the alternative fuel demand for GFI compliance along with Green Hydrogen and RE requirement for 2030 respectively for Base and Direct Compliance.

Figure 14 presents the E/Bio Methanol demand for 10 v/v% blending in Diesel or in Diesel-Biodiesel with Green Hydrogen demand and RE need for 2030.

For Scenario 1, i.e for GFI Compliance, E Methanol demand is 0.28 MT/y, whereas **supply readiness is 0.83 MT/y** including 0.0036 MT operational, 0.8 MT FID and 0.02 in concept stage. In case of **E Ammonia, demand is 0.28MT/y** with projected supply **readiness far exceeding as 20.4 MT/y by 2030** which includes 0.0018 MT operational, 15.81 MT at FID and 4.35 MT in concept stage. These demands imply **0.06 MT/y Green Hydrogen** and **2.63 GWH*10^3 Renewable RE power for E Methanol and 0.05 MT/y Green Hydrogen and 2.35GWH** *10^3 **RE power for E Ammonia by 2030.**

For Scenario 2, i.e for Blended fuel, 10% Methanol blending requires 0.11MT/y fuel with **Green Hydrogen demand 0.02 MT** and **RE requirement as 1042.12 GWH.**

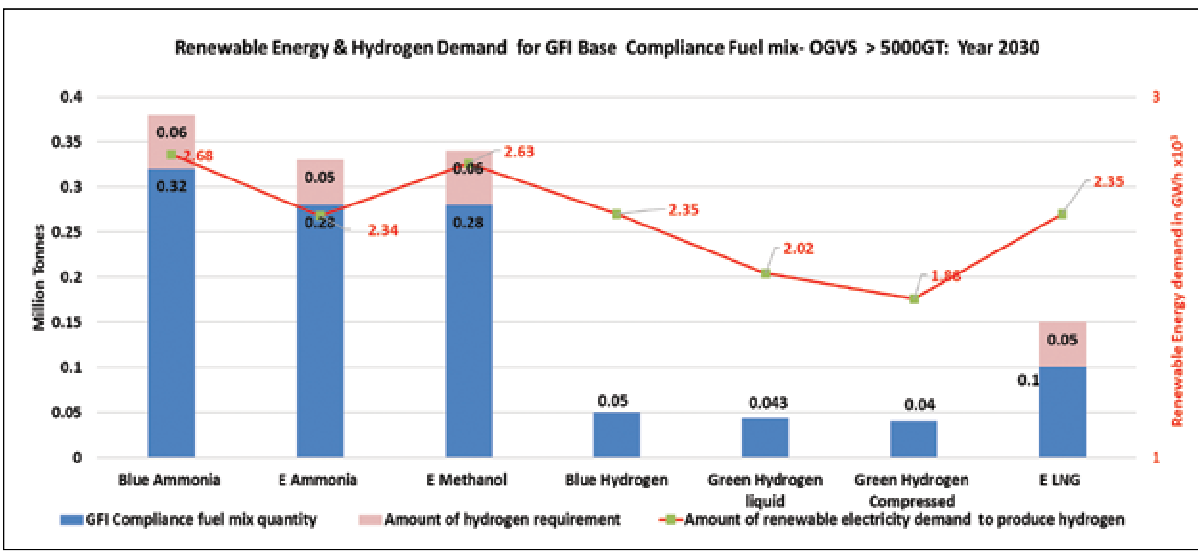


Figure 12: Alternative Fuel-Mix Demand with RE &Green Hydrogen Requirement for GFI-Compliance (>5000GT) Year 2030 (Base Compliance Category)

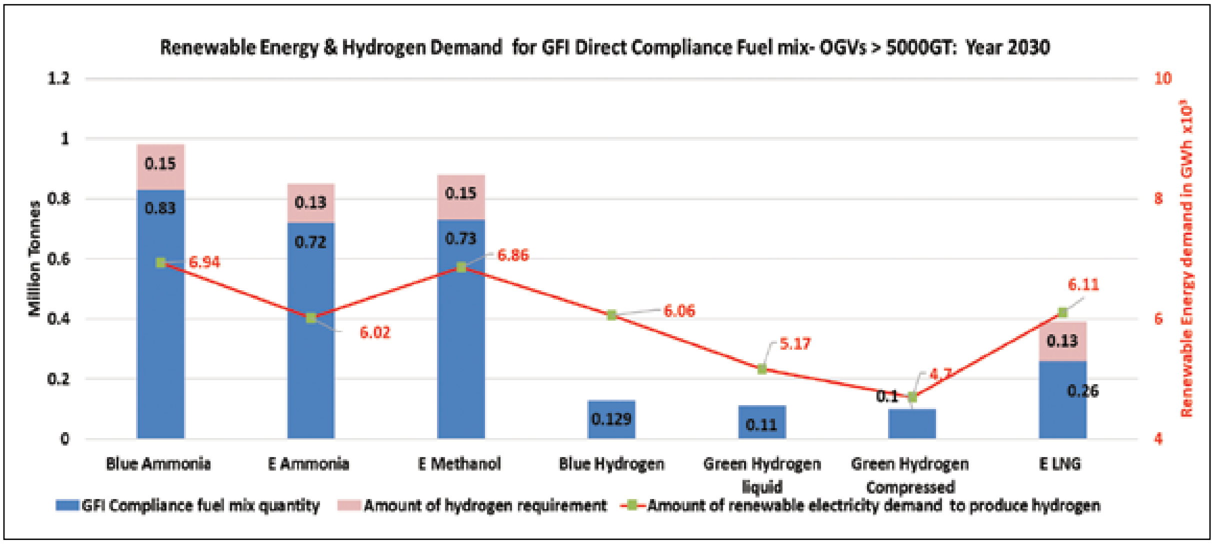


Figure 13: Alternative Fuel-Mix Demand with RE &Green Hydrogen Requirement for GFI-Compliance (>5000GT) Year 2030 (Direct Compliance Category)

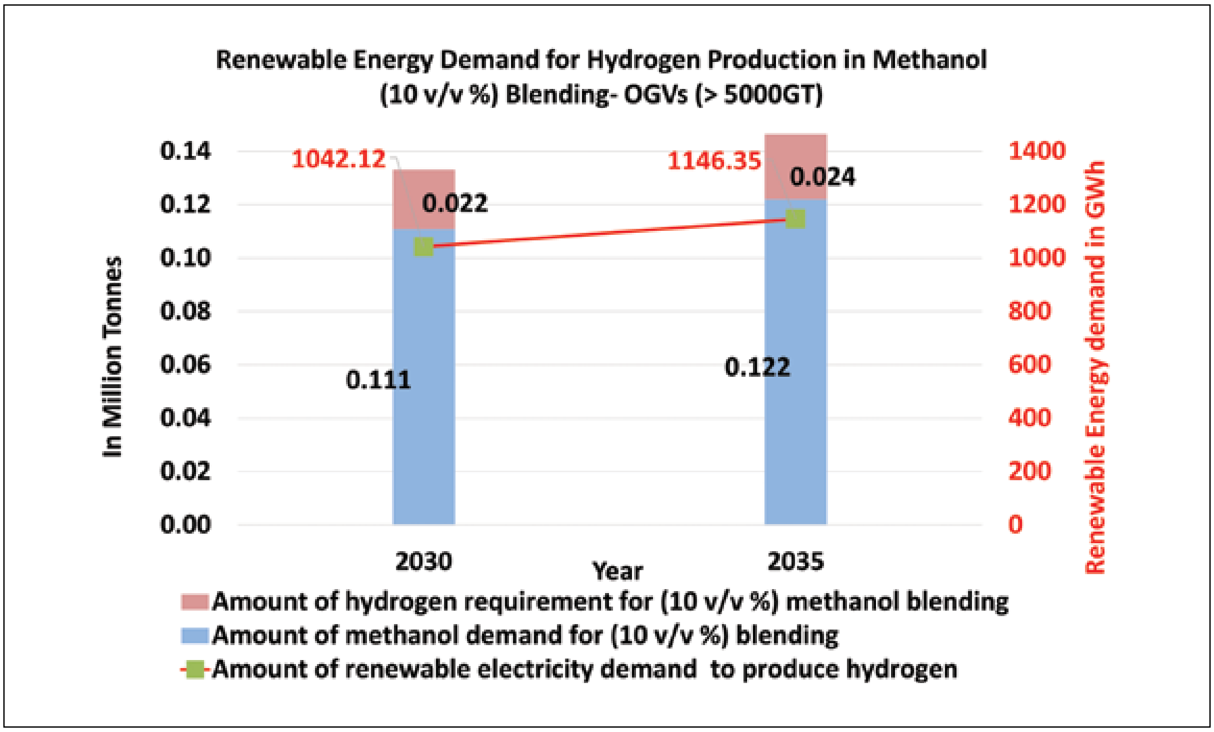


Figure 14: Alternative Fuel Demand with RE &Green Hydrogen Requirement for 10 V/V % Methanol Blending (>5000GT) Year 2030

4.3 Alternative Fuel Ranking for Maritime Applications in India

The scoring framework for comparative evaluation of alternative fuels are made based on 8 critical parameters such as

» WtW GFI of fuel

» LCA based GHG reduction potential

» Fuel supply readiness

» Storage tank capacity and bunkering infrastructure w.r.to fossil counterpart

» Global bunkering infrastructure readiness at ports

» Alternative engine and Fuel Cell ecosystem readiness

» Cost of fuels with and without IMO's carbon tax

» Standard policy and regulatory gaps

Each parameter is scored on a 5-1 scale, where 5 indicates excellent performance and 1 indicates poor Performance. The scoring criteria for ranking of alternative fuels by parameters are presented in **Table 9. Table 10 presents the final ranking of alternative fuels which highlights the following order: Biodiesel (GFI 9.4) Rank 1> Both Bio LNG (GFI 9.4) & E Methanol (GFI 6.4) Jointly Rank 2 > Bio Methanol (GFI 9.4) Rank 3 > E Methanol (GFI 17.1) Rank 4> E LNG (GFI 12.1) Rank 5> E Ammonia (GFI 12.1) Rank 6> Blue Ammonia (GFI 22.6) & Green Hydrogen Compressed (GFI 4) Jointly Rank 7> Green Hydrogen Liquid (GFI 11) Rank 8> Blue Hydrogen (GFI 22.6) Rank 9.**

Table 9: Scoring Criteria for Ranking of Alternative Fuels by Sustainability Parameters

Parameter	**Ranking**				
	5	**4**	**3**	**2**	**1**
GFI (gCO_2eq/MJ)	≤ 10	11–20	21–50	51–90	> 90
*Alternative Fuel Supply Readiness	Fully operational	Feasibility done	Feasibility started	Concept stage	Not available
Storage & Bunkering (MT)	Fully compatible	Minor modifications	Moderate infra needs	High change / cryogenic	Very complex / none
Global Bunkering (Ports)	> 200 ports	100–199	50–99	< 50	0 or concept only
Engine & Fuel Cell Ecosystem	Drop-in / no modifications	Minimal retrofit	Moderate modifications	New engines needed	Not available
**Cost (USD/ Tonne)	< $400	$400–700	$701–1000	$1001–2000	> $2000
LCA GHG Reduction	> 85%	70–85%	50–69%	20–49%	< 20% / unclear
Fuel Standards / Regulations	Fully defined / ISO/IGF	Mostly defined	Interim codes	Codes under development	None / uncertain

Colour Code of Ranking of Fuels		
Ranking of Fuels	Minimal	1
	Emerging	2
	Under Development	3
	Established	4
	Mainstream	5

Table 10: Alternative Fuel Ranking for Indian Maritime Application

	Ranking Based on 8 Sustainability Parameters									
Type of Fuels (GFI Values)	**GFI**	**LCA Based GHG Reduction Potential**	**Alternative fuel Supply Readiness**	**Storage Tank Capacity& Bunkering**	**Global Bunkering in Ports**	**Engine & Fuel Cell Ecosystem**	**Cost Of Fuels**	**Fuel Standards /Policy / Regulatory Gaps**	**Total Score**	**Rank**
HFO / LFO / DO **(GFI 91)**	1	1	5	5	5	5	4	5	31	Fossil Based Fuels Not Applicable
Fossil LNG (>87 Methane) **(GFI 80)**	2	1	1	1	5	4	4	5	23	
Fossil Methanol **(GFI 100.4)**	1	1	1	1	2	3	5	3	17	
Fossil Ammonia **(GFI 121)**	1	1	1	1	2	1	4	1	12	
Biodiesel **(GFI 9.4)**	5	5	3	5	2	5	2	5	32	**1**
Bio Methanol **(GFI 9.4)**	5	5	3	4	2	4	2	3	28	**3**
E Methanol **(GFI 17.1)**	4	4	4	4	2	4	2	3	27	**4**
E Methanol **(GFI 6.4)**	5	5	4	4	2	4	2	3	29	**2**
E-Ammonia **(GFI 3)**	5	5	4	2	2	1	4	1	24	**6**
E Ammonia **(GFI 12.1)**	4	4	4	2	2	1	4	1	22	**7**
Blue Ammonia **(GFI 22.6)**	3	4	4	2	2	1	1	1	18	**8**
Green Hydrogen Compressed **(GFI 4)**	5	5	2	1	2	1	1	1	18	**8**
Green Hydrogen Liquid **(GFI 11)**	4	5	2	1	2	1	1	1	17	**9**
Blue Hydrogen **(GFI 22.6)**	3	5	2	1	2	1	1	1	16	**10**
Bio - LNG (Methane) **(GFI 9.4)**	5	5	2	2	5	4	1	5	29	**2**
E LNG (Methane) **(GFI 12.1)**	4	4	1	2	5	4	1	5	26	**5**

Supply readiness – E-Methanol and E-Ammonia is significantly more feasible; From life cycle cost perspective blended fuels most cost-competitive across most vessel types

4.4 Alternative Fuel Bunkering

In Chapter 4, India's Alternative Fuel-Mix Demand for GFI Compliance by 2030, 2035 (both Coastal and OGVs) with Green Electricity and Green Hydrogen Requirement is estimated. This assessment aligns with IMO's fuel transition strategies with Green Fuel Index (GFI) compliance, ensuring that the alternative fuel mix meets IMO's latest targets. It also provides the estimates for additional RE Power and green Hydrogen requirement to meet India's alternative fuel-mix demand scenarios both for OGVs considering 4 types of alternative fuels viz., Methanol (bio- and e-), Ammonia (blue and e-), Hydrogen (blue, green liquid & green compressed) & LNG (bio and e-). **This can be taken as reference for setting India's Alternative Fuel and Additional RE and Green Hydrogen target towards net zero.**

To support the shift to alternative marine fuels' bunkering hub, an analysis is made in **Chapter 4** (**Figure 4.63**) for **three Indian key ports—Kandla, Paradip, and VOC—**based on their annual bunkering capacity. The study evaluates 5%, 10%, 20%, and 50% (on energy equivalence basis) bunker fuel replacement with for alternative fuels like Methanol, Ammonia, Biodiesel, LNG, and Hydrogen to assess feasibility and related infrastructure needs. **This can be taken as a reference point for developing bunkering infrastructure and establishing the fuel supply link.**

Regarding storage and bunkering, among all alternative options compared, Biofuels (Biodiesel) show attractive infrastructural compatibility features with lower risk of stranded assets. While Methanol being liquid at ambient condition is still able to use existing infrastructure to some degrees; Ammonia and Hydrogen necessitate brand new or largely modified infrastructures

Chapter 5: Fuel Cell Adoption in Shipping

Following insights are drawn from exhaustive analysis of Fuel Cell integration in global shipping. **Instead of targeting C-free operation, use of renewable /e-/green fuels with high efficiency over whole life cycle should be the focus for ship operation using Fuel Cell s. Towards zero emission, Fuel Cell should be considered promising option for Inland water and short sea/coastal shipping**

Direct Methanol Fuel Cell (DMFC) could be worth investing for India in very small vessel <100eKW (Inland water) category. India should also develop small to mid-sized (100-500ekW) LTMFC Fuel Cell ships (PSV, Ferries, RO-RO & Cargo) till storage and safety challenges of compressed or liquified hydrogen (LH2) as fuel persist. In long term, once LH2 overcome the viable technological and safety challenges, larger ships can be integrated too.

In order to avoid the challenge of Hydrogen storage at high pressure or cryogenic temperature on board, PEMFC with reforming technology using Biodiesel and/Methanol could be worth investing to especially >500 eKW.

SOFC technology should leverage its high fuel flexibility, especially Ammonia & Methanol.

For cruise, and long-haul vessels, pilot projects need to be initiated with SOFC –Battery hybrid (immediate) and SOFC/ICE hybrid with alternative fuel options like Methanol and Ammonia (medium to long term) especially for auxiliary power units (AMUs). The drawbacks of low power density, short lifetime and high capital costs are surmountable by sustained innovation, high efficiency of integrated SOFC-CHP system &and drastic GHG emission reduction which could be made favorable with emission tax

Establishing bunkering for alternate fuels, especially renewable /e/green Methanol and Ammonia, is of absolute necessity to accelerate Fuel Cell adoption in shipping. Research should be encouraged in terms of Hydrogen storage solutions, high performance membranes, reducing operating temperature of SOFC to use cheaper materials, easier assembling methods and use of off-the-shelf components

Chapter 6: On-board Carbon Capture Perspective

As it is unrealistic to achieve a complete replacement of fossil fuels in maritime sector due to lack of both fuel supply chain and alternate engines there is a heightened need to increasingly implement CO2 capture on-board and switching over to bio/ synthetic e-fuels from HFO with the advancement of alternate fuel engines. This could even lead to achieving negative emissions in the next generation of container fleets. However, there is an urgent need of larger number of Pilot demonstration of CCUS projects through valorization of adsorbed CO2 especially for the countries like India with lack of geological CO2 storage sites along with innovation in sustainable CO2 adsorption material production.

Chapter 7: Standards

Availability of standards for fuel quality and production along with presence of guidelines and regulation for safe storing, handling, transport and bunkering are of critical importance for accelerated adoption of alternative fuels. The presence status of fuel standards, policy and regulations are detailed in **Chapter 7** in the detailed report.

Fuel standards ensure that fuels are safe for purchase, and fuels that lack standardization may vary in quality and thus are less attractive to purchasers. India needs to develop blend fuel standards for alternative fuels.

In June India has set up three Working groups (WG3, WG4 and WG5) under BIS (Bureau of Indian Standards) respectively for Methanol, Green Hydrogen and Green Ammonia as a fuel for marine applications (covering technical and safety aspects for onboard). The working group reviewed the ISO 6583:2024 Methanol as a fuel for marine applications – General requirements and specifications, which defines the general requirements and specifications for methanol from all forms of production at the point of custody transfer, prior to any onboard required treatment, for use as fuel in marine diesel engines, Fuel Cell s and other marine applications. After detailed deliberation, the working group construed that the ISO 6583:2024 is suitable for adoption as an Indian Standard, however, incorporation of green Methanol aspects with appropriately defined pathways will be taken up with ISO/TC 28.The following grades are specified in the ISO standard:

» Marine methanol grade A (MMA): MMA lists the characteristics considered applicable when using methanol as a marine fuel with additional requirements in respect of lubricity and particle count

- Marine methanol grade B (MMB): MMB lists the characteristics considered applicable when using methanol as a marine fuel.
- Marine methanol grade C (MMC): MMC grade provides for wider tolerances on some of the listed characteristics as compared to MMB.

Case Study (Quantitative Financial Impact Assessement of GFI Compliance on a Model Indian Ship)

Global center for Maritime Decarbonization (GCMD) **[19]** has developed a simple cost and compliance calculator to evaluate the impact of the two-tiered GHG Fuel Intensity (GFI)-linked pricing system on Ship operational costs.Following the recently approved GHG emissions pricing framework by MEPC 83 **[2]**, Based on the Lower heating value and compound/ attained GFI of any fuel including alternative fuel, fuel-mix/and blend fuel, the calculator provides Carbon balance, Surplus or deficit under Tier-1 & 2 Compliences with financial outcome.

In order to see the effct of MEPC-83 GFI based guidelines on Indian Vessels, a special Case Study is conducted where the above mentioned cost and compliance calculator is used for quantitative evaluation of possible revenue or penalty for using different alternative fuels and fuel blends in Indian OGV Vessels named Kashi.The vessel details are obtained from Clarkson's research data bank and mentioned below [4]

Vessel 1: used for all cases

Vessel Name: Kashi, **Type:** Chemical & Oil Carrier

Built: 2006, **Gross Tonnage (GT):** 29,993, Deadweight **Tonnage (DWT):** 46,177, **Length Overall (LOA):** 183.00 m, **Status:** In Service, Flag State: India, Operator / Company: Dawn Shipping

Builder: STX SB (Jinhae), South Korea, Engine Type: Diesel, 2-Stroke

Main Engine Model: MAN B&W 6S50MC-C8.1, Fuel Type: Very Low Sulphur IFO (VLS IFO)

Service Speed: 14.8 knots, Fuel Consumption at Service **Speed:** 29.8 tonnes per day (Tpd)

Age: 18 years (as of 2024)

Fuel consumption is calculated using standard operational assumptions based on vessel type, service speed, and total annual operating days. The voyage of vessel between Kandla Port (India) and Sundai Gerong Port (Indonesia) with distance 3063.0 Nautical miles (nm) at a speed if 14.8 knots/h is considered with the following assumptions.

Fuel Consumption: 29.8 Tonnes/day.

Total Time of Travel = 3,063nm /14.8knots =206.96hours≈8.625days

Fuel Consumption for One Voyage = 8.625 days x 29.8 tonnes/day = 246.29 tonnes **(X)**

Additional Fuel Considered for Bad Weather = equlavalient to 2 days consumption.
= 2 days x 29.8 tonnes/day = 59.6 tonnes **(Y)**

Addition of 5% Unpumpables Fuel Margin (Fuel below the pump suction, including dirt and water—typically ~5% of total fuel

Adjusted fuel Consumption= (X+Y) x 1.05 = 332.46 tonness **(Z)**

Annual Total Fuel Conumption (**assuming 20 such port calls** in a year) = Z x 20= **6,649 tonnes/year.**The following fuel and alternative fuel-blends are considered for Case studies.

Table 11: Fuel and Blend Fuel Considered for Case Study

Cases	Fuel Mix	Calculated LHV (MJ/t)	Attained GFI gCO_2eq/MJ)	Table/Figure No
	Mono Fuel			
1	HFO	41000	91	12/15
2	LNG	48600	80	13/16
3a	E-Ammonia	18,600	3	14/17
3b	E-Ammonia	18,600	12.1	15/18
4a	E-Methanol	19,900	17	16/19
4b	Bio-Methanol	19,900	9.4	17/20
5	Biodiesel (B100)	39,000	9.4	18/21
	Dual-Fuel Blend			
5a	Biodiesel-Diesel Blend (BD 24 wt.%) (GFI 9.4)	41,648	73.81	19/22
5b	Biodiesel-Diesel Blend (BD 30 wt.%) (GFI 9.4)	40,713	68.44	20/23
5c	Biodiesel-Diesel Blend (BD 40 wt.%) (GFI 9.4)	40,288	60.91	21/24
5d	Biodiesel-Diesel Blend (BD 50 wt.%) (GFI 9.4)	39,769	51.86	22/25

Table 11: Fuel and Blend Fuel Considered for Case Study

Cases	Fuel Mix	Calculated LHV (MJ/t)	Attained GFI gCO_2eq/MJ)	Table/Figure No
	Multi-Fuel Blend			
6	*DM9.47BD25 (v/v%) Blend with E Methanol (GFI 17.1)	39,084	69.39	23/26
7	DM9.47BD30 (v/v%) Blend with E Methanol (GFI 17.1)	38,873	65.63	24/27
8a	*DM9.47BD40 (v/v%) Blend with Bio Methanol (GFI 9.4)	38,459	57.69	25/28
8b	*DM9.47BD40 (v/v%) Blend with E Methanol (GFI 17.1)	38,459	58.07	26/29
8c	*DM9.47BD40 (v/v%) Blend with E Methanol (GFI 4)	38,459	57.45	27/30
9a	*DM9.47BD50 (v/v%) Blend with E Methanol (GFI 17.1)	38,036	50.29	28/31
9b	*DM9.47BD50 (v/v%) Blend with Bio Methanol (GFI 9.4)	38,036	49.91	29/32
10	*DM4.48BD40 (v/v%) Blend with E Methanol (GFI 17.1)	39,322	58.98	30/33
11	*DM4.48BD50 (v/v%) Blend with E Methanol (GFI 17.1)	38,882	51.08	31/34
12a	*DE10BD40 (v/v%) Blend with 2G-Ethanol (GFI 25)	39,058	58.40	32/35
12b	*DE10BD40 (v/v%) Blend with 2G-Ethanol (GFI 17.73)	39,058	58.07	33/36

**D represents HFO/LFO/DO*

From the following analysis it is it is observed that there is multiple alter bunkering and alternative and conventional blend-fuel options which can help India achieving Base Compliance or even surpassing the Direct Compliance and thus generating revenues which could be invested for alternative fuel production technology upscaling, developing

bunkering and engine infrastructure, research and innovation to make India future ready in achieving net zero in maritime. The cases where revenue would be earned due to meeting Direct Compliance Target are highlighted in green in the following **Table 12-Table 33.**

Table 12: Case 1: Fuel HFO (LHV: 41,000 MJ/t | GFI: 91 gCO_2/MJ)

Year	Target GFI (Base/Direct) (gCO_2eq/MJ)	Balance ($t CO_2$)	Deficits (T1/T2) ($t CO_2$) or SUs Generated	Net Outcome (Cost)	T1 RU Cost (@$100/t)	T2 RU Cost (@$380/t)
2028	89.568 / 77.439	-3,696.85	Deficits: 3,306.475 / 390.376	$478,990.37	$330,647.46	$148,342.91
2029	87.702 / 75.573	-4,205.54	Deficits: 3,306.475 / 899.064	$672,291.96	$330,647.46	$341,644.50
2030	85.836 / 73.707	-4,714.23	Deficits: 3,306.475 / 1,407.753	$865,593.55	$330,647.46	$534,946.09
2031	81.731 / 69.602	-5,833.34	Deficits: 3,306.475 / 2,526.867	$1,290,857.05	$330,647.46	$960,209.59
2032	77.626 / 65.497	-6,952.46	Deficits: 3,306.475 / 3,645.982	$1,716,120.54	$330,647.46	$1,385,473.09
2033	73.520 / 61.391	-8,071.57	Deficits: 3,306.475 / 4,765.096	$2,141,384.04	$330,647.46	$1,810,736.59
2034	69.415 / 57.286	-9,190.69	Deficits: 3,306.475 / 5,884.211	$2,566,647.54	$330,647.46	$2,236,000.08
2035	65.310 / 53.181	-10,309.80	Deficits: 3,306.475 / 7,003.325	$2,991,911.04	$330,647.46	$2,661,263.58

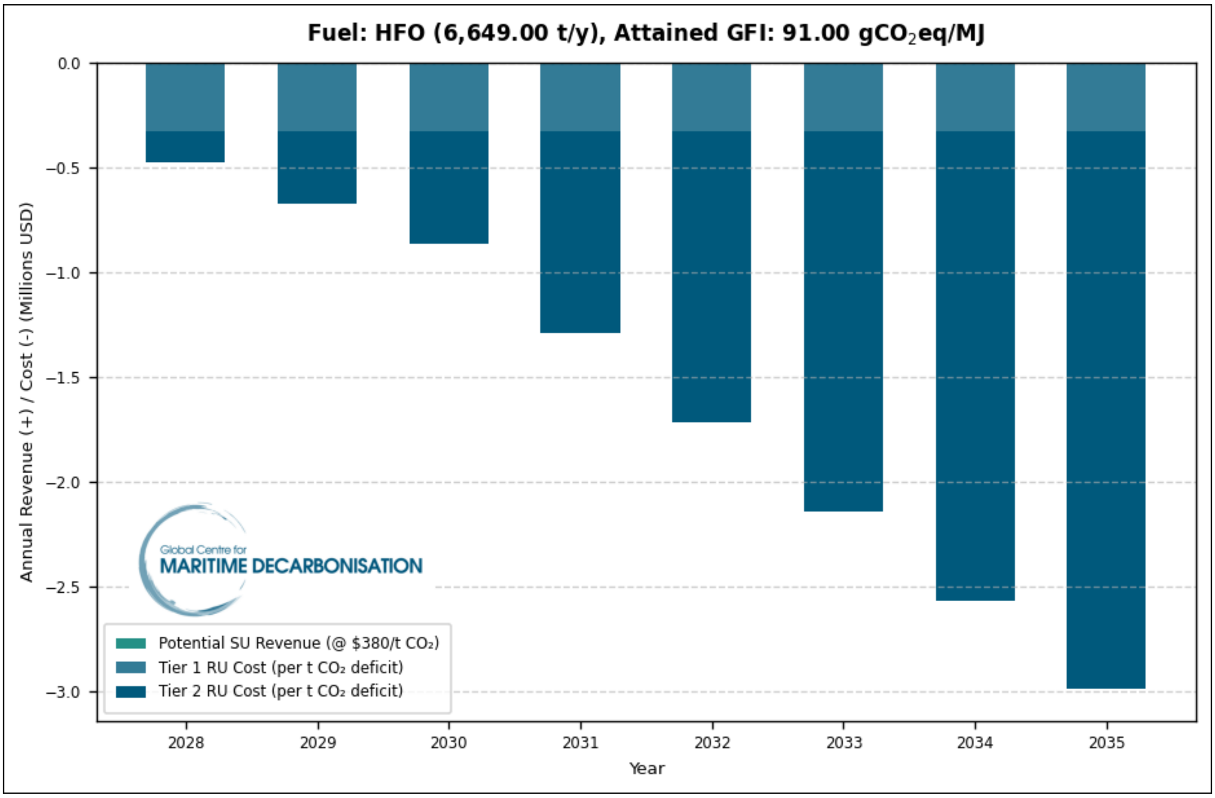


Figure 15: Result Plot for Case 1 : HFO (LHV: 41,000 MJ/t | GFI: 91 gCO2/MJ

Table 13: Case 2: Fuel LNG ((LHV: 48,600 MJ/t | GFI: 80.00 gCO_2eq/MJ)

Year	Target GFI (Base/ Direct) (gCO_2/MJ)	Balance ($t\ CO_2$)	Deficits (T1/T2) ($t\ CO_2$) or SUs Generated	Net Outcome (Cost / Revenue)	T1 RU Cost	T2 RU Cost
2028	89.568 / 77.439	-827.565	Deficits: 827.565 / 0.000	$82,756.51 (Cost)	$82,756.51	$0.00
2029	87.702 / 75.573	-1,430.55	Deficits: 1,430.547 / 0.000	$143,054.70 (Cost)	$143,054.70	$0.00
2030	85.836 / 73.707	-2,033.53	Deficits: 2,033.529 / 0.000	$203,352.88 (Cost)	$203,352.88	$0.00
2031	81.731 / 69.602	-3,360.09	Deficits: 3,360.089 / 0.000	$336,008.89 (Cost)	$336,008.89	$0.00
2032	77.626 / 65.497	-4,686.65	Deficits: 3,919.382/767.267	$683,499.64 (Cost)	$391,938.20	$291,561.44

Table 13: Case 2: Fuel LNG ((LHV: 48,600 MJ/t | GFI: 80.00 gCO_2eq/MJ)

Year	Target GFI (Base/ Direct) (gCO_2/MJ)	Balance (t CO_2)	Deficits (T1/T2) (t CO_2) or SUs Generated	Net Outcome (Cost / Revenue)	T1 RU Cost	T2 RU Cost
2033	73.520 / 61.391	-6,013.21	Deficits: 3,919.382/ 2,093.82	$1,187,592.47 (Cost)	$391,938.20	$795,654.27
2034	69.415 / 57.286	-7,339.77	Deficits: 3,919.382 / 3,420.38	$1,691,685.30 (Cost)	$391,938.20	$1,299,747.09
2035	65.310 / 53.181	-8,666.33	Deficits: 3,919.382 / 4,746.94	$2,195,778.13 (Cost)	$391,938.20	$1,803,839.92

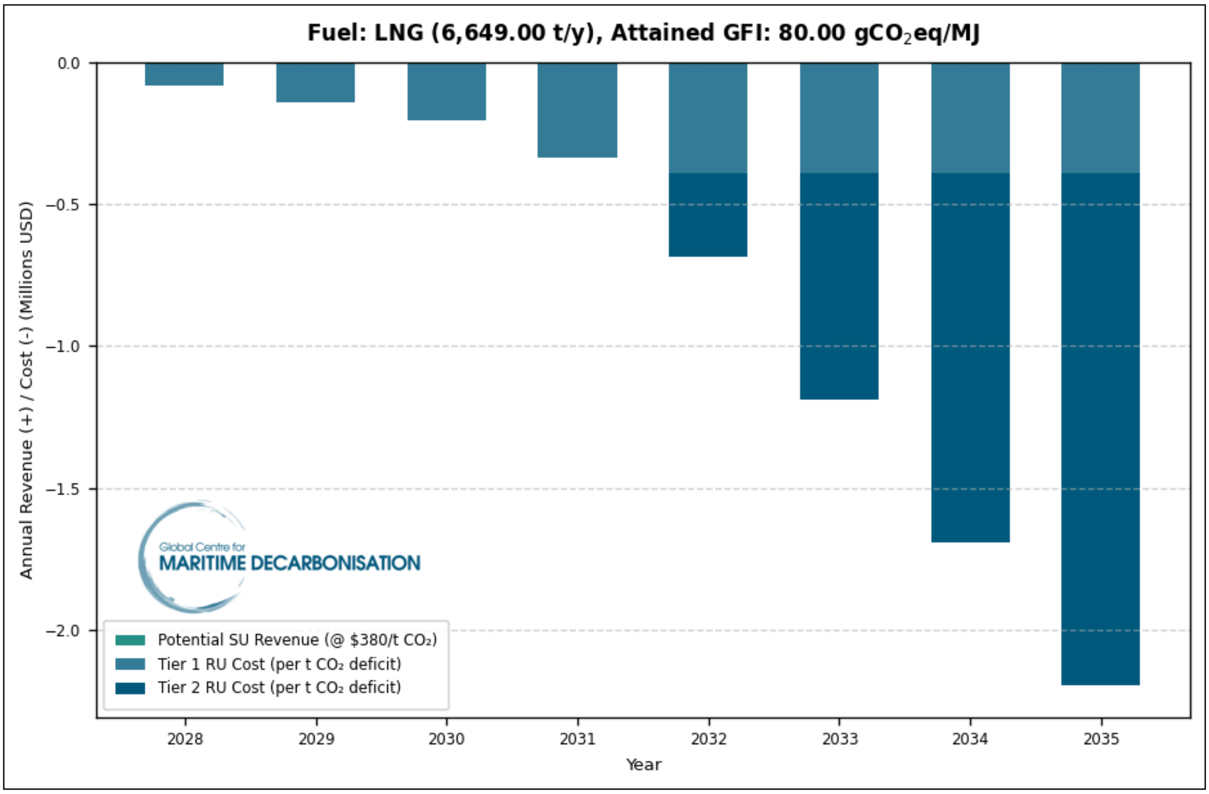


Figure 16: Result Plot for Case 2 LNG ((LHV: 48,600 MJ/t | GFI: 80.00 gCO_2/MJ))

Table 14: Case 3a: E-Ammonia (LHV: 18,600 MJ/t | GFI: 12.1 gCO_2/MJ)

Year	Target GFI (Base / Direct) (gCO_2/MJ)	Balance (t CO_2)	SUs / Deficits (t CO_2)	Net Outcome (Cost /Revenue)	T1 RU Cost	T2 RU Cost
2028	89.568 / 77.439	8,080.57	SUs Generated: 8,080.566	$3,070,614.93 Revenue	$0.00	$0.00
2029	87.702 / 75.573	7,849.80	SUs Generated: 7,849.795	$2,982,922.01 Revenue	$0.00	$0.00
2030	85.836 / 73.707	7,619.02	SUs Generated: 7,619.024	$2,895,229.10 Revenue	$0.00	$0.00
2031	81.731 / 69.602	7,111.33	SUs Generated: 7,111.328	$2,702,304.68 Revenue	$0.00	$0.00
2032	77.626 / 65.497	6,603.63	SUs Generated: 6,603.632	$2,509,380.27 Revenue	$0.00	$0.00
2033	73.520 / 61.391	6,095.94	SUs Generated: 6,095.936	$2,316,455.85 Revenue	$0.00	$0.00
2034	69.415 / 57.286	5,588.24	SUs Generated: 5,588.241	$2,123,531.43 Revenue	$0.00	$0.00
2035	65.310 / 53.181	5,080.55	SUs Generated: 5,080.545	$1,930,607.02 Revenue	$0.00	$0.00

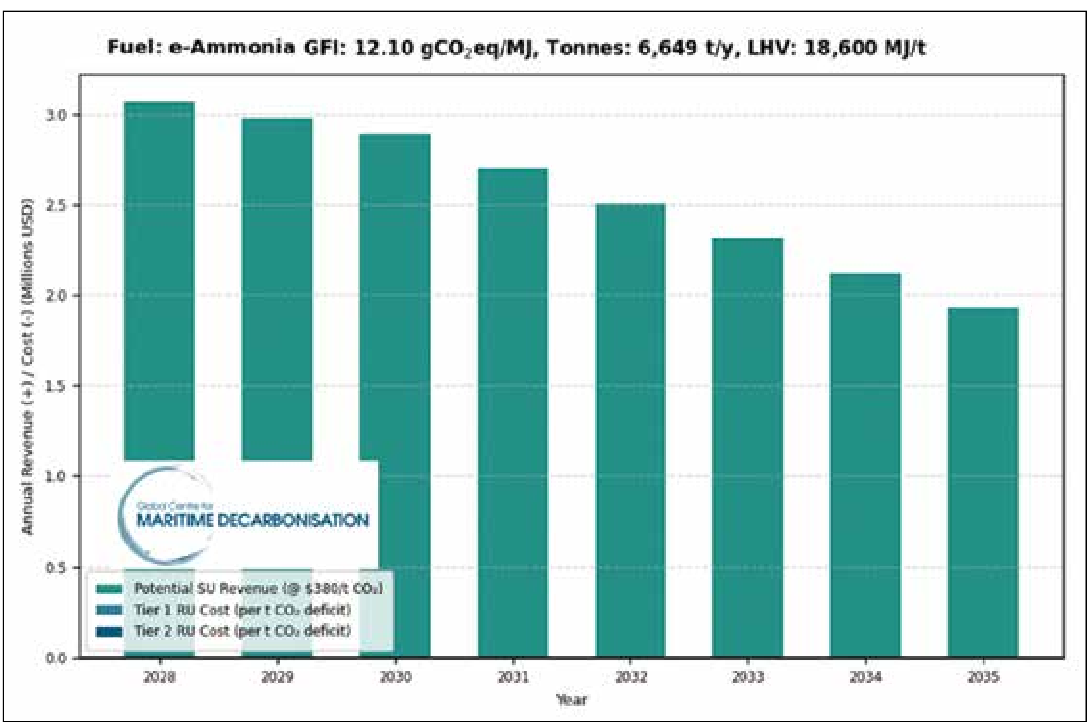


Figure 17: Result Plot for Case 3a E-Ammonia (LHV: 18,600 MJ/t | GFI: 12.10 gCO_2/MJ)

Table 15: Case 3b: E-Ammonia (LHV: 18,600 MJ/t | (GFI: 3.00 gCO_2/MJ)

Year	Target GFI (Base / Direct) (gCO_2/ MJ)	Balance (t CO_2)	Deficits (T1 / T2) or SUs Generated (tCO_2)	Net Outcome (Cost / Revenue)	T1 RU Cost	T2 RU Cost
2028	89.568 / 77.439	9,205.98	SUs Generated: 9,205.975	$3,498,270.63 (Revenue)	$0.00	$0.00
2029	87.702 / 75.573	8,975.21	SUs Generated: 8,975.205	$3,410,577.71 (Revenue)	$0.00	$0.00
2030	85.836 / 73.707	8,744.43	SUs Generated: 8,744.434	$3,322,884.80 (Revenue)	$0.00	$0.00
2031	81.731 / 69.602	8,236.74	SUs Generated: 8,236.738	$3,129,960.38 (Revenue)	$0.00	$0.00
2032	77.626 / 65.497	7,729.04	SUs Generated: 7,729.042	$2,937,035.97 (Revenue)	$0.00	$0.00
2033	73.520 / 61.391	7,221.35	SUs Generated: 7,221.346	$2,744,111.55 (Revenue)	$0.00	$0.00
2034	69.415 / 57.286	6,713.65	SUs Generated: 6,713.650	$2,551,187.13 (Revenue)	$0.00	$0.00
2035	65.310 / 53.181	6,205.96	SUs Generated: 6,205.955	$2,358,262.72 (Revenue)	$0.00	$0.00

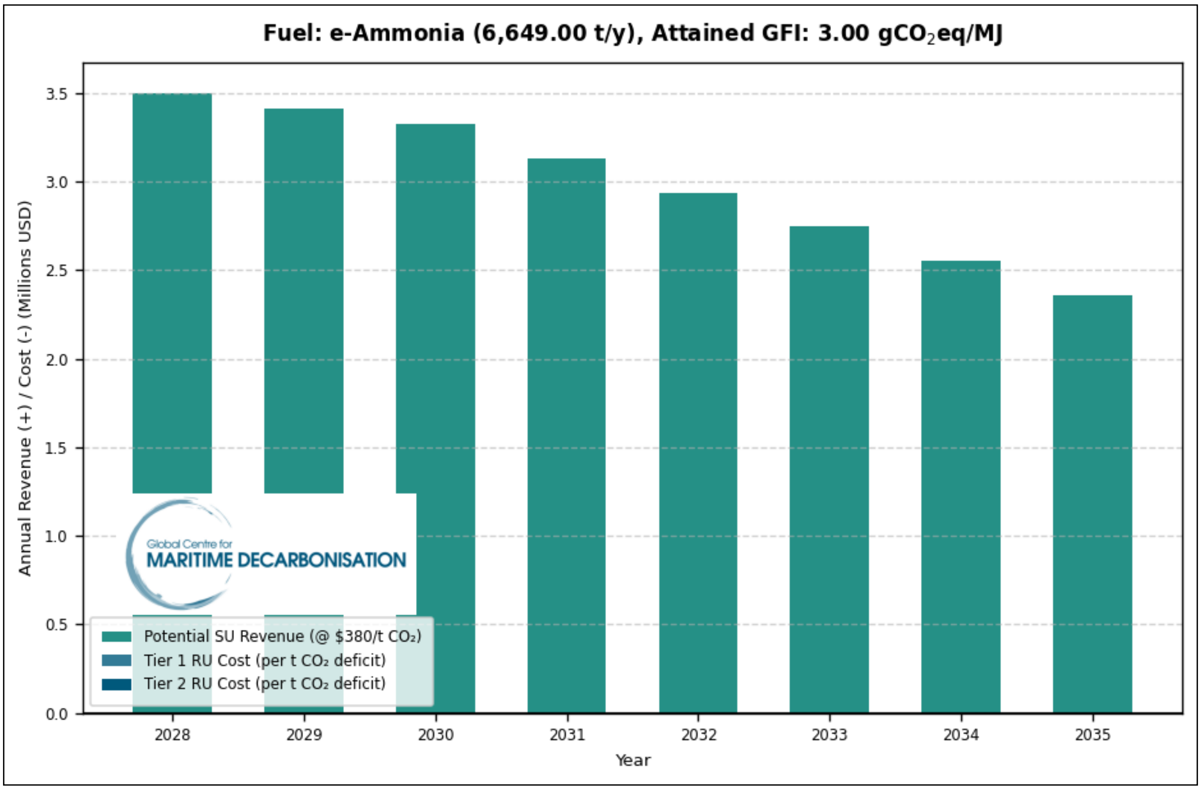


Figure 18: Result Plot for Case 3b E-Ammonia (LHV: 18,600 MJ/t | GFI: 3.00 gCO_2/MJ)

Table 16: Case 4a: Bio- Methanol (LHV: 19,900 MJ/t | GFI: 17.00 gCO_2/MJ)

Year	Target GFI (Base / Direct) (gCO_2/MJ)	Balance (t CO_2)	SUs / Deficits (t CO_2)	Net Outcome (Cost / Revenue)	T1 RU Cost	T2 RU Cost
2028	89.568 / 77.439	7,996.99	SUs Generated: 7,996.99	$3,038,857.08 Revenue	$0.00	$0.00
2029	87.702 / 75.573	7,750.09	SUs Generated: 7,750.09	$2,945,035.09 Revenue	$0.00	$0.00
2030	85.836 / 73.707	7,503.19	SUs Generated: 7,503.19	$2,851,213.10 Revenue	$0.00	$0.00
2031	81.731 / 69.602	6,960.01	SUs Generated: 6,960.01	$2,644,804.72 Revenue	$0.00	$0.00
2032	77.626 / 65.497	6,416.83	SUs Generated: 6,416.83	$2,438,396.34 Revenue	$0.00	$0.00
2033	73.520 / 61.391	5,873.65	SUs Generated: 5,873.65	$2,231,987.96 Revenue	$0.00	$0.00
2034	69.415 / 57.286	5,330.47	SUs Generated: 5,330.47	$2,025,579.58 Revenue	$0.00	$0.00
2035	65.310 / 53.181	4,787.29	SUs Generated: 4,787.29	$1,819,171.20 Revenue	$0.00	$0.00

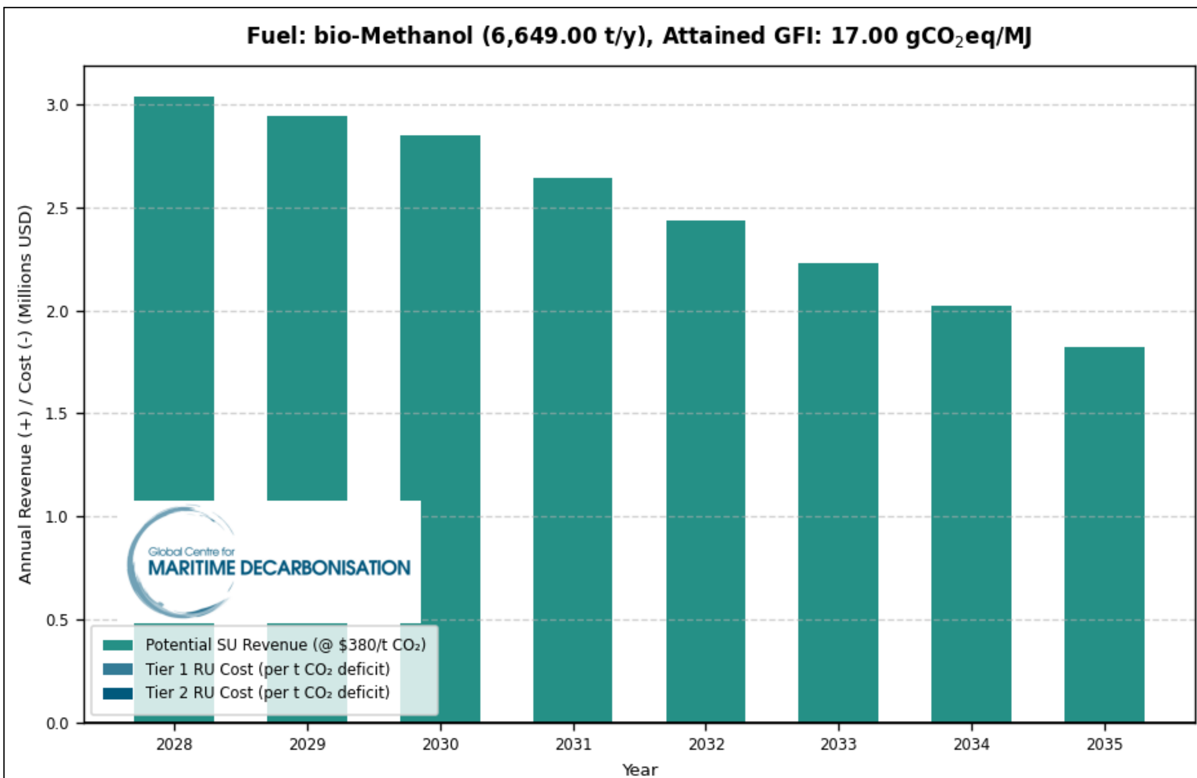


Figure 19: Result Plot for Case 4a Bio- Methanol (LHV: 19,900 MJ/t | GFI: 17.00 gCO_2/MJ)

Table 17: Case 4b: Bio- Methanol (LHV: 19,900 MJ/t | GFI: 9.4 gCO₂/MJ)

	Target GFI (Base / Direct) (gCO_2/MJ)	Balance (t CO_2)	SUs / Deficits (t CO_2)	Net Outcome (Cost / Revenue)	T1 RU Cost	T2 RU Cost / Revenue
2028	89.568 / 77.439	9,002.59	SUs Generated: 9,002.587	$3,420,983.09 Revenue	$0.00	$0.00
2029	87.702 / 75.573	8,755.69	SUs Generated: 8,755.687	$3,327,161.10 Revenue	$0.00	$0.00
2030	85.836 / 73.707	8,508.79	SUs Generated: 8,508.787	$3,233,339.11 Revenue	$0.00	$0.00
2031	81.731 / 69.602	7,965.61	SUs Generated: 7,965.607	$3,026,930.73 Revenue	$0.00	$0.00
2032	77.626 / 65.497	7,422.43	SUs Generated: 7,422.427	$2,820,522.35 Revenue	$0.00	$0.00
2033	73.520 / 61.391	6,879.25	SUs Generated: 6,879.247	$2,614,113.97 Revenue	$0.00	$0.00
2034	69.415 / 57.286	6,336.07	SUs Generated: 6,336.067	$2,407,705.59 Revenue	$0.00	$0.00
2035	65.310 / 53.181	5,792.89	SUs Generated: 5,792.887	$2,201,297.21 Revenue	$0.00	$0.00

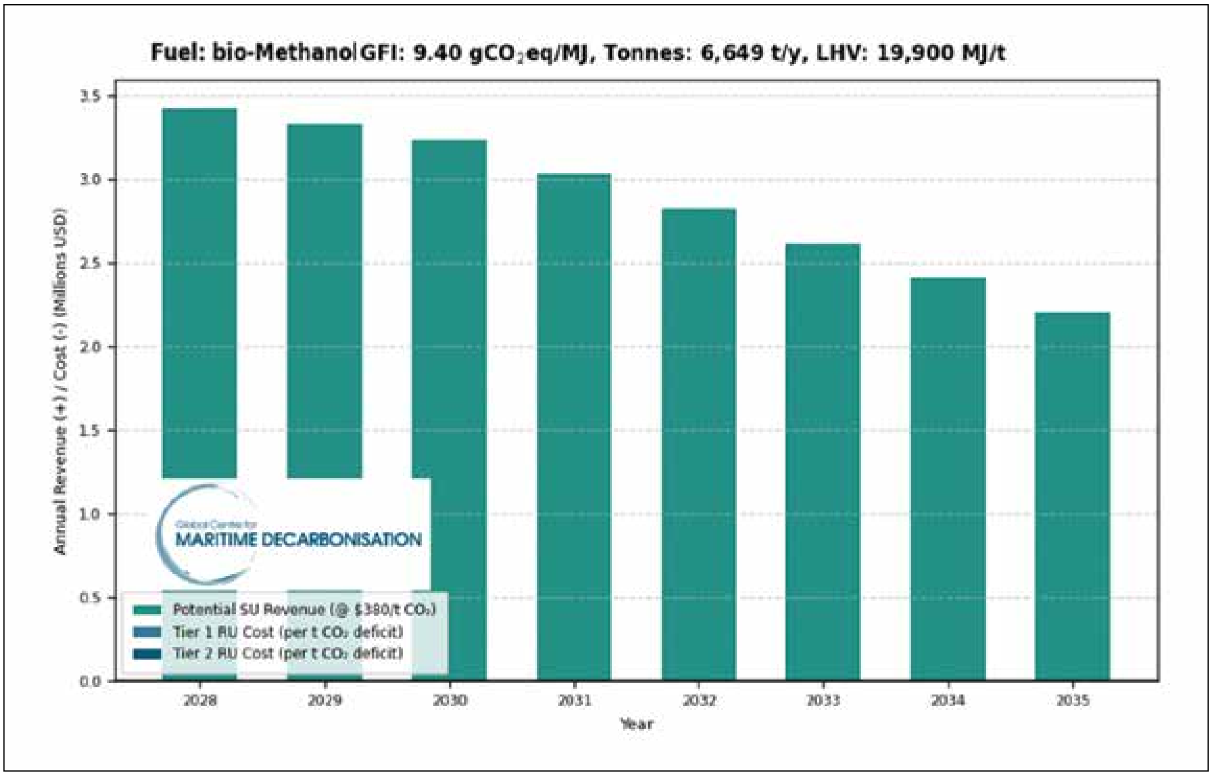


Figure 20: Result Plot for Case 4b: Bio- Methanol (LHV: 19,900 MJ/t | GFI: 9.4 gCO₂/MJ)

Table 18: Case 5: B100 or BD100 (LHV: 37,500 MJ/t) (GFI: 9.4 gCO_2/MJ)

Year	Target GFI (Base / Direct) (gCO_2/MJ)	Balance (t CO_2)	SUs Generated (t CO_2)	Net Outcome (Cost / Revenue)	T1 RU Cost	T2 RU Cost
2028	89.568 / 77.439	16,964.67	SUs Generated: 16,964.67	$6,446,576.18 (Revenue)	$0.00	$0.00
2029	87.702 / 75.573	16,499.41	SUs Generated: 16,499.41	$6,269,775.95 (Revenue)	$0.00	$0.00
2030	85.836 / 73.707	16,034.15	SUs Generated: 16,034.15	$6,092,975.71 (Revenue)	$0.00	$0.00
2031	81.731 / 69.602	15,010.57	SUs Generated: 15,010.57	$5,704,015.20 (Revenue)	$0.00	$0.00
2032	77.626 / 65.497	13,986.99	SUs Generated: 13,986.99	$5,315,054.68 (Revenue)	$0.00	$0.00
2033	73.520 / 61.391	12,963.41	SUs Generated: 12,963.41	$4,926,094.17 (Revenue)	$0.00	$0.00
2034	69.415 / 57.286	11,939.83	SUs Generated: 11,939.83	$4,537,133.65 (Revenue)	$0.00	$0.00
2035	65.310 / 53.181	10,916.25	SUs Generated: 10,916.25	$4,148,173.13 (Revenue)	$0.00	$0.00

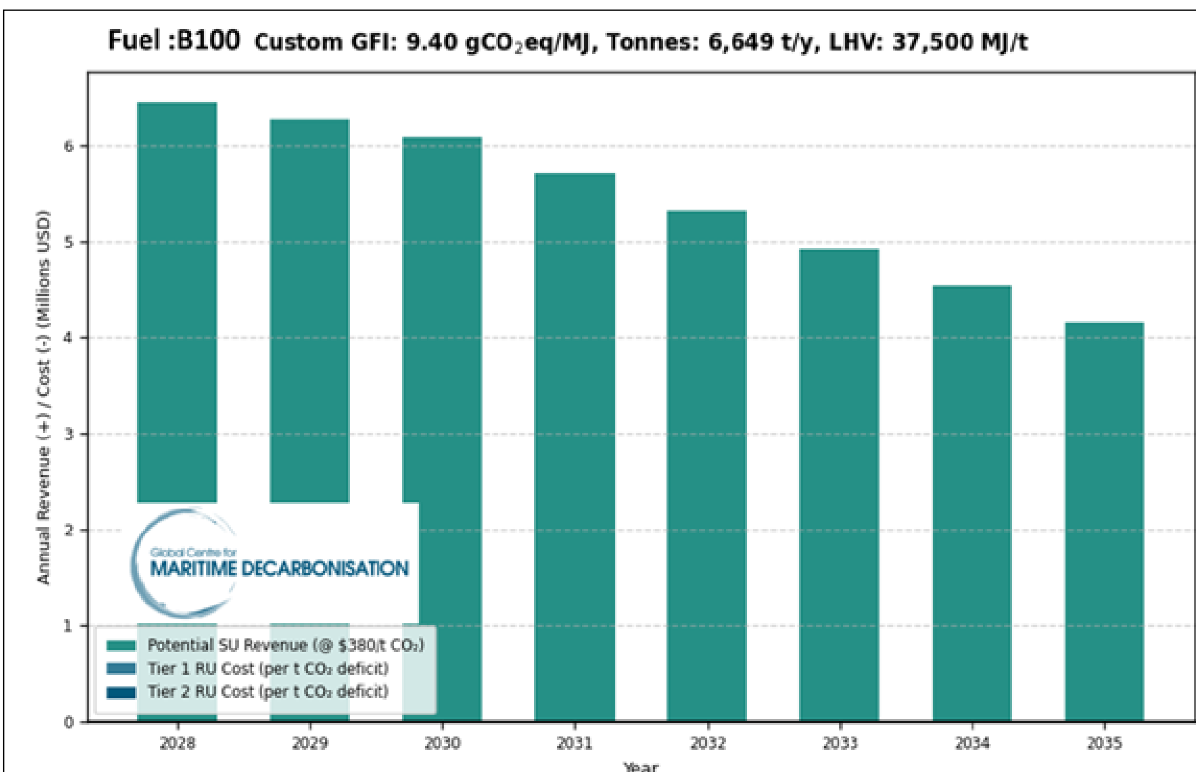


Figure 21: Result Plot for Case 5: Biodiesel 100 (B100 orBD100) (LHV: 19,900 MJ/t | GFI: 9.4 gCO_2/MJ)

Table 19: Case 5a: B24 or BD24 ((LHV: 41,001MJ/t GFI: 73.81 gCO_2eq/MJ)

Year	Target GFI (Base / Direct) (gCO_2/MJ)	Balance (t CO_2)	SUs / Deficits (t CO_2)	Net Outcome (Cost / Revenue)	T1 RU Cost	T2 RU Cost
2028	89.568 / 77.439	989.322	SUs: 989.322 / 0.000	$375,942.43 (Revenue)	$98,932.20	$277,010.23
2029	87.702 / 75.573	480.621	SUs: 480.621 / 0.000	$182,636.13 (Revenue)	$48,062.10	$134,574.03
2030	85.836 / 73.707	−28.079	Deficits: 28.079 / 0.000	$2,807.94 (Cost)	$2,807.94	$0.00
2031	81.731 / 69.602	−1,147.22	Deficits: 1,147.221 / 0.000	$114,722.12 (Cost)	$114,722.12	$0.00
2032	77.626 / 65.497	−2,266.36	Deficits: 1,499.096 / 767.267	$226,636.29 (Cost)	$149,909.60	$291,561.44
2033	73.520 / 61.391	−3,385.51	Deficits: 1,291.685 / 2,093.82	$1,187,592.47 (Cost)	$129,168.50	$795,654.27
2034	69.415 / 57.286	−4,504.65	Deficits: 1,084.267 / 3,420.38	$1,691,685.30 (Cost)	$108,426.70	$1,299,747.09
2035	65.310 / 53.181	−5,623.78	Deficits: 876.544 / 4,746.94	$2,195,778.13 (Cost)	$87,654.40	$1,803,839.92

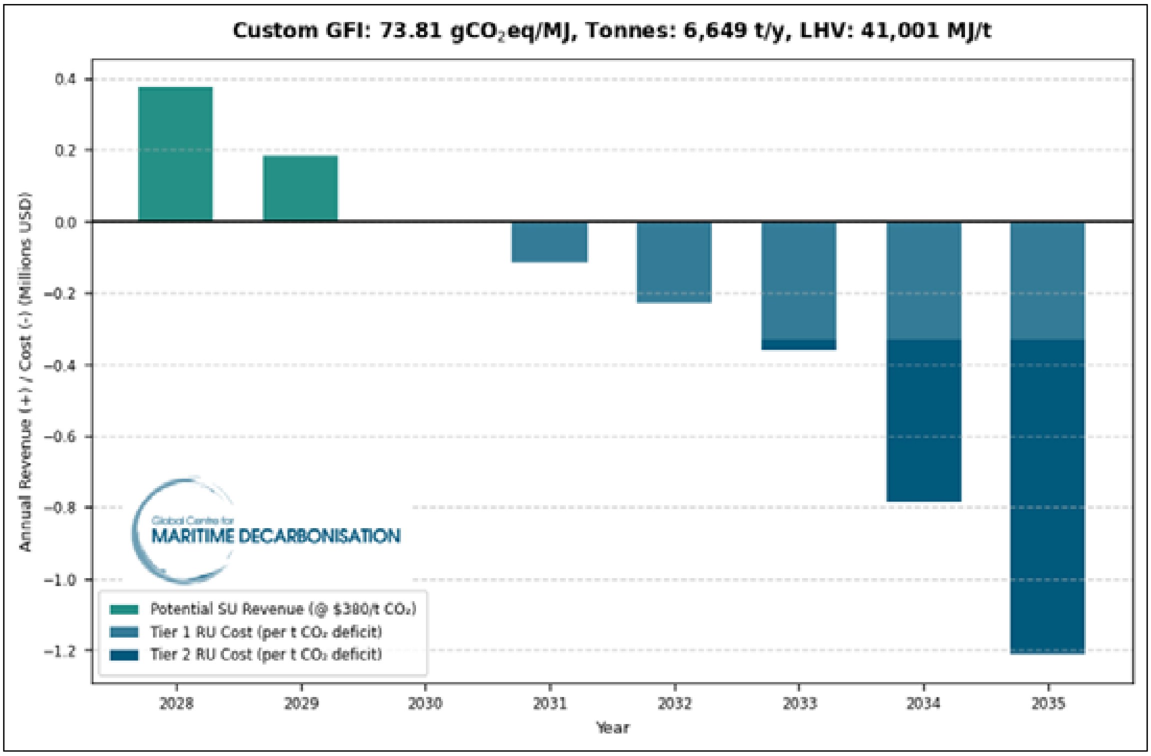


Figure 22: Result Plot for Case 5a B24 or BD24 ((LHV: 40,648 MJ/t | GFI: 75.92 gCO_2/MJ) (i.e. D(HFO/LFO/DO)—Biodiesel blend) (*B or BD both represents Biodiesel blend)

Table 20: Case 5b: B30 or BD30 i.e D(HFO/LFO/DO)-Biodiesel (LHV: 40,713 MJ/t) (GFI: 68.44 gCO_2/MJ)

Year	Target GFI (Base / Direct) (gCO_2/MJ)	Balance (t CO_2)	SUs / Deficits (t CO_2)	Net Outcome (Cost / Revenue)	T1 RU Cost	T2 RU Cost
2028	89.568 / 77.439	2,437.113	SUs Generated: 2,437.113	$926,102.92 Revenue	$0.00	$0.00
2029	87.702 / 75.573	1,931.762	SUs Generated: 1,931.762	$734,069.58 Revenue	$0.00	$0.00
2030	85.836 / 73.707	1,426.411	SUs Generated: 1,426.411	$542,036.24 Revenue	$0.00	$0.00
2031	81.731 / 69.602	314.639	SUs Generated: 314.639	$119,562.88 Revenue	$0.00	$0.00
2032	77.626 / 65.497	−797.133	Deficit: 797.133	$79,713.28 Cost	$79,713.28	$0.00
2033	73.520 / 61.391	−1,908.905	Deficit: 1,908.905	$190,890.48 Cost	$190,890.48	$0.00
2034	69.415 / 57.286	−3,020.677	Deficit: 3,020.677	$302,067.68 Cost	$302,067.68	$0.00
2035	65.310 / 53.181	−4,132.449	Deficit: 3,284.781 (T1) / 847.668 (T2)	$650,591.89 Cost	$328,478.09	$322,113.81

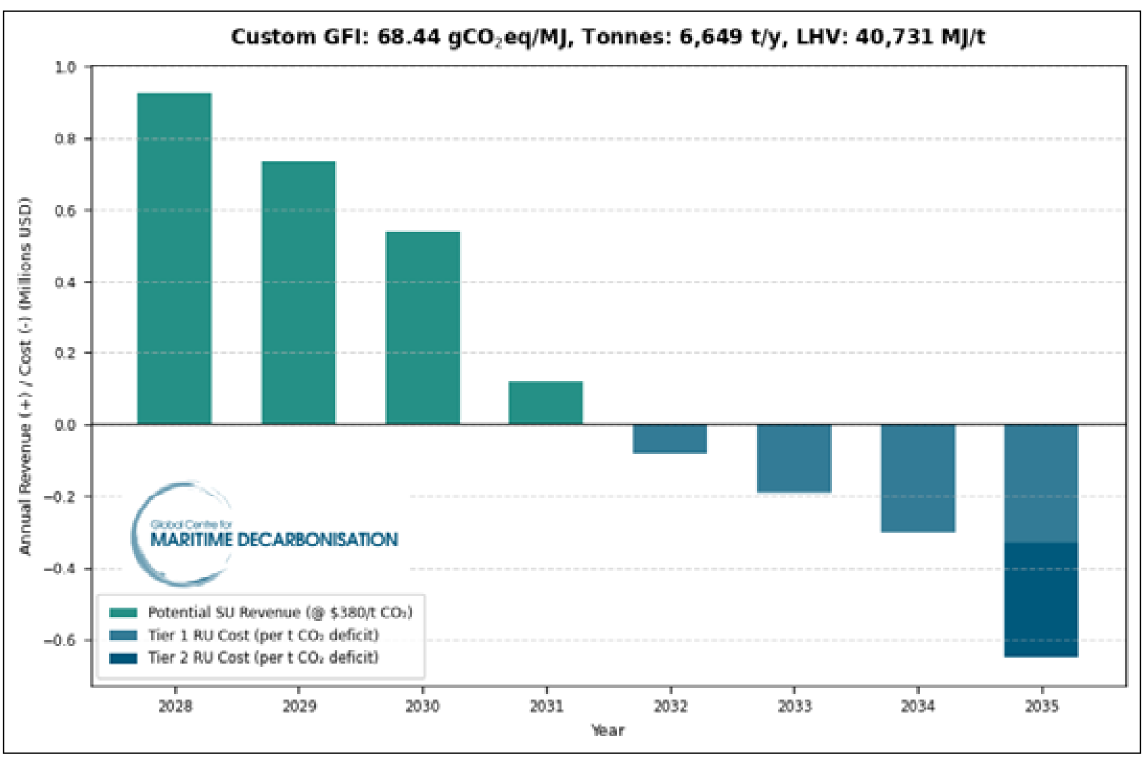


Figure 23: Result Plot for Diesel-Biodiesel Case 5b: B30 or BD 30 (LHV: 40,713 MJ/t) (GFI: 68.44 gCO_2/MJ) (i.e. D(HFO/LFO/DO)—Biodiesel blend)

Table 21 : Case 5c: B40 or BD 40 i.e. D(HFO/LFO/DO)-Biodiesel (LHV: 40,288 MJ/t) (GFI: 60.91 gCO_2/MJ)

Year	Target GFI (Base / Direct) (gCO_2/MJ)	Balance (t CO_2)	SUs / Deficits (t CO_2)	Net Outcome (Cost / Revenue)	T1 RU Cost	T2 RU Cost
2028	89.568 / 77.439	4,427.70	SUs Generated: 4,427.704	$1,682,527.68 Revenue	$0.00	$0.00
2029	87.702 / 75.573	3,927.85	SUs Generated: 3,927.850	$1,492,582.94 Revenue	$0.00	$0.00
2030	85.836 / 73.707	3,428.00	SUs Generated: 3,427.995	$1,302,638.19 Revenue	$0.00	$0.00
2031	81.731 / 69.602	2,328.32	SUs Generated: 2,328.315	$884,759.76 Revenue	$0.00	$0.00
2032	77.626 / 65.497	1,228.64	SUs Generated: 1,228.635	$466,881.33 Revenue	$0.00	$0.00
2033	73.520 / 61.391	128.955	SUs Generated: 128.955	$49,002.89 Revenue	$00	$0.00
2034	69.415 / 57.286	−970.725	Deficit: 970.725	$97,072.51 Cost	$97,072.51	$0.00
2035	65.310 / 53.181	−2,070.405	Deficit: 2,070.405	$207,040.52 Cost	$207,040.52	$0.00

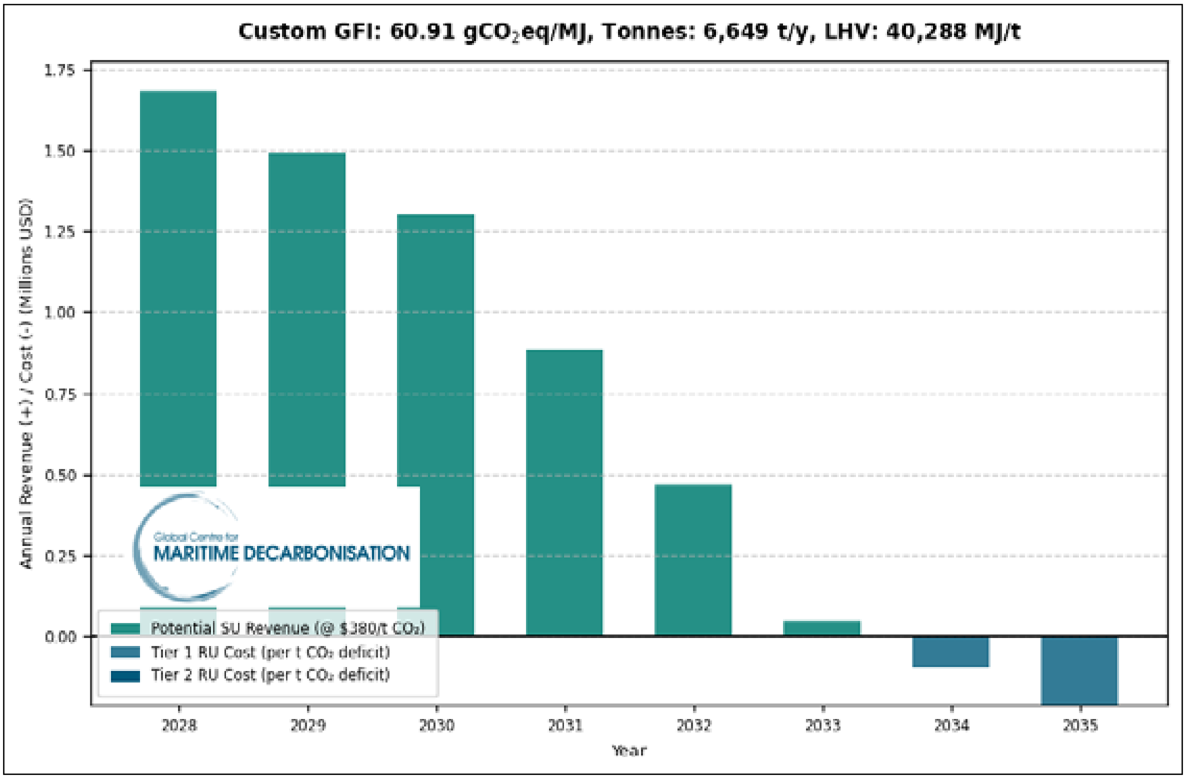


Figure 24: Result Plot for D(HFO/LFO/DO)-Biodiesel Case 5c: B40 or BD40 (LHV: 40,288 MJ/t) (GFI: 60.91 gCO_2/MJ) (i.e. D(HFO/LFO/DO)-Biodiesel blend)

Table 22 : Case 5d: B50 or BD50 i.e. D(HFO/LFO/DO)-Biodiesel (LHV: 39,769 MJ/t) (GFI: 51.86 gCO_2/MJ)

Year	Target GFI (Base / Direct) (gCO_2/MJ)	Balance ($t\ CO_2$)	Deficits / SUs ($t\ CO_2$)	Net Outcome (Cost / Revenue)	T1 RU Cost	T2 RU Cost
2028	89.568 / 77.439	6,763.70	SUs Generated: 6,763.704	$2,570,207.36 Revenue	$0.00	$0.00
2029	87.702 / 75.573	6,270.29	SUs Generated: 6,270.288	$2,382,709.53 Revenue	$0.00	$0.00
2030	85.836 / 73.707	5,776.87	SUs Generated: 5,776.873	$2,195,211.70 Revenue	$0.00	$0.00
2031	81.731 / 69.602	4,691.36	SUs Generated: 4,691.359	$1,782,716.48 Revenue	$0.00	$0.00
2032	77.626 / 65.497	3,605.85	SUs Generated: 3,605.845	$1,370,221.26 Revenue	$0.00	$0.00
2033	73.520 / 61.391	2,520.33	SUs Generated: 2,520.332	$957,726.04 Revenue	$0.00	$0.00
2034	69.415 / 57.286	1,434.82	SUs Generated: 1,434.818	$545,230.82 Revenue	$0.00	$0.00
2035	65.310 / 53.181	349.3	SUs Generated: 349.304	$132,735.60 Revenue	$0.00	$0.00

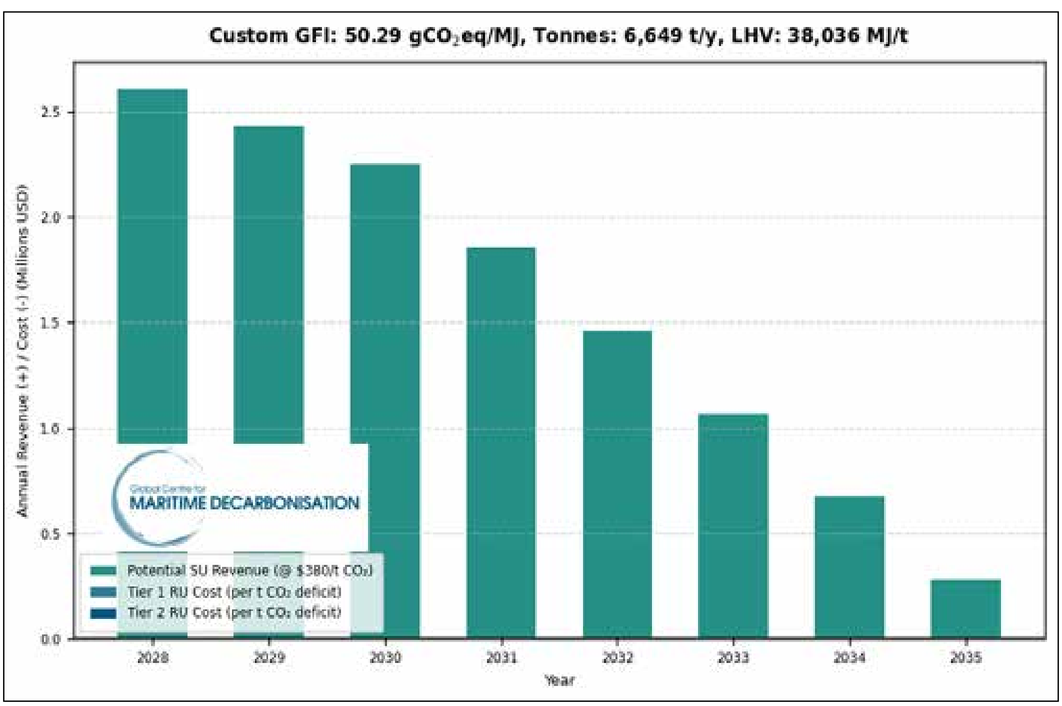


Figure 25: Result Plot for D(HFO/LFO/DO)-Biodiesel Case 5d: B50 or BD50 (LHV: 39,769 MJ/t |GFI: 51.86 gCO_2/MJ) (i.e. D(HFO/LFO/DO)-Biodiesel blend)

Table 23: Case 6: D(HFO/LFO/DO) M9.47BD25 (LHV: 39,084 MJ/t) (Attained GFI: 69.39gCO_2/MJ) (blend with E-Methanol)

Year	Target GFI (Base / Direct) (gCO_2/MJ)	Balance (t CO_2)	SUs / Deficits (T1 / T2) (t CO_2)	Net Outcome	T1 RU Cost	T2 RU Cost / Revenue
2028	89.568 / 77.439	+2,091.690	SUs: 2,091.690	$794,842.10 (Revenue)	$0.00	$0.00
2029	87.702 / 75.573	+1,606.773	SUs: 1,606.773	$610,573.82 (Revenue)	$0.00	$0.00
2030	85.836 / 73.707	+1,121.857	SUs: 1,121.857	$426,305.55 (Revenue)	$0.00	$0.00
2031	81.731 / 69.602	+55.040	SUs: 55.040	$20,915.34 (Revenue)	$0.00	$0.00
2032	77.626 / 65.497	−1,011.776	Deficit: 1,011.776 / 0.000	$101,177.60 (Cost)	$101,177.60	$0.00
2033	73.520 / 61.391	−2,078.592	Deficit: 2,078.592 / 0.000	$207,859.23 (Cost)	$207,859.23	$0.00
2034	69.415 / 57.286	−3,145.409	Deficit: 3,145.409 / 0.000	$314,540.86 (Cost)	$314,540.86	$0.00
2035	65.310 / 53.181	−4,212.225	Deficit: 3,151.957 / 1,060.268	$718,097.43 (Cost)	$315,195.74	$402,901.70

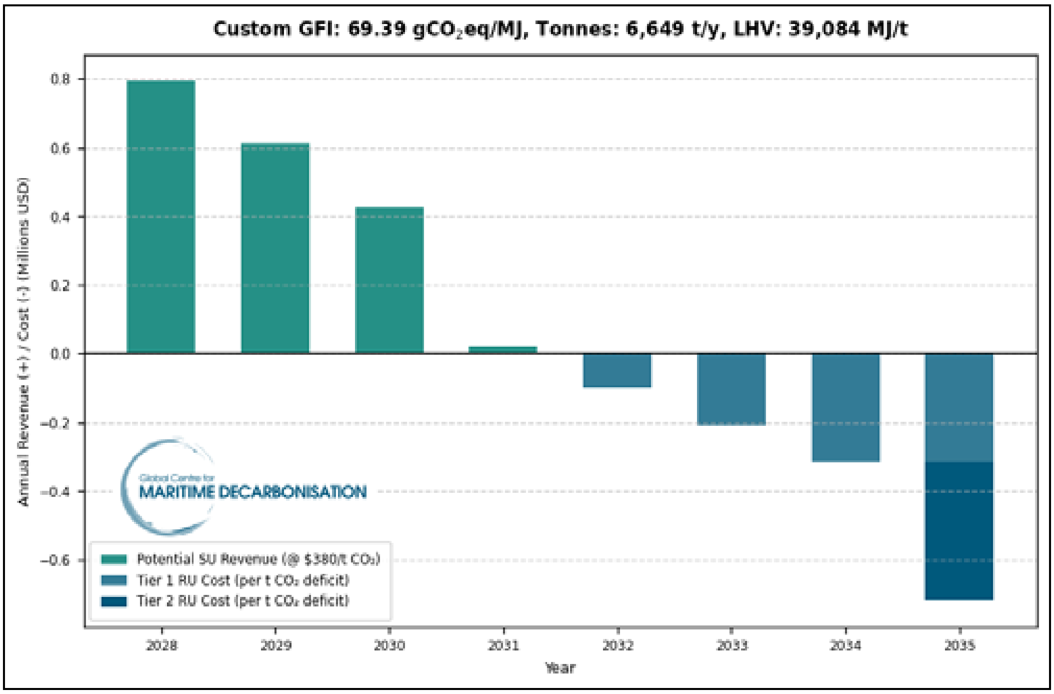


Figure 26: Result Plot for Case 6: D(HFO/LFO/DO) M9.47BD25 (LHV: 39,084 MJ/t) (Attained GFI: 69.39gCO_2/MJ) (i.e. D(HFO/LFO/DO)-Methanol-Biodiesel blend)

Table 24: Case7: D(HFO/LFO/DO) M9.47BD30(LHV: 38,873 MJ/t) (GFI: 65.63 gCO_2/MJ) (blend with E-Methanol)

Year	Target GFI (Base / Direct) (gCO_2/MJ)	Balance (t CO_2)	Deficits / SUs (t CO_2)	Net Outcome (Cost / Revenue)	T1 RU Cost	T2 RU Cost
2028	89.568 / 77.439	3,052.23	SUs Generated: 3,052.232	$1,159,848.09 Revenue	$0.00	$0.00
2029	87.702 / 75.573	2,569.93	SUs Generated: 2,569.933	$976,574.61 Revenue	$0.00	$0.00
2030	85.836 / 73.707	2,087.64	SUs Generated: 2,087.635	$793,301.13 Revenue	$0.00	$0.00
2031	81.731 / 69.602	1,026.58	SUs Generated: 1,026.578	$390,099.47 Revenue	$0.00	$0.00
2032	77.626 / 65.497	-34.479	Deficit: 34.479 t / 0.000 t	$3,447.94 Cost	$3,447.94	$0.00
2033	73.520 / 61.391	-1,095.54	Deficit: 1,095.536 t / 0.000 t	$109,553.64 Cost	$109,553.64	$0.00
2034	69.415 / 57.286	-2,156.59	Deficit: 2,156.593 t / 0.000 t	$215,659.34 Cost	$215,659.34	$0.00
2035	65.310 / 53.181	-3,217.65	Deficit: 3,134.941 t / 82.709 t	$344,923.65 Cost	$313,494.11	$31,429.54

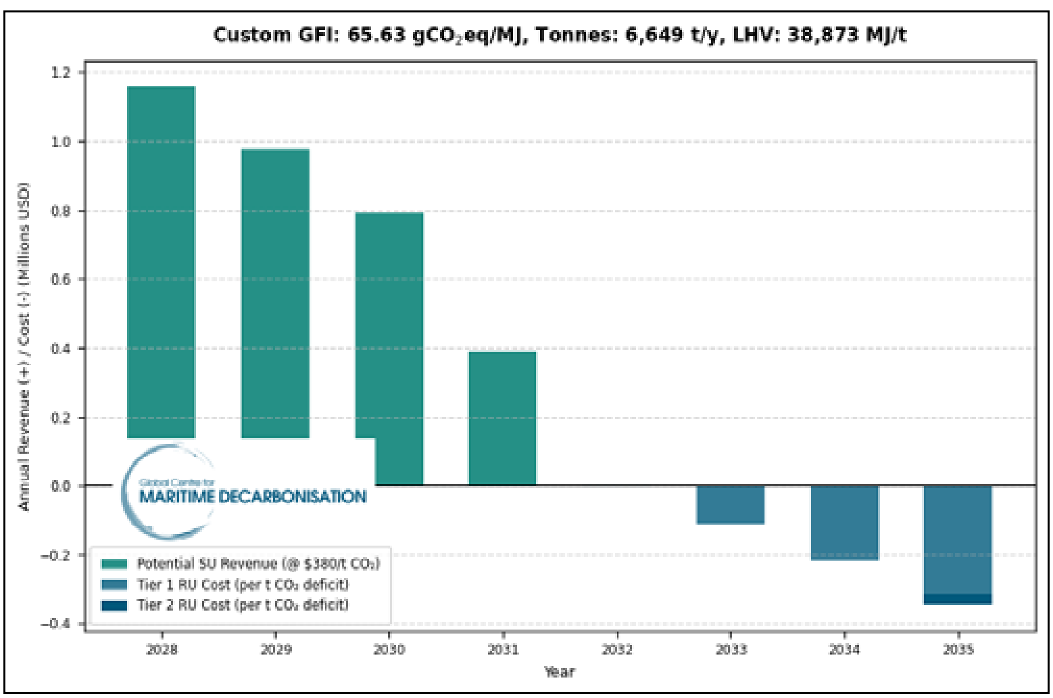


Figure 27: Result Plot for Case 7: D (HFO/LFO/DO) M9.47BD30(LHV: 38,873 MJ/t | GFI: 65.63 gCO_2/MJ) (i.e. D(HFO/LFO/DO)-Methanol-Biodiesel blend)

Table 25: Case 8 a: D(HFO/LFO/DO) M9.47BD40(LHV: 38,459 MJ/t) (GFI: 57.69 gCO_2/MJ) (blend with Bio-Methanol GFI 9.4)

Year	Target GFI (Base / Direct) (gCO_2/MJ)	Balance (t CO_2)	SUs / Deficits (t CO_2)	Net Outcome (Cost / Revenue)	T1 RU Cost	T2 RU Cost
2028	89.568 / 77.439	5,050.09	SUs Generated: 5,050.094	$1,919,035.58 Revenue	$0.00	$0.00
2029	87.702 / 75.573	4,572.93	SUs Generated: 4,572.932	$1,737,713.97 Revenue	$0.00	$0.00
2030	85.836 / 73.707	4,095.77	SUs Generated: 4,095.769	$1,556,392.37 Revenue	$0.00	$0.00
2031	81.731 / 69.602	3,046.01	SUs Generated: 3,046.013	$1,157,484.84 Revenue	$0.00	$0.00
2032	77.626 / 65.497	1,996.26	SUs Generated: 1,996.256	$758,577.30 Revenue	$0.00	$0.00
2033	73.520 / 61.391	946.499	SUs Generated: 946.499	$359,669.77 Revenue	$0.00	$0.00
2034	69.415 / 57.286	-103.257	Deficit: 103.257 (T1)	$10,325.73 Cost	$10,325.73	$0.00
2035	65.310 / 53.181	-1,153.01	Deficit: 1,153.014 (T1)	$115,301.39 Cost	$115,301.39	$0.00

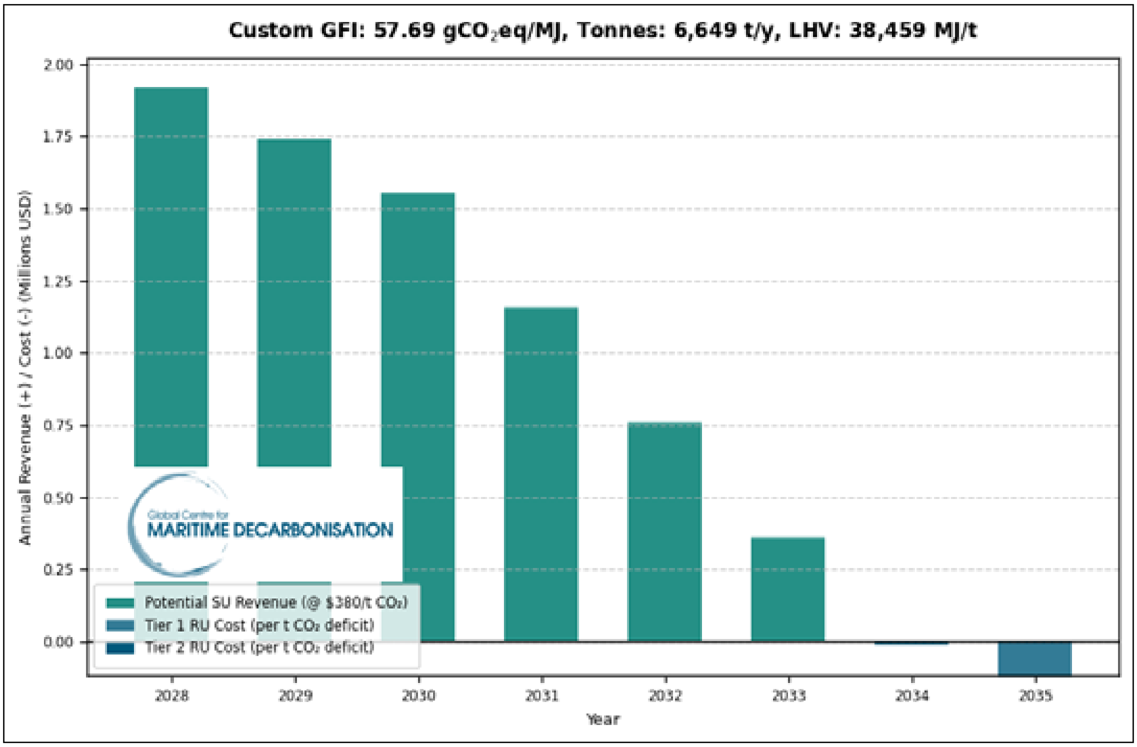


Figure 28: Result Plot for Case 8a: D(HFO/LFO/DO) M9.47BD50 (LHV: 38,459 MJ/t) (GFI: 57.69 gCO_2/MJ) (i.e. D(HFO/LFO/DO)-Methanol-Biodiesel blend)

Table 26: Case 8 b: D(HFO/LFO/DO) M9.47BD40(LHV: 38,459 MJ/t) (GFI: 58.07 gCO_2/MJ) (blend with E- Methanol GFI 17.1)

Year	Target GFI (Base / Direct) (gCO_2/MJ)	Balance (t CO_2)	SUs / Deficits (t CO_2)	Net Outcome (Cost / Revenue)	T1 RU Cost	T2 RU Cost
2028	89.568 / 77.439	4,952.92	SUs Generated: 4,952.922	$1,882,110.49 Revenue	$0.00	$0.00
2029	87.702 / 75.573	4,475.76	SUs Generated: 4,475.760	$1,700,788.89 Revenue	$0.00	$0.00
2030	85.836 / 73.707	3,998.60	SUs Generated: 3,998.598	$1,519,467.28 Revenue	$0.00	$0.00
2031	81.731 / 69.602	2,948.84	SUs Generated: 2,948.841	$1,120,559.75 Revenue	$0.00	$0.00
2032	77.626 / 65.497	1,899.09	SUs Generated: 1,899.085	$721,652.22 Revenue	$0.00	$0.00
2033	73.520 / 61.391	849.328	SUs Generated: 849.328	$322,744.68 Revenue	$0.00	$0.00
2034	69.415 / 57.286	-200.429	Deficit: 200.429 (T1)	$20,042.85 Cost	$20,042.85	$0.00
2035	65.310 / 53.181	-1,250.19	Deficit: 1,250.185 (T1)	$125,018.52 Cost	$125,018.52	$0.00

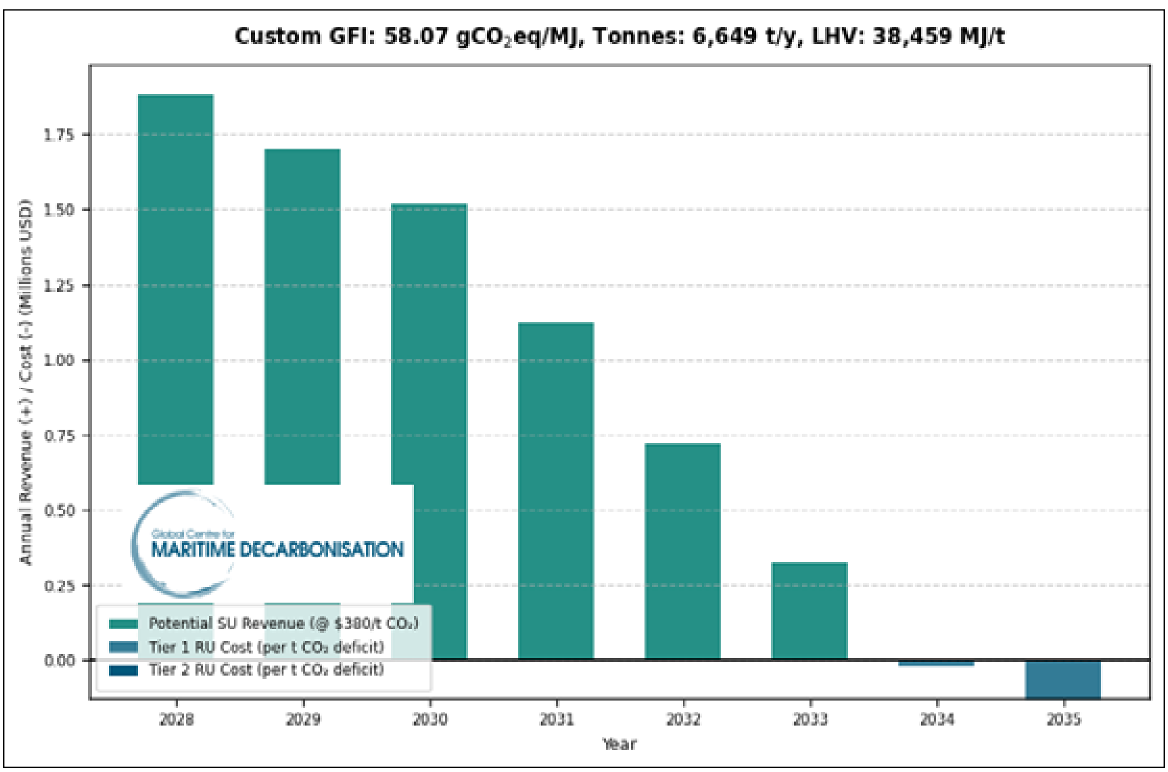


Figure 29: Result Plot Case 8: D(HFO/LFO/DO) M9.47BD50 (LHV: 38,459 MJ/t) (GFI: 58.07 gCO_2/MJ) (i.e. D(HFO/LFO/DO)-Methanol-Biodiesel blend)

Table 27: Case 8 c: D(HFO/LFO/DO) M9.47BD40(LHV: 39,058 MJ/t) (GFI: 57.45 gCO_2/MJ) (blend with E- Methanol GFI 4)

Year	Target GFI (Base / Direct) (gCO_2/MJ)	Balance (t CO_2)	SUs / Deficits (t CO_2)	Net Outcome (Cost / Revenue)	T1 RU Cost	T2 RU Cost
2028	89.568 / 77.439	5,191.08	SUs: 5,191.076 / 0.000	$1,972,608.95 (Revenue)	$519,107.60	$1,453,501.35
2029	87.702 / 75.573	4,706.48	SUs: 4,706.482 / 0.000	$1,788,463.25 (Revenue)	$470,648.20	$1,317,815.05
2030	85.836 / 73.707	4,221.89	SUs: 4,221.888 / 0.000	$1,604,317.56 (Revenue)	$422,188.80	$1,182,128.76
2031	81.731 / 69.602	3,155.78	SUs: 3,155.782 / 0.000	$1,199,197.03 (Revenue)	$315,578.20	$883,618.83
2032	77.626 / 65.497	2,089.68	SUs: 2,089.675 / 0.000	$794,076.50 (Revenue)	$208,967.50	$585,109.00
2033	73.520 / 61.391	1,023.57	SUs: 1,023.568 / 0.000	$388,955.97 (Revenue)	$102,356.80	$286,599.17
2034	69.415 / 57.286	−42.538	Deficits: 42.538 / 0.000	$4,253.83 (Cost)	$4,253.83	$0.00
2035	65.310 / 53.181	−1,108.645	Deficits: 1,108.645 / 0.000	$110,864.50 (Cost)	$110,864.50	$0.00

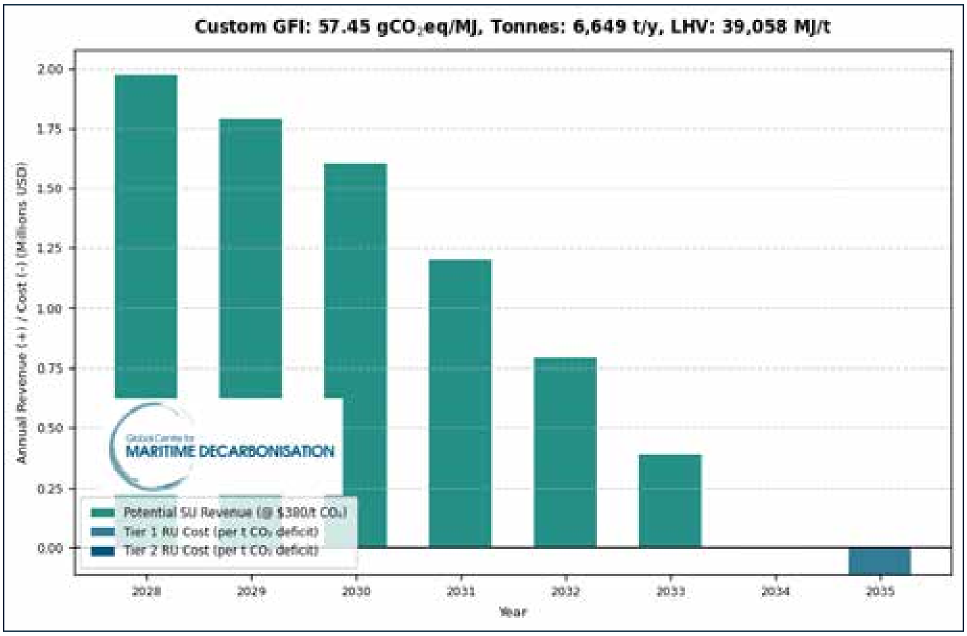


Figure 30: Result Plot for Case 8 c: D(HFO/LFO/DO) M9.47BD40(LHV: 39,058 MJ/t) (GFI: 57.45 gCO_2/MJ) (blend with E- Methanol GFI 4)(i.e. D(HFO/LFO/DO)-E Methanol-Biodiesel blend)

Table 28: Case 9 a: D(HFO/LFO/DO) M9.47BD50(LHV: 38,036 MJ/t) (GFI: 50.29 gCO₂/MJ) (blend with E-Methanol)

Year	Target GFI (Base / Direct) (gCO_2/MJ)	Balance (t CO_2)	SUs / Deficits (T1 / T2) (t CO_2)	Net Outcome	T1 RU Cost	T2 RU Cost / Revenue
2028	89.568 / 77.439	6,866.019 t CO_2 (Surplus)	6,866.019 t / 0 t CO_2	$2,609,087.27 Revenue	$686,601.90	$0.00
2029	87.702 / 75.573	6,394.105 t CO_2 (Surplus)	6,394.105 t / 0 t CO_2	$2,429,759.97 Revenue	$639,410.50	$0.00
2030	85.836 / 73.707	5,922.191 t CO_2 (Surplus)	5,922.191 t / 0 t CO_2	$2,250,432.67 Revenue	$592,219.10	$0.00
2031	81.731 / 69.602	4,883.981 t CO_2 (Surplus)	4,883.981 t / 0 t CO_2	$1,855,912.61 Revenue	$488,398.10	$0.00
2032	77.626 / 65.497	3,845.770 t CO_2 (Surplus)	3,845.770 t / 0 t CO_2	$1,461,392.56 Revenue	$384,577.00	$0.00
2033	73.520 / 61.391	2,807.559 t CO_2 (Surplus)	2,807.559 t / 0 t CO_2	$1,066,872.50 Revenue	$280,755.90	$0.00
2034	69.415 / 57.286	1,769.349 t CO_2 (Surplus)	1,769.349 t / 0 t CO_2	$672,352.44 Revenue	$176,934.90	$0.00
2035	65.310 / 53.181	731.138 t CO_2 (Surplus)	731.138 t / 0 t CO_2	$277,832.38 Revenue	$73,113.80	$0.00

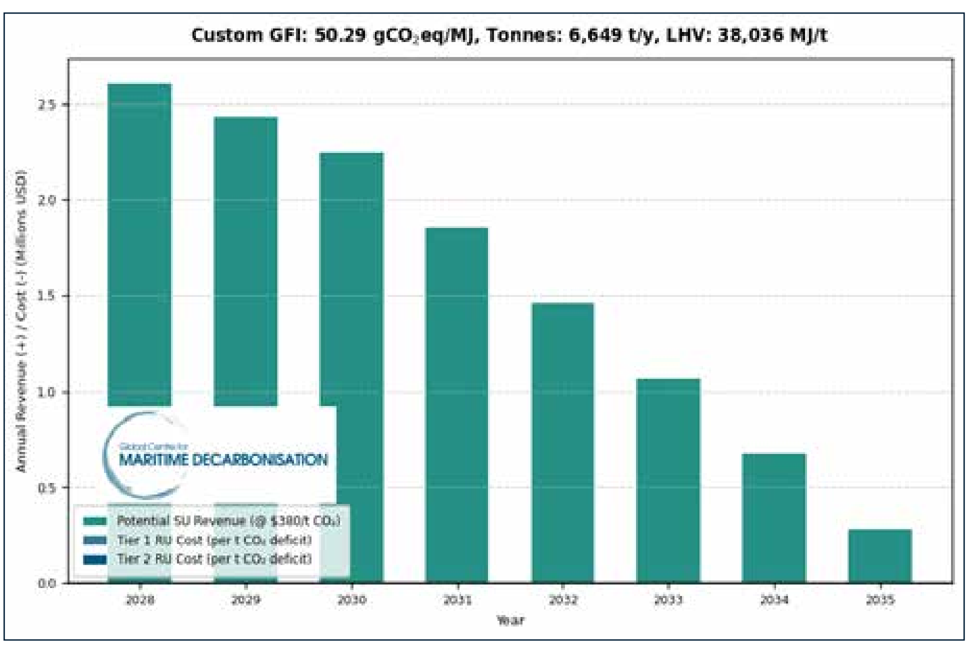


Figure 31: Result Plot for Case 8: D(HFO/LFO/DO) M9.47BD50 (LHV: 38,036 MJ/t) (GFI: 50.29 gCO₂/MJ) (i.e. D(HFO/LFO/DO)-E Methanol-Biodiesel blend)

Table 29: Case 9 b: D(HFO/LFO/DO) M9.47BD50 (LHV: 38,036 MJ/t)(GFI: 49.91 gCO_2/MJ) (blend with Bio Methanol)

Year	Target GFI (Base / Direct) (gCO_2/MJ)	Balance (t CO_2)	SUs Generated (t CO_2)	Net Outcome (Cost / Revenue)	T1 RU Cost	T2 RU Cost
2028	89.568 / 77.439	6,962.12	SUs Generated: 6,962.122	$2,645,606.23 (Revenue)	$0.00	$0.00
2029	87.702 / 75.573	6,490.21	SUs Generated: 6,490.208	$2,466,278.93 (Revenue)	$0.00	$0.00
2030	85.836 / 73.707	6,018.29	SUs Generated: 6,018.294	$2,286,951.63 (Revenue)	$0.00	$0.00
2031	81.731 / 69.602	4,980.08	SUs Generated: 4,980.083	$1,892,431.57 (Revenue)	$0.00	$0.00
2032	77.626 / 65.497	3,941.87	SUs Generated: 3,941.872	$1,497,911.51 (Revenue)	$0.00	$0.00
2033	73.520 / 61.391	2,903.66	SUs Generated: 2,903.662	$1,103,391.45 (Revenue)	$0.00	$0.00
2034	69.415 / 57.286	1,865.45	SUs Generated: 1,865.451	$708,871.40 (Revenue)	$0.00	$0.00
2035	65.310 / 53.181	827.24	SUs Generated: 827.240	$314,351.34 (Revenue)	$0.00	$0.00

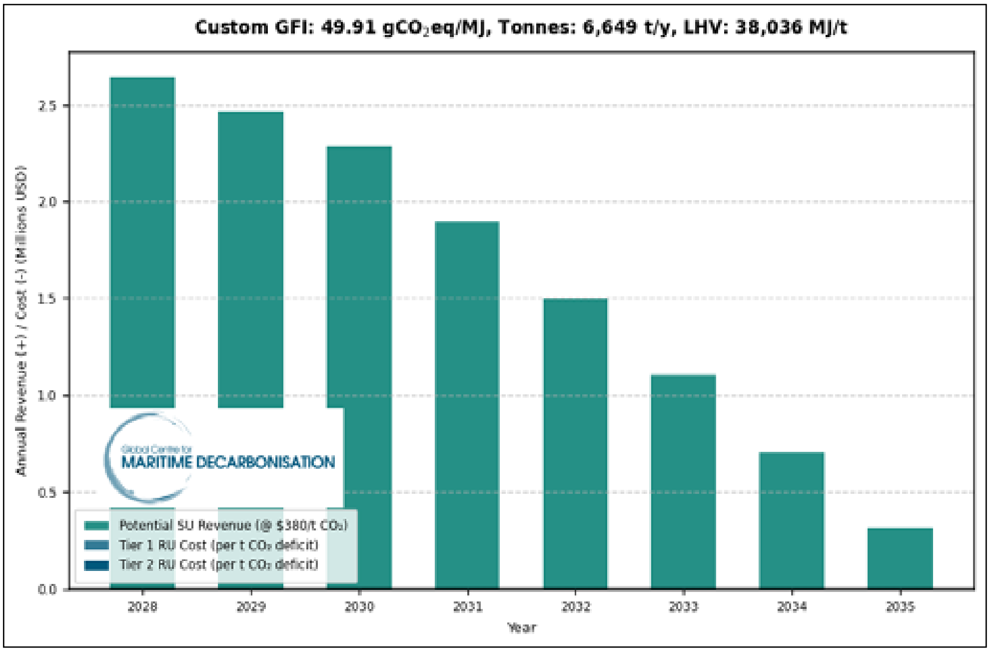


Figure 32: Result Plot for Case 9: D(HFO/LFO/DO) M9.47BD50 (LHV: 38,036 MJ/t) (GFI: 49.91 gCO_2/MJ) (i.e. D(HFO/LFO/DO)-Bio Methanol-Biodiesel blend)

Table 30: Case 10: D (HFO/LFO/DO) M4.8BD40(LHV: 39,322 MJ/t | GFI: 58.98 gCO_2/MJ) (blend with EMethanol)

Year	Target GFI (Base / Direct) (gCO_2/ MJ)	Balance (t CO_2)	Deficits / SUs (t CO_2)	Net Outcome (Cost / Revenue)	T1 RU Cost	T2 RU Cost
2028	89.568 / 77.439	4,826.14	SUs Generated: 4,826.142	$1,833,933.98 Revenue	$0.00	$0.00
2029	87.702 / 75.573	4,338.27	SUs Generated: 4,338.273	$1,648,543.61 Revenue	$0.00	$0.00
2030	85.836 / 73.707	3,850.40	SUs Generated: 3,850.403	$1,463,153.25 Revenue	$0.00	$0.00
2031	81.731 / 69.602	2,777.09	SUs Generated: 2,777.091	$1,055,294.44 Revenue	$0.00	$0.00
2032	77.626 / 65.497	1,703.78	SUs Generated: 1,703.778	$647,435.62 Revenue	$0.00	$0.00
2033	73.520 / 61.391	630.47	SUs Generated: 630.465	$239,576.81 Revenue	$0.00	$0.00
2034	69.415 / 57.286	-442.85	Deficit: 442.847 t / 0.000 t	$44,284.74 Cost	$44,284.74	$0.00
2035	65.310 / 53.181	-1,516.16	Deficit: 1,516.160 t / 0.000 t	$151,616.00 Cost	$151,616.00	$0.00

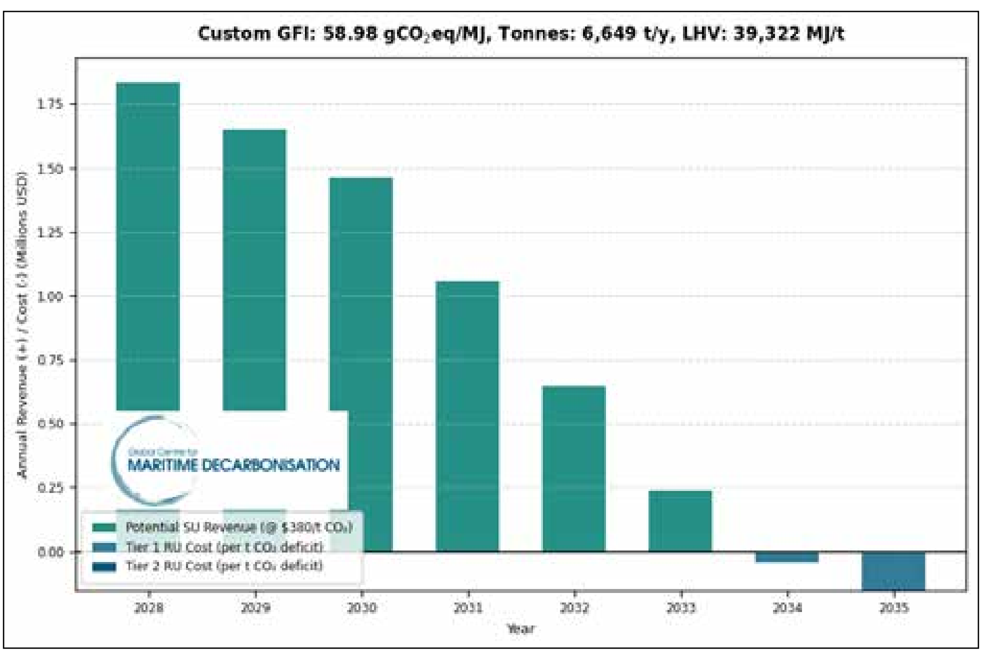


Figure 33: Result Plot for Case 10: D (HFO/LFO/DO) M4.8BD40(LHV: 39,322 MJ/t | GFI: 58.98 gCO_2/MJ) (i.e. D(HFO/LFO/DO)-E Methanol-Biodiesel blend)

Table 31: Case 11: D (HFO/LFO/DO) M4.8BD50 (LHV: 38,882 MJ/t) (GFI: 51.08 gCO_2/MJ)(blend with E Methanol)

Year	Target GFI (Base / Direct) (gCO_2/MJ)	Balance (t CO_2)	SUs Generated (t CO_2)	Net Outcome (Cost / Revenue)	T1 RU Cost	T2 RU Cost
2028	89.568 / 77.439	6,814.50	SUs Generated: 6,814.498	$2,589,509.18 (Revenue)	$0.00	$0.00
2029	87.702 / 75.573	6,332.09	SUs Generated: 6,332.088	$2,406,193.27 (Revenue)	$0.00	$0.00
2030	85.836 / 73.707	5,849.68	SUs Generated: 5,849.677	$2,222,877.36 (Revenue)	$0.00	$0.00
2031	81.731 / 69.602	4,788.38	SUs Generated: 4,788.375	$1,819,582.35 (Revenue)	$0.00	$0.00
2032	77.626 / 65.497	3,727.07	SUs Generated: 3,727.072	$1,416,287.34 (Revenue)	$0.00	$0.00
2033	73.520 / 61.391	2,665.77	SUs Generated: 2,665.769	$1,012,992.34 (Revenue)	$0.00	$0.00
2034	69.415 / 57.286	1,604.47	SUs Generated: 1,604.467	$609,697.33 (Revenue)	$0.00	$0.00
2035	65.310 / 53.181	543.164	SUs Generated: 543.164	$206,402.32 (Revenue)	$0.00	$0.00

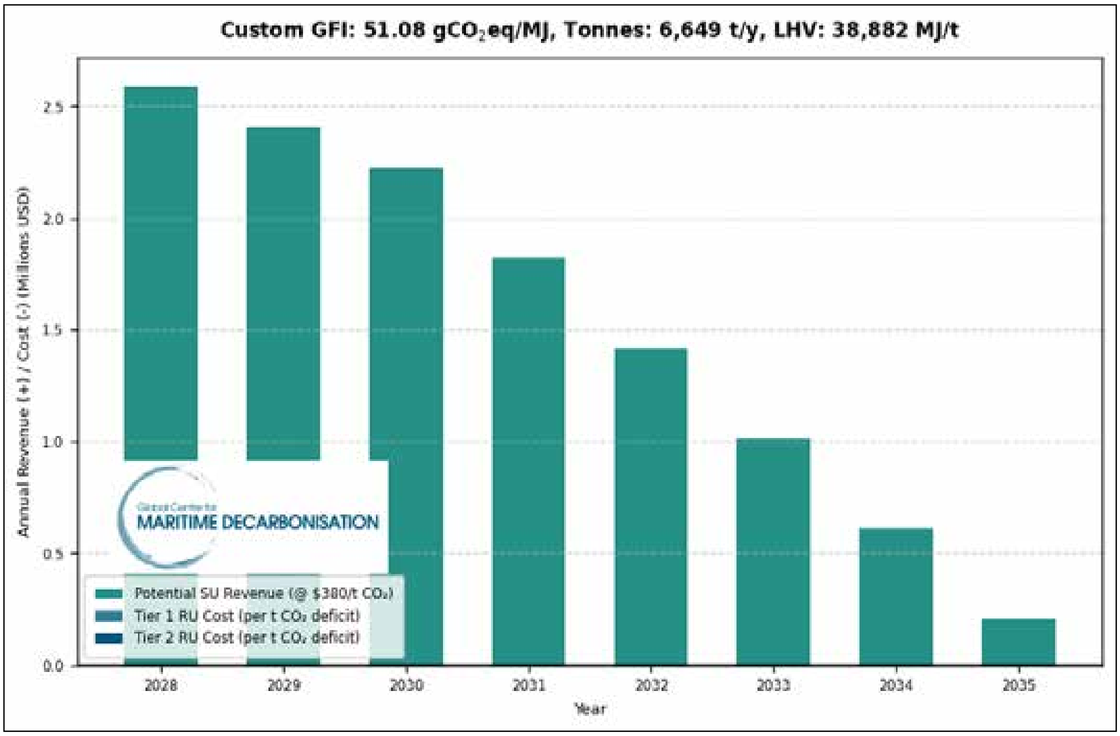


Figure 34: Result Plot for Case 11: D(HFO/LFO/DO) M4.8BD50 (LHV: 38,882 MJ/t) (GFI: 51.08 gCO_2/MJ) (i.e. D(HFO/LFO/DO)-E Methanol-Biodiesel blend)

Table 32: Case 12 a: D (HFO/LFO/DO) E10BD40 (LHV: 39,058 MJ/t) (GFI: 58.40 gCO_2/MJ)(blend with 2G-Ethanol of GFI 25)

Year	Target GFI (Base / Direct) (gCO_2/MJ)	Balance (t CO_2)	SUs / Deficits (t CO_2)	Net Outcome (Cost / Revenue)	T1 RU Cost	T2 RU Cost
2028	89.568 / 77.439	4,944.36	SUs Generated: 4,944.364	$1,878,858.46 Revenue	$0.00	$0.00
2029	87.702 / 75.573	4,459.77	SUs Generated: 4,459.770	$1,694,712.76 Revenue	$0.00	$0.00
2030	85.836 / 73.707	3,975.18	SUs Generated: 3,975.176	$1,510,567.07 Revenue	$0.00	$0.00
2031	81.731 / 69.602	2,909.07	SUs Generated: 2,909.070	$1,105,446.54 Revenue	$0.00	$0.00
2032	77.626 / 65.497	1,842.96	SUs Generated: 1,842.963	$700,326.01 Revenue	$0.00	$0.00
2033	73.520 / 61.391	776.857	SUs Generated: 776.857	$295,205.48 Revenue	$0.00	$0.00
2034	69.415 / 57.286	−289.250	Deficits: 289.250	$28,925.01 Cost	$28,925.01	$0.00
2035	65.310 / 53.181	−1,355.357	Deficits: 1,355.357	$135,535.68 Cost	$135,535.68	$0.00

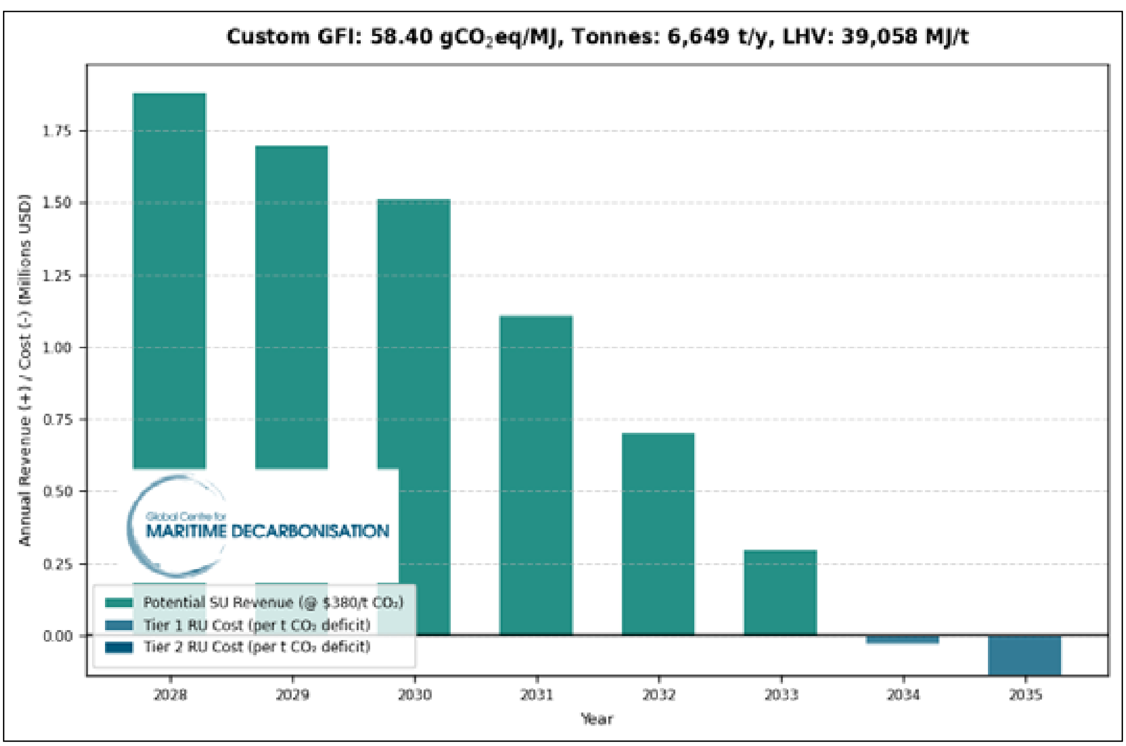


Figure 35: Result Plot for Case 12 a: : D(HFO/LFO/DO) E10BD40(LHV: 38,882 MJ/t) (GFI: 58.40 gCO_2/MJ) (i.e. D(HFO/LFO/DO)-2G Ethanol-Biodiesel blend)

Table 33: Case 12 b: D(HFO/LFO/DO) E10BD40 (LHV: 39,058 MJ/t) (GFI: 58.07 gCO_2/MJ)(blend wit 2G- Ethanol of GFI 17.73)

Year	Target GFI (Base / Direct) (gCO_2/MJ)	Balance (t CO_2)	SUs / Deficits (t CO_2)	Net Outcome (Cost / Revenue)	T1 RU Cost	T2 RU Cost
2028	89.568 / 77.439	5,030.06	SUs Generated: 5,030.064	$1,911,424.42 Revenue	$0.00	$0.00
2029	87.702 / 75.573	4,545.47	SUs Generated: 4,545.470	$1,727,278.72 Revenue	$0.00	$0.00
2030	85.836 / 73.707	4,060.88	SUs Generated: 4,060.876	$1,543,133.03 Revenue	$0.00	$0.00
2031	81.731 / 69.602	2,994.77	SUs Generated: 2,994.770	$1,138,012.50 Revenue	$0.00	$0.00
2032	77.626 / 65.497	1,928.66	SUs Generated: 1,928.663	$732,891.97 Revenue	$0.00	$0.00
2033	73.520 / 61.391	862.556	SUs Generated: 862.556	$327,771.44 Revenue	$0.00	$0.00
2034	69.415 / 57.286	−203.550	Deficit: 203.550	$20,355.02 Cost	$20,355.02	$0.00
2035	65.310 / 53.181	−1,269.657	Deficit: 1,269.657	$126,965.69 Cost	$126,965.69	$0.00

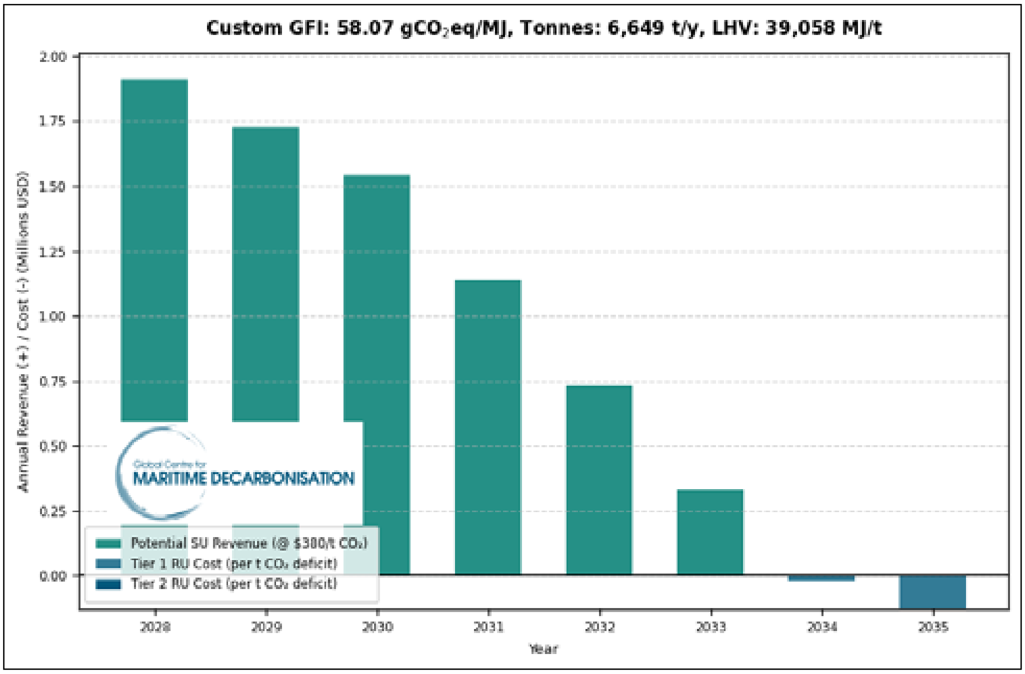


Figure 36: Result Plot for Case 12 b: D(HFO/LFO/DO) E10BD40(LHV: 38,882 MJ/t) (GFI: 58.07 gCO_2/MJ) (i.e. D(HFO/LFO/DO)-2G Ethanol-Biodiesel blend)

Overall Conclusions and Recommendations

- Reported literature based on detailed cost analysis for four ship categories (Large Ferries, General Cargo Ships, Bulk Carriers, and Container Ships) reveals that Bio-Methanol has the lowest Total Cost of Ownership (TCO). Among E-fuels, E-Methanol is closely competitive with E-DME and E-Ammonia, especially for bulk carriers and large ferries.
- The TERI-NCoEGPS study shows supply readiness for E Methanol and E Ammonia as significantly more feasible compared to Hydrogen, which currently lacks storage & transport technology, infrastructure and scalability. From a life cycle cost perspective, however blended oils remain the most cost-competitive solution across most vessel types.
- To comply with IMOs proposed GHG emission reduction targets (MEPC 83 presently applicable to vessels> 5000GT), Indian vessels must achieve a minimum 8% reduction in greenhouse gas (GHG) emissions under the Base scenario, and 21% reduction under the Direct compliance scenario by 2030. The emission targets would become increasingly stricter with a Base target of 30% reduction and Direct compliance reduction target upto 43 %.
- Under new framework, ships achieving emission targets are eligible to earn Surplus Units (SUs) which can be traded, saved, or cancelled. Tier-1 (Base compliance) shortfalls need to purchase Remedial Units (RUs) at \$100/tCO_2 whereas, Tier-2 (Direct compliance) shortfalls need to either pay \$380/tCO_2 or use Surplus Units (SUs). Interestingly, use of Zero or Near-Zero (ZNZ) fuels would now-on qualify for rewards from the IMO Net-Zero Fund. It implies that ships that use zero or near-zero (ZNZ) fuels having GFI below 19 g CO_2e/MJ before 2035 and 14 g CO_2e/MJ after 2035 are eligible for financial rewards. This will be reviewed every five years, and the corresponding compensation amounts will be updated based on future IMO guidelines.
- The definition of ZNZ fuels is awaited and the reward mechanism is yet to be developed and announced by IMO. Once the rewards are defined, the quantitative value of reward and the Surplus Unit (SU) collectively will attract the investments towards these ZNZ fuels and ships. There is a possibility of introducing differentiated reward mechanism by IMO based on type of ZNZ fuels and its LCA based WtW GFI values.
- Ramping up production of low carbon and ZNZ fuel as well as integration of new propulsion systems require high capex which needs additional National policy support in addition to the SU and rewards expected from IMO. It is required to have the adequate bankability to bridge the price gap along with long term certainty for ships to adopt/integrate alternative fuel-based systems.
- India needs to voice the concerns in order to ensure that IMO framework reflect common yet differentiated responsibilities and capacities of the developing countries.
- Global fuel adoption trends in vessel orderbooks shows LNG accounts for approximately 67%, Methanol at 17%, LPG at 8%, Ethane at 3%, Biodiesel, Hydrogen, and Ammonia make up the remaining 5%.

» Alternative low Carbon and ZNZ fuels are not only pivotal for avoiding 2 tier GHG emission cost in short to medium term but also in achieving net zero in shipping over long term.

» Although LCA guidelines have been adopted by IMO, nevertheless, unavailability of default WTW values of many of the Low C and ZNZ fuels poses a serious impediment in assessing true economics of alternative fuels. Thus, there is also a need for tracking of Technology Pathways for all Low Carbon, Bio and E fuels produced by fuel suppliers in India for realistic GFI Calculation of these Fuels to evaluate its' suitability for marine application and certification for domestic and global use. It is also recommended to develop WtW GFI calculation methodology for all scalable alternate fuel pathways in India.

» Use of most of the low carbon and alternative ZNZ fuels in ship necessitates dual-fuel ICE or Fuel Cell system integration in the ship. Presently there is a huge demand supply gap both for ICE and Fuel cell to cater the global need and these also require significant capital investments. Currently, Hydrogen and Ammonia-based engines are not fully commercially viable for large-scale marine applications, which limits their immediate adoption.

» Indian OGV data highlights a concentration of existing vessels in the 11-20 years age range, particularly in the 30k-50k GT category, reflecting the industry's reliance on mid-aged vessels for medium tonnage operations which is not suitable for expensive retrofitment and better to be operated with drop in/blend fuels

» **Given Global supply readiness as well as India's current limitations in ICE and Fuel Cell manufacturing capacity, dual-fuel and multi-fuel blends offer a practical, economical GFI compliance path at least until 2035 especially through Diesel-Biodiesel and Alcohol (Methanol and Ethanol). Methanol (10% V/V)-D(HFO/LFO/DO)-Biodiesel blends and 2G Ethanol (10% V/V)-D(HFO/LFO/DO)-Biodiesel blends are possible blend options. India can achieve the Base and Direct Compliance targets with dual and or multi-fuel blends which doesn't need change of existing engine and hence would be one of the most cost-effective options for existing vessels between 2028-2035.**

For D(HFO/LFO/DO)- Blend with Biodiesel (GFI 9.4)

- **B30 or BD30 (Attained GFI 68.44): Meet Direct Compliance till 2031, Biodiesel need 0.35 MT (2030)**
- **B40 or BD40 (Attained GFI 60.91): Meet Direct Compliance → generates SUs till 2033, Biodiesel need 0.47 MT (2030)**
- **B50 orBD50 (Attained GFI 51.86): Meet Direct Compliance → generates SUs till 2035, Biodiesel need: 0.58 MT (2030), Biodiesel need: 0.64 MT (2035)**

For Multifuel/Diesel-Biodiesel-Alcohol(Methanol/Ethanol) Blend

- **Only Biodiesel and Alcohols (Bio/E) (Methanol and Ethanol) are feasible for blending with D(HFO/LFO/DO), while Methanol is preferred over Ethanol. Due to lower GFI values achieved till date. LNG (E/Bio), Ammonia, Hydrogen not feasible for blending**
- **Alcohol being octane fuel, blending up to 10 v/v% feasible technically with minor adjustment in flash point**

- **Only D(HFO/LFO/DO)-10 v/v% Alcohol (Bio/E-Methanol/2G-Ethanol) blend-unable to meet GFI Compliance beyond 2028.**
- **10% (Bio/E) Methanol with B40- Meet Direct Compliance→ generates SUs till 2033 , Bio/E Methanol need 0.11MT**
- **10% 2G Ethanol with B40/BD40- Meet Direct Compliance→ generates SUs till 2033**
- **10% (Bio/E) Methanol and B50/BD50 –Meet Direct Compliance→ generates SUs till 2035, Methanol need 0.12 MT**
- **India should focus on scaling up alternative low Carbon and ZNZ fuels with lower GHG Fuel Intensity (GFI) to become global hub catering both domestic and global demand. Fuels like Biodiesel, Bio & E Methanol (immediate), Bio/E-Methane and E Ammonia (long term) will be having increasingly high global demand.**

» **Since Biodiesel required for B40 for direct compliance till 2035 might face feedstock supply issue, India should also start adopting E-Fuels with dual fuel engines in parallel for new built. For long term decarbonization options moving towards ZNZ fuels are inevitable with dual-fuel or alternate fuel engine. Dual-fuel combustion systems should be preferred for new builds or as retro fitment strategy for vessels <7 years to enable long-term regulatory compliance and avoid costly future upgrades.**

» **The stricter GFI regulations will necessitate higher % use of low C and ZNZ fuels beyond 2035.Unlike use as blend-fuel in existing engines up to 10 v/v %, Alcohol % is not a imitation when used in dual-fuel or alternative engines. For long-term decarbonisation, among fuel mix-options with engine change (> 5000GT OGV), the following seems most viable for India**

- **Methanol (E/Bio) with Dual Fuel Engine appears most preferred based on 8 sustainability parameters. India's E-Methanol need 0.73 MT by 2030, 1.31 MT by 2035F.**
- **LNG (only E/Bio-LNG/Bio-Methane) with Dual Fuel LNG Engine appears as 2nd best choice India's E-LNG /E/Bio- Methane demand 0.26 MT by 2030, 0.47 MT by 2035 bio/E LNG at present faces supply constraints.**
- **Ammonia with Dual Fuel Engine adoptions need to be slow paced as Ammonia engine supply readiness and safety and regulatory issues are major concern till 2035. India's E Ammonia need 0.72 MT by 2030, 1.40MT by 2035. Presently smaller pilots in experimental engines is underway. Recent report shows that there are ~ 40 ships which majorly are liquified petroleum gas (LPG)/Ammonia carriers and large bulk carriers. Although there is no carbon emission, highly toxic ammonia slip, NO_x and N_2O emission (a GHG gas 273 times stronger than CO2 over a 100-year lifetime) needs address prior to its' larger deployment.**

» **In comparison to E-Methanol and Bio/E-Methane, although E-Ammonia supply readiness would exceed the projected demand from 2030 onwards, India should start investing on Ammonia Engine Pilot testing for coastal ships rather than OGVs.**

- In case of dual-fuel engines, for Methanol the modifications are needed only in the injectors, cylinder heads, and the fuel delivery system and not inside the engine, while for Ammonia readiness the engines internals /combustion system itself need replacement. This makes Methanol engines presently more cost effective against Ammonia engines. Although commercial Hydrogen engines are presently being developed it still await few critical technical challenges to be fully overcome as mentioned later in this chapter. Towards long term decarbonization, India needs to initiate alternative fuel IC Engine manufacturing and alternatively developing strong strategic partnership with Global key players in ICE development.
- **Instead of targeting C-free operation, use of renewable/e-/green fuels with high efficiency over whole life cycle should be the focus for ship operation using Fuel Cell s. Towards zero emission, Fuel Cell should be considered as promising option for Inland water and shortsea/ coastal shipping. Direct Methanol Fuel Cell (DMFC) could be worth investing for India in very small vessel <100eKW (Inland water) category. However, as DMFC relies on Methanol which produces CO2 as a byproduct, this technology will be considered carbon neutral/green only when Methanol is sourced from greener means. Thus, while complete adoption of DMFC could be a medium to long term option, the LT-PEMFC could make the technology adoption immediate and completely green in short to medium term. India should also develop small to mid-sized (100-500ekW) LTMFC Fuel Cell ships (PSV, Ferries, RO-RO & Cargo) till storage and safety challenges of compressed or liquified hydrogen (LH2) as fuel persist. In long term once LH2 overcome the become viable technological and safety challenges, larger ships can be integrated too.**
- To avoid the challenge of Hydrogen storage at high pressure or cryogenic temperature on board, PEMFC with reforming technology using Biodiesel and/Methanol could be worth investing to especially >500 eKW. SOFC technology should leverage its high fuel flexibility especially Ammonia & Methanol. For cruise, and long-haul vessels, pilot projects need to be initiated with SOFC – Battery hybrid (immediate) and SOFC/ICE hybrid with alternative fuel options like Methanol and Ammonia (medium to long term) especially for auxiliary power units (AMUs).
- **There is a heightened need to increasingly implement CO2 capture on-board and switching over to Bio/ synthetic E-fuels from HFO with the advancement of alternate fuel engines. This could even lead to achieving negative emissions in the next generation of container fleets.**
- **There is an urgent need of larger number of Pilot demonstration of CCUS projects through valorisation of adsorbed CO2 especially for India with lack of geological CO2 storage sites along with innovation in sustainable CO2 adsorption material production.**
- **In order to facilitate early transition to ZNZ fuels, India urgently needs to develop standards for Hydrogen derived fuels Bio & E (Methanol, Ammonia, Methane) along with blend fuels, such as, dual-fuel (Alcohol-Diesel, Diesel-Biodiesel B30, B40 & B50) and mixed-fuels for Alcohol (Methanol/Ethanol), Diesel and Biodiesel for maritime application through BIS**
- As indicated in the consultative document on proposed National Green Shipping Policy (NGSP) it is high time to set regulatory GHG Emission limits with timeline and also enforce phase-wise GHG emission pricing, adoption of Low Carbon/ZNZ fuels and technologies.

» Additionally, India should invest in futuristic research and innovation to other alternative biofuels such as SVO, Biocrude, and Pyrolysis and Hydrothermal (HTL) bio-oil, where a lack of standardization still present barriers to their adoption although these technologies undoubtedly show present economic attractiveness globally and are in high Technology Readiness Level (TRL7-9). ASTM, EU, and ISO authorities carry the responsibility to clarify potential barriers to and timelines for developing and disseminating future alternative fuel quality standards. In concern with path dependence, fuels already standardized and those poised for quick standardization like Biodiesel and Methanol have started showing initial advantages in global markets.

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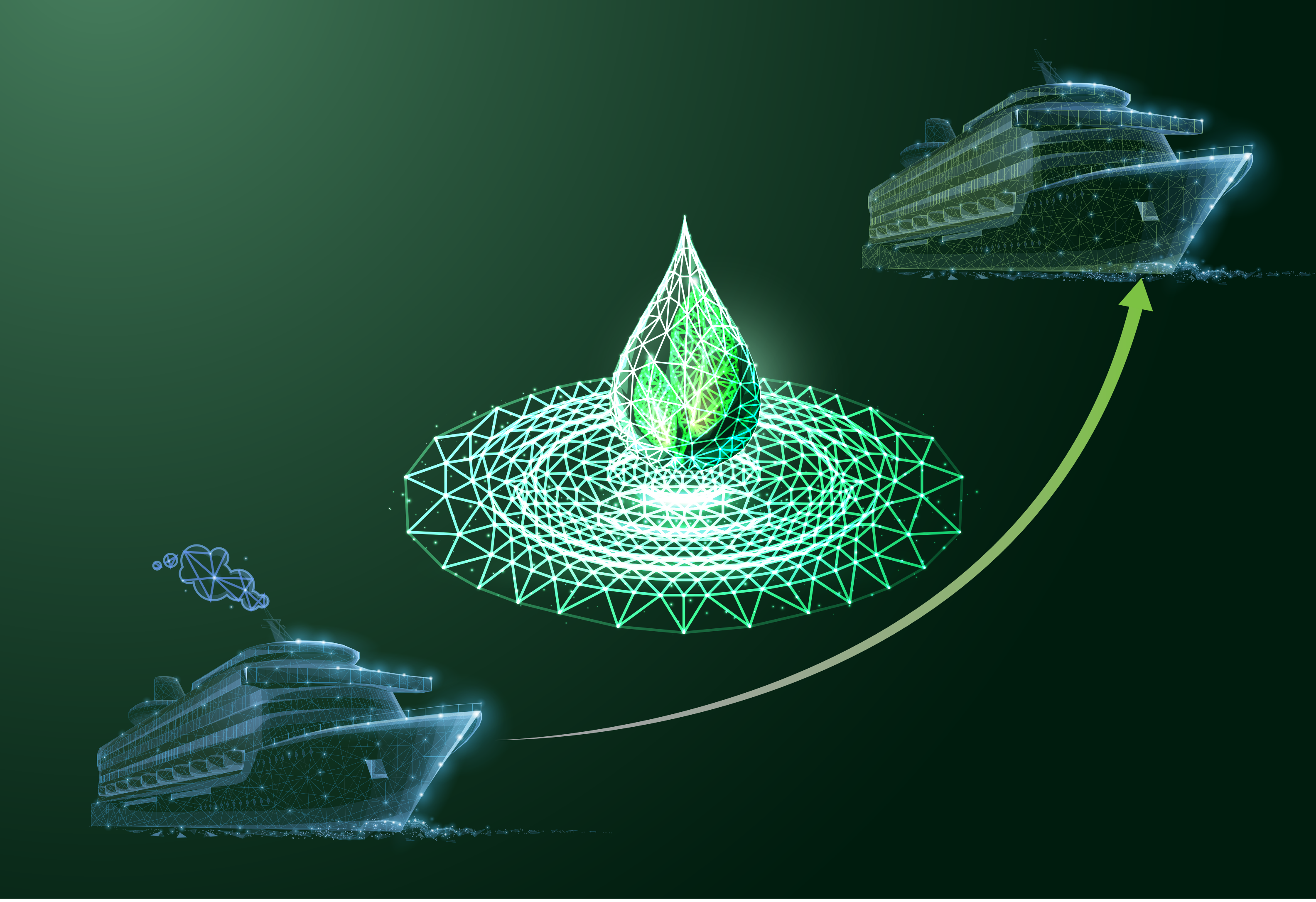


Chapter 1

Statistics: Global and Indian Vessels and Fuel Consumption

Introduction

This section presents the Indian and Global vessel statistics covering all types of vessels along with transition trend of alternative fuels vessels including green/sustainable fuels (Bio & E-fuels) in shipping across ship types and gross tonnage (GT).

It is worth mentioning that all ships < 5000 GT are considered under coastal ship category while those >5000GT are marked as Ocean-Going Vessels (OGVs) or Vessels in International water. This is interesting to observe that non-withstanding the earlier trends of alternate green fuel adoption exclusively in large category vessels i.e. OGVs, the present transition of alternative green fuels is across all ship types including large, medium and small sized vessels including inland water and coastal fleets.

Among all alternative fuels there is a recognizable trend towards LNG (although fossil based) and Methanol adoption followed by Biofuels (majorly Biodiesel) close contenders in IC engines (ICE). Hydrogen and Ammonia are largely seen transitioning into smaller inland water vessels and Fuel Cell powered ships respectively.

Methodology

All Data are collected from peer reviewed International and National research publications, reports in addition to Governmental, Industrial and Institutional websites. A large volume of Inland water, Coastal and Ocean-Going Vessel (OGV) data are accessed from Clarkson's database (subscribed in 2024). All the collected data are analyzed and used for making the present roadmap paper.

Regarding Clarkson's Research database, a total number of 112,479 vessels data is accessed for this study. This includes ocean-going vessels (OGVs) > 5000 GT, coastal vessels < 5000 GT, and inland waterway vessels, powered by both conventional and alternative fuels.

Globally (excluding India), the total number of OGVs and coastal vessels are found as 107,531. After filtering out abandoned, commissioned, damaged/not in-service, detained, idle, laid-up, under repair, in-storage, and hijacked vessels; around 100,708 in-service vessel data are used for final analysis. Among these vessels data, 66,244 belong to coastal vessels and 34,464 to OGVs.

Regarding Indian fleets, Clarkson's Research database indicates a cumulative 2,171 number for coastal vessels and OGVs. After focusing only on in-service vessels, 2,008 vessel data are selected for analysis which comprises of 1,558 coastal vessels and 450 OGVs.

In terms of alternative fuels and battery/hybrid systems, 1447 in-service vessels are finally identified. This includes vessels powered by alternative fuels (such as Ammonia, Methanol, Hydrogen, LPG, LNG, Biofuels, etc.), which have been the main focus for the analysis. **Similarly, for the orderbook status, 1477 vessels are collected.** Among the alternative fuels, the main power types include combinations like Fuel Cell & Diesel, Diesel Electric, Batteries & Diesel, Battery Propulsion, Fuel Cell & Battery, and hybrid systems with Batteries, Diesel & Fuel Cell.

1.1 Coastal Vessel Statistics

1.1.1 Vessels Details (Indian Coastal)

Figure 1.1 presents the age distribution of Indian coastal vessels across various gross tonnage (GT). It is observed that the majority of coastal vessels fall within the 0-500 GT category, totaling 748 vessels, followed by 515 vessels in the 1000-2000 GT category. The number of vessels decreases as GT increases, with the 4000-5000 GT category having the fewest vessels around 20. Among 0-10 years, i.e. newer vessels there are 181 in the 0-500 GT category and 65 in the 1000-2000 GT category, but none in the 4000-5000 GT category. 11–20-year age group is notably large in the 1000-2000 GT category with 332 vessels and substantial in the 0-500 GT with 195 vessels and 2000-3000 GT with 55 vessels. 21–30-year age group is more evenly distributed, with 170 vessels in the 0-500 GT and 80 in the 1000-2000 GT categories. 31-40 years and above, i.e. older vessels predominantly fall in the smaller GT categories, with the 0-500 GT category maintaining the highest numbers. **This pattern in Indian coastal vessels suggests a higher turnover rate smaller vessel, indicating the potential need for fleet renewal, especially among smaller vessels, to sustain operational efficiency and safety standards**.

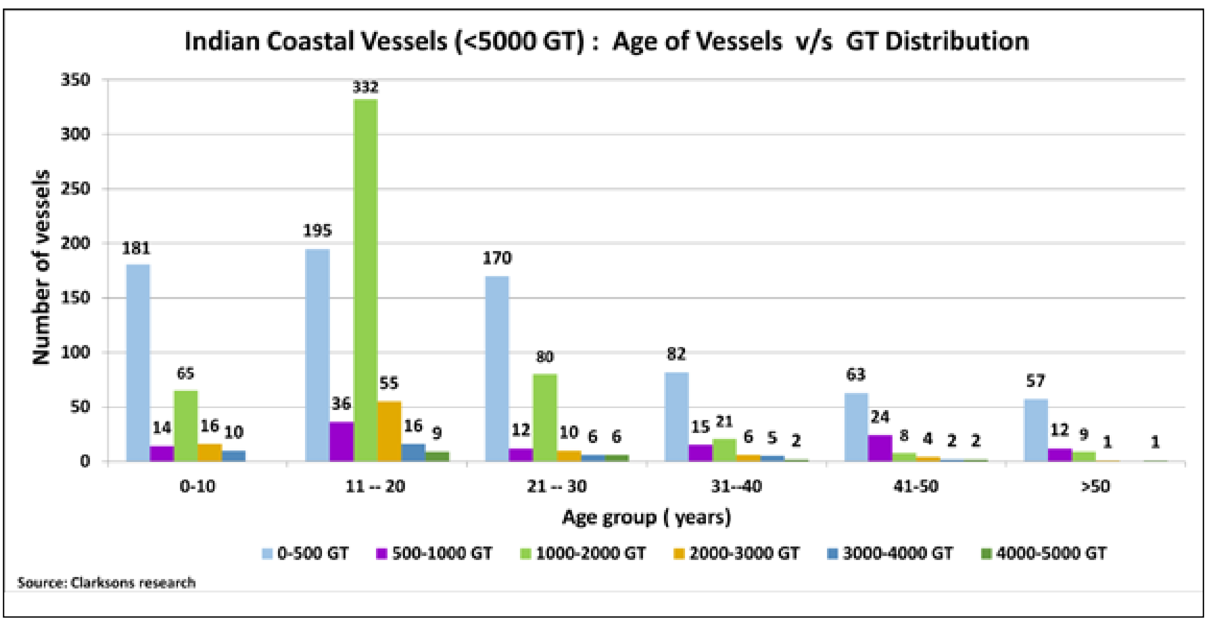


Figure 1.1: Indian Coastal Vessels (< 5000GT): Age Of vessels v/s Gross Tonnage wise Distribution

Figure 1.2 summarizes the total number of coastal vessels across different gross tonnage (GT) categories. The majority of the vessels fall within the 0-500 GT category, with a total of 748 vessels. This category significantly outnumbers the others, indicating a higher prevalence of smaller vessels in the Coastal fleet. The 1000-2000 GT category follows with 515 vessels, showing a substantial presence of moderate sized vessels. The 500-1000 GT category contains 113 vessels, while the 2000-3000 GT category has 92 vessels. The number of vessels continues to decrease with increasing GT, with the 3000-4000 GT and 4000-5000 GT categories containing 39 and 20 vessels, respectively. This distribution reflects the dominance of smaller vessels in the fleet, with progressively fewer vessels in the higher GT categories.

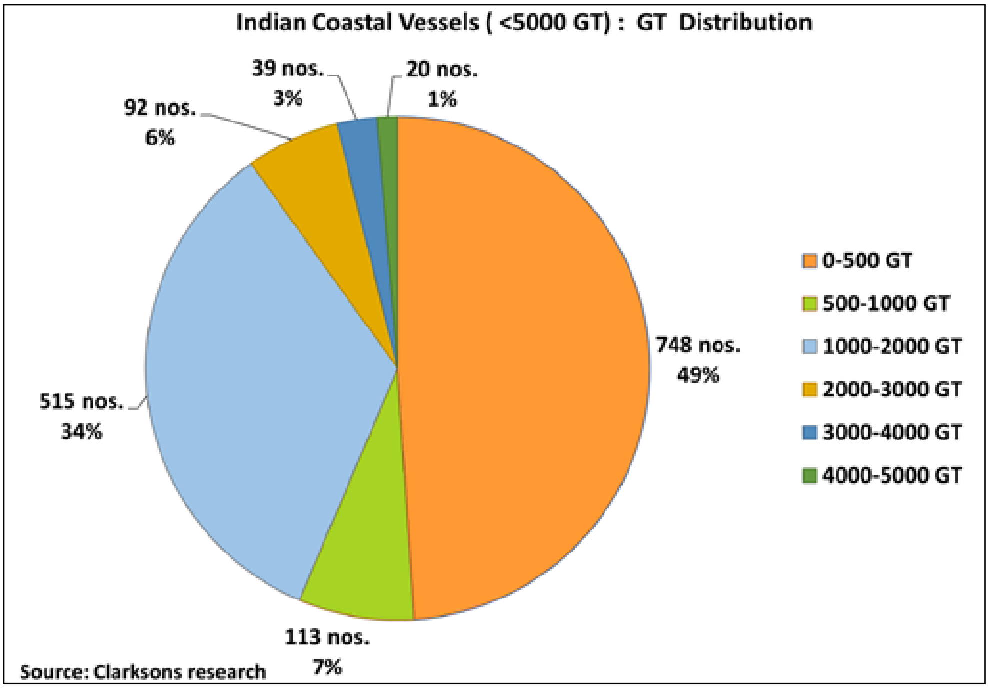


Figure 1.2: Indian Coastal Vessels (< 5000GT): Gross Tonnage wise Distribution

1.1.2 Vessel Details and Fuel Distribution (Global Coastal)

As per Clarkson Data (accessed on August 2024), total number of Global coastal vessels appears to be 72030 whereas in-service vessels are 67802**. Figure 1.3** offers a detailed snapshot of the distribution of vessels across different gross tonnage (GT) ranges and their corresponding fuel types. Each column represents a distinct fuel type or combination whereas, each color delineates a specific GT range, ranging from 0-500 to 4000-5000 GT. The total number of vessels under each category and GT range are mentioned inside each color bar.

It is worth noticing the presence of alternative and environmentally friendly fuels which are utilized across various GT ranges, albeit with varied frequencies. Biofuel (Majorly Biodiesel) shows nearly consistent usage across all GT categories, with a significant share of the 0-500 and 1000-2000 GT brackets. Hydrogen, on the other hand, is seen to be primarily employed among smaller vessels within the 0-500 GT range. Traditional marine fuels like Marine Diesel Oil (MDO) and Marine Gas Oil (MGO) also feature prominently, with usage spread across multiple GT ranges, majorly in vessels with GT ranging from 0-500 to 2000-3000. Ultra-Low Sulfur (ULS) variants of IFO, MDO, and MGO are utilized as well, especially in vessels within the same 0-500 to 2000-3000 GT range. Moreover, the data highlights the widespread adoption of Very Low Sulfur (VLS) fuels, including VLS MDO, Intermediate Fuel Oil (IFO), and VLS MGO. These fuels exhibit robust usage across all GT ranges, particularly prevalent in vessels ranging from 0-500 to 1000-2000 GT.

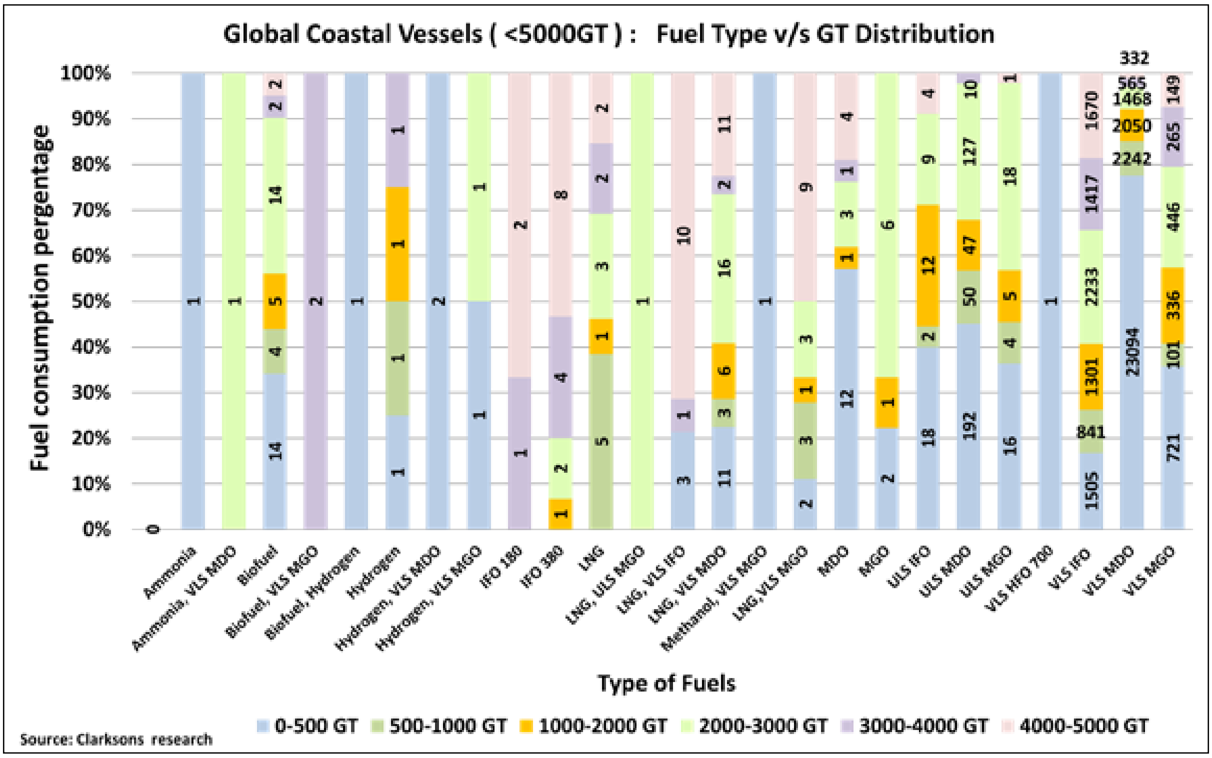


Figure 1.3: Global Coastal Vessels (<5000 GT): Fuel Type v/s GT Distribution with Number of Vessels

Overall, the data underscores a diversified fuel landscape within the maritime industry, reflecting a blend of conventional and alternative fuel choices. The distribution of vessels across different GT ranges, coupled with the corresponding fuel preferences, provides insights into the evolving dynamics of fuel usage within the maritime sector. Additionally, traditional fuels are still prevalent but are often supplemented or replaced by low-sulfur and alternative fuel options to meet environmental regulations and sustainability goals. Summing up the following trend is observed w.r.to conventional and alternate fuel use in global coastal vessels today.

Conventional Fuel Use

» VLS MDO: 29751 Vessels (majority 0-500 GT)

» VLS IFO: 8967 Vessels (majority 2000-300 GT)

» VLS MGO: 2018 Vessels (majority 0-500GT)

Alternative Fuel Use

» LNG & Dual Fuel: 95 Vessels

» Biofuel & Dual Fuel: 44 Vessels

» Hydrogen and Dual Fuel: 9 Vessels

Figure 1.4 shows a comprehensive breakdown of the age distribution of vessels against gross tonnage (GT) ranges. Each of the columns here represents a specific GT range, while each cluster of columns delineates the age range of the vessels, ranging from 0-10 years to over 100 years. The total number of vessels under each GT category and age group are mentioned at the top of each column.

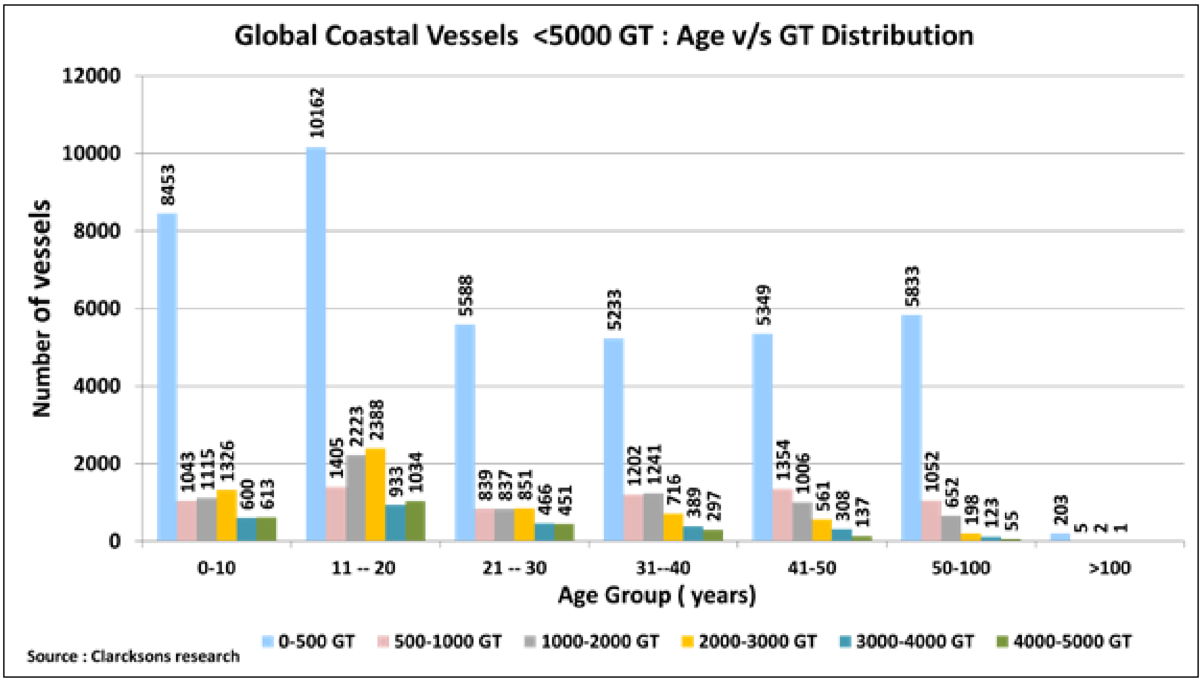


Figure 1.4: Global Coastal Vessels (<5000 GT) : Age v/s GT Distribution with Number

This data indicates a clear correlation between vessel age and GT range. **There's a higher concentration of younger vessels in the lower GT categories, particularly within the 0-10- and 11-20-year age bracket**. For instance, within the 0-500 GT range, there is a substantial number of vessels aged 0-10 years. Similarly, in the higher GT ranges, such as 4000-5000 GT, there are fewer vessels aged 0-10 years compared to the lower GT categories, with a notable increase in vessels aged 11-20 years and older

Figure 1.5 presents an overview of the distribution of vessels among gross tonnage (GT) ranges. Across various segments, from 0-500 GT to 4000-5000 GT, distinct numbers of vessels are observed, reflecting the diverse composition of fleets within the coastal vessels. It is observed that 0-500 GT range stands out with the highest total number of vessels, totaling 40,821, indicating a significant presence of smaller vessels. Such insights into the distribution of vessels by GT range provide valuable context for understanding the scale and composition of maritime fleets, aiding in strategic decision-making and industry analysis for future transition to green fuels through dual fuel/ retrofitting.

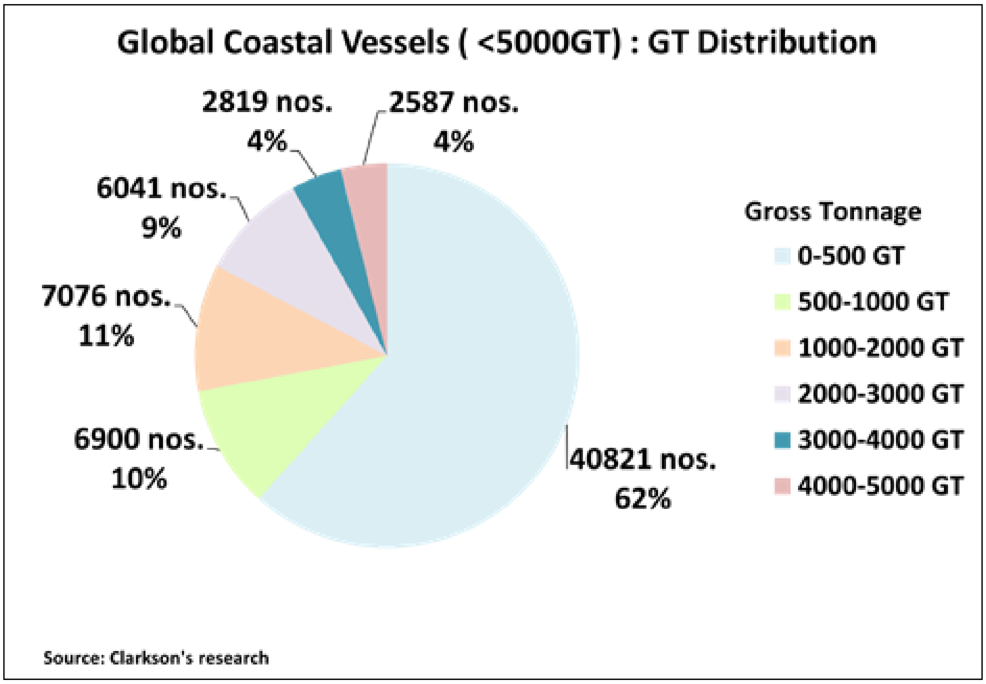


Figure 1.5: Global Coastal Vessels (<5000 GT): GT Distribution

1.2 Ocean Going Vessels OGV's Statistics

1.2.1 Vessel Details and Fuel Consumption (Indian OGVs)

Figure 1.6 represents distinct distribution pattern of ocean going vessel ages across various gross tonnage (GT) categories, underscoring trends in fleet composition and operational practices.

Newer vessels, aged 0-10 years, are significantly present across all GT categories, particularly in the 5k-10k GT range, suggesting a steady influx of new vessels in smaller tonnage classes. The 11-20 years age range is the most populated, especially within the 30k-50k GT category, indicating a substantial number of mid-aged vessels in medium tonnage categories which likely reflect peak operational efficiency and common fleet ages in the industry. Vessels aged 21-30 years also show notable numbers across all GT categories, particularly in the 10k-30k GT and 50k-100k GT ranges, implying they are nearing the end of their typical operational lifespan but still actively used. Older vessels, aged 31-50 years, are much less prevalent, predominantly found in the lower GT ranges.

Overall, the data highlights a concentration of vessels in the 11-20 years age range, particularly in the 30k-50k GT category, reflecting the industry's reliance on mid-aged vessels for medium tonnage operations.

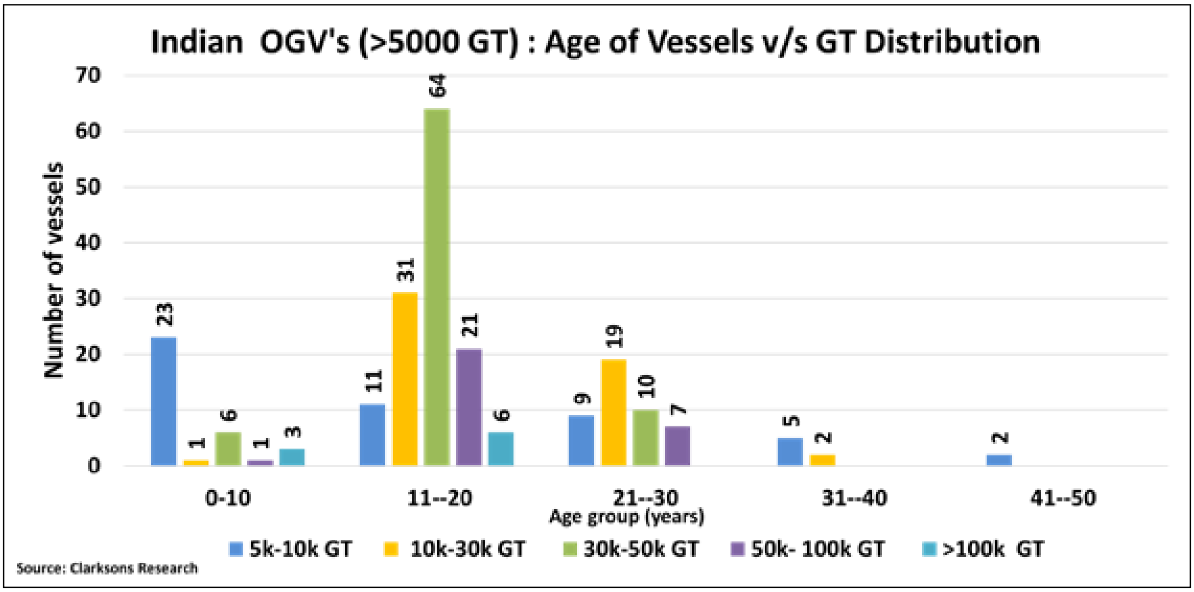


Figure 1.6: Indian Ocean-Going Vessel (>5000 GT): Age of Vessels v/s GT Distribution with Number

Figure 1.7 shows the gross tonnage (GT) versus the number of vessels for Indian Ocean-going vessels. This illustrates the present distribution of 520 vessels across various size categories within the Indian OGV category.

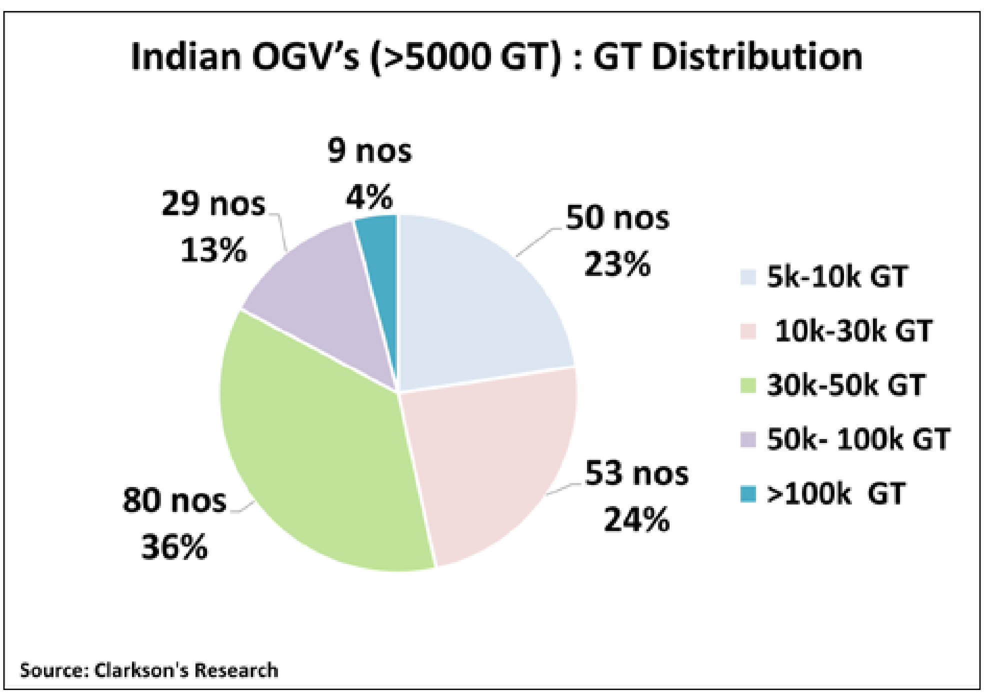


Figure 1.7: Indian Ocean-Going Vessels (>5000GT): GT Distribution

It shows that mid-sized vessels (30k-50k GT) dominate the fleet with 178 vessels, accounting for 34% of the total. This is followed by medium-sized vessels (10k-30k GT), which make up 119 vessels or 23%. Larger vessels (50k-100k GT) also have a significant presence, with 115 vessels representing 22% of the fleet. Smaller vessels (5k-10k GT) account for 80 vessels, or 16%, while the very large vessels (>100k GT) comprise 28 vessels, making up 5% of the total fleet. This distribution underscores the prominence of mid to medium-sized vessels among ocean going vessel category within the industry.

1.2.2 Vessel Details and Fuel Consumption (Global OGVs)

Figure 1.8 represents a comprehensive overview of fuel usage across various vessel sizes categorized by gross tonnage (GT) globally. **The analysis highlights that Very Low Sulfur Fuel Oil (VLS IFO) is the predominant fuel choice across all GT categories, indicating widespread industry compliance with sulfur regulations. For vessels in the 5k-10k GT range, VLS IFO is used in 5863 vessels, followed by significant counts for VLS MDO (345 vessels), VLS MGO (179 vessels), and vessels with unspecified fuel types (Blanks, 967 vessels).**

In the 10k-30k GT category, VLS IFO continues to lead with 9798 vessels, complemented by IFO 380 (919 vessels), LNG, VLS IFO (61 vessels), and Blanks (485 vessels). This trend persists in the 30k-50k GT range, with 7417 vessels using VLS IFO, followed by IFO 380 (1173 vessels), LNG, VLS IFO (16 vessels), and Blanks (96 vessels). The 50k-100k GT category similarly shows VLS IFO as the dominant fuel with 3542 vessels, alongside IFO 380 (1620 vessels), LNG, VLS IFO (157 vessels), and Blanks (141 vessels). For vessels over 100k GT, VLS IFO remains prevalent with 969 vessels, followed closely by IFO 380 (1587 vessels), LNG, VLS IFO (500 vessels).

Key observation indicates that while VLS IFO and IFO 380 are extensively used, reflecting cost-effectiveness and regulatory adherence, there is a growing inclination towards Liquefied Natural Gas (LNG), especially for larger vessels. However, fuels like Biofuel, Hydrogen, and Nuclear started showing usage, suggesting these are emerging or applications that may gain traction as technology advances and environmental regulations become stricter.

Figure 1.9 provides a detailed breakdown of the number of global Ocean-going vessels within various gross tonnage (GT) ranges along the age of the vessels. **In the 5k-10k GT category, the highest concentration of vessels is found in the 11-20 years age range with 3516 vessels, followed by 2071 vessels in the 0-10 years range and 1199 vessels in the 21-30 years range, summing up to a total of 7601 vessels. The 10k-30k GT category exhibits the highest vessel count in the 11-20 years range with 5000 vessels, followed by 3948 vessels in the 0-10 years range, totaling 11625 vessels**. For the 30k-50k GT range, there are 4384 vessels in the 11-20 years range and 3542 in the 0-10 years range, contributing to a total of 8884 vessels. The 50k-100k GT category shows significant numbers in the 11-20 years range (3173 vessels) and the 0-10 years range (1731 vessels), amounting to 5704 vessels in total. In the >100k GT category, the distribution is more even, with 1943 vessels in the 0-10 years range and 1116 in the 11-20 years range, culminating in a total of 3338 vessels.

This data represents that across all GT categories, the 11-20 years age range holds the largest number of vessels, followed by the 0-10-year-age range, suggesting a concentration of relatively newer vessels within these ranges. The higher counts in these younger age brackets might reflect the addition of newer vessels to the fleet or more frequent updates. Overall, the data

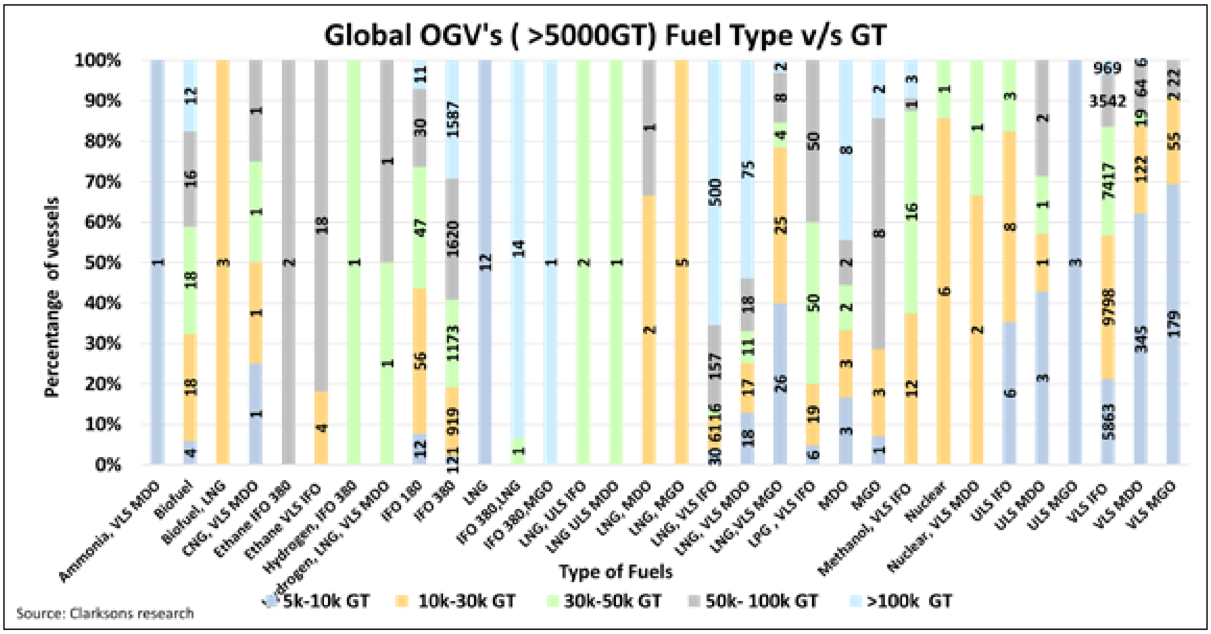


Figure 1.8: Global Ocean-Going Vessels(>5000GT): Fuel Type v/s GT with Number

showcases a significant distribution of vessels across these age ranges, providing insights into the age composition and modernization trends within the maritime fleet.

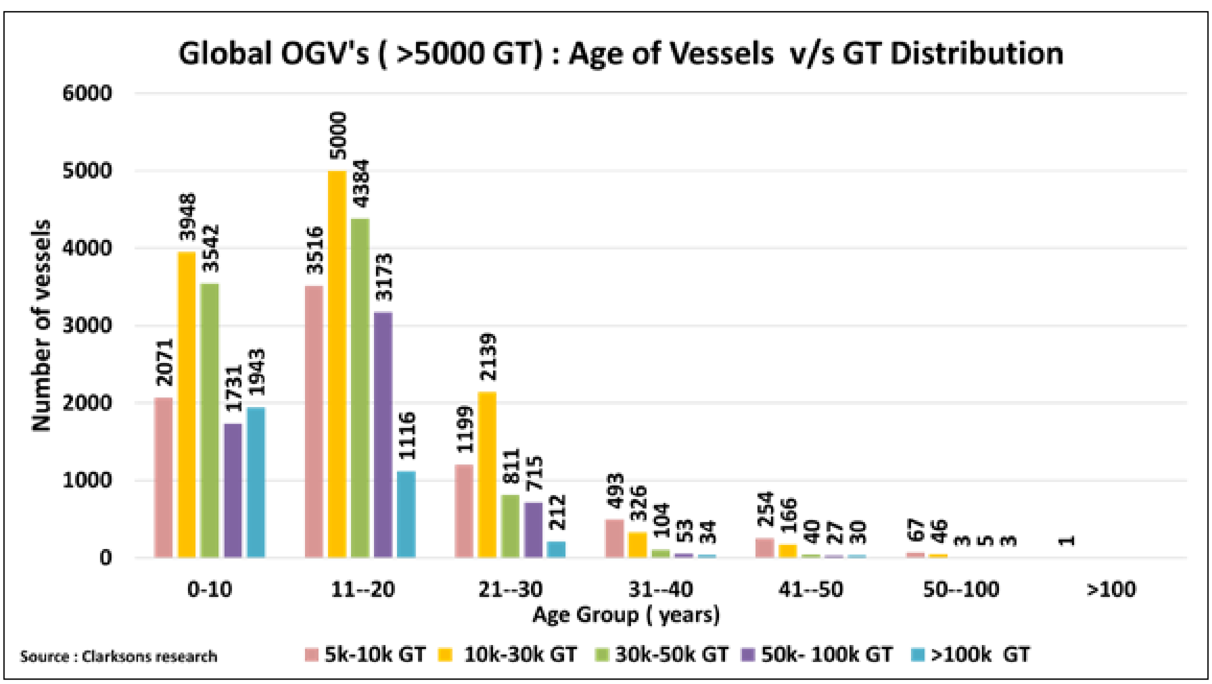


Figure 1.9: Global Ocean-Going Vessels(>5000 GT): Age of vessels v/s GT Distribution with Number

Figure 1.10 provides the snapshot of gross tonnage versus the number of vessel distribution with a total of 37,152 OGV vessels excluding the Indian data. **Medium-sized vessels in the 10k-30k GT category dominate, accounting for 11,625 vessels or 31% of the total fleet. This is followed by mid-sized vessels (30k-50k GT), which make up 8,884 vessels or 24%. Smaller vessels in the 5k-10k GT category comprise 7,601 vessels, representing 21% of the total**. Larger vessels (50k-100k GT) account for 5,704 vessels or 15%, while the very large vessels (>100k GT) number 3,338, making up 9% of the fleet. **This distribution highlights a significant presence of medium to mid-sized vessels, with smaller and larger vessels also playing substantial roles in the Global maritime industry.**

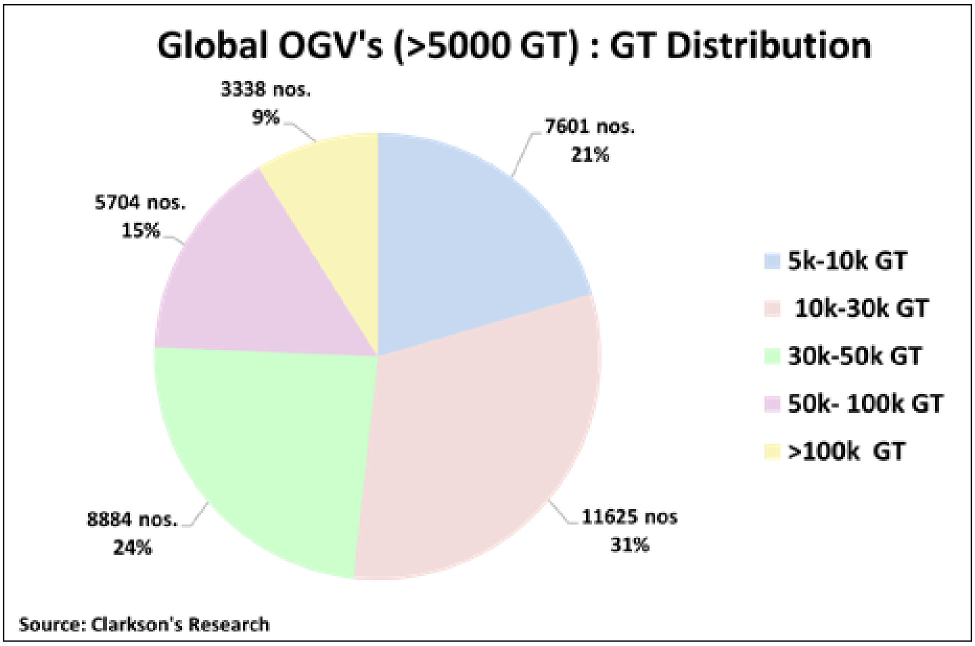


Figure 1.10: Global Ocean-Going Vessels (>5000GT): GT Distribution with Number

Top countries with total vessel ownerships are presented in **Figure 1.11** the chart of the top 25 countries by vessel ownership reveals that China P.R. leads significantly with 13,864 vessels, followed by Indonesia with 11,994 vessels and Japan with 8,731 vessels. Greece, the United States, and an unspecified category labeled "Unknown" also have substantial fleets, with 5,978, 4,890, and 4,066 vessels respectively. Mid-tier countries include Singapore (3,623 vessels), South Korea (3,061 vessels), and Turkey (2,986 vessels). European countries such as Russia, Norway, and Germany have significant maritime sectors, with vessel counts of 2,948, 2,773, and 2,643 respectively. The U.A.E. stands out in the Middle East with 2,608 vessels. Other notable countries are the Philippines (2,212 vessels) and Vietnam (2,151 vessels). Italy, Malaysia, the Netherlands, and Hong Kong contribute further with vessel counts ranging from 1,651 to 2,143. The list is rounded out by the United Kingdom, Taiwan, Denmark, Spain, and Canada, showcasing a diverse and widespread distribution of maritime ownership across Asia, Europe, and North America. This chart illustrates the global distribution of vessel ownership, with a clear dominance by Asian countries, followed by strong representations from Europe and North America, and highlights India's significant contribution with 2,179 vessels.

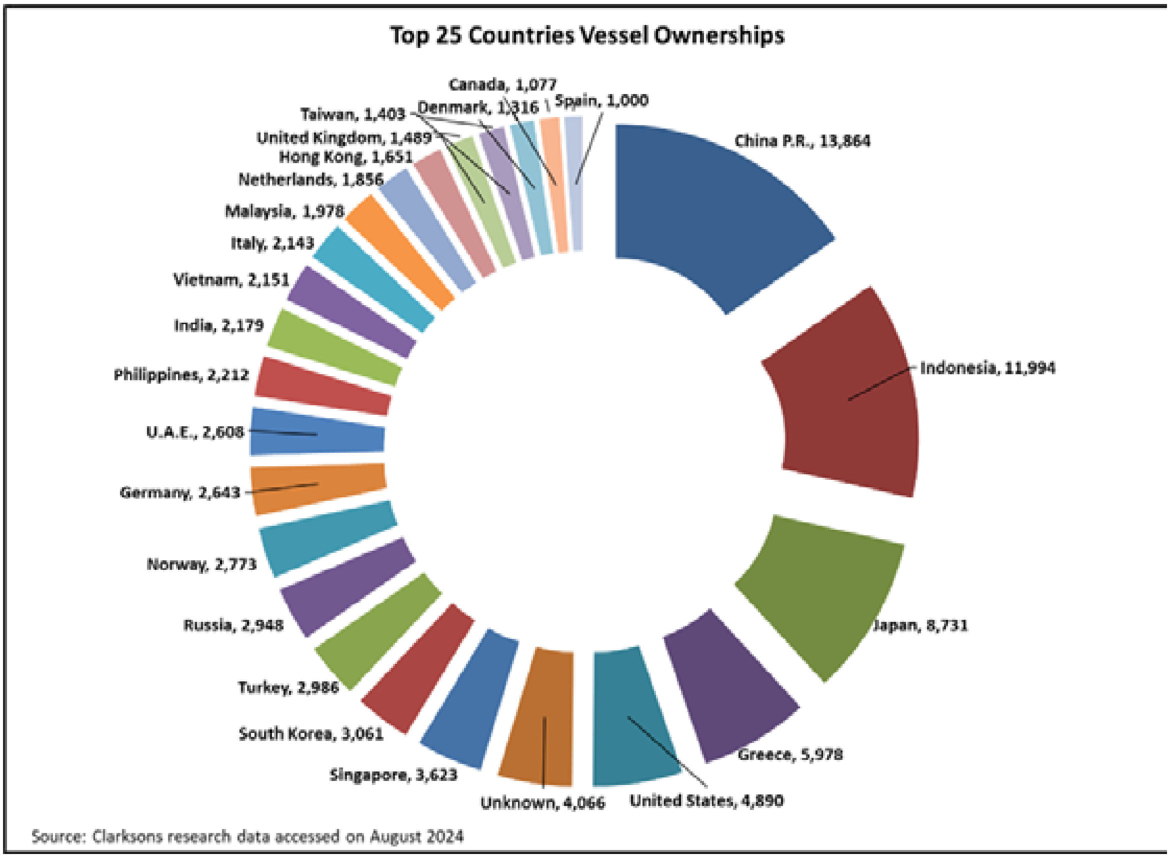
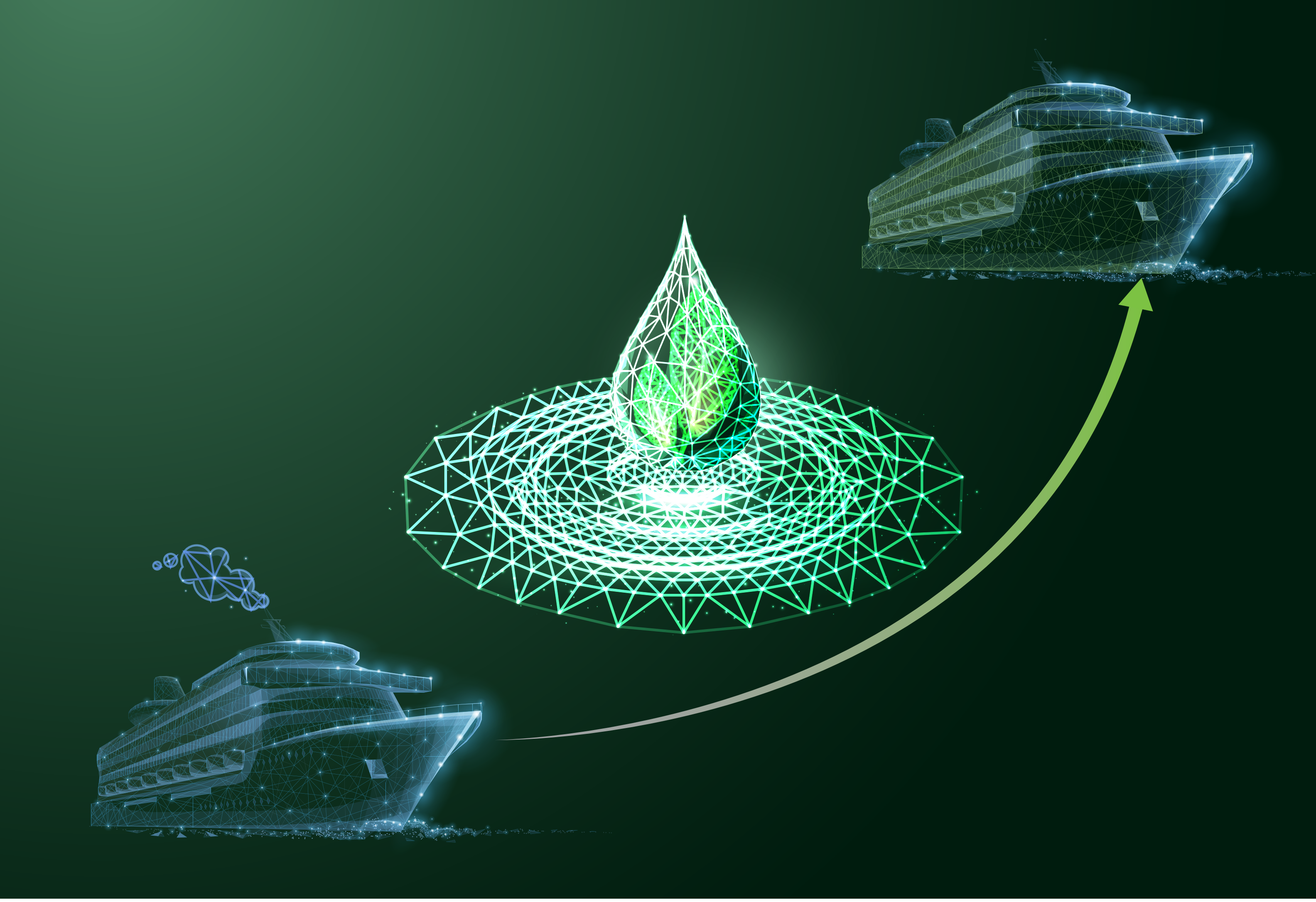


Figure 1.11: Top 25 Countries with Vessel Ownership



Chapter 2

Alternative Fuel Transition in Marine Vessels

Introduction

As the maritime industry speeding up its journey towards decarbonization, Alternative Fuels are becoming essential for meeting global climate targets. This chapter takes a closer look at the current state and trends in the use of alternative marine fuels, such as methanol, ethanol, ammonia, Hydrogen, LNG, and biodiesel. While around 98% of vessels still depend on traditional fuels, an increasing number of ships are now being fitted with alternative propulsion systems. This shift is largely driven by IMO regulations and the growing demand for sustainable operations. By examining data from both in-service vessels and those on order, this chapter sheds light on the adoption of various alternative fuels and explores the key factors—like technology readiness, port infrastructure, cost, safety, storage, and reductions in greenhouse gas emissions—that play a crucial role in fuel choice and long-term viability.

The alternative fuels considered here are Methanol, Ethanol, Ammonia, Hydrogen, Liquified Natural Gas (LNG), and Biodiesel. As seen from in-service data procured from Clarckson Research Database [1] in **Section 2.1** today **~98% of ships operate on conventional fuels, and only ~2% are on alternative fuels/propulsion systems. This 2% in turn comprises of number of propulsions using different alternative fuels such as, 1105 LNG, 125 Liquified Petroleum Gas (LPG), 123 Biofuel (primarily Biodiesel), 37 Methanol, 24 Ethane, 20 Hydrogen, 3 Ammonia and 10 nuclear vessels**. In addition, there are around **743 Battery/Hybrid based** vessels sailing globally.

Thus, among in-service vessels, only looking from green/ sustainable (Bio & e-fuel) alternative fuel options, Biofuel (mainly Biodiesel) based vessels dominate, with Methanol, Hydrogen, and Ammonia ranked next in descending order. Surprisingly, in the order-book data, Methanol is visibly emerging as the front-runner with 251 vessels followed by Biofuel with 24 vessels, Hydrogen with 23 vessels and Ammonia 22 vessels.

These data reflect two important things: (i) Globally ship owners are increasingly moving towards alternative fueled ships to meet the IMO regulations, and (ii) Each country focusing on its maritime sectors to lower greenhouse gas (GHG) emissions and eventually, net-zero emissions. The selection of alternative fuel is very crucial which is ultimately influenced by critical parameters such as (i) Technological issues, (ii) Infrastructure and bunkering readiness at port/ships, (iii) Cost-effectiveness (iv) Safety aspects (v) Storage capacity and last but not the least (vi) GHG emission reduction potential (Well to Wake) in the overall value chain.

2.1 Alternative Fuels Vessel Statistics (in-service and order-book)

The maritime industry is increasingly adopting alternative fuels to meet stringent environmental regulations and reduce greenhouse gas (GHG) emissions. The data available from Clarkson Research Services provides valuable insights into the landscape of both in-service alternative fueled vessels currently operational across the globe and those in orderbook. Through meticulous analysis of these data a perspective on the adoption and utilization trend of various alternative fuels in the maritime sector is obtained. These datasets also shed light on the diversity of propulsion technologies being employed to drive the industry towards a greener future using **8 alternative fuels mainly Biodiesel, Methanol, Ammonia, Hydrogen, Ethane, LNG and LPG and Nuclear.**

The global status of green fuels powered vessels currently in-service is shown in **Table 2.1. Figure 2.1 a represents** global share of all 8 selected alternative fuels whereas **Figure 2.1 b** represents only the global share of H_2 derived fuels

Table 2.1: Alternative Fuel Vessels (Global in-service as on August 2024)

S. No.	Alternative Fuel Type	Mono/ Dual fuel with	Number of vessels (%)	GT Range Min-Max	Dominated by GT Range
1	LPG	VLS IFO	125	5,494 - 54,696	50000-54000
2	LNG	ULS IFO, ULS MDO VLS IFO, VLS MDO, VLS MGO	1105	276 - 248,663	100000-200000
3	Biofuel (Biodiesel)	Hydrogen, LNG, VLS MGO	123	179 – 195636	1000-10000
4	Methanol	ULS MGO, VLS IFO, VLS MDO, VLS MGO	37	20- 172093	27000- 30000
5	Ethane	VLS IFO, IFO 380	24	27,546 – 61,272	60,611 – 61,272
6	Hydrogen	IFO 380, LNG, VLS IFO, VLS MDO, VLS MGO	20	50-55051	179 - 749
7	Nuclear	VLS MDO	10	20,646 - 38,226	20000-28000
8	Ammonia	LNG, VLS MGO,VLS MDO	3	272- 5073	272- 5073
Total number of alternative fuel vessels: 1447					

Ammonia **Hydrogen** **Methanol** **Ethane** **Biofuel** **LNG** **LPG** **Nuclear**

Methanol fuel adoption has also started happening for smaller vessels as low as 20 to 50 GT range. **Figure 2.1** shows among all the alternate fuels, liquefied natural gas (LNG) stands out as the most extensively researched option, constituting approximately **76% (1105 Nos)** of the total instances. Following closely behind is liquefied petroleum gas (LPG), representing around **9% (125 Nos)** of the total vessels. Biofuels (biodiesel) emerge as another prominent focus, comprising about **8% (123 Nos)** of the total vessels, while methanol constitutes approximately **3 % (37 Nos).** Ammonia, although less prevalent, remains a significant contender, making up about <1% (3 Nos) of the Vessells. Hydrogen and ethane hold smaller but noteworthy shares, with percentages of **1% (20 Nos)** and **2% (24 Nos)** respectively. Nuclear power, while less common, represents around **<1% (10 Nos)** of the total instances. These figures illustrate a diverse array of fuel types being explored in the maritime sector, with LNG leading the research landscape with 76% share for in-service vessel with Biofuel at a distant 8% share, interestingly among Hydrogen derived fuels Methanol leading with 62% share followed by Hydrogen with 33% share.

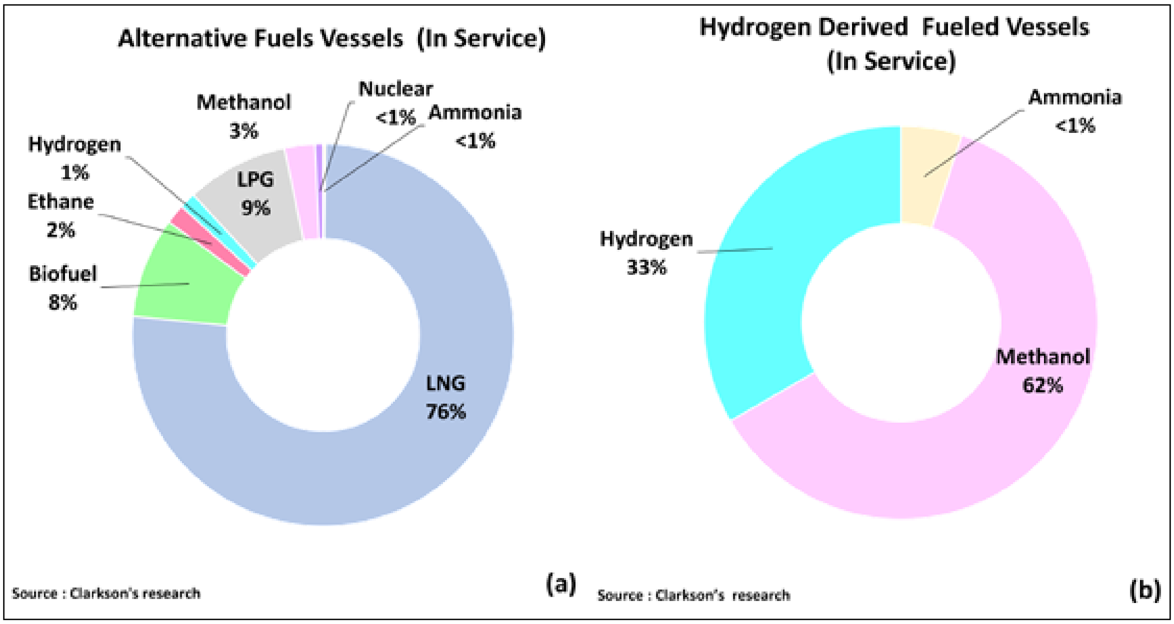


Figure 2.1: Alternative Fuel Vessels Global (In-Service): Fuel Types v/s Total Number of Vessel (as on August 2024) Number with Percentage (as on August 2024) Figure 2.2(a): Relative Share Of All Alternative Fuels Figure 2.1 (b): Relative Share of only Hydrogen Derived Fuels

Table 2.2: Alternative Fuel Vessels (Global Order Book as on August 2024)

S. No.	Alternative fuel type	Mono/ dual fuel with	Number of vessels	GT range Min-max	Dominated by GT Range
1.	Methanol	ULS MGO,ULS MDO, ULS IFO , IFO 380 , VLS IFO, VLS MDO, VLS MGO	251	300- 236000	>100000
2.	LPG	VLS IFO	114	6,249 - 55,460	50000-54000
3.	LNG	VLS IFO, VLS MGO	991	313 – 250,800	100000-200000
4.	Ethane	VLS IFO	45	18,965- 54,112	52100-54112
5.	Biofuel	Hydrogen, Methanol	24	179 - 20000	4000-7000
6.	Hydrogen	IFO , LNG, VLS MDO, VLS MGO	23	100- 72,800	3000-10000
7.	Ammonia	VLS IFO,VLS MDO	22	500 - 110,000	15000-27000
8.	Nuclear	VLS MDO	7	30000-68000	30000-33000
Total number of alternative fuel vessels: 1477					

Ammonia **Hydrogen** **Methanol** **Ethane** **Biofuel** **LNG** **LPG** **Nuclear**

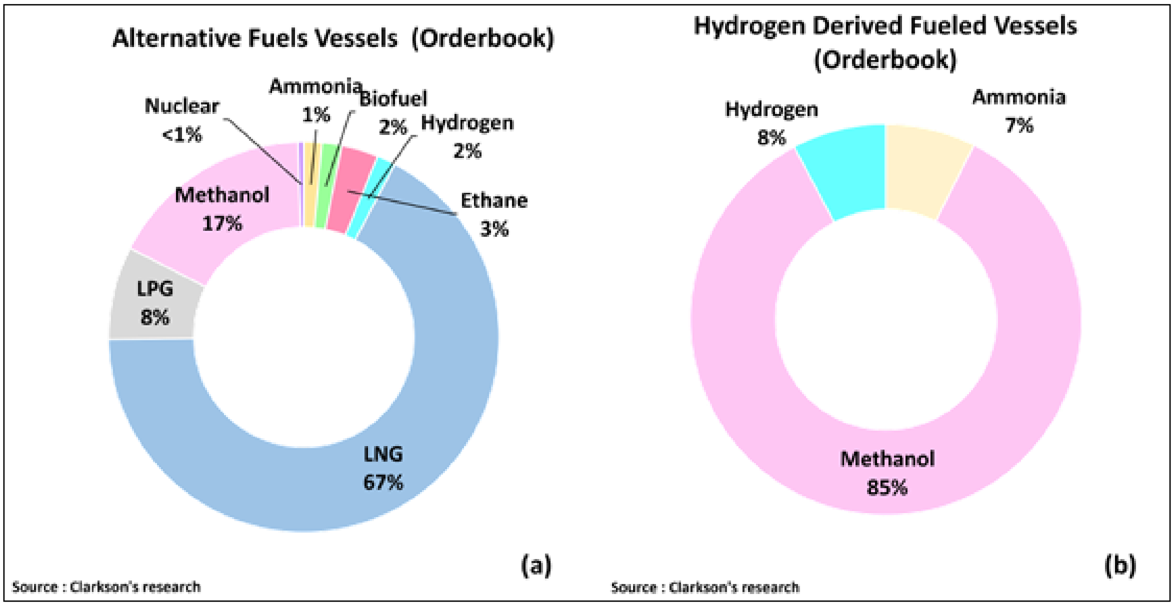


Figure 2.2: Alternative Fuel Vessels Global Order Book: Fuel Types v/s Total Vessel Number with Percentage (as on August 2024) Figure 2.2(a): Relative Share of All Alternative Fuels Figure 2.2 (b): Relative Share of only Hydrogen Derived Fuels

It is apparent from **Figure 2.2 (order book data)** that among all the alternative fuel considered, LNG still dominates with **991 vessels (67%)** followed by Methanol with **251** vessels ordered respectively, constituting **17%** of the total orders. Following closely, LPG accounts for **114 vessels (8%).** Ethane follows with **45 vessels (3%),** while Ammonia, Biofuel, and Hydrogen occupy smaller but significant shares, with **22 vessels (1%), 24 vessels (2%), and 23 vessels (2%)** respectively. Nuclear propulsion occupies a minor share of **7 vessels (<1%).** These figures illustrate a diverse array of fuel types being explored in the maritime sector, with LNG leading the research landscape with 76% share for in-service vessel with Biofuel at a distant 8% share, interestingly among Hydrogen derived fuels Methanol leading with 62% share followed by Hydrogen with 33% share. Methanol emerges as a particularly popular choice, possibly due to its versatility and availability, while LNG and LPG also stand out as viable alternatives.

2.1.1 Distribution of Alternative Fuel Vessels Across Gross Tonnage (GT) Ranges

Figure 2.3 provides insights into the distribution of 1447 Inservice vessels using alternative fuels across different GT ranges. The type of alternative fueled vessels operational are presented in descending numbers against their transition in different sized (GT) vessels. **Figure 2.4** shows the distribution of alternative fuel types across various gross tonnage (GT) categories in orderbook. Analyzing the numbers, it is observed that a diverse landscape where different fuels exhibit varying degrees of prominence across different vessel sizes.

Table 2.3: Alternative Fuel Vessels Statistics: Comparative Assessment (w.r.t Fuel Types)

In service				Orderbook			
All Alternative Fuels		**Hydrogen Derived Fuels**		**All Alternative Fuels**		Hydrogen Derived fuel	
Fuels	Total Number & % among all Alternative Fuels	Fuels	Total Number & % among Hydrogen Derived Fuel	Fuels	Total Number & % among Alternative Fuels	Fuels	Total Number & % among Hydrogen Derived Fuel
LNG	**1105(76 %)**	Methanol	37 (62%)	**LNG**	**991 (67 %)**	Methanol	251 (85%)
LPG	125 (9 %)	Hydrogen	20 (33%)	Methanol	251 (17%)	Hydrogen	23 (8%)
Biofuel*	123 (8%)	Ammonia	3 (<1%)	LPG	114 (8%)	Ammonia	22(7%)
Methanol	37 (3%)			Ethane	45 (3%)		
Ethane	24 (2%)			Biofuel*	24 (2%)		
Hydrogen	20 (1%)			Hydrogen	23(2%)		
Nuclear	10 (<1%)			Ammonia	22(1%)		
Ammonia	3 (<1%)			Nuclear	7(<1%)		

**Majorly Biodiesel or Biodiesel blends along with few other biofuels like Green Diesel, Biobutanol, Bioethanol etc. This excludes Methanol*

Figure 2.3: Alternative Fuel Vessels (in-service): Gross Tonnage Distribution with Total Number of Vessels

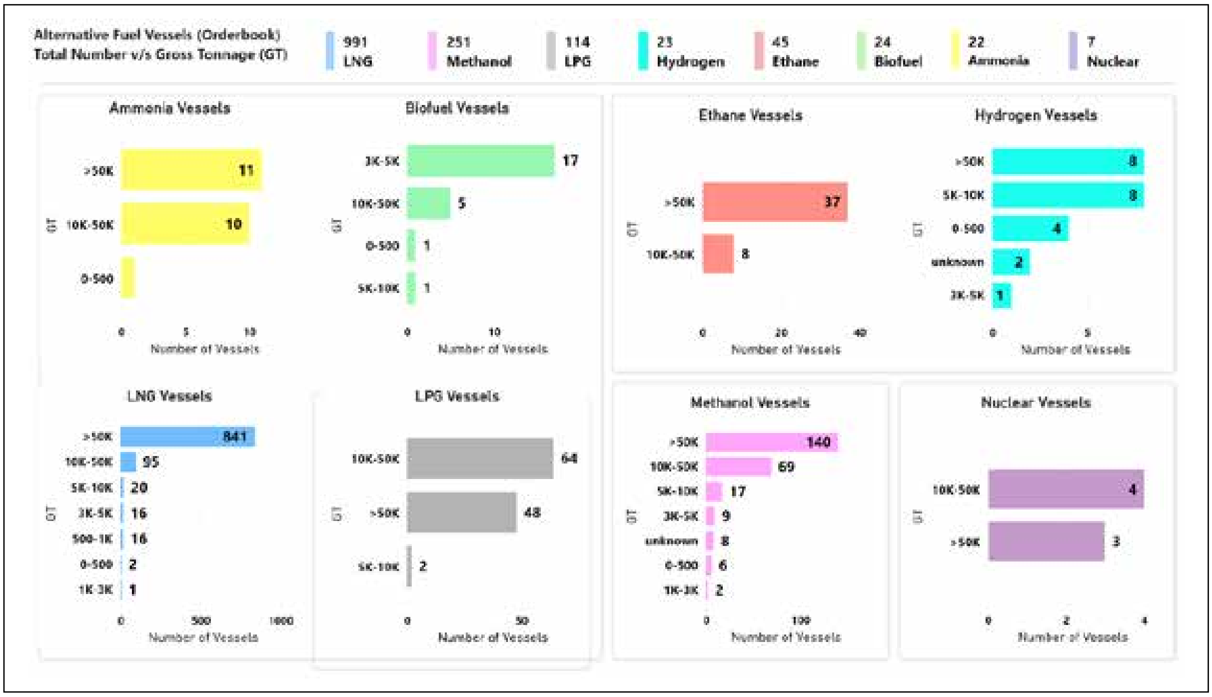


Figure 2.4: Alternative Fuel Vessels (order-book): Gross Tonnage Distribution with Total Number of vessels

Analyses of Figures 2.2 & 2.3 show that

In-service

- **LNG (Liquefied Natural Gas)** is used in **1105 vessels** demonstrating broad adoption across all GT ranges, particularly in the **100000-150000 GT range (**488 vessels). **This significant presence underscores LNG's popularity which could be met through greener options likeE-LNG or bio based CBG as a cleaner alternative to traditional LNG.**
- **LPG (Liquefied Petroleum Gas), with 125** vessels, is predominantly used in the largest GT ranges **(>50000 GT and 10000-50000 GT**) highlighting its specific application in large gas carriers and making up a substantial portion of the market.
- **Biofuel (Biodiesel) shows significant adoption with 123 vessels** spread across all GT ranges. The highest concentration of biofuel vessels (39) is **in the 10000-50000 GT** range, indicating its acceptance among medium to large vessels and showcasing its versatility as a sustainable fuel option.
- **Methanol** is present in 37 vessels, with significant usage in the **10000-50000 GT range** (28 vessels). **Its liquid state at ambient condition provides the adaptability from very small vessels as low as 20 to 50 GT range to medium and large vessels**.

» **Ethane is limited to 24 vessels**, primarily used in larger vessels, **especially in the >50000 GT range** (20 vessels). This niche application highlights its use in very large gas carriers and specialized ships.

» **Hydrogen,** with 20 vessels spanning multiple GT ranges, shows growing interest across various vessel sizes. The highest number of Hydrogen-powered vessels is in the smallest GT range (0-500 GT).

» **Nuclear-powered vessels** are the least common, with only **10 vessels, all in the 10000-50000 GT** range. This reflects the specialized nature and stringent requirements for nuclear propulsion, limiting its widespread adoption.

» **Ammonia,** with only three vessels recorded across the **0-500, 1000-3000, and 5000-10000 GT** ranges, suggests that it is still an emerging fuel option, with ongoing research and development to establish its viability.

Orderbook

» Comparison of order book data against in-service data makes it evident that the trend in alternate fuel adoption along the GT distribution is identical for both only with the exception for **Ammonia, Hydrogen and Biodiesel.**

» **In orderbook LNG is leading with 991 vessels, primarily** in the **>50K GT category**, **with 841 vessels in large-scale shipping,** especially among bulk carriers and container ships.

» **Methanol, with 251 vessels** out of these, **140 vessels are in the >50K GT** range, has presence in the mid and smaller GT categories.

» **LPG is utilized in 114 vessels**, mainly concentrated in the 10K–50K GT range 64 vessels and the >50K GT category 48 vessels specifically role in the larger gas carrier.

» **Hydrogen is represented by 23 vessels** across various size categories, with a notable presence in both the **>50K GT and 5K–10K GT ranges (8 vessels each).**

» **Ethane appears in 45 vessels**, predominantly large ones, especially in the **>50K GT category (37 vessels),** which aligns with its specialized role in large ethane carriers.

» **Biofuel-powered vessels** totaling **24**, fall within the smaller GT ranges, particularly the **3K–5K GT category.**

» **Ammonia is still in its early stages, with 22 vessels**, mostly found in the **10K–50K GT (10 vessels) and >50K GT (11 vessels) categories.**

» **Nuclear-powered vessels** are the rarest, with 7 **in total—4 in the 10K–50K GT range and 3 in the >50K GT category** only in highly specialized vessels (icebreakers).

2.1.2 Integration of Alternative-FuelPowered Engines with Main Engine Types

Figure 2.5 and 2.6 offers detailed insight into the integration of alternative fueled engines with various main engine power types for in-service vessels and orderbook Vessels respectively. It is observed that observe a diverse range of alternative fuels being utilized alongside different engine configurations. Ammonia, for instance, is paired with Diesel 2-Stroke, Diesel 4-Stroke engines. Similarly, biofuels find application in both Batteries & Diesel and Batteries, Diesel & Fuel Cell engines, Diesel 4-Stroke highlighting the industry's exploration of hybrid propulsion systems.

Ethane predominantly integrates with Diesel 2-Stroke engines, indicating a preference for this fuel type in certain vessel segments. Hydrogen, LNG, LPG, and Methanol are also prominently featured, often in combination with Diesel 2-Stroke engines but also in conjunction with other configurations such as Diesel Electric and Fuel Cell & Battery setups. Furthermore, nuclear power stands out as a standalone option, showcasing a specialized approach to propulsion technology.

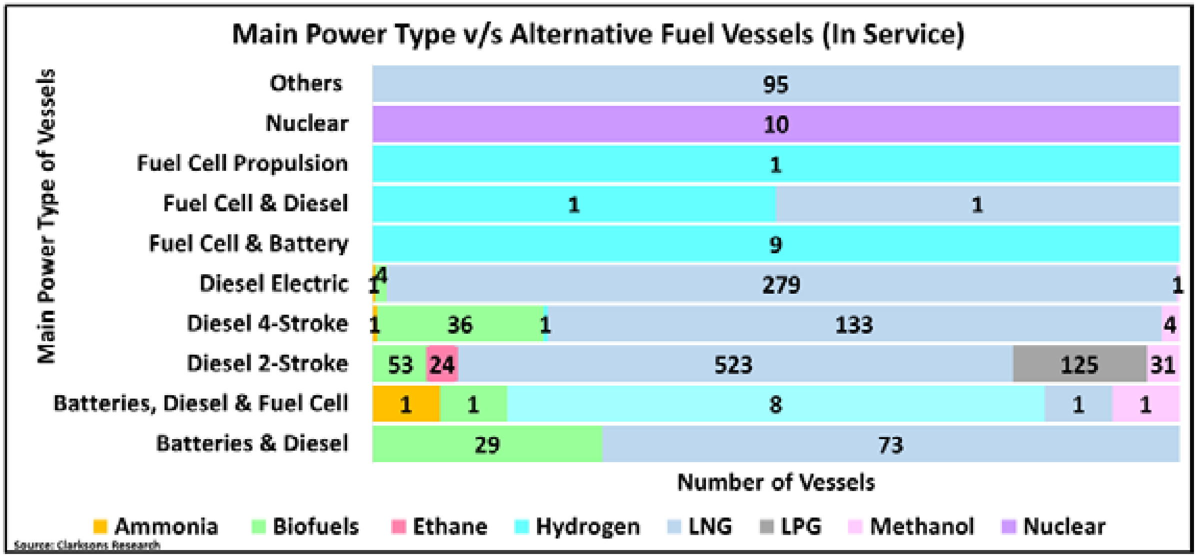


Figure 2.5: Alternative Fuel Vessels Global (in-service): Power Types Across Different Engines

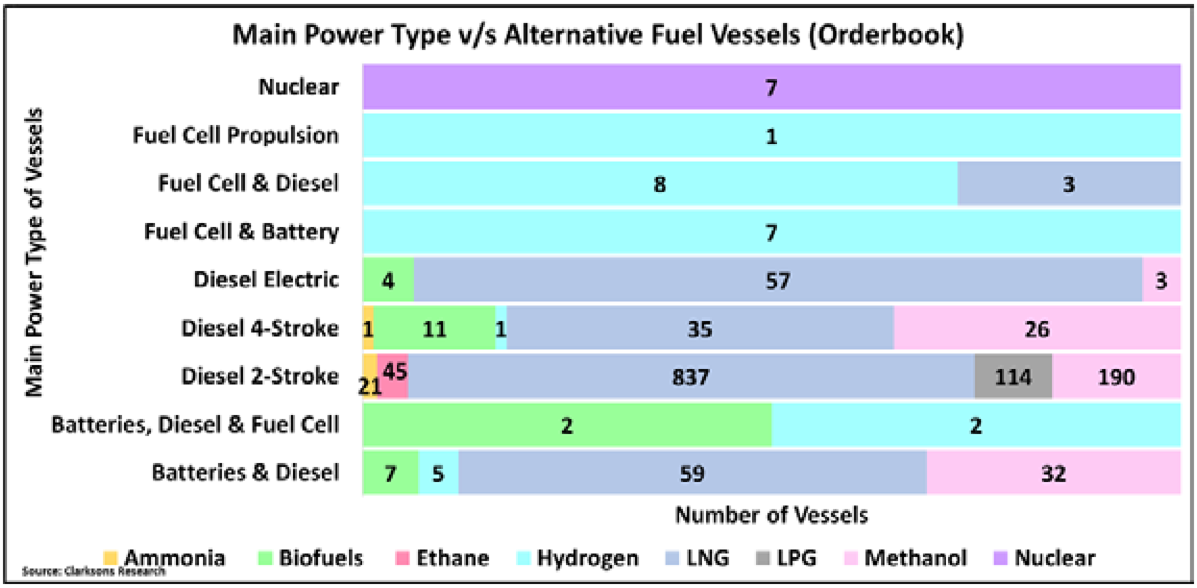


Figure 2.6:Alternative Fuel Vessels Global (Orderbook): Power Types Across Different Engine

2.1.3 Top Countries by Alternative-Fuel Vessel Ownership (Inservice and Orderbook)

This section takes a closer look on the global momentum on how alternative marine fuels are spread across different regions and how countries are adopting them on a national level, using data from both active vessels and those on order. It dives into how various nations are incorporating fuels such as biofuel, methanol, Hydrogen, ammonia, LNG, LPG, and ethane, showcasing both what's currently possible and what strategies are being planned. The findings show clear regional preferences influenced by things like the readiness of infrastructure, support from regulations, and available technologies. While LNG and LPG continue to lead because of the well-established supply chains, greener options like methanol, biofuel, Hydrogen, and ammonia are quickly also gaining traction.

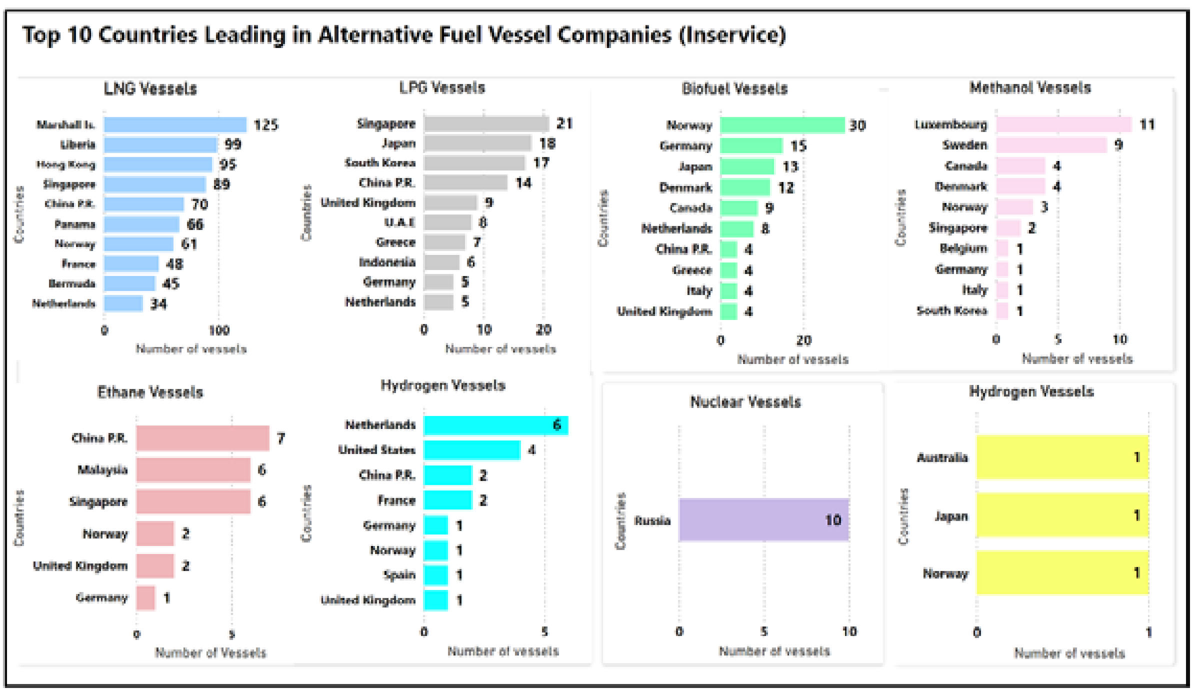


Figure 2.7: Top Countries with Alternative Fueled Vessel Ownership with Number- Inservice (as on August 2024)

Figure 2.5 & 2.6 provides an overview of the global distribution of vessels using alternative fuels, highlighting the adoption rates of these fuels across different countries. This information reveals trends in the maritime industry's shift towards cleaner energy sources and regional preferences for various types of alternative fuels.

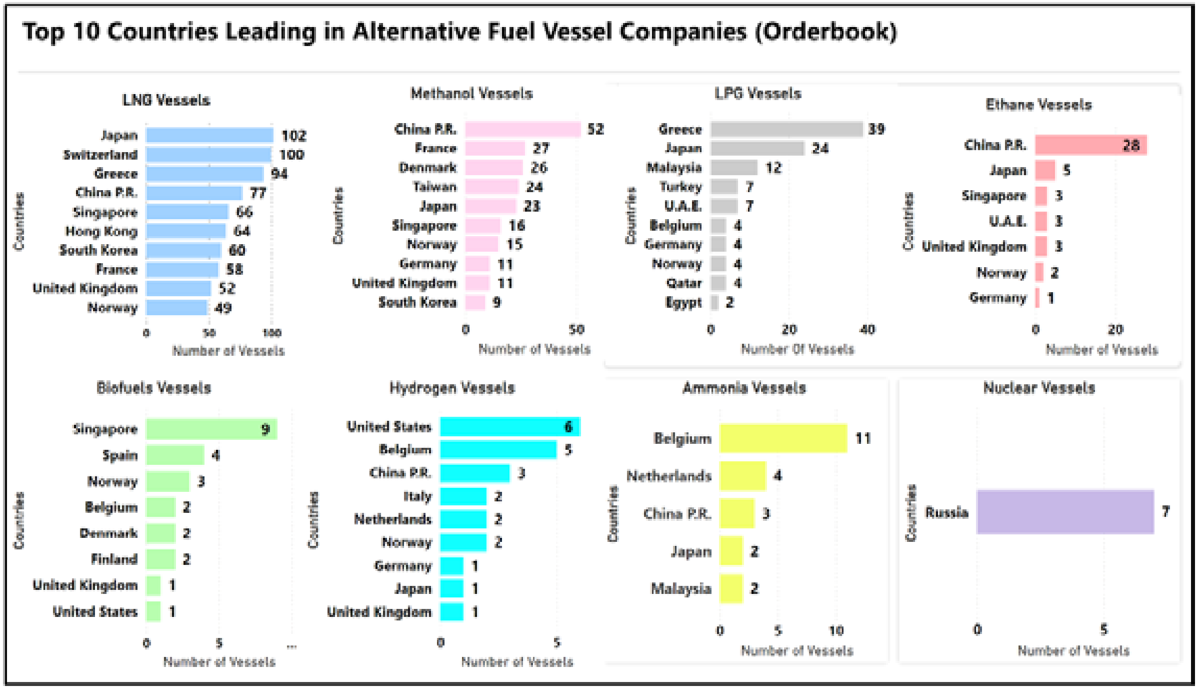


Figure 2.8: Top Countries with Alternative Fueled Vessel Ownership with Number -Orderbook (as on August 2024)

Among Green/e-Fuel options

In-service analysis shows

- **Biofuel (Biodiesel)** is widely adopted, with 123 vessels distributed across 22 countries. The Norway (30 vessels) and Germany (15 vessels) &Japan (13 vessels) have the highest number of biofuel-powered vessels, indicating strong regional support and infrastructure for biofuel use.
- **Methanol** is used in 37 vessels, with significant adoption in Japan (11 vessels), Norway (3 vessels) and Sweden (9 vessels).
- **Hydrogen**-powered 20 vessels have notable concentrations in Netherlands (6 vessels) and USA (4 vessels). The spread of Hydrogen vessels across 11 countries indicates a growing interest in Hydrogen as a clean fuel, though it remains relatively modest compared to other alternatives.
- **Ammonia** fueled 3 vessels belongs to Australia, Japan and Norway.

Order book analysis shows

- **Methanol** comprised of the highest in all the category spread its adoption across different countries led by Denmark, China P.R, France, Germany, Japan, Taiwan, Singapore and many more, suggesting diverse strategies and regulatory frameworks.
- Among 24 B**iodiesel** vessels ordered, Singapore and Norway led by 9 and 4 vessels respectively.
- The China P.R, Belgium, USA and UK stand out in **Hydrogen**-powered vessels orderbook.
- **Ammonia** powered 11 vessels will be owned by Belgium and 4 by Netherlands.

Among other alternatives, the country wise adoption

In-service data analysis reveals

- With 125 vessels, **LPG** is predominantly used in Singapore (21 vessels), Chaina P.R (14 Vessels) Japan (18 vessels), and South Korea (17 vessels).
- **LNG** is used in 1105 vessels, with significant adoption in Marshall Island (125 vessels), Liberia (99) & Hong Kong (95). The widespread use of LNG across 45 countries underscores its popularity as a cleaner alternative to traditional marine fuels, supported by robust infrastructure and favorable regulatory environments in these regions.
- **Ethane** is used in 24 vessels, primarily in the China P.R (7 vessels), Malaysia and Singapore (6 vessels), and USA (2 vessels).
- 10 **Nuclear**-powered vessels, all are in Russia.

Orderbook data reveals

- Japan, Switzerland & Greece demonstrate substantial adoption of **LNG**, highlighting regional priorities and infrastructural capabilities.
- Notably, Russia's exclusive involvement in **Nuclear**-powered vessels a unique technological pathway pursued.
- China P. R emerges as a frontrunner in **Ethane**-powered vessels with 28, followed and distributed across Germany, Japan, Norway, Singapore and UAE too indicating localized preferences and infrastructure readiness.

2.1.4 Top Shipbuilders by Alternative-Fuel Vessel Construction (Inservice and Orderbook)

This section 2.9 a-f presents an overview of the leading global shipbuilders actively engaged in the construction of alternative fuel vessels, including those currently in service and on order. It highlights the capacity, technological readiness, and market positioning of key shipyards contributing to the maritime energy transition through the adoption of low- and zero-emission propulsion technologies. The data reflects current trends in shipbuilding aligned with international decarbonization goals and regulatory developments. **Figures 2.9a, 2.10b, 2.10c, 2.10d, 2.10e, 2.10f, 2.10g, 2.10h show the country wise capacity in building alternative fuel ships/vessels.**

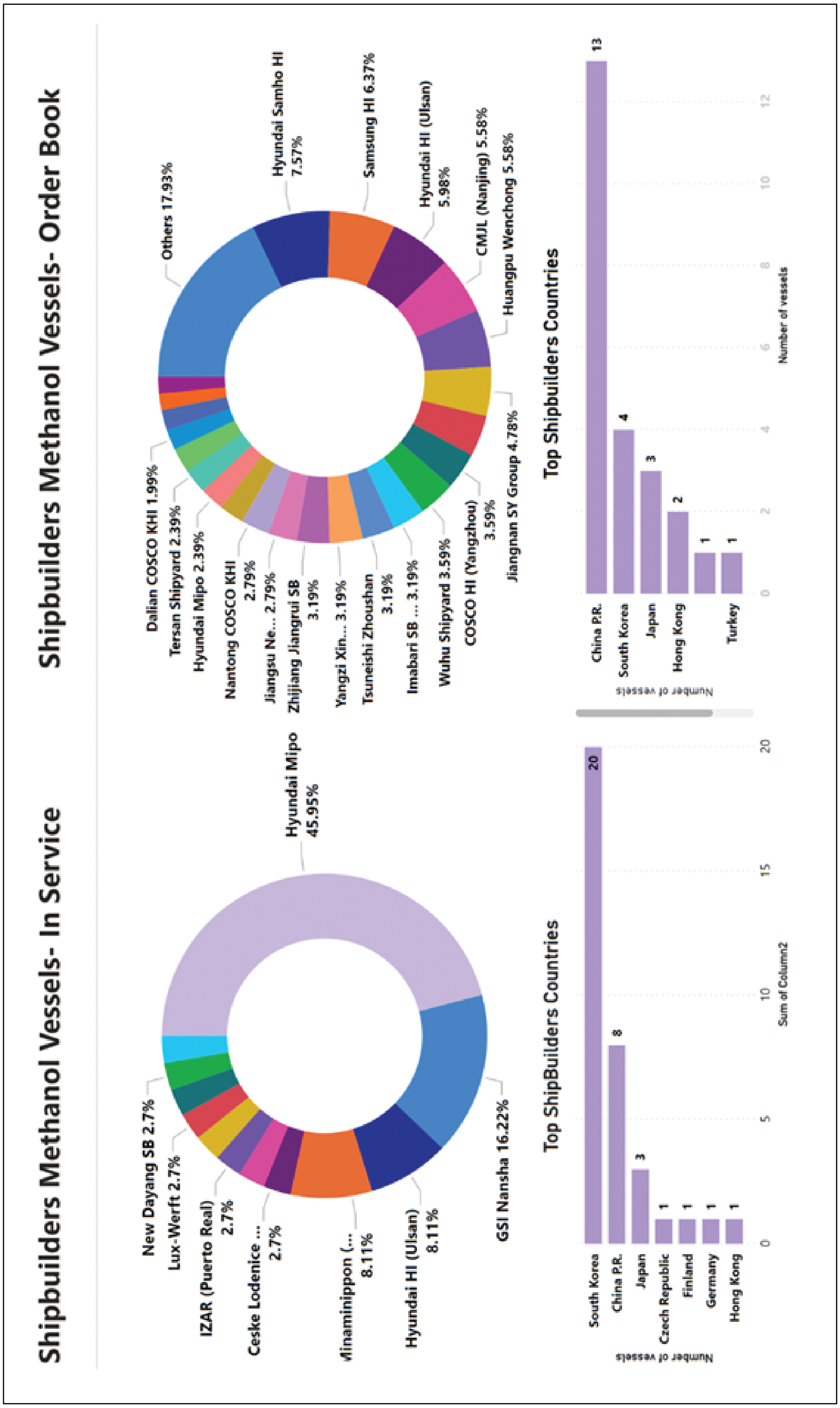


Figure 2.9 (a): Top Countries with Methanol Fuel Shipbuilder Companies and Number (In-Service & Orderbook) as on August 2024

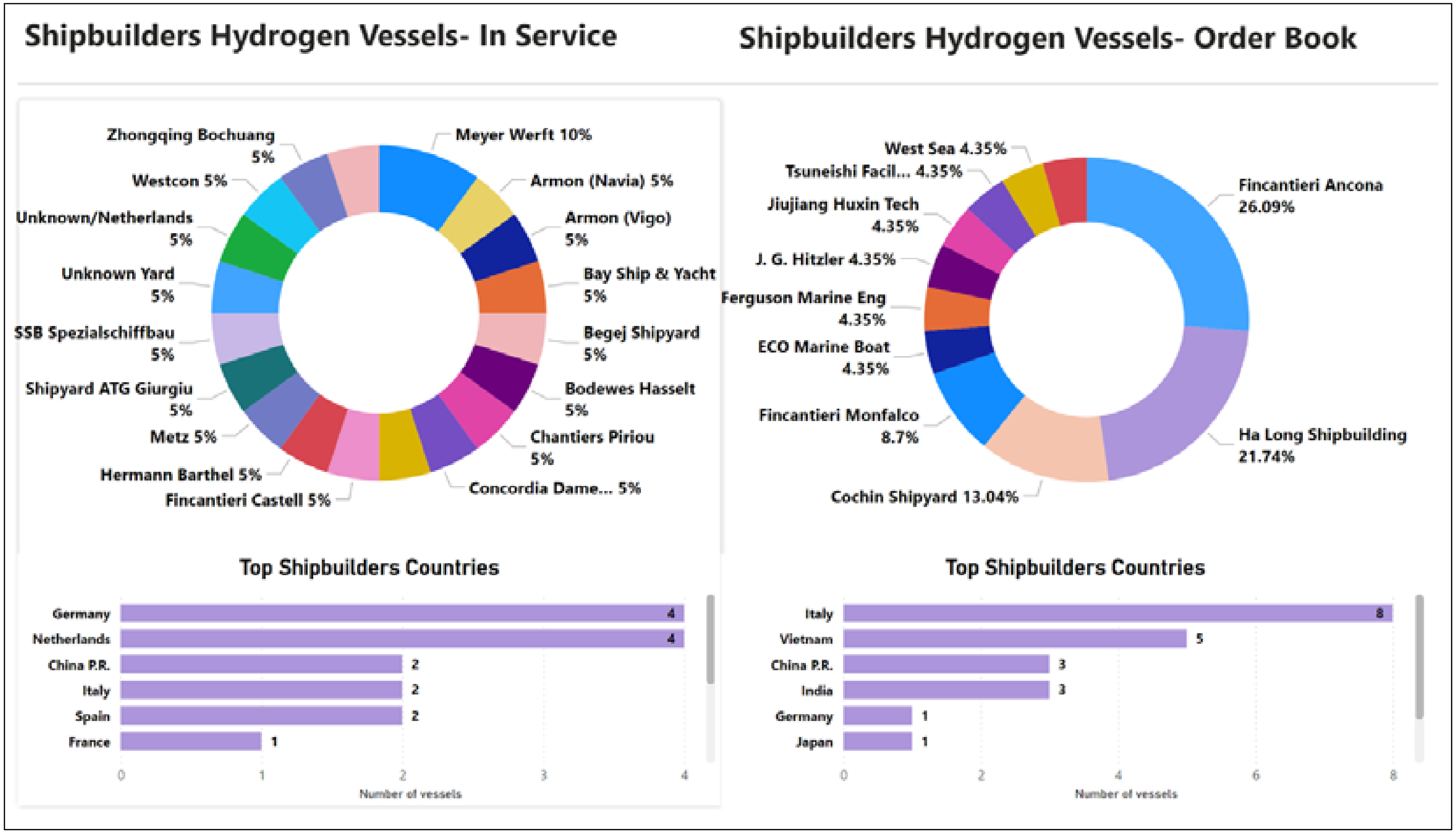


Figure 2.9 (b): Top Countries with Hydrogen Fuel Shipbuilder Companies and Number (In-Service & Orderbook) as on August 2024

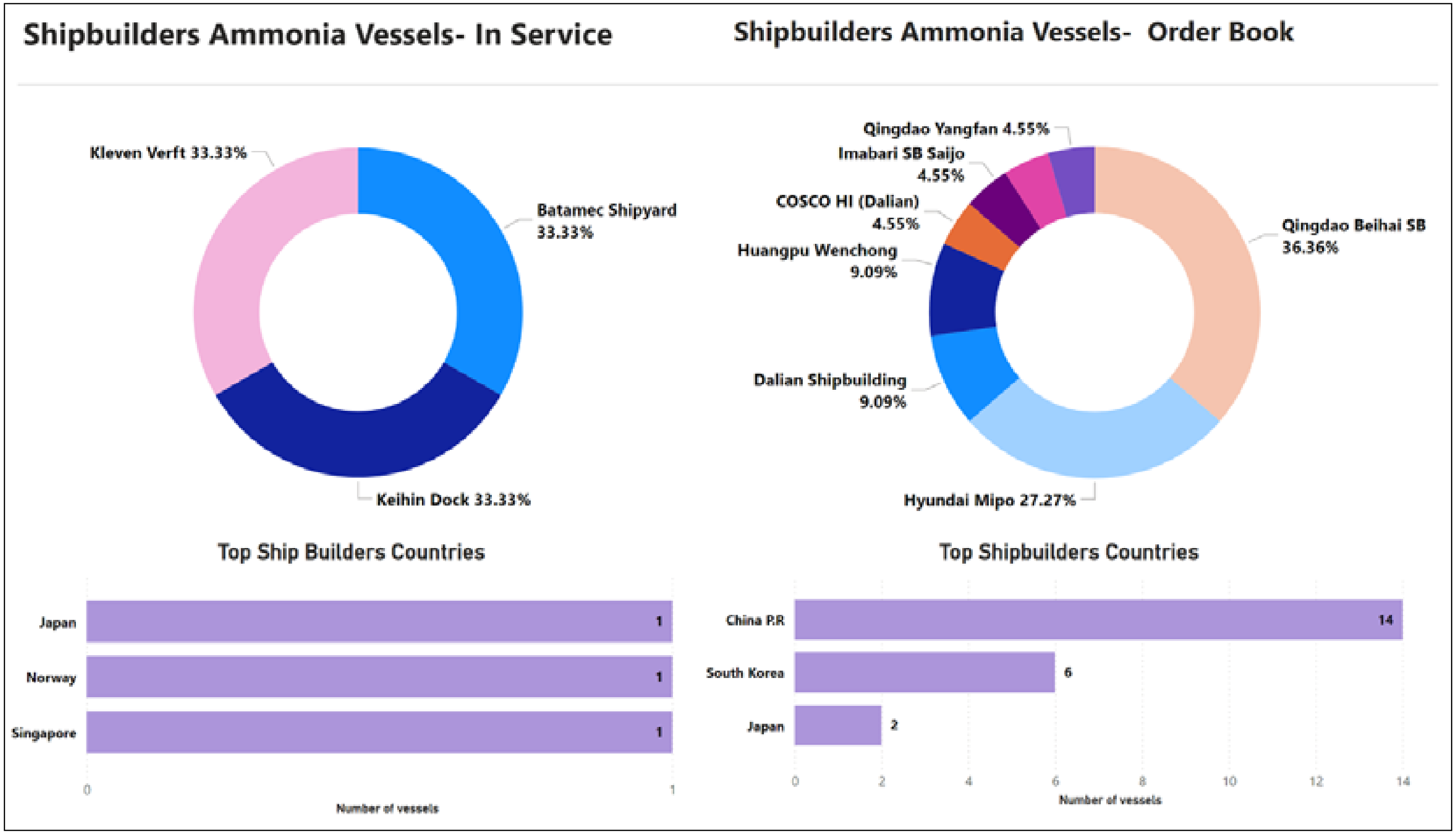


Figure 2.9 (c): Top Countries with Ammonia Fuel Shipbuilder Companies and Number (In-Service & Orderbook) as on August 2024

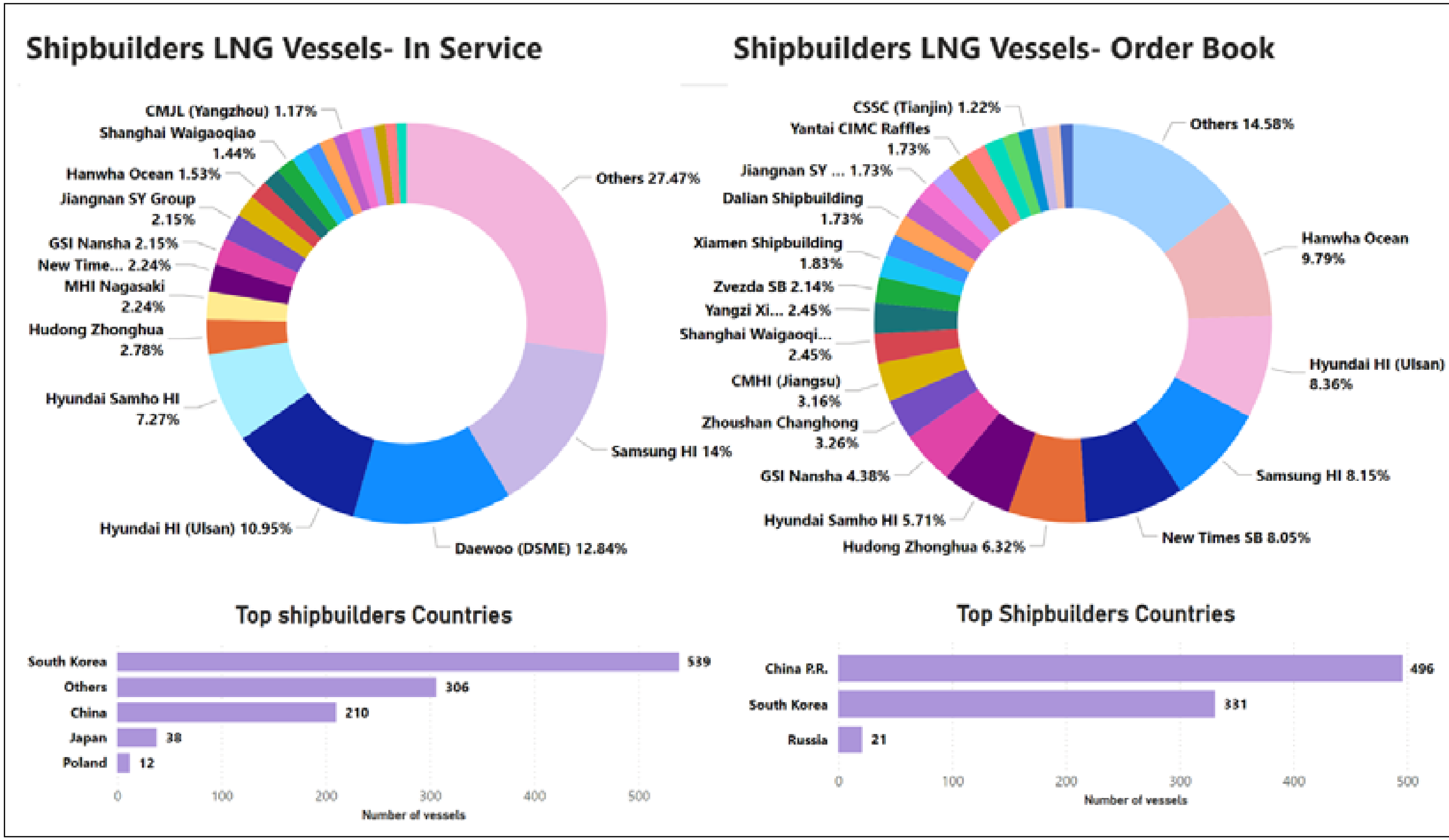


Figure 2.9 (d): Top Countries with LNG Fuel Shipbuilder Companies and Number (In-Service & Orderbook) as on August 2024

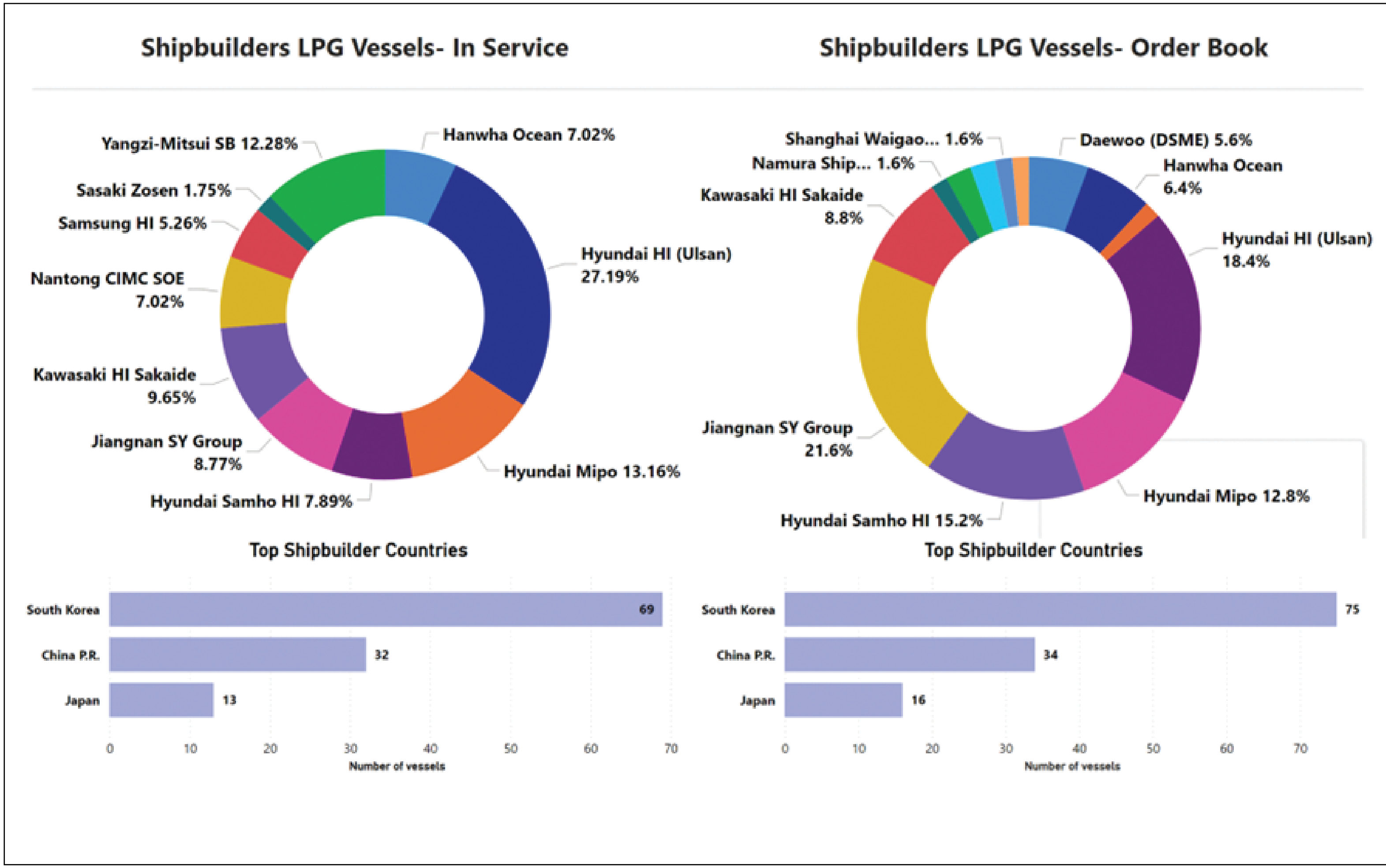


Figure 2.9 (e): Top Countries with LPG Fuel Shipbuilder Companies and Number (In-Service & Orderbook) as on August 2024

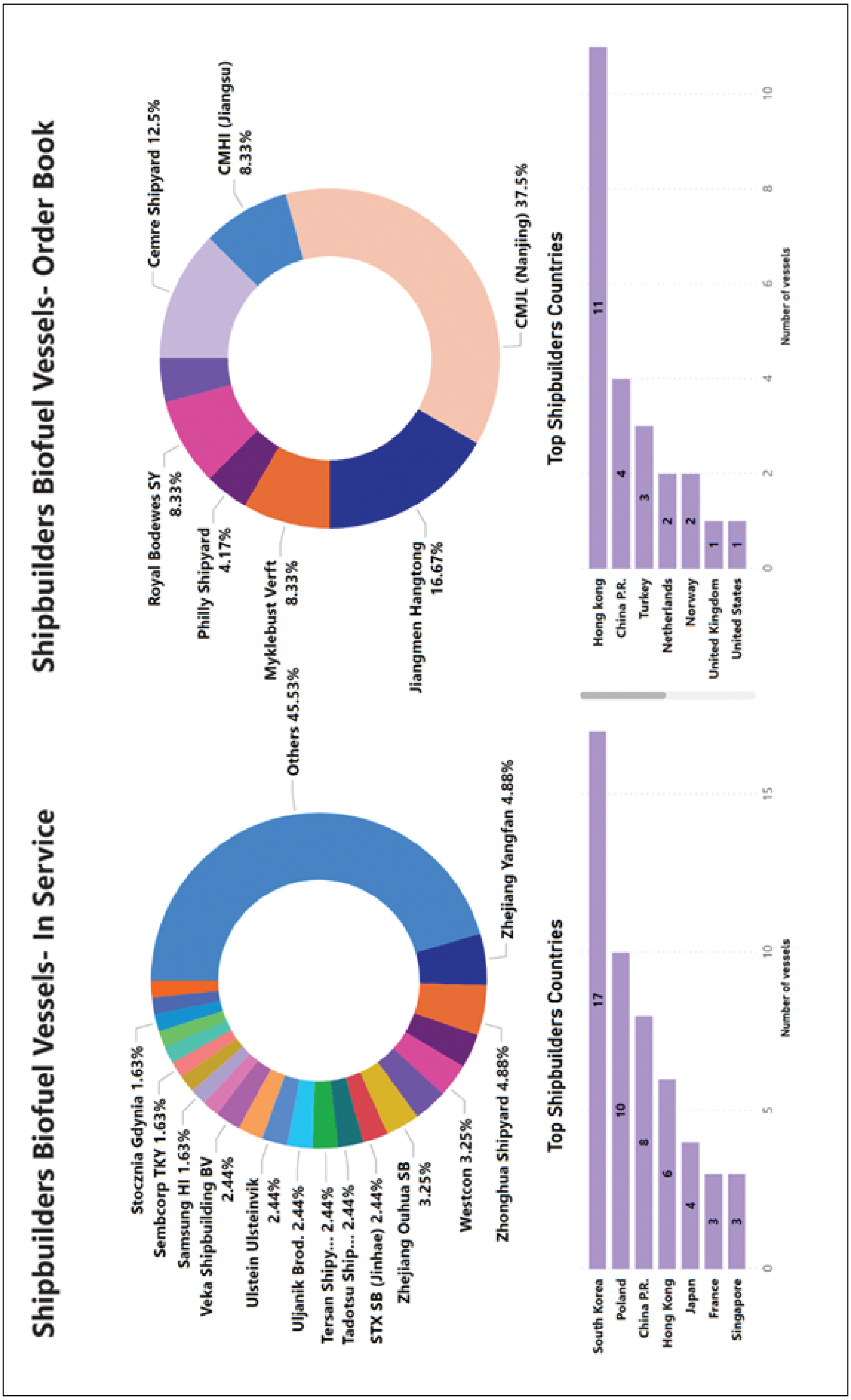


Figure 2.9 (f) : Top Countries with Biofuel (Biodiesel) Fuel Shipbuilder Companies and Number (In-Service & Orderbook) as on August 2024

Among the Alternative Fuel Shipbuilders

Analysis of in-service data shows

- **Biofuel (majorly Biodiesel)**: **Zhejiang Yangfan** as the leading shipbuilder, accounting for **4.88% share** in-service biofuel fleet, with **Zhejiang Ouhua** and **Wright Shipyard Co.** following with **3.25%** share each and many smaller plyers
- **Methanol**: **Hyundai Mipo** dominates Methanol vessel construction, contributing **45.95%** of the active fleet. **GSI Nansha** and **Hyundai HI (Ulsan)** also play key roles, holding **16.22%** and **8.11%** shares respectively.
- **Hydrogen**: **Meyer Werft** leadsin hydrogen-fuel shipbuilding with a **10%** share, while **Armon's Navia** and **Vigo yards** each contributes **5%**.
- **Ammonia vessel builders include Batamec Shipyard**, **Keihin Verft**, and **Keihin Dock having one vessel each** indicating early-stage development in this segment.
- **LPG vessels** led by **Hyundai HI** and **Hyundai Mipo** are equally dominant in LPG shipbuilding, each accounting for **13.16%** of the fleet, followed by **Hyundai Samho HI** with **7.89%**.
- **LNG**: **Hyundai HI** leads LNG vessel construction with **14%** of the global fleet, closely followed by **Daewoo Shipbuilding (DSME)** at **12.84%** and **Hyundai HI (Ulsan)** with **10.95%**.

Orderbook analysis shows

- **Biofuel (majorly Biodiesel)**:Top shipbuilders **CMJL Nanjing** holds**37.5%**, **Jiangmen**
- **Hangtong** with **16.67%**, and **Myklebust Verft** at **8.33%** of the orderbook fleet.
- **Methanol**: **Hyundai Samho** leads with **7.57%**, share followed by **Samsung Hyundai HI** at **6.37%** and **(Ulsan)** with **5.58%** of the orderbook vessels.
- **Hydrogen**: **Fincantieri Ancona** dominates with **26.09%**, while **Ha Long shipbuilding** follows with **21.74%**, indicating regional specialization in hydrogen-ready construction.
- **Ammonia** vessels are built by **Qingdao Beihai** which leads with **36.36%** market share, followed by **Hyundai Mipo** with **27.27%** and **Dalian Shipbuilding** at **9.09%**.
- **For LPG vessels Hyundai HI** is in the lead with **18.4%** share, closely followed by **Hyundai Samho HI** at **15.2%**, and **Hyundai Mipo** at **12.8%** share.
- **LNG shipbuilder Hanwha Ocean** leads with **9.79%** share, while **Hyundai HI** follow **(Ulsan)** and **Samsung HI** with **8.36%** and **8.15%** share respectively.

Leading Shipbuilder Countries

In-service data analysis shows

- As shipbuilding nations**, S. Korea China P.R. tops in Biofuel** vessel construction with **17** builds, followed by Poland 10 and China PR 8 vessels**.**

» In **Methanol propulsion**, **South Kore**a leads the yard count at **20 vessels, China P.R. 8 vessels** and **Japan 3** vessels**.**

» **Germany and the Netherlands** have each delivered **4 Hydrogen** vessels, while **China P.R.** yards account for **2** vessels.

» For A**mmonia, Japan, Norway, and Singapore** shipyards have each made **1** vessel.

» South Korean yards dominate **LPG construction with 69 vessels, ahead of China P.R. (32) and Japan (13).**

» In **LNG** shipbuilding, S**outh Korea leads with (539) vessels built, China P.R. follows with (210), and Japan with (38)**.

Orderbook analysis shows

» **Hong Kong leads the Biofuel (Biodiesel)** orderbook with 11 vessels, followed by China P.R. with 4 and Turkey with 3 vessels building.

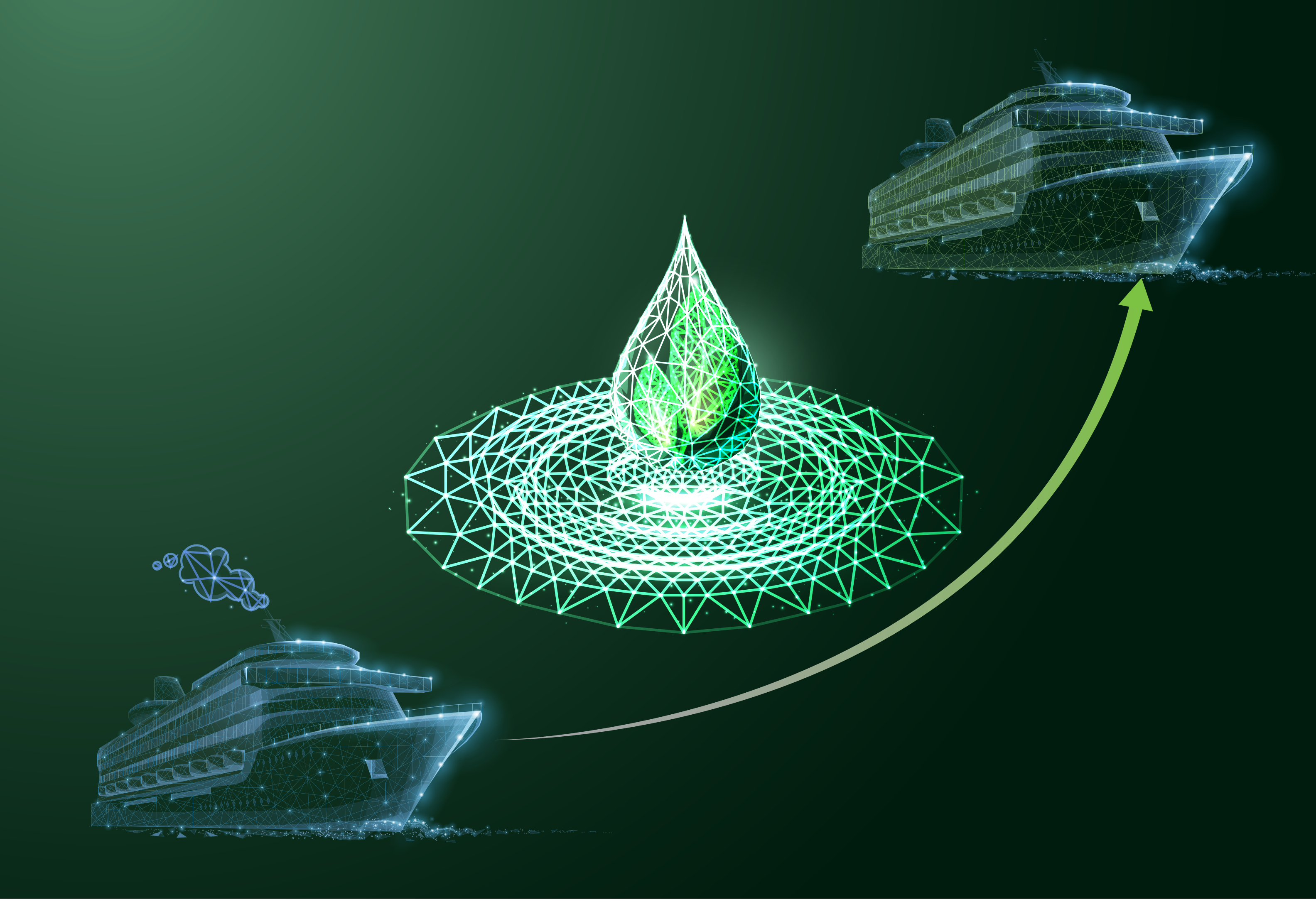
» Among **Methanol** vessel orders, China P.R. takes lead with 13 vessels, trailed by South Korea with 4 and Japan with 3 vessel building.

» Italy leads the **Hydrogen** vessel orderbook with 8 vessels, followed by Vietnam with 5)and China P.R. with 3 vessel building.

» **Ammonia** vessels, China P.R. leads the orderbook with 14 vessels, followed by South Korea with 6 and Japan with 2 vessel building.

» In **LPG** vessel newbuild orders, South Korea is ahead with 75 vessels, followed by China P.R. with 34 and Japan with 16.

» For **LNG** vessels on order, China P.R. leads with 496 vessels, followed by South Korea with 331 and Russia with 21 vessel.



Chapter 3

Alternative Fuel Powered Marine Engines (ICE) for Decarbonizing Shipping

Introduction

India's Net Zero ambitions needs its shipping industry to move towards adoption of alternative fuels-operated marine engines. The use of alternative fuels in marine engines will contribute to (i) the promotion of "indigenous" fuels, thereby making Atmanirbhar Bharat (ii) lowering greenhouse gas emissions (GHG), supporting the country's Net Zero Vision and (iii) Reducing fuel import dependency/bill.

Although Fuel cell-based propulsion and battery pack-based systems will penetrate, nevertheless, adoption of alternate fueled ICEs will be of much larger dimension and thus pivotal. Globally, various countries are actively transitioning towards alternative fuel-based ICEs to operate ships over wide distribution of gross tonnage vessels as well as different types of ships. It is worth mentioning that the existing marine engines and fuel system components are compatible only with conventional fuels, whereas most of the alternate fuels not only differ in their distinct physio-chemical properties, but they also have distinct combustion characteristics and thus demand different material supply chains. The respective bunkering systems also need varying degrees of upgradation to comply with the IMO guidelines for storage, handling and safety protocols which is still evolving. Thus, in order to accelerate the alternate fuel adoption in marine propulsion, not only the IC Engine (ICE) development research, but a larger ecosystem needs to be built which is largely missing in Indian maritime sector both in short sea and international water. Eventually, this ecosystem would also benefit decarbonization of propulsion systems in India's inland water transports which has a significant share in overall water transport too.

In this chapter, first Section presents the comprehensive global and national status of alternative fuel powered marine engines development and future projections in the light of present global trends. Following Section throws light on the Methanol, Ammonia and Hydrogen combustion engines development trajectory and proposed roadmap strategy for Indian.

From an engine manufacturer's perspective, MAN is the dominant player in several fuel categories: commanding 86.1% of methanol-fueled in-service engines, 100% of ethane engines, and full market share in LPG-powered ships. Wärtsilä leads the LNG segment with 57% of in-service engines, while in the hydrogen segment, it holds 33.3% of the current fleet, followed by Scania and Caterpillar. For ammonia-powered vessels, Cummins, Wärtsilä, and Niigata share the market equally (33.3% each) one vessels of each in-service.

Looking at order-book trends, Methanol leads with MAN maintaining a 79% share, showing clear industrial alignment toward this fuel. Ammonia engine developments are increasingly led by WinGD (80%), with other contributions from MAN, J-Eng, and CRRC Dalian. In biofuel orders, Yanmar is the frontrunner with 64.3%, while MAN continues to hold influence in the broader market. In hydrogen-fueled vessels, MAN and ABC-MAN collectively account for over 78% of upcoming deployments.

These data reflect two important things: (i) Ship owners are increasingly moving towards alternative fueled ships to meet the International Maritime Organization (IMO) regulations, and (ii) Each country focusing on its maritime sectors to lower greenhouse gas (GHG) emissions and eventually, net-zero emissions.

The selection of alternative fuel is very crucial which is ultimately influenced by critical parameters [3, 4, 5, 6, 7] such as (i) Technological issues, (ii) Infrastructure and bunkering readiness at port/ ships, (iii) Cost-effectiveness (iv) Safety aspects (v) Storage capacity and last but not the least (vi) GHG emission reduction potential (Well to Wake) in the overall value chain.

Looking from the perspectives of technology readiness and relative market share of alternate fuel ICE, among these Methanol ICE has a high level of technological readiness & commercial availability. **It is also worth mentioning that in the case of dual-fuel engines, for Methanol the modifications are needed only in the injectors, cylinder heads, and the fuel delivery system and not inside the engine, while for Ammonia readiness the engines internals /combustion system itself need replacement. This makes Methanol engines more cost effective against Ammonia engines at present. Although commercial Hydrogen engines are presently being developed it still await few critical technical challenges to be fully overcome as mentioned later in this chapter.**

The commercial availability of Methanol-fueled two-stroke and four-stroke engines is important due to their potential wide scale use in shipping. The inherent advantage of two-stroke engines is that it is about 1.8 times more powerful over four-stroke engines for a given weight and thus can use inferior-grade fuel with higher efficiency and lesser maintenance, which in turn reduces operating costs**[8].** Two-stroke engines has reported a 54.3 % share of the marine engine market in 2020 **[9]**. However, four stroke engines are expected to have higher growth up to 2028, due to lower noise levels, higher speeds, and lower capital cost.

Looking from the lens of engine manufacturing capacity and country wise ICE vessel ownership lead, **Figures 3.1a, 3.1b, 3.1c, 3.1d, 3.1e, 3.1f 3.1g provide very significant insight for Methanol, Ammonia, Biofuel (Biodiesel), Hydrogen, Ethane, LNG, LPG fueled engine respectively in marine application. Figure 3.1h is related to nuclear energy powered vessels. Similarly,**

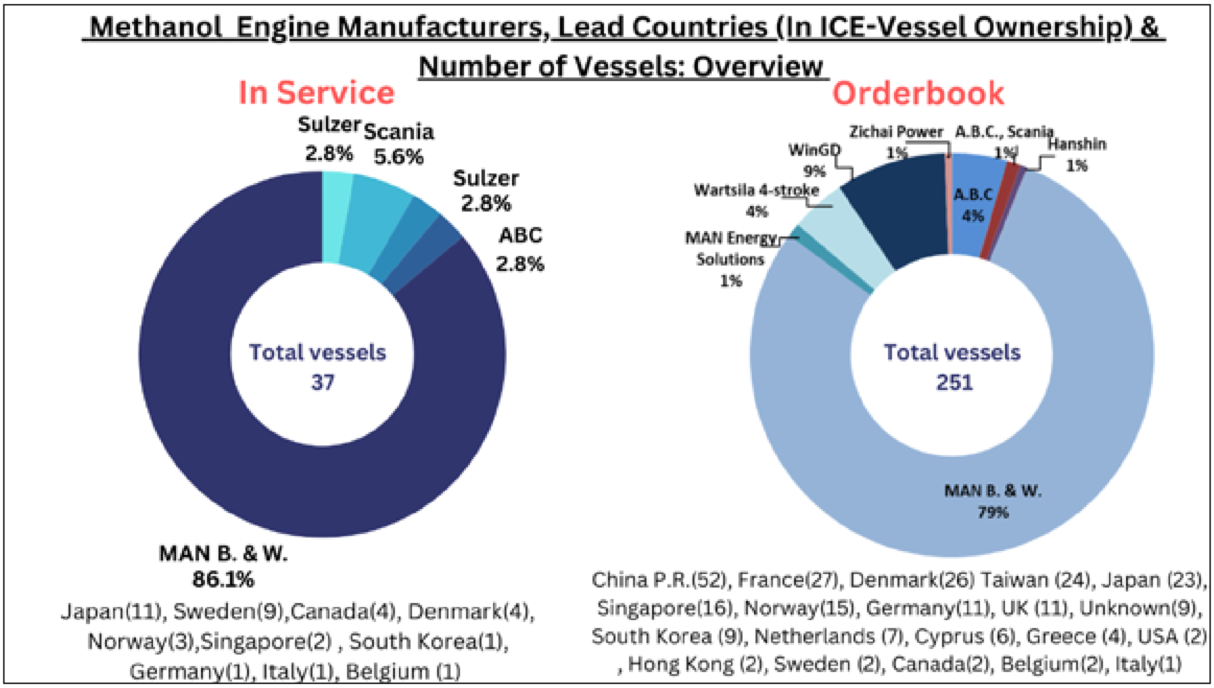


Figure 3.1 (a) : Methanol ICE Overview (in-service vs orderbook): Manufacturers, Countries (In ICE-Ownership) and No of Vessels

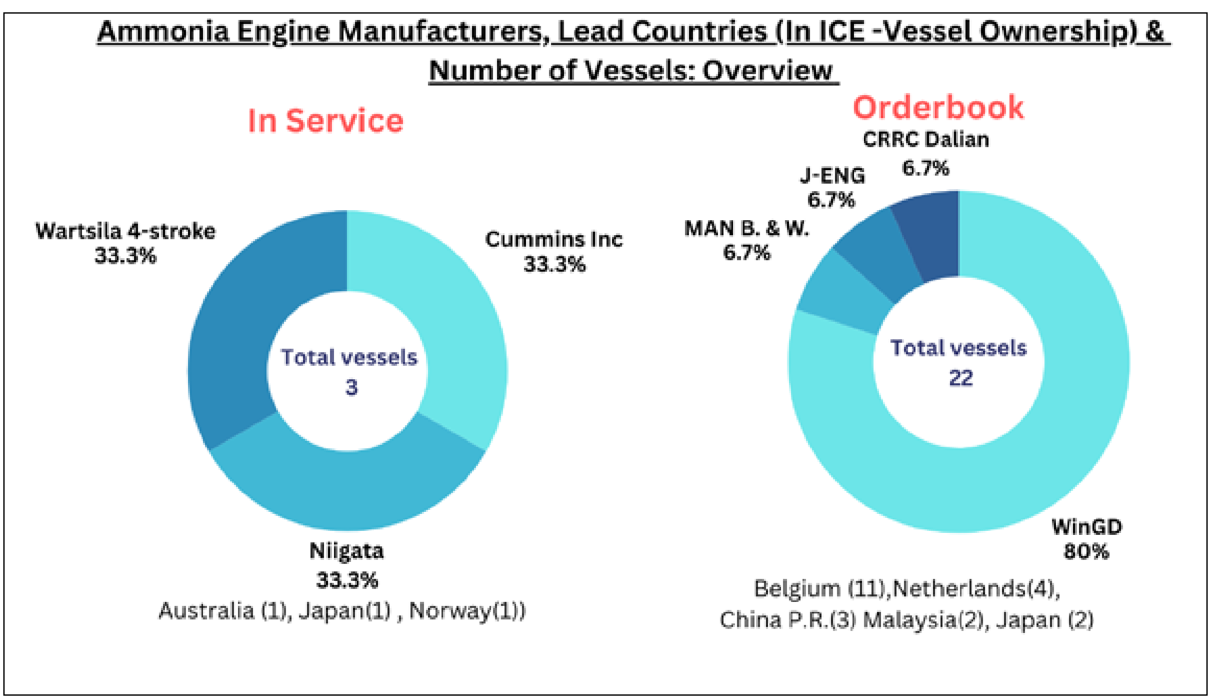


Figure 3.1(b) : Ammonia ICE Engine Overview (in-service vs orderbook): Manufacturers, Countries In ICE-Ownership) and No of Vessels

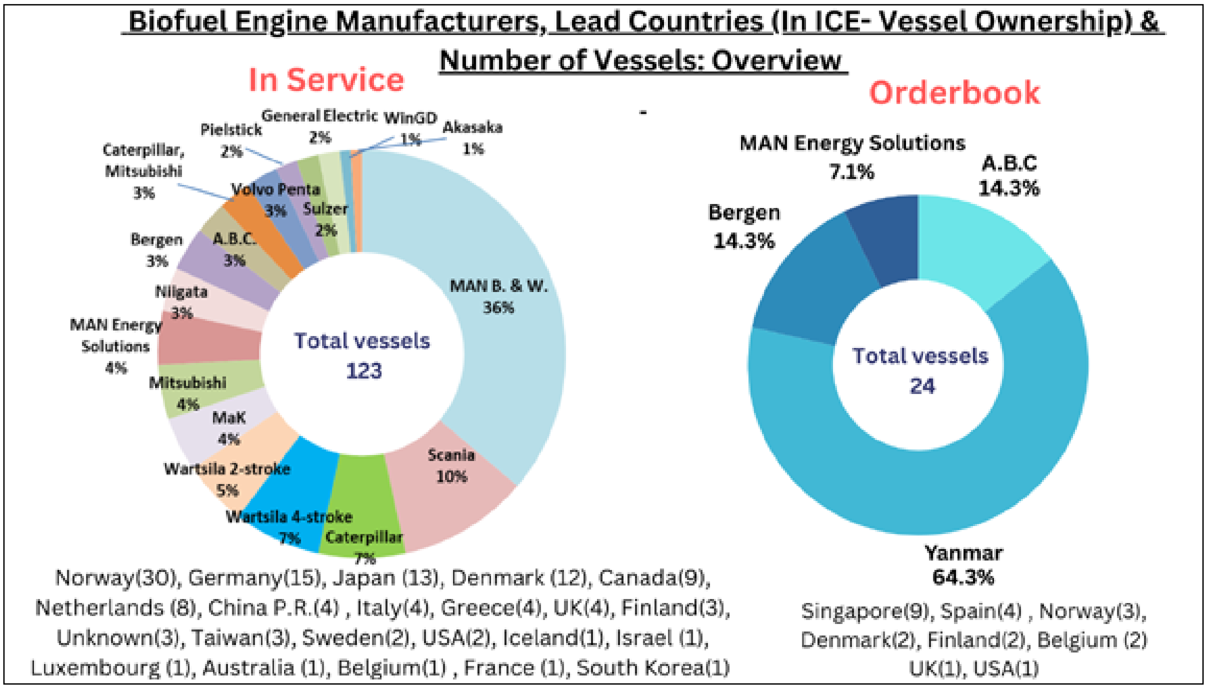


Figure 3.1(c): Biofuel (Biodiesel) ICE Engine Overview (in-service vs orderbook): Manufacturers, Countries (In ICE-Ownership) and No of Vessels

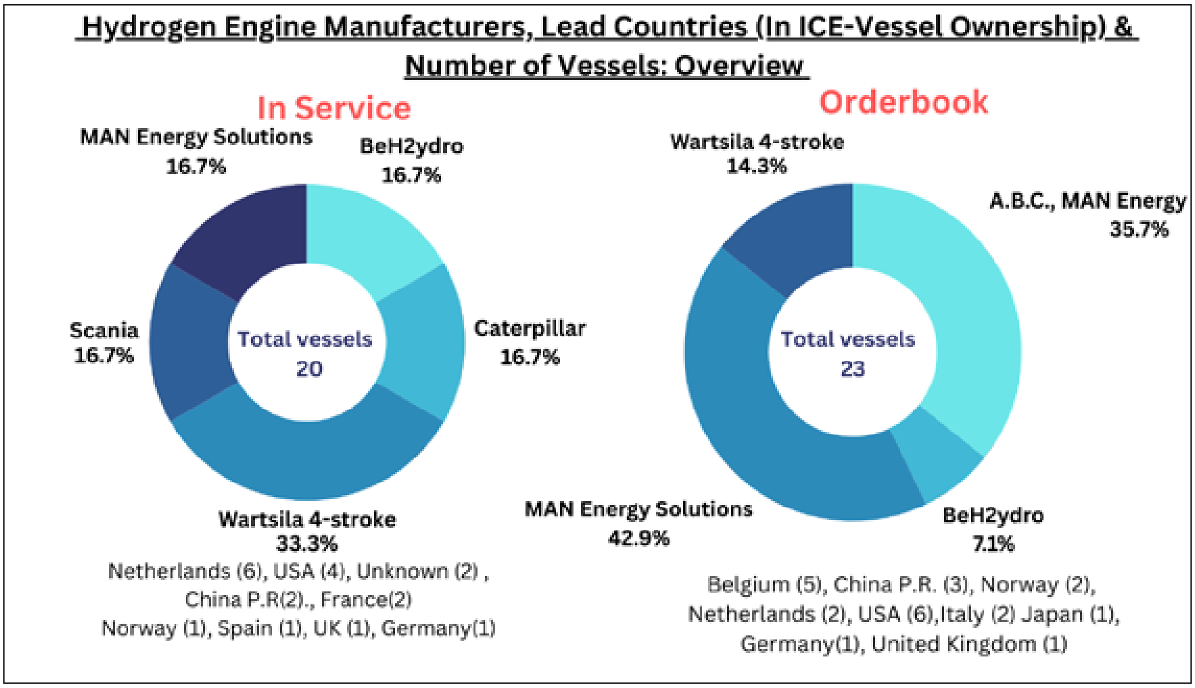


Figure 3.1 (d) : Hydrogen ICE Overview (in-service vs orderbook: Manufacturers, Countries (In ICE-Ownership) and No of Vessels

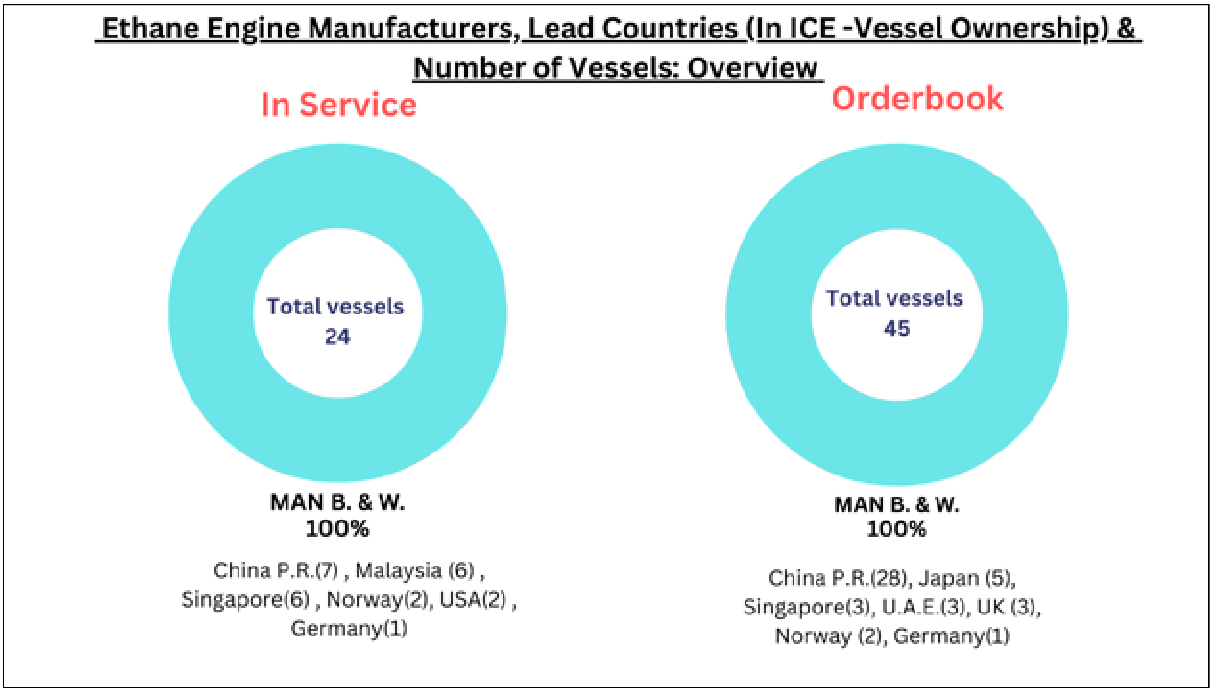


Figure 3.1 (e): Ethane Fueled Engine Overview (in-service vs orderbook): Manufacturers, Countries (In ICE-Ownership) and No of Vessels

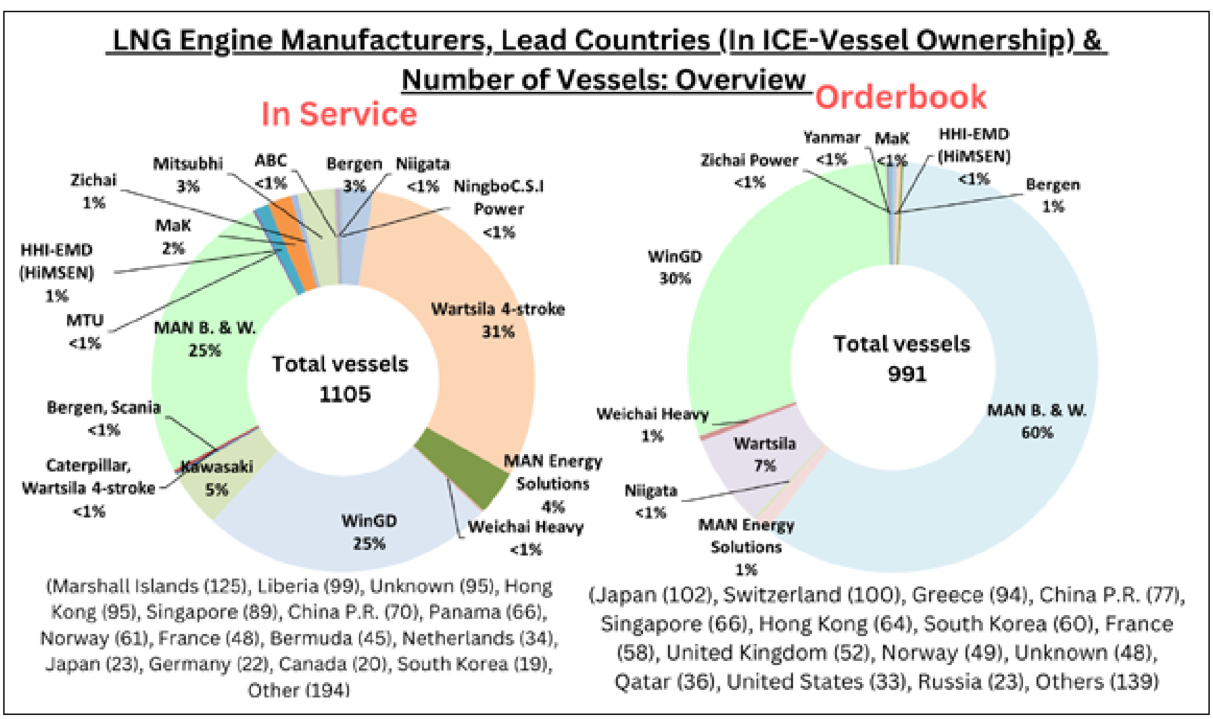


Figure 3.1(f) : LNG Fueled Engine Overview (in-service vs orderbook): Manufacturers, Countries (In ICE-Ownership) and No of Vessels

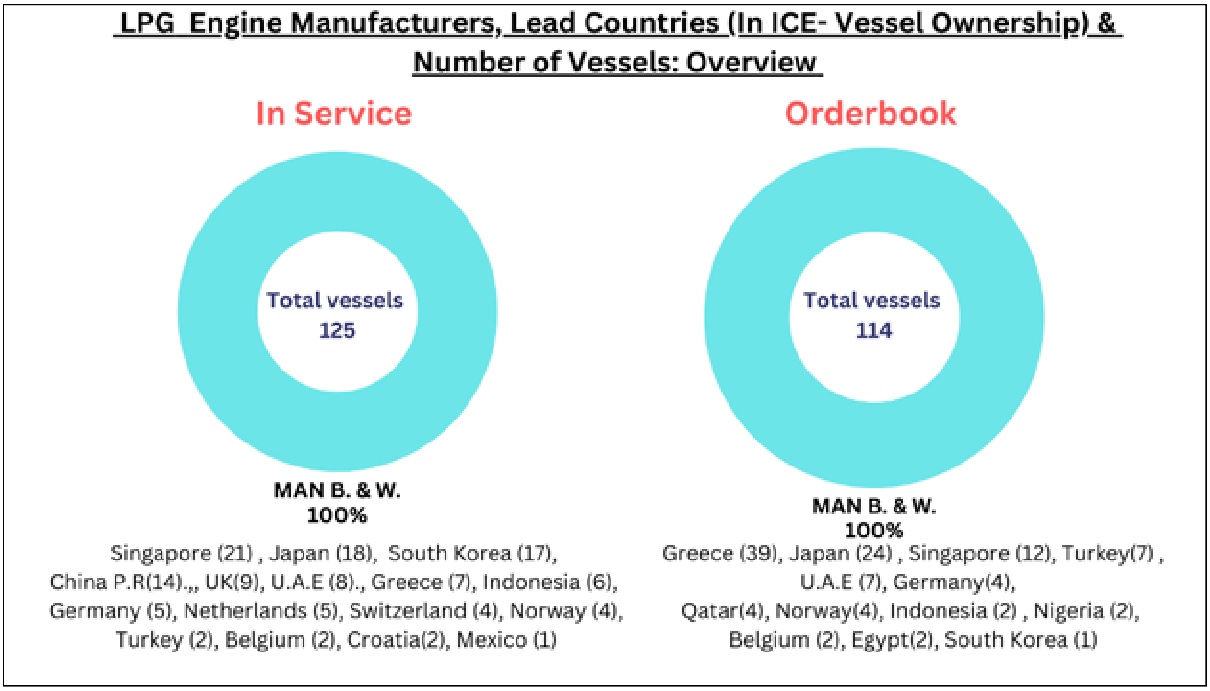


Figure 3.1 (g): LPG Fueled Engine Overview (in-service vs orderbook): Manufacturers, Countries (In ICE-Ownership) and No of Vessels

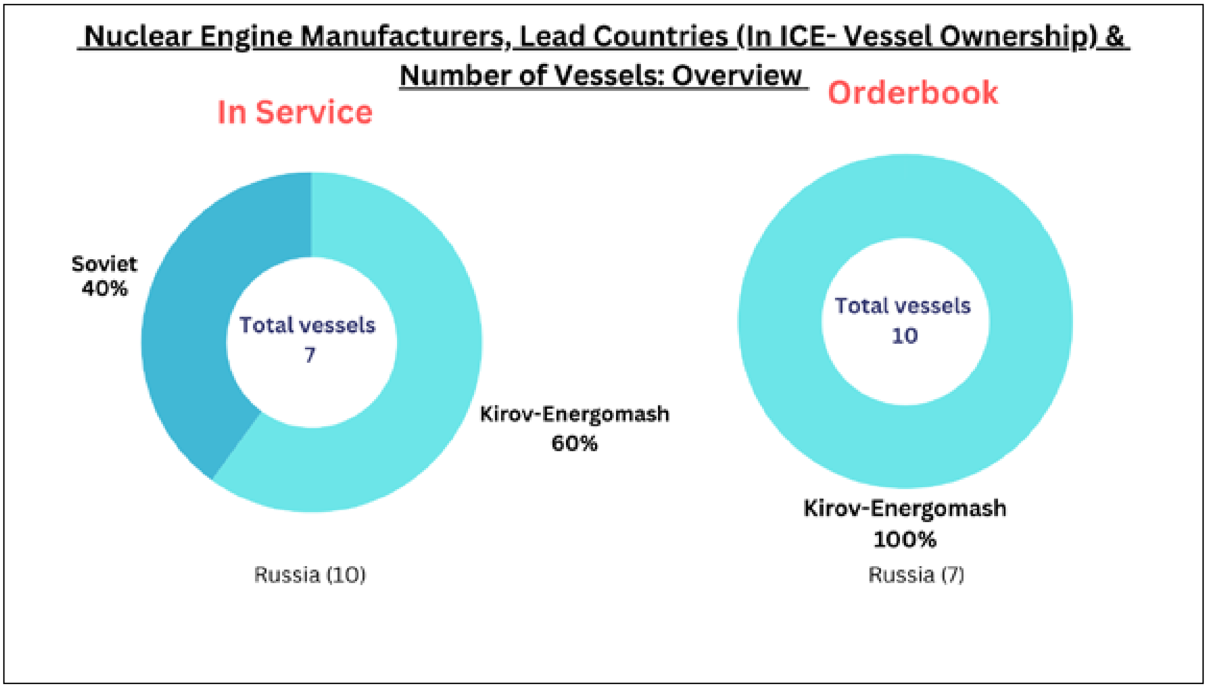


Figure 3.1(h): Nuclear Engine Overview (in-service vs orderbook): Manufacturers, Countries (In ICE-Ownership) and No of Vessels

3.1 Alternative Fuel Operated Large Bore Marine Engines (Technology Status)

Based on combustion cycles, typically marine propulsion is classified under two categories such as

1. Two-stroke engines, known as low-speed primary propulsion engines used in large marine vessels and
2. Four-stroke engines, known as medium/high-speed engines and used in smaller vessels as either the primary propulsion system and/ auxiliary power generation system

Figure 3.2 depicts the relative percentage of fuel use in these engines adopted as ship's main propulsion type under different types of vessels in global maritime sector **[8].** The main propulsion engines for large containers such as bulk carriers, and tanker vessels etc. typically belong to large low speed, two-stroke engines (up to 12 m tall) which generate up to 80MW Power. Ship classes like LNG tankers, fishing vessels, ro-ro and ro-pax, and cruise ships use medium-speed, four-stroke engines with generating power in the 1–20MW range. Whereas smaller inland and coastal/ short sea vessels use high-speed, four-stroke engines with power generation around 500 kW **[9]. Figure 3.3** illustrates the size scale across the marine engines used in these vessel types **[9].** The low-speed, two-stroke, crosshead main propulsion engines used in large, ocean-going cargo vessels are among the world's most efficient energy conversion devices **[9].**

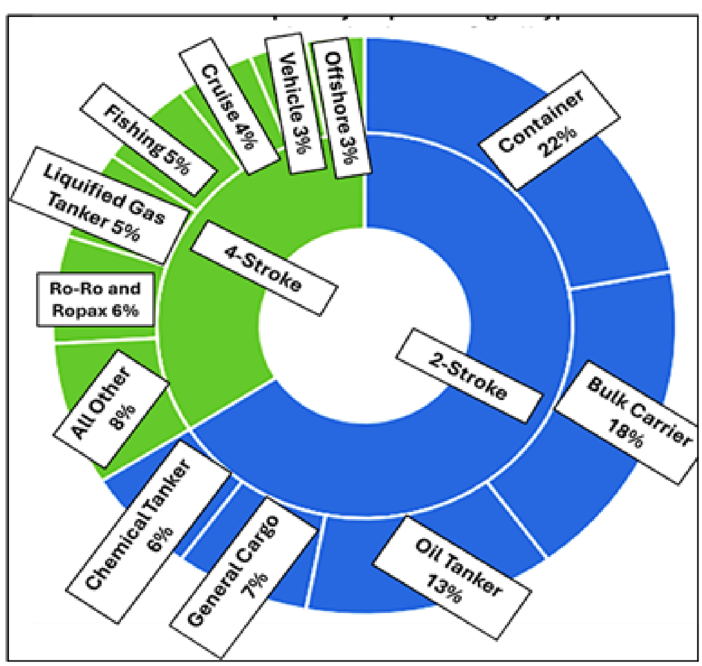


Figure 3.2: Main Propulsion Engines Across Vessel Types with Relative Fuel Consumption

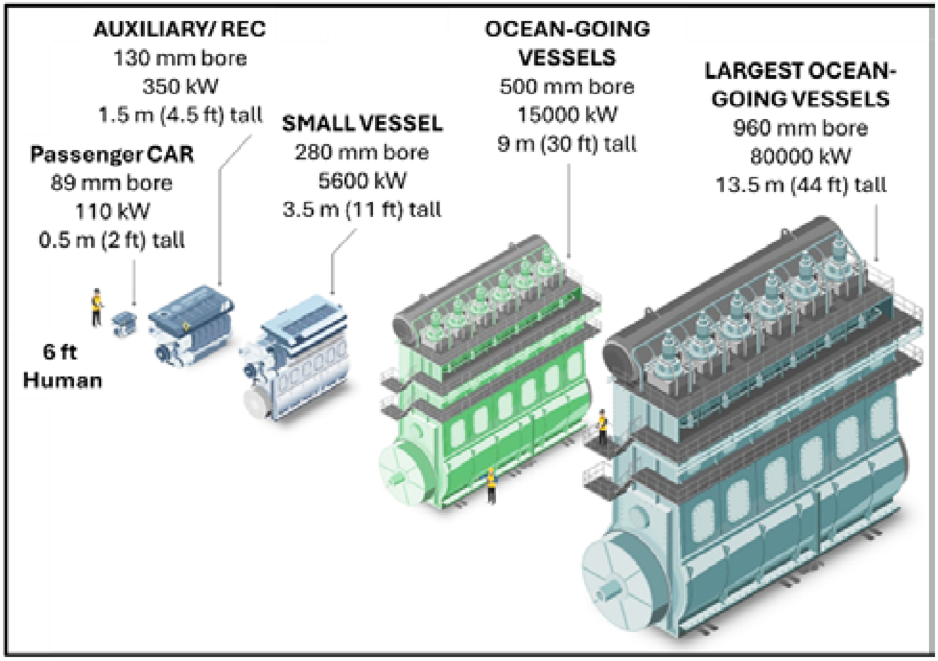


Figure 3.3: Engine Size for Passenger Car, Auxiliary, Small Vessel, Oceangoing

Some significant completed/ongoing projects related to alternate fueled ICE development are detailed in **Table 3.1**

Table 3.1: Important Global Project on Methanol, Ammonia and Hydrogen Fuel Marine Engines

S. No	Project Title	Important Details
1	**MeOHmare - Methanol fuel system for maritime engines** (CO_2-neutral high-speed marine combustion engines based on renewably produced Methanol) **Status: Ongoing**	**Coordination:** Rolls-Royce Solutions GmbH **[10]** **Partner:** WTZ Roßlau gGmbH, Woodward L'Orange GmbH **[55]** **Duration:** 01.2023 - 12.2025 **Funding volume:** €7.7 million **[10]** ("BMWK - MeOHmare - Methanol fuel system for maritime engines")
2.	**MethaShip - Green Cruises with Methanol** (Methanol (MeOH) as a base fuel for medium-speed ship engines in passenger shipping) **Status: Completed**	**Coordination:** MEYER WERFT GmbH & Co. KG **[11]** **Partner:** Flensburger Schiffbau-Gesellschaft mbH& Co. KG, Lloyd's Register EMEA Branch Germany **[11]** **Duration:** 09.2014 - 05.2018 **Funding volume:** €0.6 million **[11]** ("BMWK - MethaShip - Green cruises with methanol,")

Table 3.1: Important Global Project on Methanol, Ammonia and Hydrogen Fuel Marine Engines

S. No	Project Title	Important Details
3.	**CliNeR-Eco - Climate-neutral E-Methanol and Ammonia in Large Maritime Engines** (Evaluation of multi-fuel retrofit solutions for climate-neutral e-methanol and Ammonia in large maritime engines)**Status: Ongoing**	**Coordination:** MAN Energy Solutions SE **Partner:** Scientific-Technical Center for Engine and Machine Research Roßlau gGmbH, Technical University of Darmstadt **[12]** **Coordination:** MAN Energy Solutions SE **Duration:** 01.2023 - 12.2025 **Funding volume:** €4.8 million **[12]** ("BMWK - MethaShip - Green cruises with methanol")
4.	**Ammonia Engine – Ammonia as the Maritime Fuel of the Future** (Development of simulation tools for future maritime ammonia combustion engines) **Status: Completed**	**Coordinator:** Research Center for Combustion Engines and Thermodynamics Rostock GmbH **Partner:** Loge Deutschland GmbH, University of Rostock **[13]** **Duration:** 06.2021 - 05.2023 **Funding volume:** €0.9 million **[13]** ("BMWK - Ammonia Engine – Ammonia as the maritime fuel of the future,")
5.	**AmmoniaMOT- Ammonia as the Ship Fuel of the Future** (Renewable-produced Ammonia as the fuel of the future for marine combustion engines in a decarbonized world.) Status: Completed	**Coordination:** Scientific-Technical Center for Engine and Machine Research Roßlau gGmbH **Partner:** MAN Energy Solutions SE, Woodward L'Orange GmbH, Technical University of Munich, Neptun Ship Design GmbH **[14]** **Duration:** 12.2020 - 02.2024 **Funding volume:** €3.1 million **[14]** ("BMWK - AmmoniaMot - Ammonia as the ship fuel of the future,")
6.	**Ammonia Mot$_2$ - Demonstration of a Ship Propulsion System Powered by Climate-Neutral Ammonia.** (Development of a demonstrator full engine with modularized fuel system technology for operation with renewably produced Ammonia as marine fuel) Status: Ongoing	**Coordination:** MAN Energy Solutions SE **Partner:** WTZ Roßlau gGmbH, Woodward L'Orange GmbH, SFM TU-Munich, Neptun Ship Design GmbH, LKV Rostock, GenSys GmbH, MNR GmbH **[15]** **Duration:** 08.2024 - 01.2028 **Funding volume:** €12.8 million **[15]**

Table 3.1: Important Global Project on Methanol, Ammonia and Hydrogen Fuel Marine Engines

S. No	Project Title	Important Details
7.	**HydroPoLEn - Hydrogen Engines as an Alternative for Deep-Sea Shipping** Large, high-power density engines for hydrogen operation **Status: Ongoing**	**Coordination:** MAN Energy Solutions SE **Partner:** Scientific-Technical Center for Engine and Machine Research Roßlau gGmbH, Tenneco Inc., Technical University of Munich NMA, Carnival Maritime GmbH **Duration:** 09.2022 - 08.2025 **Funding volume:** €8.8 million **[16]**
8.	**FAST Track to Clean and Carbon-Neutral WATERborne Transport through Gradual Introduction of** **Methanol Fuel:** Developing and Demonstrating an Evolutionary Pathway for Methanol Technology and Take-up. **Status: Ongoing**	**Coordination:** Lund University, BALance, ABC, Heinzmann Group, Ghent University, ScandiNAOS AB, SSPA, Meyer Werft Shipyard (MW), Lloyd's Register, National Technical University of Athens, Super Toys, Methanex, Swedish Maritime Administration (FASTWATER Project) **[17]** **Duration:** Completed **Funding Volume:** Total budget of €6,357,962.50 and €4,999,217.51 from the European Union.
9.	**MariNH$_3$** **Status: Ongoing**	**Coordination:** University of Nottingham, University of Birmingham, University of Brighton, Cardiff University (MariNH$_3$) **[18]** **Funding Volume:** £ 7.5 million (5.5 million by the Engineering and Physical Sciences Research Council + £2 million by industry)

3.1.1 Alternative Fuel Based ICE & Fuel Cell (FC)- Technological Maturity Comparison [19]

Technological maturity refers to both the maturity level achieved by ICE and FC Technology and associated systems. The following **Table [3.2]** shows the relative score against degree of maturity attained by ICE & Fuel Cell (FC) technologies. The score numbering is defined as

1. Measures that are off the shelf and commonly used on new ships
2. Measures that are commonly available, but not fully mature
3. Measures that are under piloting, and/or with only a few commercial applications
4. Measures that have not been tested on a full scale and no piloting or full-scale testing Underway

Table 3.2 : Technological Maturity Levels [19]

Fuel	Converter	Components	Maturity
LNG	ICE 4-stroke Lean Burn Spark Ignition/Dual Fuel Low Pressure (4S LBSI/LPDF)	Engine Storage tanks Process system	1
	ICE 2-stroke Dual Fuel Low Pressure (2S LPDF)	Engine Storage tanks Process system	1
	ICE 2-stroke Dual Fuel High Pressure (2S HPDF)	Engine, Storage tanks Process system NOx reduction system (EGR/SCR)	1
	FC	Fuel cell Storage tanks Electric motor & reformer Battery	3
Hydrogen	FC	Fuel cell Storage tanks Electric motor & reformer Battery	3
	ICE	Engine Storage tanks Process system	4
Ammonia	FC	Fuel cell Storage tanks Electric motor & reformer Battery	3-4
	ICE	Engine Storage tanks Process system Nox reduction system (EGR/SCR)	3-4
Methanol	FC	Fuel cell Storage tanks Electric motor & reformer Battery	3
	ICE 2-stroke Dual Fuel High Pressure	Engine Storage tanks Process system NOx reduction system (EGR/SCR)	2

Table 3.2 : Technological Maturity Levels [19]

Fuel	Converter	Components	Maturity
	ICE 4-stroke	Engine Storage tanks Process system	2
LPG	ICE - 2-stroke	Engine, Storage tanks, Process system NOx reduction system (EGR/SCR)	2-3
	ICE - 4-stroke	Engine, Storage tanks, Process system	4
HVO	ICE	Engine, Storage tanks, Process system	2
Battery-electric	Battery	Electric motor Battery, Battery management system	1

3.2 Methanol Fuel Marine Engines (Global Status)

Presently Methanol Internal combustion engines (ICE) are most advanced among all other Hydrogen and Hydrogen derived fuel engines. This has high level of technological readiness and are available commercially. Several companies have developed Methanol-ready shipping engines and supply systems. A list of Methanol fueled vessels, either in operation or in the order books, can be found **[20].** MAN Energy Solutions already commercialized dual-fuel, Methanol-ready two-stroke engines, few of them in operation since 2016. MAN Energy Solutions has 82 Methanol dual-fuel engines in their order books, with additional 120 orders being undertaken. **It is worth highlighting that in these dual-fuel engines, the modifications are performed only in the injectors, cylinder heads, and the fuel delivery system and not inside the engine to enable it to run with Methanol. Methanol also has a lower adiabatic flame temperature than conventional fuels such as diesel. This means engine cylinders can operate at lower peak temperatures than with standard fuels, limiting the formation of NOX. This may not be enough to comply with IMO Tier III requirements on NOX if methanol is used on its own. But when blended with water in a high-pressure injection system, it is possible to meet Tier III standards without the need for selective catalytic reduction (SCR) or exhaust gas recirculation (EGR).**

MAN Energy Solutions has also initiated Methanol retrofits for four-stroke engines from 2024, after successfully resolving challenges relating to fuel system and injection technology. MAN is largely promoting Methanol four-stroke engine's use in container ships, ferries, fishing boats, and cruise ships, **[21,22]** while two-stroke dual fuel engines are believed more suitable for tankers carrying Methanol, container ships, and potentially for other ship applications. Four-stroke marine engines in small vessels are similar to diesel locomotive engines used in railways. The low cetane number of Methanol presents challenges for its direct use in diesel engines. Several techniques are used to introduce Methanol into large-bore marine diesel engines, which includes (i) Blending **[23]** (ii) Emulsification with diesel, (iii) Port injection of Methanol and Direct injection of pilot diesel **[24]** (iv) High Pressure direct injection HPDI of ethanol **[25-27]** and (v) the glow plug concept

The HPDI techniques are implemented in two ways: injecting Diesel and Methanol individually through different injectors or injecting both the fuels simultaneously via special coaxial injector. **Figure 3.4** displays the layout of an HPDI-controlled, Methanol-fueled, 16-cylinder, large bore marine engine with two independent injectors. Methanol combustion with 5% pilot-injected diesel enhances the thermal efficiency and emission characteristics **[28]** Large-bore engines benefit from electronic fuel injection systems to meet strict emission norms by optimizing various injection parameters concerning varying loads and speeds **[29].**

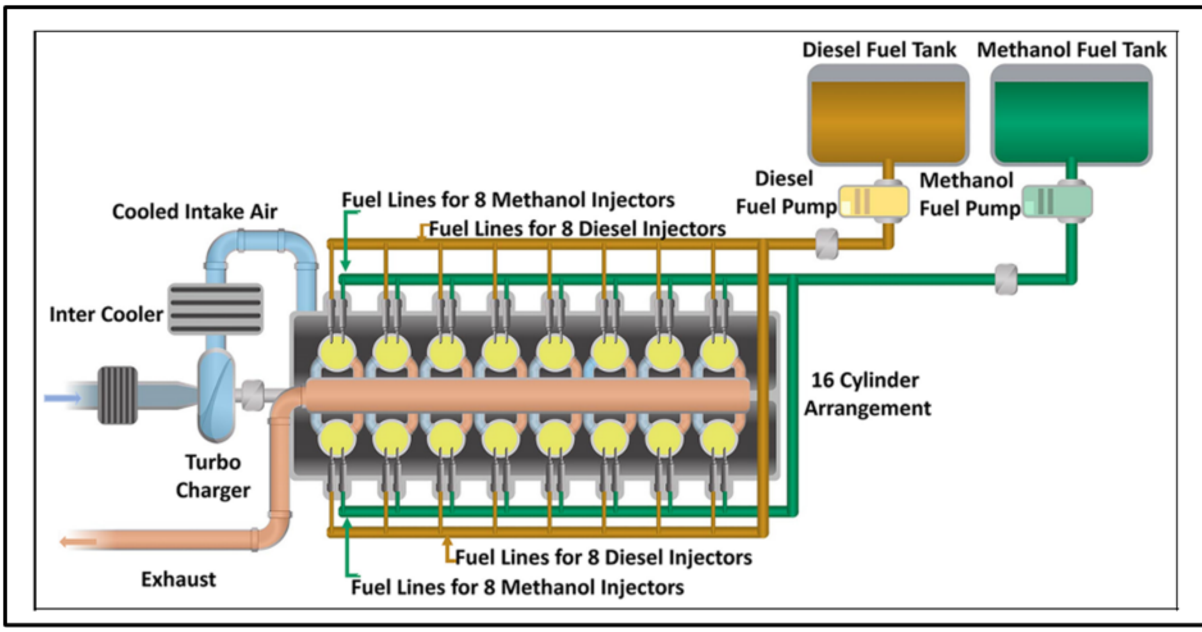


Figure 3.4: Schematic of HDPI Technique using two Injectors for Large Bore Marine Diesel Engine[9]

A new "**co-axial injector"** concept also being adopted as a practical solution to fit the two injectors in compact cylinder heads. The co-axial injector accomplishes dual-fuel capability in a single injector body without modifying the cylinder head**. Figure 3.5** illustrates a coaxial (methanol-fueled), injector-operated, large-bore marine engine demonstrated by Wartsila **[9]** Using a unique coaxial injector concept, Wartsila has enabled a sizeable deep sea passenger ferry called the Stena Germanica **[30]**. Fuel injection pressure plays a critical role in this concept. The fuel injection pressures for Methanol and Diesel are sustained at 600 and 1300 bar, respectively. The coaxial injector approach exhibits no knocking and engine derating; low total hydrocarbon (THC), CO, and formaldehyde emissions but high NOx emissions – and a cost-effective adaption of Methanol. Nevertheless, this NOx is related to the pilot fuel quantity and expected to be improved via optimization.

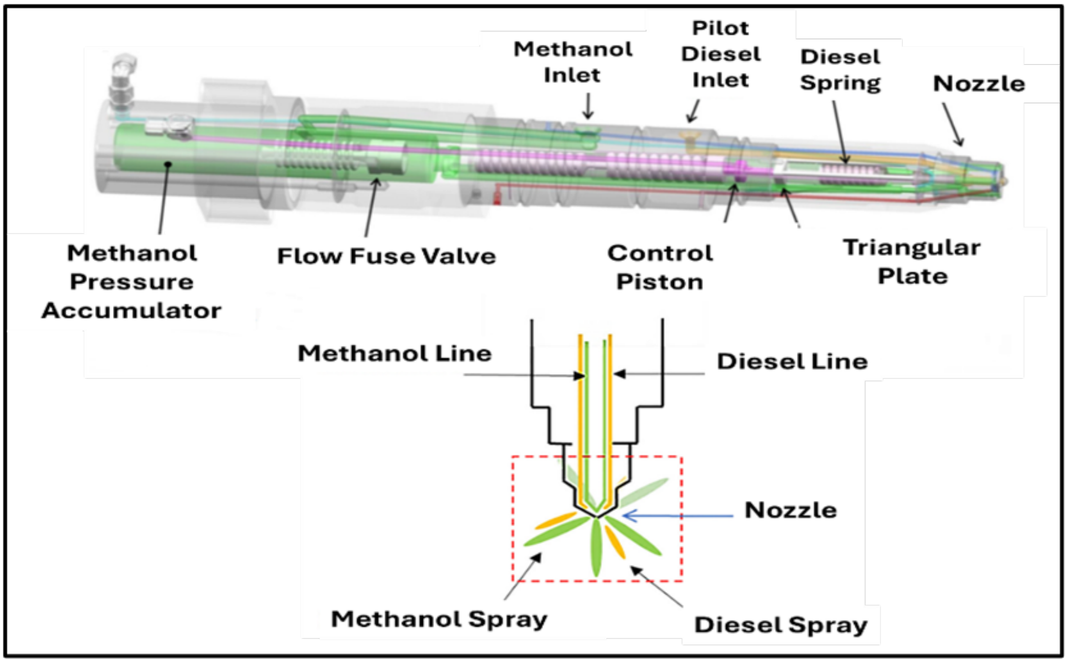


Figure 3.5: Co-axial Injector. Reproduced from [30]

3.2.1 Commercial Methanol Fuel Marine Engine

According to the Clarkson's in-service and order book data, MAN Energy Solutions (formerly MAN Diesel & Turbo) has the highest share in making methanol-fueled vessels. MAN Energy Solutions has developed the entire engine family to assist dual-fuel engine-operated ships in decarbonizing the maritime industry. This whole engine series has been labeled as the ME-LGI series. The typical engine in order and service book are

- 1 x Diesel MAN B. & W. 5S50ME-C9.6-LGIM
- 1 x Diesel - MAN B. & W. 7S50ME-B9.3-LGI
- 1 x Diesel - MAN B. & W. 6S60ME-C10.5-LGIM
- 1 x Diesel - MAN B. & W. 7S60ME-C10.5-LGIM
- 1 x Diesel - MAN B. & W. 6G50ME-C9.6-LGIM
- 1 x Diesel - MAN B. & W. 6G50ME-C9.5-LGIM
- 1 x Diesel - MAN B. & W. 6G80ME-C10.5-LGIM
- 1 x Diesel - MAN B. & W. 8G95ME-C10.5-LGIM
- 1 x Diesel - MAN B. & W. 7G80ME-C10.5-LGIM
- 1 x Diesel - MAN B. & W. 7G50ME-C9.6-LGIM

This entire series adds dual fuel-assisting technology to the already available electronically controlled ME engine series. Low and High-Pressure Methanol Supply Systems are developed by several Companies **[31].** Anglo Belgian Corporation NV, MAN Energy Solutions, Rolls-Royce-owned mtu Solutions, Caterpillar, China State Ship Building, and Hyundai Heavy Industries have developed a low-pressure system which injects Methanol into the engine at 10 bar and between 25°C and 50°C **[31]**. Wärtsilä and others use a high-pressure injection method where Methanol enters the engine at around 400 bar This configuration is recently proposed for a general cargo vessel called the MV Eemsborg, equipped with a 4.5 MW Wärtsilä engine **[32].**

Methanol Engine Manufacturers and their Engine profiles are briefed in **Table 3.3**

Table 3.3: Methanol Engine Manufacturers [31]

S. No.	Manufacturer	Details
1.	**Anglo Belgian Corporation (ABC)**	DZC dual-fuel engine portfolio, with 6 and 8 cylinder inline engines and 12 and 16 cylinder V-engines, covers a power range from 600 kW up to 10.4 MW.
2.	**Caterpillar**	Cat® 3500E-series marine engines can be modified to run on methanol.
3.	**China State Shipbuilding Corporation (CSSC) Power Research Institute, Anqing CSSC Diesel Engine, and Hudong Heavy Machinery**	Developed the 6M320DM methanol fuel engine, first ignited on August 28. The engine can be adapted to various ships of up to 20,000 GT.
4.	**Hyundai Heavy Industries - Engine & Machinery Division (HHI-EMD)**	14 methanol dual-fuel, two-stroke engines delivered, and 17 more on order (as of Feb 2022).
5.	**MAN Energy Solutions**	ME-LGIM two-stroke dual-fuel methanol engines have accumulated more than 145,000 hours of operation. Four-stroke methanol engines are currently being developed.
6.	**mtu Marine solutions (by Rolls-Royce)**	Launching methanol engines based on the mtu Series 4000 from 2026, and Fuel Cell s from 2028.
7.	**Nordhavn Power Solutions A/S**	Offers 13 liter/6 cylinder and 16 liter/8 cylinder marine methanol engines, in partnership with ScandiNAOS.
8.	**Wärtsilä**	W32 and W46 methanol engines already in the market draw from the experience accumulated since 2015 on the conversion of a Wärtsilä Z40 engine and its operation in the ropax vessel Stena Germanica. Additionally, two-stroke engine retrofits in collaboration with MSC.
9	**WinGD and HSD Engine**	Methanol-fueled engines under development in a joint development program. It aims to launch the first engines by 2024.

Waterfront Shipping Canada has achieved dual-fuel Methanol two-stroke engines operation over 145,000 hours and owns 19 Methanol ready vessels [53]. Another Company, Marinvest Shipping, one of Waterfront Shipping's partners, is using Methanol over five years. Although Dual fuel engines leads to ~7 % increase in maintenance costs over single-fuel variants [**32],** these provide flexibility to switch to lower-priced fuels depending on market fluctuation.

Anglo Belgian Corporation (ABC) DZC dual-fuel engine portfolio, with 6- and 8-cylinder inline engines and 12 and 16 cylinder V-engines, has power range between600 kW to 10.4 MW. Caterpillar Cat® 3500E-series marine engines have are capable to use Methanol with minor modification. China State Shipbuilding Corporation (CSSC) Power Research Institute, Anqing CSSC Diesel Engine, and Hudong Heavy Machinery has developed the 6M320DM Methanol fuel engine whic can be adapted to ships of up to 20,000 GT. Hyundai Heavy Industries - Engine & Machinery Division (HHI-EMD) developed 14 Methanol dual-fuel, two-stroke engines with 17 more under development **[33].**

MAN, Energy Solutions ME-LGIM two-stroke dual-fuel Methanol engines have accumulated more than 145,000 hours of operation. Four-stroke Methanol engines are currently being developed. mtu Marine solutions (by Rolls-Royce) planned to Launch Methanol engines based on the mtu Series 4000 from 2026, and Fuel Cell s from 2028. Nordhavn Power Solutions A/S Offers 13 liter/6 cylinder and 16 liter/8-cylinder marine Methanol engines, in partnership with ScandiNAOS. Wärtsilä W32 and W46 Methanol engines. In addition, two-stroke engine retrofits in collaboration with MSC. WinGD and HSD Engine Methanol fueled engines are presently under development **[33].**

In conjunction to Methanol ICE, there are great advancement in Low and High pressure Methanol supply system development. Companies such as Anglo Belgian Corporation NV, MAN Energy Solutions, Rolls-Royce-owned mtu Solutions, Caterpillar, China State Ship Building, and Hyundai Heavy Industries have developed a low pressure system that involves injecting methanol into the engine at around 10 bar and between 25ºC and 50ºC **[34]** In the case of MAN Energy Solutions, the fuel supply system operates at fairly low pressure (approximately 10 bar) in order to move the fuel from tank to engine room, where it is prepped (pre-heated in some cases to 50 °C for optimized combustion) before entering MAN's proprietary Fuel Booster Injection Valve (FBIV) at up to 300 bar46. Wärtsilä and others, meanwhile, use a high-pressure injection method where methanol enters the engine at around 400 bar (see Figure 40). This allows water to be mixed with the fuel to provide a methanol-aqueous solution, reducing costs and emissions. This configuration has already been proposed for a general cargo vessel called the MV Eemsborg, equipped with a 4.5 MW Wärtsilä engine **[32].**

3.3 Ammonia Fuel Marine Engines

Anhydrous Ammonia is presently being considered as a carbon-neutral fuel for Marine propulsion. Ammonia liquefaction is achieved easily with compression at 0.8 MPa, 20 °C or by cooling at 33°C under atmospheric conditions. Ammonia has strong polarity due to its trigonal pyramidal asymmetrical shape, where nitrogen is more electronegative than the rest of the three H atoms. As a result, Ammonia becomes a highly hygroscopic characteristic, which forms undesirable moisture and corrodes metals such as brass and gaskets. The onboard safety of Ammonia is also quite good in terms of storage as it has a narrow flammability range (15%–28% by volume in air). The octane rating of Ammonia is 120, higher than Gasoline's, typically in the range of 86-93. making it a fuel more suitable for Spark Ignition engines. It can be ignited in CI engines with some different ignition strategies. Also, it can be easily used in Fuel Cell s. One of the major drawbacks of using Ammonia as fuel includes its high resistance to auto ignition, high ignition energy and low laminar flame speed (burning velocity as shown in **Figure 3.6**

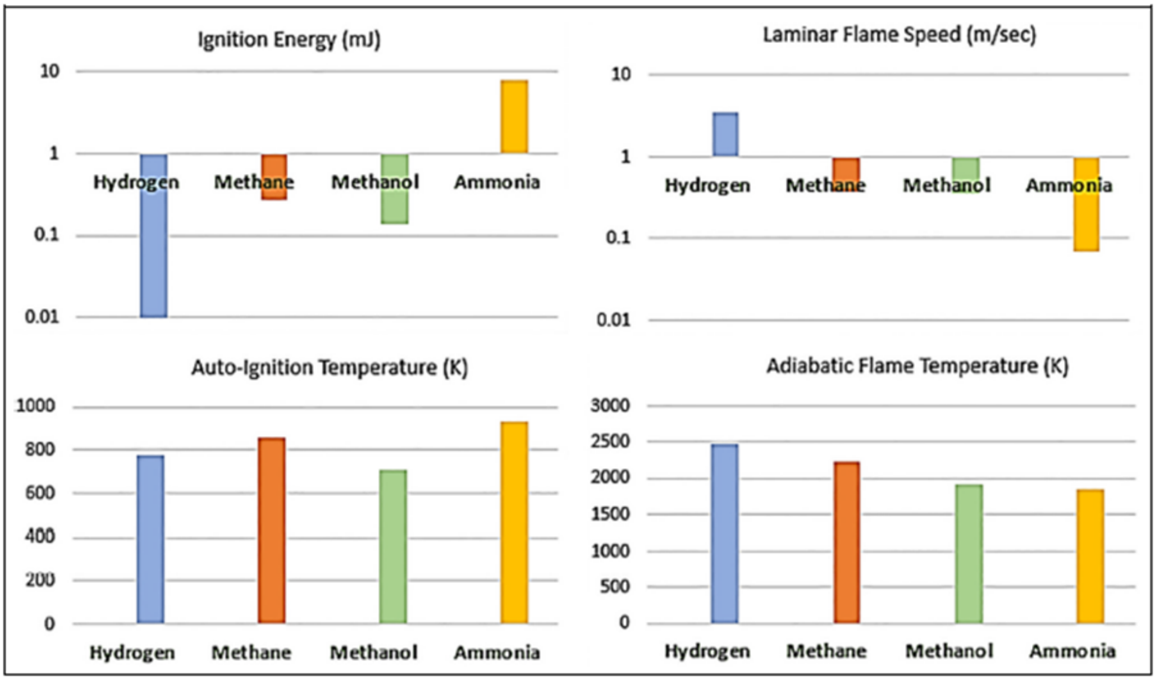


Figure3.6: Comparaison of Selected Alternative Fuel Properties (Ignition Energy, AutoignitionTemperature, Laminar Flame Speed and Adiabatic Flame Temperature)

The ignition of Ammonia is relatively poor as its minimum ignition energy is quite high, i.e., 680 mJ compared to other potential fuels (0.6 mJ for Ethanol, 0.14 mJ for Methanol, 0.016 mJ for Hydrogen, ~0.14 mJ for Gasoline and ~0.23 mJ for Diesel). Also, the Ammonia powered vehicles may face cold start issues as it has quite a high latent heat of vaporization (1370 KJ/kg) than other fuels (840 KJ/kg for Ethanol, 445.6 KJ/kg for Hydrogen, 305 KJ/kg for Gasoline). In addition, the exceptionally high latent heat of vaporization reveals that the moment ammonia is injected into the in-cylinder combustion chamber, it would reduce the cylinder temperature, eventually leading to incomplete combustion and some engine efficiency losses. Presently one of the major challenges associated with Ammonia fueled engines is the high NOx emissions,

Two fuel injection techniques presently being employed are Port Injection of Ammonia with direct Injection of Diesel into the combustion chamber and the High-Pressure Direct Injection (HPDI) of Ammonia with pilot Diesel strategy. The latter can also be achieved in two ways: (i) a Co-axial Injector concept and (ii) a Two Separate injector concept. Rarely is any study demonstrated using a co-axial injector, especially for marine engines. In the latter approach, one injector injects Diesel into the combustion chamber, and another injector injects Ammonia into the chamber. The Diesel in this case is injected earlier to start combustion, and the Ammonia is injected in the hot Environment.

3.3.1 Commercial Ammonia Fuel Marine Engines

The low reactivity of Ammonia makes it a suitable fuel for Spark Ignition (SI) and a challenging fuel for compression ignition (CI) engines. However, Ammonia has been pushed for the Maritime Industry, where large-bore low-speed, two-stroke CI engines operate huge ships. Generally large CI engines in ships are unaffected by slow-burning velocity of Ammonia on the initiation of combustion. A large amount of Ammonia injection into the engine can potentially overcome the energy demand in order to meet the engine torque [9]. The use of Ammonia as a fuel for low-speed, two-stroke engines focuses largely on minimizing Nox emissions. For high-speed, four-stroke engines, Ammonia–Diesel combustion-initiation and duration improvements are absolute necessity **[9].** It is perceived that in order to consume the unburnt NH3 in the exhaust gases, advanced techniques like flue gas recirculation or humidification process or even using post-combustion techniques such as selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR) could be resorted to. Therefore, Ammonia ship engines equipped with advanced SCR techniques are expected to make moderate penetration in the market. The mariNH3 research program has also announced the development of the technology to operate marine-fueled vessels as seen in **Table 3.1**. This is primarily funded by the Engineering and Physical Sciences Research Council **[18].** The utmost requirement for operating the Ammonia-fueled ship here is the green ammonia production technology, advanced combustion and new fuel injection system development and the effective policy framework for Ammonia usage and its supply chain. The tri-fuel strategy is also being explored, where Diesel will be injected directly into the combustion chamber, and Ammonia/ Hydrogen will be injected into the port.

Global engine developers like MAN, WinGD, and Wartsila are actively working on Ammonia 2-stroke and 4-stroke marine engines development. Wartsilla has developed world's first commercial medium-speed 4-stroke Ammonia engine. More details are given in Annexure III. Presently Win-GD is leading the Ammonia engine development as seen from orderbook data Figure3.1(b)

3.4 Hydrogen as Fuel in Marine Engines

Hydrogen is a non-Carbon energy carrier with a low volumetric energy density (4.5 MJ/L) and need minimum 700 bar pressure for liquefaction under cryogenic condition (-252.90C). Compression ignition (CI) and spark ignition (SI) engines are considered most preferable for Hydrogen as a fuel in single or dual-fuel mode of operation. Hydrogen flame speed is responsible for operating less cyclic variation-based engines. Where gasoline-air mixtures need 0.24 MJ energy, hydrogen-air mixture needs only 0.02 MJ energy for ignition [35]. Hydrogen's required auto-ignition temperature is ~ 585 °C, which is significantly higher than the other fuels [36]. This means that the ignition of hydrogen combustion necessitates another ignition source, and the combustion initiation cannot happen with heat alone.

Hydrogen-fueled large-bore CI engines are being investigated, especially for large ship engines. However, some properties such as a small ignition energy requirement and a wider combustion spectrum, make it an explosive fuel. On the other hand, hydrogen leaks easily and spreads quickly and it becomes highly challenging to find the leakage spot as it has no color or smell. Hydrogen embrittlement is another challenge for metal parts, eventually affecting their mechanical properties and longevity **[37]**. Thus, hydrogen usage requires strict practical standards to be followed for hydrogen purification, hydrogen production, and transportation purposes.

The development and operation of hydrogen-fueled engines highly depend on using a fuel injection system. One of the significant challenges for hydrogen-fueled internal combustion engines is the backfiring of hydrogen flames from the intake system—this kind of backfiring results in uneven operation of hydrogen-fueled engines. Therefore, selecting a fuel injection technique is the priority for the suitability of hydrogen-fueled engines. The fuel injection techniques adopted i.e. Port fuel injection and HDPI injection are discussed below.

In the port fuel injection of Hydrogen and direct injection of Diesel approach, Hydrogen is injected into the port, and Diesel is injected into the combustion chamber, as shown in **Figure 3.7 [38]**. In this approach, controlling the precision injection timing for diesel and hydrogen injection is the major challenge. It is important to note that precision injection timing with the fuel droplet size plays a vital role in achieving ultra-combustion efficiency. Although this approach enables hydrogen usage for powering ICE, it comes with several challenges such as (i) Engine power reduces up to a certain extent as the hydrogen injection takes place in the intake manifold, which eventually occupies some portion of air, and the volumetric efficiency decreases drastically. (ii) Port fuel injection technology-based hydrogen-powered engine resulted in higher NOx emissions at the tailpipe, (iii) Backfiring of Hydrogen is the major challenge for this approach.

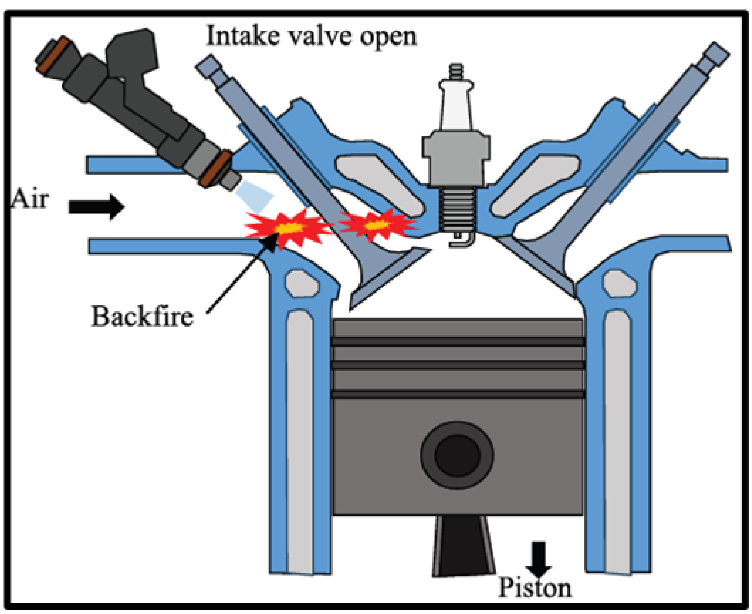
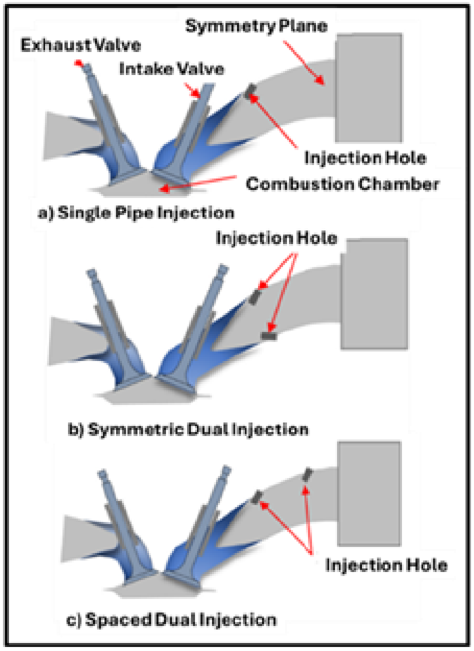


Figure 3.7: Port Injection of Hydrogen and Direct Injection of Diesel

Low ignition energy requirement, shorter quenching distance, lower lean burn limits of Hydrogen, and higher flame velocity are the reasons for hydrogen backfiring. “Backfiring” is generally defined as the abnormal combustion that occurs during the intake stroke. A backfire is an abnormal combustion inside the intake manifold during the intake stroke that happens in the engine’s intake manifold. In the worst case, it elevates the engine knock phenomenon and eventually damages the cylinders and pistons.

Several researchers have suggested that the control of injection timing and location of the hydrogen injector positions can be optimized to eliminate backfire issues [**39]**. Also, injection angles could play a significant role, as shown in **Figure 3.8 and Figure 3.9 [39]**.



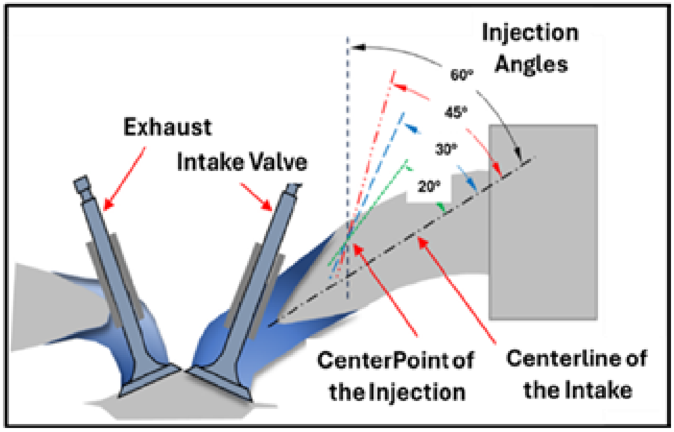


Figure 3.8: Different Positions for Hydrogen Injectors & Figure 3.9: Different Angles for Hydrogen Injections in the Intake Manifold

In case of HPDI of Diesel and Hydrogen approach, Diesel and Hydrogen are both directly injected into the combustion chamber[40]. This approach could replace ~ 90% of diesel energy with Hydrogen. This is an essential dual-fuel strategy, where Diesel and Hydrogen can be injected at different crank angles.

The significant advantage of this technology is that high compression ratios can be easily achieved to increase the engine's efficiency. This approach would eliminate volumetric efficiency loss and is easily used to improve the power output of hydrogen-fueled engines. In this approach, Hydrogen is injected directly into the combustion chamber upon closing intake valves, thus eliminating the backfiring of Hydrogen, which is a common problem in port fuel injection technology. Equipping Hydrogen directly into the combustion chamber achieves stratification combustion quickly, eventually accelerating the flame propagation. Therefore, engine knocking can be avoided easily, and heat transfer loss is achieved easily through the in-cylinder wall.

Hence, this technology once developed commercially can resolve the NOx and particular matter (PM) emission problems.

Blending Hydrogen with Methane (in long-term replacing with bio- or e- Methane) could be another viable option for using Hydrogen. Critical analysis of the Hydrogen-Methane blending effect on power capability and emissions characteristics has shown that blending upto 20 vol %

Hydrogen can significantly reduce CO2 emissions while maintaining the Methane concentration at a moderate level **[41]**. Focused research should be carried out in this direction.

3.4.1 Commercial Hydrogen Fueled Marine Engines

MAN Energy Solutions (formerly MAN Diesel & Turbo) has developed MAN D2862 Hydrogen Dual Fuel Engine for marine applications. In this engine, Hydrogen is inducted into the charge using an adapter. Combustion happens according to the diesel principle; thus, a 5% diesel injection is needed to initiate diesel combustion. Photos of newly developed engine components are shown in **Figure 3.10. Technical details of Hydrogen Commercial engines are given in Annexure III**

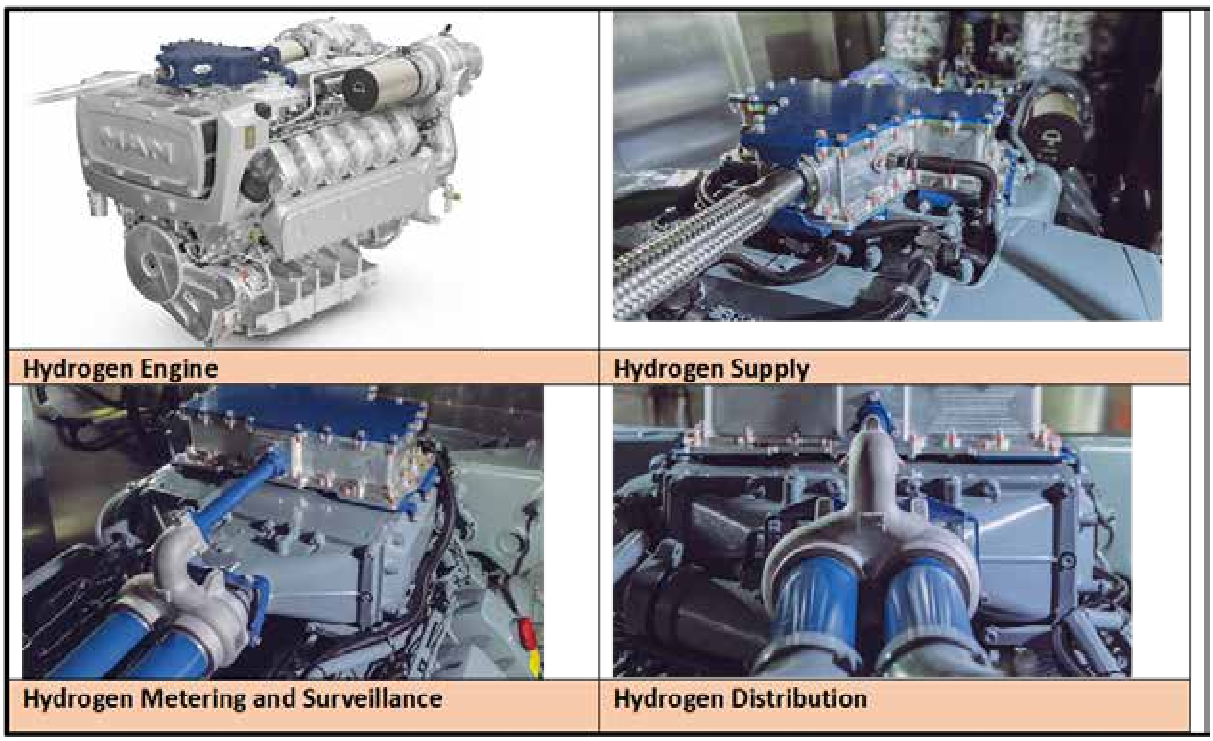


Figure 3.10: Hydrogen engine by MAN Energy Solutions (formerly MAN Diesel & Turbo) [6]

Conclusions and Recommendations for India

» ICE will inevitably play a key role in marine shipping with a gradual shift towards low carbon and carbon neutral fuel options.

» Among different low Life Cycle Fuels (LLCF) Methanol (bio and e fuels), Ammonia (green and e-fuels), Hydrogen (green) LNG (e and bio fuels) show great potential for adoption in ICE

» For Alternative fuels, focus should be on scaling up production technologies with least GFI factor (e.g. towards 2030 Priority could be Biofuel (GFI 9.4), Bio LNG (GFI 9.4), E-Ammonia (GFI 12.1), bio-Methanol (GFI 13.3), blue Ammonia (22.6), E-Methanol (29).

- Appropriate carbon pricing, decrease of green Hydrogen cost, availability of additional RE will encourage green fuel developers to invest in large scale Bio and E-Methanol as well as E-Ammonia production plants to make India not only self-reliant but to become a global hub both for Methanol and Ammonia.
- Till large scale development and deployment of alternate fuel-based ICE, mixed fuel strategy holds the key especially with blended fuel towards 2030 and beyond at least upto 2035.
- Global transition for use of alternative fuels in vessels shows clear domination of **LNG with 67% share followed by Methanol 17 %, LPG 8%, Ethane 3%, Biodiesel 2%, Hydrogen 2%, Ammonia 1% in orderbook.**
- Global alternative fuel engine manufacturing shows clear domination of engine makers **LNG engines with Wartsila 57% market share (in-service) and Wartsila 50.9% and MAN 49.1 % in (orderbook)**
- Among Sustainable fuel (Bio and E fuel) based options, Methanol with 47% market share followed by Biofuel(Biodiesel) (5%)> Hydrogen (4%) and Ammonia (4%).
- Alternative fueled engines are critically Important for green shipping transition. Present global market is dominated by International engine manufacturers (**MAN** B&W leads with 79% for Methanol, 42.9% for Hydrogen, and varying shares in 49.1% LNG, 100% LPG, and Ethane; **Wartsila** follows with significant shares 57% in LNG, 33% in Hydrogen, 33.3% in Ammonia; **WinGD** focuses on Methanol with 9% share and Ammonia 80% share; **Yanmar** leads in biofuel with 64.3% share).
- India needs to initiate alternative fuel IC Engine manufacturing and alternatively developing strong strategic partnership with Global key players in ICE development.
- Ammonia transition is projected between 2035 onwards due to ammonia-ICE development trajectory is in infancy. The ammonia engines deals with a new combustion systems including fuel systems to withstand their challenging properties like high corrosivity, low lubricity, vapor pressure and extreme safety issues.
- **Although Hydrogen is promising, nevertheless owing to high liquefaction cost, safety challenges and absence of present large scale global distribution infrastructure, its adoption using Fuel Cell and Fuel Cell hybrid propulsions rather than ICE would be most suitable for India's inland waterways or domestic green corridors towards 2030 over deep sea/ocean going vessels.**
- Methanol shows the highest adoption potential in ICE owing to large scale commercial development, ease of storing and bunkering being liquid at room temperature and more cost-effective w.r.to retro fitment in comparison to its other contenders like Hydrogen and Ammonia.
- DME should also be looked into as a high cetane Diesel replacing renewable fuel which can easily be produced from Methanol through catalytic dehydration.
- Methane slip concerns make LNG and E-LNG still unattractive in medium to long run although it has the easy retro fitment and bunkering aspects. LNG conversions lack the use of their full potential owing to unacceptable levels of high methane slip. HPDF, RCCI, and Stoic-EGR-TWC methods

can reduce methane slip to enable LNG ships and mitigate the adverse effects of obtaining GHG reduction (Methane Slip 1 g/kWh).

» Dual-fuel combustion systems as retro fitment strategy also for new vessels are of absolute necessity towards achieving decarbonization in shipping without the risk of investment in stranded assets

» Dual fuel combustion technologies are equally suitable to both types of engine classes i.e. four-stroke (medium- and high-speed) and two-stroke (low-speed engines).

» Dual-fuel systems can enable advanced combustion modes such as reactivity-controlled compression ignition (RCCI) **[25]** that are suitable for low-reactivity fuels such as Methanol, Ammonia and LNG.

» High pressure direct injection (HPDI) can be adopted with two separate injectors or a single coaxial injector. Conventional and advanced turbocharging architectures are essential in ship engines to achieve high efficiency and clean combustion targets with carbon neutral fuels

» Factors such as price per ton of CO2, geographic scope, schedule of implementation, and how the revenues from the carbon levy are used will have a decisive impact on the maritime industry

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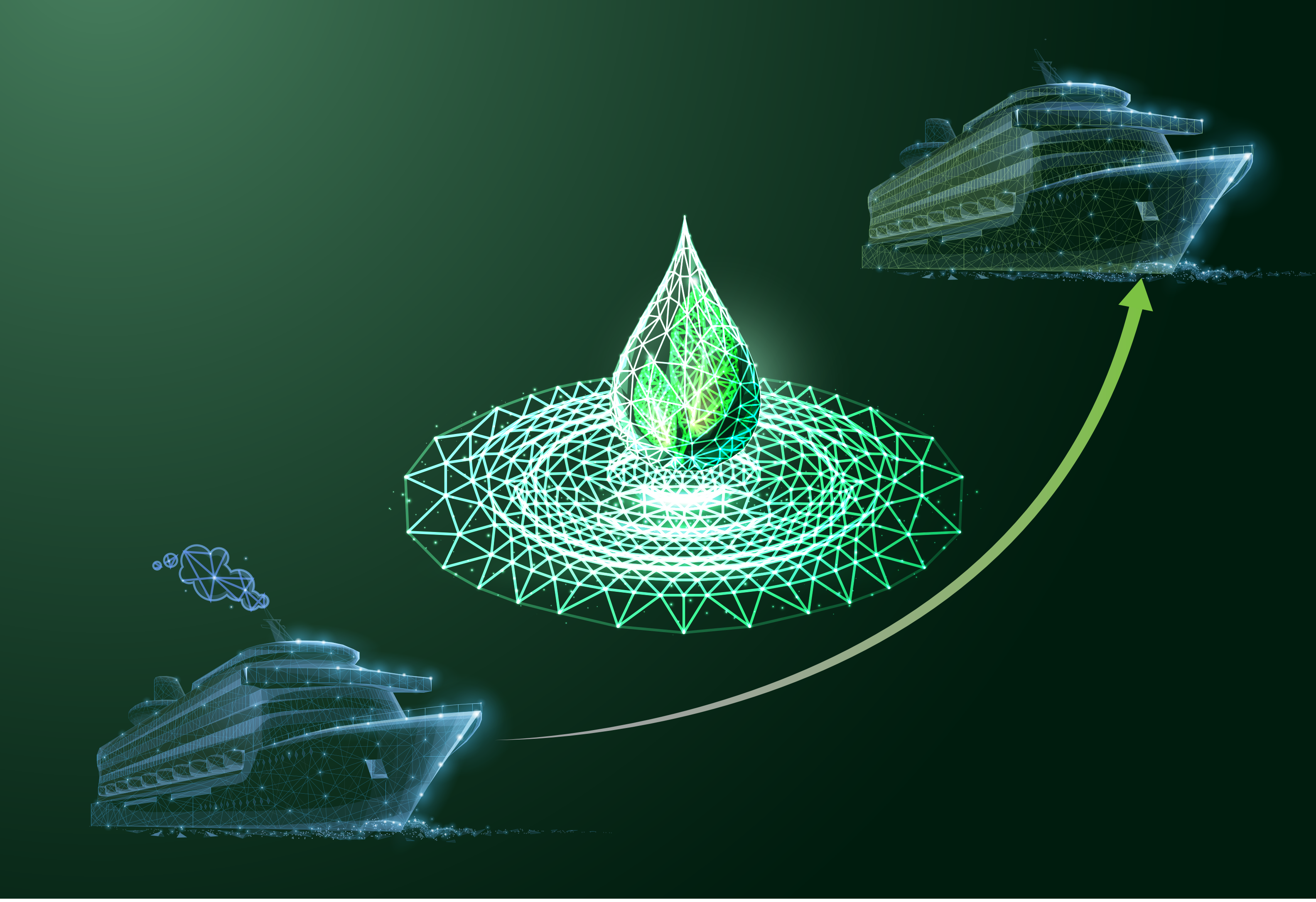


Chapter 4

Comparative Assessment of Alternative Fuels

In this Chapter, the Section 4.1 provides a comparative assessment of the alternative fuels based on their sustainability aspect like properties and production pathways (4.1.1), Cost (4.1.2) and LCA performance (4.1.3).

In **Section 4.2 alternative fuel and fuel-mix demand scenarios** are built to estimate the fuel required for India in meeting **IMO's revised emission targets as per MEPC 83 revised guidelines [1]. Three Scenarios are built where the Scenario-1 estimates fuel/fuel-mix demand for meeting GFI based emission targets by year 2030 and 2035. Scenarios-2 is built for replacing fossil fuels' 5% energy equivalence with alternative fuel by 2030 as per IMO's earlier guidelines in MEPC 80. Scenarios-3 on the other hand is based on the blend fuels approach which considers dual or multifuel blending of possible low carbon/zero carbon fuels such as (Methanol- Diesel & Methanol- Biodiesel -Diesel etc.). In the blend-fuel strategy, the major advantage is the use of existing engines without the need for expensive retrofitting or replacement in short to mid-terms.**

Section 4.3 gives the overview of alternative fuel production status for India and global. **Section 4.4** presents the India's alternative fuel demand and supply readiness gap. As most of these alternative fuels, owing to their distinct physical and chemical properties, demand new or highly modified existing storage and bunkering infrastructure, hence, **Section 4.5 deals with the status of alternative fuel-based storage and bunkering readiness in global ports. In order to achieve India's aspirational goals of making Indian ports as global green fuel hubs, an estimation is also made on the need of excess fuel and additional bunkering infrastructure for 5,10,20,30% bunker fuel transition to its' alternative's counterparts.**

Additionally, the excess Green Hydrogen and excess Renewable Energy (RE) requirements for meeting the alternative fuel and the fuel-mix demand is also evaluated.

4.1 Ranking of Alternative Fuels based on Sustainability Aspects

4.1.1 Alternative Fuels Properties-Comparative Assessment

Alternative fuels considered in this study are Methanol (bio & e-), Ammonia (e, green and blue), Hydrogen (Green), Biofuels (Biodiesel, Bio Ethanol) & Methane (bio and e-LNG) for their potential in decarbonizing Indian maritime sector. These fuels are assessed with respect to multiple production pathways and properties as marine fuels. In particular, e-fuels are defined as green synthetic fuels which include e-Methanol, Hydrogen, e-Ammonia, e-LNG etc. In theory, e-fuel are seen as a photovoltaic enrichment product, where the production process is also termed as Power-to-X, which can achieve net-zero carbon emissions in principle **[3,4]**. However, e-fuels are still in the early stages of development, and there are few case studies concerning the lifecycle carbon emission of e fuels. **Figure 2.1** Compares the alternative fuel properties from energy, environmental, design and safety related aspects.

Table 4.1: Comparison of Alternative fuels properties from energy, environmental, design and safety aspects [data from 2, 3]

Fuel Properties (Overview)								
Fuel type	**HFO**	**LNG (Methane)**	**LPG**		**Methanol**	**Ammonia**	**Hydrogen**	**Biodiesel**
			Propane	**Butane**				
TtW CO_2 Emission [HFO=1]	1	0.73	0.85	0.86	0.90	0	0	0.94
TtW GHG Emmision [HFO=1]	1	0.82	0.86	0.86	0.92	0.04	0.01	0.42
Required to Obtain the Same Amount of Energy Fuel ton [HFO=1]	1	0.84	0.87	0.88	2.02	2.16	0.34	0.92
In Liquid Form Fuel Tank Capacity [HFO =1]	1	1.89	1.69	1.41	2.47	3.07	4.63	0.84
Flammability (Lower Explosive Limit)	0.70 vol%	5.0 vol%	2.1 vol%	1.8 vol%	6.0 vol%	15.0 vol%	4.0 vol%	-
Toxicity (TLV-TWA*)	-	-	-	-	200 ppm	25ppm	-	-
Cyrogenic (Boiling point)	- (Liquid at room temp.)	-161 °C	- 42 °C	-0.5 °C	- (Liquid at room temp)	-33 °C	- 253 °C	- 100-350

Table 4.1: Comparison of Alternative fuels properties from energy, environmental, design and safety aspects [data from 2, 3]

Fuel Properties (Overview)								
Fuel type	**HFO**	**LNG (Methane)**	**LPG**		**Methanol**	**Ammonia**	**Hydrogen**	**Biodiesel**
			Propane	**Butane**				
Fuel properties (Environment-related)								
Emissions	NOX SOX PM	NOX Methane slip	NOX		NOX Methanol slip Formaldehyde	NOX Ammonia slip N2O	NOX Hydrogen slip	NOX CO PM
List of fuel properties (Design-related)								
In liquid form Energy Density per unit Volume [HFO=1]	1	1.89	1.69	1.41	2.47	3.07	4.63	0.86-0.9
Liquid density [ton/m3]	0.96	0.42	0.5	0.6	0.79	0.68	0.70	0.88
Liquefaction temp. (Boiling point)	-	-161 °C	-42 °C	-0.5°C	65 °C	-33 °C	-253°C	340°C to 375°C
Lower calorific value [MJ/kg]	40.5	49.1	46	46	19.9	18.6	120.0	37.8
Engine type (2 stoke)	Diesel	Diesel / Otto	Diesel	Diesel	Diesel	Diesel		Diesel
Engine type (4stroke)	Diesel	Otto	Diesel	Diesel	Diesel /Otto	Otto		Diesel

Table 4.1: Comparison of Alternative fuels properties from energy, environmental, design and safety aspects [data from 2, 3]

Fuel Properties (Overview)								
Fuel type	**HFO**	**LNG (Methane)**	**LPG**		**Methanol**	**Ammonia**	**Hydrogen**	**Biodiesel**
			Propane	**Butane**				
Onboard storage methods	Gravity tank	Type A/B/C Membrane	Type A/B/C Membrane		Gravity tank	Type A/B/C Membrane	Low temp.(Type C Membrane),High pressues (Type 1/2/3/)	Gravity tank
List of fuel properties (Safety-related)								
Flammability [Vol%]	0.7 – 5	5 - 15	2.1 - 9.5	1.8 – 8.4	6 – 50	15 – 33.6	4 - 75	0.6-7.5%
Flash point	>60 ℃	-187 °C	-104 °C	-60 °C	9 °C	132 °C	-	140 to 180°C
Ignition point	>400 °C	537 °C	450 °C	365 °C	440 °C	630 °C	560 °C	705-840 °C
Minimum ignition Energy	-	0.3 mJ	0.26 mJ	0.26 mJ	0.14 mJ	680 mJ	0.017 mJ	1 mJ to 1000 mJ
Toxicity [ppm] (ACGIH, TWA-LV*1)	-	-	-	200	25	-		-
Toxicity [ppm] (ACGIH, TWA-LV*2)	-	-		1000	250	35	-	-

Comparison of the properties of alternative fuels gives the following insight

- GHG Emission performance (WtW) of alternative fuels in descending order is Blue Hydrogen=Blue Ammonia (22.6) > E Methanol (17.1)> E Ammonia (12.1) >E Hydrogen (12.1) > Biodiesel (9.4)= Bio Methanol (9.4) with WtT and TtW in the following order respectively
- Storage tank size variation (considering HFO as 1) in descending order Hydrogen (4.6 x), Ammonia (3.07 x), Methanol (2.47x), LNG (1.89x) LPG (1.49- 169 x), Biodiesel (0.84x)
- Hydrogen requires storage at -253°C, making it extremely difficult to handle.
- Ammonia storage easily at -33°C better than hydrogen.
- Methanol being liquid at ambient temperatures is easy to store, handle and transport.
- LNG (Methane) offers a 27% CO_2 and 18% GHG reduction, making it a good transitional fuel, though still fossil based.
- LNG requires cryogenic storage at -161°C.
- LPG (propane and butane) offers moderate emission reductions and easier storage (no cryogenics).
- Ammonia is highly toxic, with a Threshold Limit Value -Time Weighted Average i.e.TLV-TWA of 25 ppm, requiring advanced safety protocols in handling and onboard systems.
- Methanol is also toxic (TLV-TWA: 200 ppm), though more manageable than ammonia, and already used in some pilot vessels.
- Hydrogen is non-toxic but highly flammable, requiring extreme caution in storage and transport.
- Flammability varies across fuels: Hydrogen (4.0 vol%) and LNG (5.0 vol%) are highly flammable, while Ammonia is only flammable above 15.0 vol%, making it less prone to explosions, Biodiesel is not having flammability issue.
- Tank size requirements significantly affect ship design, cargo capacity, and voyage planning, especially for Hydrogen and Ammonia and Methanol.
- Cryogenic storage demands increase complexity and cost of fuel systems for Hydrogen, LNG, and Ammonia.
- No single fuel is perfect—each option involves trade-offs between emissions, safety, energy density, and infrastructure readiness.
- Short-term adoption favours LNG and Methanol, while Ammonia and Hydrogen are best suited for future zero-carbon strategies as technology matures.

A brief glimpse of individual production pathways of (bio- and e -) alternative fuels are presented below.

Methanol (Bio & E)

Currently, Methanol is generated from fossil fuels (either Natural gas or Coal) with global production around 98 Million Tons (MT) per year which emits around 0.3 Gigatons (GT) of CO2 annually. This accounts for about 10% of the emissions from chemical sector. Methanol demand is expected to rise to around 500 MT by 2050, leading to ~1.5 GT of annual CO2 emission. In order to reduce emission from its production, bio- & e-Methanol production pathways are absolutely necessary. **Figure 4.1** presents the schematic of different colored Methanol production pathways depending on varying feedstocks it is made from [4,5]. Present 65% of global Methanol production is from Natural gas and the rest from Coal, whereas, renewable Methanol comprises ~0.42% [**5]**. Methanol is produced via catalytic hydrogenation of CO2 at 200-300^{0}C and 50-100 bar pressure as per following **Equation 1**

Equaltion 1:

$$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O \quad \Delta H_r = -49.2 \text{ kJ / mol}$$

As seen from **Figure 4.1** Methanol produced via coal gasification (Brown Methanol) or Natural gas reforming (Grey Methanol) are termed as high carbon intensive Methanol, whereas Methanol produced from renewable resources is considered low carbon intensify fuel (Blue and e-Methanol). Methanol can offer ~25% CO2 emissions reduction potential compared to HFO. In addition, Methanol can reduce SOx, NOx and PM by 99%, 60% and 95% respectively **[6].** 100% renewable Methanol / Green Methanol) is produced via bio or e- production pathways. **Bio-methanol is obtained from gasification of biomass feedstocks. E-methanol is produced using from captured CO2 and renewable based green Hydrogen. The captured CO2 can be of two types renewable CO2 which is originated from biomass and from direct air capture (DAC), whereas non-renewable CO2 is recycled from fossil fuels-based industries and power plants [6].** Blue Methanol on the other hand is produced using blue Hydrogen which in turn is generated with grey hydrogen integrated with CCS. Methanol is miscible in water, biodegradable and can be 100% renewable. The life-cycle environmental footprint of bio-Methanol is "greener" in comparison to LNG.

Ammonia (Bio & E)

Presently around 98% of Ammonia (NH_3) is conventionally produced by catalytic steam reforming of Natural gas. This process accounts for around 1.8% of global CO2 Emission **[4].** MPa and temperatures between 350 °C to 550 °C [**7**]. According to the source of hydrogen, ammonia fuel can be classified into three categories: grey Ammonia, blue Ammonia, and green Ammonia. Conventionally, Industrial Hydrogen which is produced via steam reforming of Methane SMR) is used with Nitrogen obtained through air separation for Ammonia production as per Haber Bosh (HB) process according to the following reaction shown in Equation 2. The enhanced HB process employs renewable electricity for

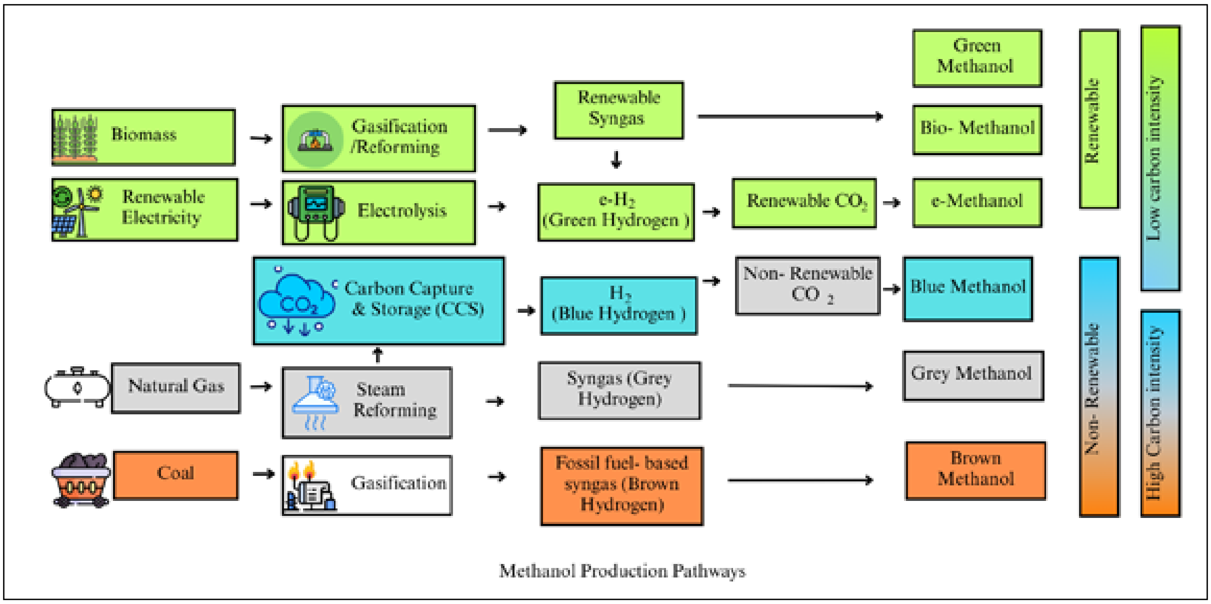


Figure 4.1 : Methanol Production Pathways [based on 4]

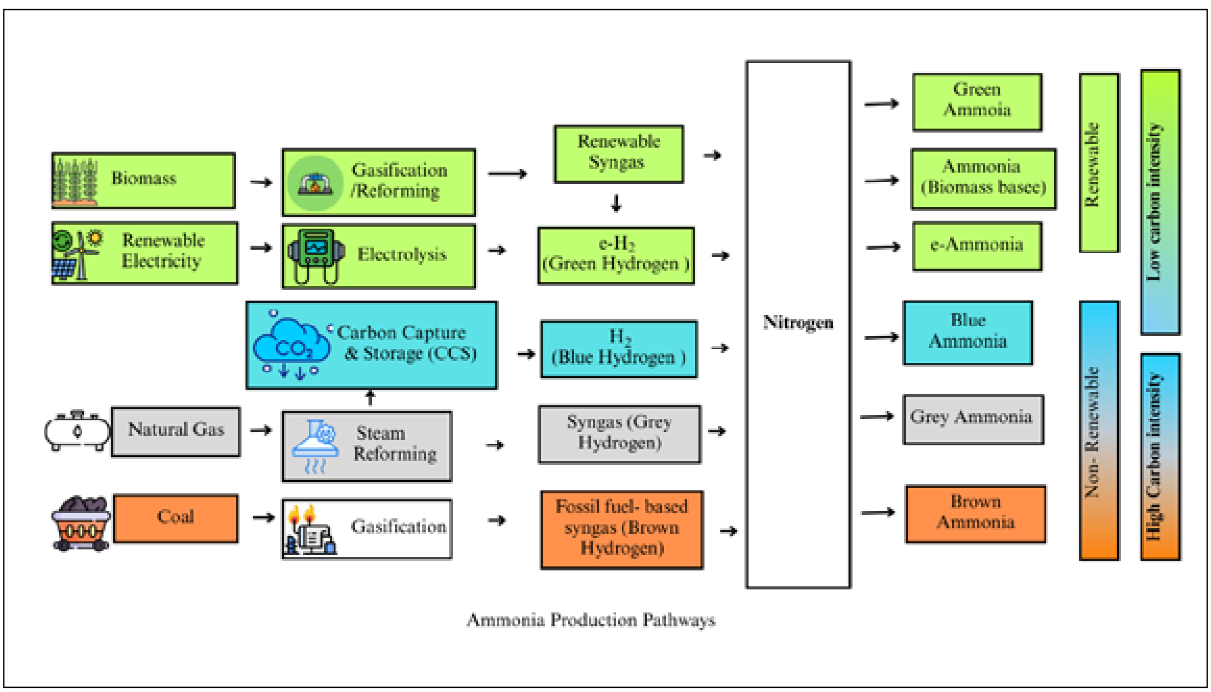


Figure 4.2: Ammonia Production Pathways [based on 4]

water splitting/ electrolysis to generate green Hydrogen and the resulting Ammonia is termed as green Ammonia.

Equation 2:

$$3H_2 + N_2 \rightarrow 2NH_3 \quad \Delta H_r = -91.8\ kJ/mol$$

This reaction takes place at 400- 500 °C and 100-450 bar pressure with iron catalyst at Hydrogen to Nitrogen molar ratio of 2:1 to 3:1 **[7]. Figure 4.2** presents the schematic of different coloured Ammonia production pathways. Green Ammonia is produced by Net Zero Emission or water electrolysis or using biomass-based hydrogen. The Ammonia produced from Natural gas, and other fossil-based feedstocks is termed as brown Ammonia whereas fossil-based production integrated with CCS is termed as blue Ammonia.

The National Fire Protection Association (NFPA) rates anhydrous Ammonia as a 3 (on a scale of 4) as most serious toxic health hazard and as a 1 (on a scale of 4) as flammable gas [8]. That is, it can have a great burden to human and ecosystem health risks. From an environmental perspective, ammonia leakage into soil, air and water can cause biodiversity losses, eutrophication, air pollution, greenhouse gases emissions and stratospheric ozone loss [9, 10]. Thus, all these risks should be considered to effectively minimize and eliminate Ammonia hazards. The cost of Green/ e Ammonia is directly proportional to the cost of green Hydrogen however Ammonia transport and pipeline and storage and costs much lesser than hydrogen. As per published data, storing hydrogen in the form of Ammonia for 182 days costs 0.54 $/kg, however, for storing hydrogen for 182 days it is 14.95 $/kg [4]. Among the flip side is **high Nitrous Oxide (N2O)** production during combustion of Ammonia which needs treatment like selective catalytic reduction (SCR) in order to comply with IMO GHG emission regulations **[11, 12].**

Methane and LNG (Bio and E-)

Methane is synthesized through reaction of one mole of CO2 with four mole of Hydrogen by Sabatier process (R3) as given in the **Equation 3**

Equation 3:

$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O \quad \Delta H_r = -165\frac{kJ}{mol}$$

The highly exothermic catalytic reaction occurs at 250-400⁰ C and 5-50 bars pressure **[13,14].** This process, although is simple and straightforward, requires a large quantity of CO2 (5.5 kg for each kg of H2) which is difficult to obtain as CCS systems usually are located far away from renewable plants and that adds the cost of CO2 transportation **[4] Figure 4.3 depicts** different coloured Methane production pathways. Although presently Methane is produced largely from fossil resources (grey and brown), e-Methane is considered sustainable and have lower GHG emission where the Green hydrogen is produced from water electrolysis and renewable electricity (green Methane).

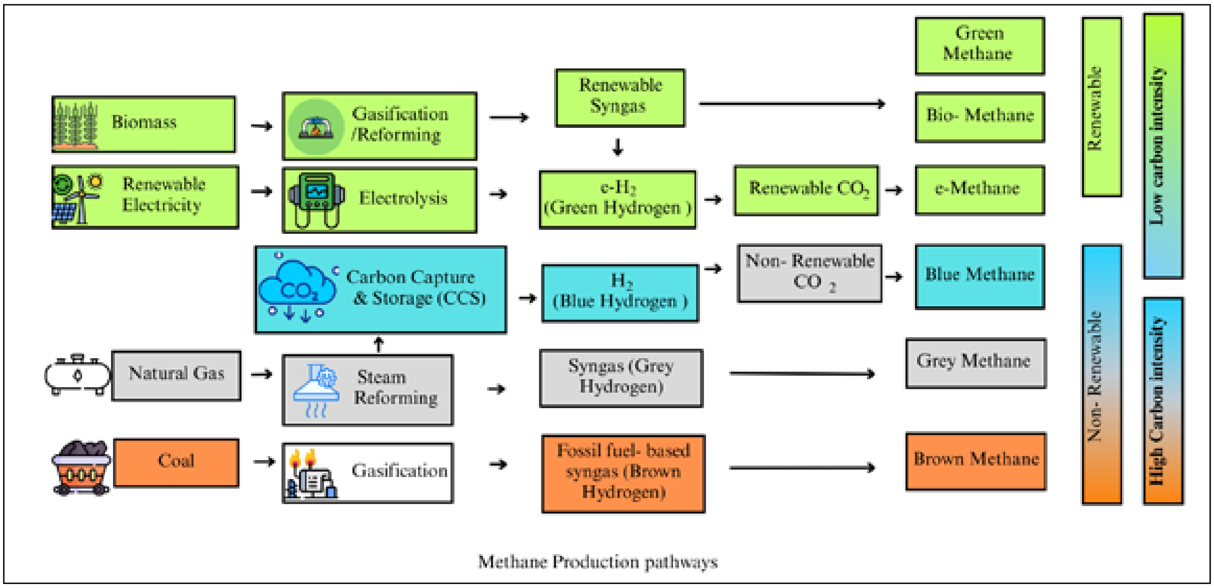


Figure 4.3: Methane Production Pathways [based on 4]

LNG is primarily composed of Methane, with minor constituents of light hydrocarbon gases such as Ethane, Propane, and Butane. The composition of LNG highly depends on the liquefication process followed and the locations. **Table 4.2** shows the variety of LNG compositions, subject to location.

Table 4.2: Variety of LNG composition in different countries [15]

Terminal	Methane	Ethane	Propane	Butane	Nitrogen
Abu Dhabi	87.07	11.41	1.27	0.14	0.11
Alaska	99.8	0.10	NA	NA	NA
Algeria	91.40	7.87	0.44	0.00	0.28
Australia	87.82	8.30	2.98	0.88	0.01
Brunei	89.40	6.30	2.80	1.30	0.00
Indonesia	90.60	6.00	2.48	0.82	0.09
Malaysia	91.15	4.28	2.87	1.36	0.32
Oman	87.66	9.72	2.04	0.69	0.00
Qatar	89.87	6.65	2.30	0.98	0.19
Trinidad	92.26	6.39	0.91	0.43	0.00
Nigeria	91.60	4.60	2.40	1.30	0.10

Liquefied Natural Gas (LNG), occupies 600 times less space for storage and transportation compared to its gaseous state, hence Natural gas is liquefied by cooling at –162 ^{0}C. Currently, LNG is the cleanest available fuel for shipping which are available in large volumes and comply with the SOx and NOx requirements while reducing CO2 emissions upto 20–30%. However, from the environmental Life Cycle perspective Methane/LNG has a Global Warming Potential (GWP) value of 28 on a 100-year timescale (GWP100) which means that a leakage of one tonne of Methane is equivalent of 28 tons of CO2 and thus absorb more heat per molecule compared to CO2 [4]. Current LNG engines have a methane slip of 2–5%.

LNG is categorized into fossil LNG, biological LNG, and synthetic LNG according to their source. At present, large-scale marine LNG fuel is fossil LNG, and its production process mainly includes Natural gas extraction, pre-treatment, compression, cooling, and separation. Bio-LNG is produced by anaerobic fermentation and purification of various types of organic waste, such as food wastes, agricultural and forestry residues, Municipal solid wastes (MSW) and it has the advantages of being green and renewable. Synthetic LNG, also known as E-LNG, is manufactured through a renewable power-to-gas process. Given that LNG is an extremely low-temperature and flammable liquid, ensuring the safety of the marine LNG filling and storage is important. In case LNG spills happen, it floats over the water as its density ranges between 410 and 500 kg/m3. LNG is not explosive, even if its vapor is exposed to undesirable environments. It is a colourless, non-corrosive, odourless, non-toxic, and safe gasthe transportation of natural gas from different parts (gas producing to the consuming areas.

Hydrogen and Liquid Hydrogen (LH2)

The **Figure 4.4 [16]** shows the production pathways for different coloured Hydrogen. The India has set out an ambitious green hydrogen production target of 5 Million Metric Tonnes (MMT) per annum by 2030, with an associated renewable energy capacity of about 125 GW by 2030. India's National Green Hydrogen Mission initiatives with timeline is presented in **Figure 4.4.** Among all the colours, the ideal Hydrogen colour is green, where hydrogen is produced from renewable energy sources (wind, solar, hydropower, etc.) and thus considered as zero GHG and carbon negative fuel.

	Coal Gasification	Methane Reforming	Methane Reforming + Carbon Capture	Methane Pyrolysis	Water Electrolysis	Bio Waste To Hydrogen	Waste to Hydrogen (Non Bio)	Nuclear	Naturally Occurring
Nomenclature	Black / Brown Hydrogen	Grey Hydrogen	Blue Hydrogen	Turquoise Hydrogen	Green Hydrogen (Water Electrolysis)	Green Hydrogen (Biowaste-to-Hydrogen)	Green Hydrogen (Waste-to-Hydrogen, non-bio)	Pink Hydrogen	White Hydrogen
Feedstock	Thermal Coal, Steam	Natural gas / Naphtha	Natural gas	Natural gas	Water	Biowaste	Non-biowaste	Steam	Naturally occurring
Energy source	Thermal heat	Thermal heat	Thermal heat	Power	Renewable power	Power	Power	Nuclear power	Naturally occurring
Hydrogen production tech.	Gasification	Reforming	Reforming with carbon capture	Pyrolysis	Alkaline / PEM / AEM / SOEC	Gasification / Pyrolysis	Gasification / Pyrolysis	SOEC / Alkaline / PEM / AEM	Reaction between heat and sub-surface minerals
Benefits	Cost competitive Syngas (process byproduct) has several uses	• Large-scale, widely used • High H2 Yield • Mature Supply Chain for Licensors and Technology • Easily available feedstock supply • Cost Competitive	• Large-scale, easily available & scalable • Carbon capture is maturing but the rate is still low	• Large-scale & potential • Avalibli feedstock supply • Zero direct emissions without need for additional infrastructure • Supply of solid carbon	• Coupling of electrolysis with renewables & gas sectors • Can decarbonize Hard to Electrify sectors • Being Widely considered as Decarbonization pathways	• Utilising available local Biowaste Feedstock • Abating otherwise unabated emission • Carbon recycling Potential • Can highly localized	• Availability of local non-recyclable waste • Can be localized • Can Utilize general & municipal waste	• Can be highly cost competitive • With Small & Medium nuclear Reactors still scale up • Utilities process heat that would otherwise be wasted	• Extraction process requires no external energy input • Replenishment of natural H2 is a continuous phenomenon
Carbon intensity* (kgCO2e/kgH2)	20-26	7- 12	2-7	2-16	0 (With 100% RE)	Carbon negative	Carbon negative	1-2	0
Other key emissions	CO, SO2, NOX, Hg	CO, CO2	CO2	Solid carbon	Oxygen	-	CO_2, NO_x	-	-

Figure 4.4 : Hydrogen production pathways [16]

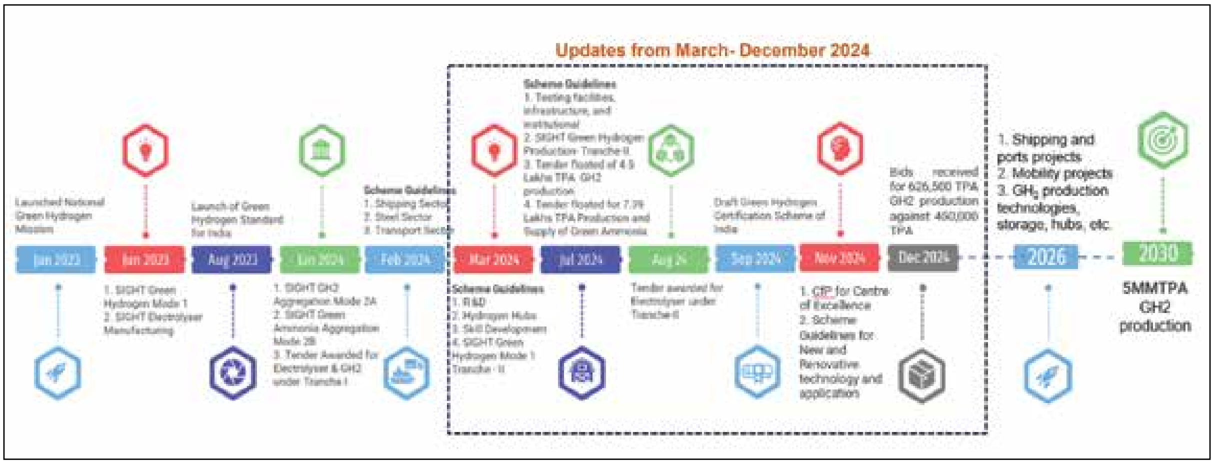


Figure 4.5: India's National Green Hydrogen Mission Initiatives with Timeline

Liquid hydrogen (LH2) has several advantages over other potential zero-emission fuels for shipping **[17]**. Nevertheless, storage of LH2 is complicated and expensive and has severe safety issues owing to its requirement of cryogenic storage (at high pressures and low temperatures –252.9 ℃). Another critical challenge is related to its low temperature fuelling process. Advanced insulation materials are needed for the tank materials in order to avoid evaporation of LH2 and subsequent avoidance of large heat fluxes into the tank **[18,19].** Innovative novel insulation systems under cryogenic conditions are proposed by some researchers which has great future potential **[19].** Besides the first ever pilot project by Kawasaki Heavy Industries transporting LH2 in a tanker ship **[18, 20],** no large-scale ship is operational using liquid hydrogen due to storage complexities and the present unavailability of global market. In the pilot study by Kawasaki Heavy Industries **[20],** it was found that it is technically and economically possible to transport and store LH2 from Australia to Japan **[20].**

Liquid Biofuels (Biodiesel, Bio Methanol and Bio Ethanol)

In 2023, uptake of biofuels amounted to about 0.7 Mtoe in shipping [22,23]. Two major biofuels adopted in shipping are FAME and HVO known as Biodiesel and Renewable Diesel, respectively. Besides FAME and HVO, a limited volume of Ethanol (4,137 tonne) is also reportedly consumed by major ships in 2023 **[23**]. As alternative bunker fuel Bio-LNG, Bio-Methanol and Bio-Ethanol are also reported **[24].** The most common blends range from 20% (B20 or BD24) to 30% (B30 or BD30) biofuel content by volume. For example, B24 or BD24 biofuel accounted for 518,000 tonne or 99% of the bio-blended fuel bunkered in Singapore in 2023. In Rotterdam, B30 or BD30 biofuel is reportedly the most common blend sold. Although B24 and B30 account for the largest volumes of biofuel delivered to ships, there are many examples of vessels bunkering other fuel blends, including B5, B10, B20, B50, B80, and B100 alternatively termed as BD5,BD10,BD20,BD50,BD80 and BD100 respectively. **Currently, as per MARPOL 11 Annex II and the IBC12 code, biofuel blends containing FAME delivered by bunkering barges or vessels classified as oil tankers are restricted to a maximum biofuel share of 25% (by volume). That is one of the reasons why, for example, in Singapore, the vast majority of biofuel bunkered in 2023 was B24 or BD24. For bunkering of higher FAME**

biofuel content blends from bunkering ships (e.g. B30or BD30, B50 or BD 50), B100 or BD100), IMO Type 2 chemical tankers are needed. This is considered a bottleneck for the uptake of biofuels containing FAME biodiesel, especially for blends with 25% or higher biofuel content. In Rotterdam, a high percentage of biofuel bunkering operations is made by inland waterway barges. These barges are subject to different regulations compared to bunkering vessels or barges operating in international waters and may therefore carry higher blends (including B30 or BD30) without additional requirements. Bio-blended residual fuel oil accounts for the largest share of Bio-blended fuel, followed by Bio-blended distillate fuel. Bio-blended Methanol and Bio-blended LNG accounted for about 4,600 tonnes and 1,000 tonnes, respectively, of Bio-blended fuel sales in 2024. An estimation shows Singapore and Rotterdam has accounted for about half of all biofuels supply to shipping in 2023 (only accounting for biogenic fuel**) [24].** The voluntary market for biofuels has been the most important driver for certain ship types (e.g. containerships) to date and is largely pushed by cargo owners. However, this may change in the future as new GHG requirements come into force. Supply-side constraints for shipping due to competition with other end users of biofuel, scarce supplies of biofuel produced from sustainable feedstocks, and logistical challenges are also important factors to consider.

FAME and HVO are fundamentally different fuels with distinct properties. Until 2024, there was no widely accepted fuel standard for HVO and FAME, other than the inclusion of biofuel blends with a FAME content of up to 7% in ISO 8217:2017. It is important to note that energy-rich or paraffinic diesel fuels, such as HVO, GTL (gas to liquid), and BTL (biomass to liquid), have been permitted in previous versions of ISO 8217. These are classified as petroleum distillates and do not affect the classification of blends that include paraffinic diesel fuel. An updated version of the standard, ISO 8217:2024 is recently published titled'' Products from Petroleum, Synthetic, and Renewable Sources — Fuels (Class F) — Specifications of Marine Fuels '[**24].** The revision includes

» Distillate and Bio-Distillate Marine Fuels, now allow up to 100% FAME (DF-grades).

» Bio-Residual Marine Fuels now allow up to 100% FAME.

» Marine fuels containing 100% FAME shall meet EN 14214 (except for sulfur, cloud point [CP] and cold filter plugging point [CFPP]) or ASTM D6751 (except for sulfur requirement) and ISO 8217:2024.

» Marine fuel consisting of 100% Paraffinic Diesel fuel (HVO) shall meet EN 15940 (except EN 15490:2023) and ISO 8217:2024 (important since EN15940 has a minimum flashpoint of 55°C).

Ethanol is already getting attention for replacing gasoline in spark-ignition engines. Ethanol is also produced from renewable and biomass through fermentation route. Ethanol has a high-octane number (100 -105) thus, it improves the SI engine performance with high flammability and high latent heat of vaporization. However, researchers are now trying to harness Ethanol's potential for diesel engines. Like Methanol, Ethanol also has a poor miscibility with diesel; it warrants emulsifiers/additives/surfactants to make Diesel and Ethanol miscible to each other. ARAI, India has explored the possibilities of using Ethanol-Diesel blends in an Ethanol proportion of 5% (v/v), 7.7% (v/v), 10%

(v/v), 12.5% (v/v), and 15% (v/v) using stabilizers for Road transport engines **[25].** The additives are selected to improve combustion stability, lubricity, and efficiency. The study indicated that the 7.7% (v/v) and 10% (v/v) Ethanol concentrated blend with 2% (v/v) solubilizer is optimum which improves engine performance and reduces emissions. As per Diesel vehicle trials, a 7% Ethanol concentrated blend emits ~13% less than commercial Diesel fuel. Overall, **Ethanol up to 10% v/v can be used as fuel in marine engines, provided it meets the material compatibility declared by the engine manufacturers [26]. However, it is seen from Clarckson's order and service-book data shows that Ethanol is not promoted as a marine fuel.**

Butanol, being a candidate of the alcohol family, also emerged as a strong candidate as an alternative fuel for internal combustion engines. It is recommended more than Ethanol and Methanol as they have a lower auto-ignition temperature, which means the ignition inside the combustion chamber is easier than that of Methanol and Ethanol. Also, diesel has strong miscibility (30-40% v/v Butanol can be blended with Diesel). However, its miscibility depends on the isomer of the Butanol. Butanol is also a lower volatile fuel with a higher energy density than Ethanol. The fermentation of the biomass is the best way to use corn and other waste materials. Although Butanol has a high-octane number, it is promoted for spark ignition engines; however, effort has now been made to utilize it as a Butanol-Diesel blend in the CI engines. Among other members of alcohols, Butanol is preferred as a fuel as it has a high cetane number and lower latent heat of vaporization than Ethanol and Methanol. Butanol also has a higher laminar speed than the baseline diesel, thus improving the combustion efficiency. In addition, Butanol has higher viscosity and lubricity than Ethanol and Methanol, thereby providing more protection against the wear of the engine parts such as fuel injectors, fuel pumps, and fuel rails. **However, the use of butanol in ICEs is minimal and rarely promoted for use as a marine fuel as far as order and service book data are concerned.**

4.1.2 Alternative Fuels Cost-Comparative Assessment

There are significant number of reports which provide alternative fuel cost comparison based on present and projected future data **[27-33]**. These reports although differs in absolute value, however largely ranking fuel w.r.to their cost likewise

The study conducted by Ricardo and DNV for the IMO FFT Project **[27**] which includes meta-analysis of others' price forecasts, predicts that many of the alternative fuels would be within the fuel price volatility already often accommodated by industry as shown in **Figure 4.6-1, left**. It also indicates that timely intervention of policies on carbon pricing (e.g EU ETS policy measures) would lower the forecast prices of the alternative fuels to within ±50% of the forecast price of VLSFO in 2050 as seen in **Figure 4.6- right.**

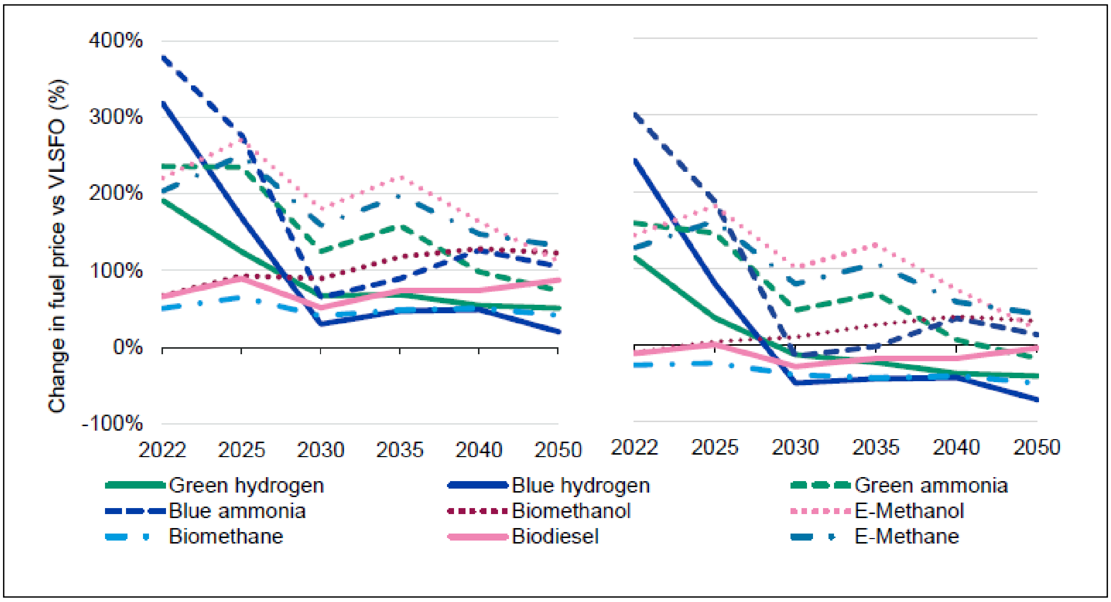


Figure 4.6: Forecast of fuel costs relative to VLSFO after accounting for the impact of additional energy efficiency measures, without a Euro 100/t carbon price (left) and with a Euro 100/t carbon price (right)

Another important position paper on alternative fuel options scenarios developed by e Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping [**29**], also endorsed by different classification societies including ClassNK (Japan), shows the following relative fuel cost as illustrated in **Figure 4.7**. This estimation is based on global weighted average for non-subsidized, stand-alone commercial scale plant-based cost.

It shows there is a wide cost gap between the alternative fuel options, especially for the bio and e-fuels with their fossil counterpart. While for bio-based fuels the critical factors affecting the cost include feedstock cost, there competitive use in other transport fuel options; for e-fuels price those are green Hydrogen and Renewable Electricity (RE). Additionally, in order to make the low Carbon and Carbon neutral fuels price competitive for accelerating their transition, appropriate Carbon pricing alongside efficiency measures is absolute necessity. **This analysis shows Bio oil/ Pyrolysis oil as the most cost competitive options globally followed by Bio Methanol, Bio-Methane (alternatively known as Biogas), blue ammonia, e Ammonia and e Methanol. For all these fuels, scaling is the key towards securing global supply chain while sustaining the price advantage.** From India's perspective, this offers a huge opportunity to upscale the technologies for producing bio-oil/ upgraded pyrolysis oil and bio-Methanol as sustainable marine fuel alternatives from MSW and surplus-agro residues. e fuels, the fuel cost for e Ammonia is lowest followed by e Methanol, e Methane and e Methanol with Direct Air Capture (DAC). Blue fuels look competitive only until lower RE cost makes e-Fuels appealing. However, it would be worth considering the **Total Cost of Ownership (TCO)** while making decisions for alternative fuel options by shipowners [**29,30,31].**

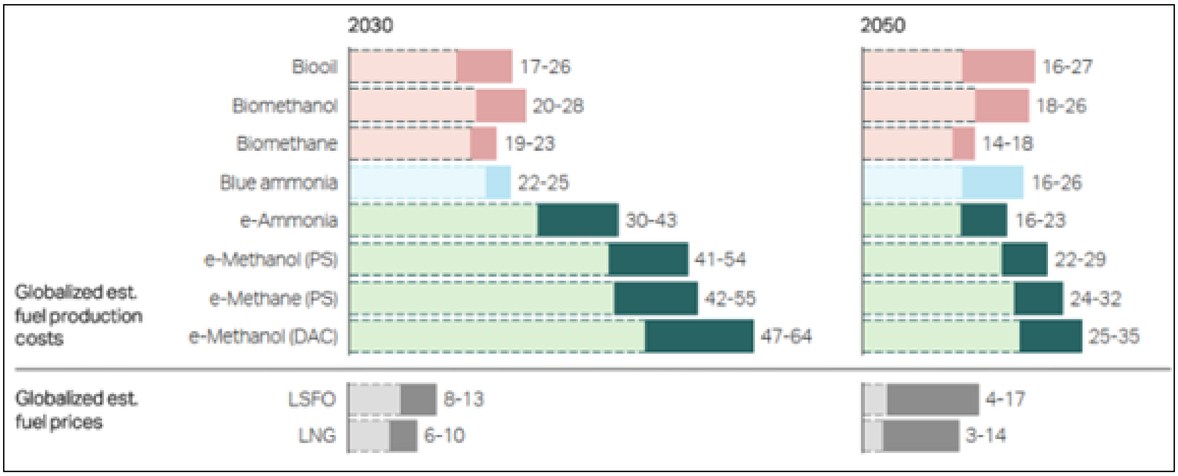


Figure 4.7: Fuel Costs1 (USD/GJ) Decline Over Time, Though There Remains Uncertainty on Absolute Fuel Cost Levels [29]

[1] Production, Logistics & Storage at Port [2] Assumptions provided in Annexure [3] Assumptions related to cost of Renewable energy as outlined in Annexure XX

Another comprehensive study is conducted by Aalborg University and Chalmers University. This study has considered the critical aspects such as, propulsion technology, fuel types and their suitability of adoption against types of ships, onboard fuel cost, cost of lost cargo space etc. in order to arrive at the **Total Cost of Ownership as presented in Figure 4.8, Table 4.3a and Table 4.3 b.**

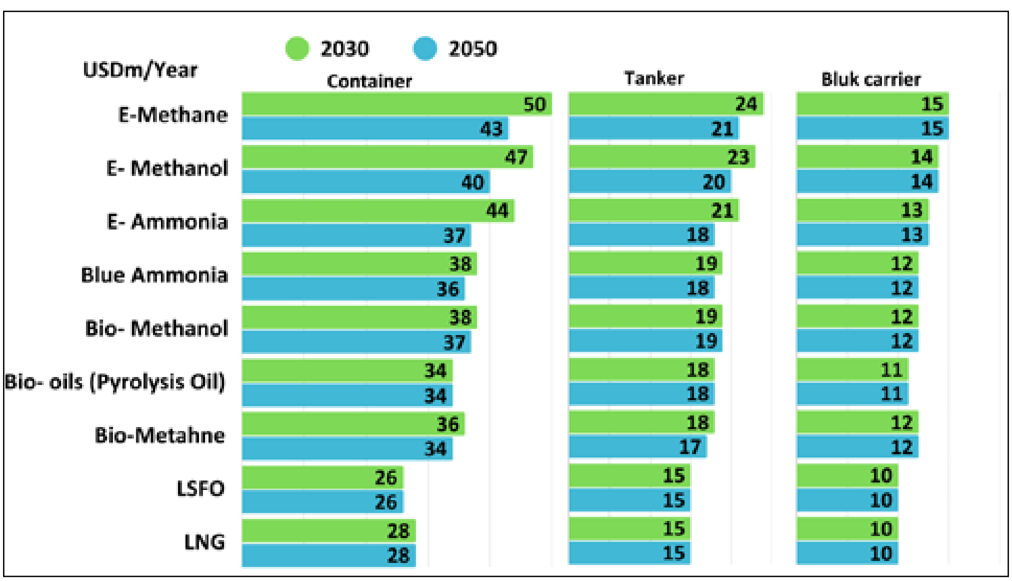


Figure 4.8: Estimated Total Cost of Ownership (TCO) of Vessels by Type of Fuel [reproduced from 29,30]

*Note: Hydrogen is not considered fuel-suitable for deep sea shipping because of immaturity in safe storage and conversion of Hydrogen as an onboard fuel. Typical vessels refer to: Container: 8000 TEU capacity, Tanker: LR2 85-125 Kdwt; Bul Carrier: Paramax 70-99Kdwt. Typical operation profiles have been assigned to each vessel type. *Uses pyrolysis oil availability and cost projections*

Total Cost of Ownership by Type of Ship (Millions of euros per year, base case) [30,31]

Table 4.3 a: Total Cost of Ownership by Type of Ship (Millions of euros per year, base case)

		Large Ferries									General Cargo Ships					
Utilization/trip		Short			Medium			Long			Short		Medium		Long	
Propulsion		ICE	FC	BE	ICE	FC	BE	ICE	FC	BE	ICE	FC	ICE	FC	ICE	FC
MGO		0.9			1.7			2.4			1.3		1.5		1.8	
Biofuels	Bio Methanol	2.0	4.2		3.9	5.7		5.7	7.2		3.0	3.8	3.7	4.4	4.6	5.1
	Bio DME	2.3			4.2			6.2			3.3		4.0		4.9	
	Biodiesel	2.7			5.2			7.6			4.0		4.8		5.8	
	Bio LMG	3.0	4.9		5.4	6.8		7.8	8.7		4.2	4.8	5.1	5.6	6.2	6.6
	Bio LBG	2.8	4.8		5.1	6.6		7.4	8.4		4.0	4.6	4.8	5.4	5.9	6.4
	HVO	2.4			4.6			6.8			3.6		4.3		5.2	
Bio-electrofuels	E-Bio Methanol	2.6	4.7		4.9	6.6		7.3	8.5		3.8	4.5	4.7	5.2	5.8	6.1
	E-Bio DME	2.9			5.4			7.9			4.1		5.0		6.2	
	E-Biodiesel	3.2			6.2			9.2			4.8		5.8		7.0	
	E-Bio LMG	3.6	5.4		6.6	7.8		9.6	10.2		5.1	5.6	6.2	6.5	7.7	7.7
	E-Bio LBG	3.6	5.3		6.5	7.7		9.5	10.1		5.1	5.5	6.1	6.5	7.5	7.7
Electrofuels	E-methanol	3.3	5.3		6.5	7.8		9.7	10.3		5.0	5.5	6.1	6.3	7.6	7.5
	E-DME	3.7			7.0			10.3			5.4		6.5		8.0	
	E-diesel	4.3			8.4			12.5			6.5		7.8		9.5	
	E-LMG	4.3	5.9		8.0	8.9		11.8	11.9		6.2	6.4	7.6	7.6	9.3	9.0
	Ammonia	3.7	5.5		6.9	8.0		10.2	10.6		5.3	5.6	6.4	6.5	8.0	7.8
LH_2		4.7	5.3		8.8	8.6		13.0	11.9		7.0	6.5	8.7	8.0	11.0	9.9
Electricity				2.8			5.5			8.3						

Table 4.3b: Total Cost of Ownership by Type of Ship (Millions of euros per year, base case) [30,31]

		Bulk Carrier Ships						Container Ships					
Utilization/trip		Short		Medium		Long		Short		Medium		Long	
Propulsion		ICE	FC	ICE	FC	ICE	FC	ICE	FC	ICE	FC	ICE	FC
MGO		3.2		3.7		4.4		13.5		16.1		17.5	
Biofuels	Bio Methanol	7.2	9.7	8.9	11.3	11.3	13.3	30.9	39.7	38.4	46.3	42.4	49.9
Biofuels	Bio DME	7.7		9.5		11.8		33.2		40.9		45.1	
Biofuels	Biodiesel	9.1		10.9		13.2		39.8		48.3		52.6	
Biofuels	Bio LMG	9.9	11.9	12.2	13.8	15.0	16.3	42.4	48.9	52.5	57.9	58.5	63.2
Biofuels	Bio LBG	9.4	11.4	11.6	13.3	14.3	15.7	40.3	47.0	49.9	55.6	55.6	60.7
Biofuels	HVO	8.2		9.8		11.9		35.8		43.4		47.3	
Bio-lectrofuels	E-Bio Methanol	9.0	11.4	11.1	13.2	14.0	15.7	39.0	46.9	48.2	55.1	53.1	59.5
Bio-lectrofuels	E-Bio DME	9.6		11.8		14.6		41.7		51.2		56.4	
Bio-lectrofuels	E-Biodiesel	11.0		13.1		15.9		48.0		58.3		63.5	
Bio-lectrofuels	E-Bio LMG	12.1	13.8	14.7	16.1	18.2	19.2	51.8	57.4	64.0	68.3	71.0	74.5
Bio-lectrofuels	E-Bio LBG	11.9	13.6	14.5	16.0	17.9	18.9	51.1	56.7	63.1	67.5	70.0	73.7
Electrofuels	E-methanol	11.7	13.8	14.3	16.1	17.9	19.3	50.8	57.6	62.7	68.1	68.9	73.7
Electrofuels	E-DME	12.4		15.1		18.7		54.0		66.3		72.9	
Electrofuels	E-diesel	14.8		17.7		21.5		64.7		78.7		85.8	
Electrofuels	E-LMG	14.5	16.0	17.7	18.8	21.8	22.4	62.6	67.1	77.2	80.1	85.4	87.4
Electrofuels	Ammonia	12.5	14.2	15.4	16.8	19.3	20.2	53.9	59.3	66.3	70.4	73.1	76.4
LH_2		16.6	16.5	21.4	20.7	27.5	26.2	71.4	70.2	90.8	87.6	102.6	98.2

This analyses [30,31] show Bio Methanol with lowest TCO across 4 ship categories, viz., Large Ferries, General Cargo, Bulk Carrier Ships and Container Ships under all degrees of utilisation. Among e-Fuel category, especially for ship types Bulk Carrier and large Ferries, e Methanol has close proximity to e DME and e Ammonia.

A recent policy study also has reported relative fuel cost for alternative marine fuels considering dual perspective of shipowners interest and public/social interest **[32].** It is highlighted that driven by economic interests, shipowners' primary focus is centred around the private cost in the entire life cycle of a newbuilding, including shipbuilding costs, investment and operating costs of emission reduction equipment, operating costs of ship, and fuel costs. Thus, from shipowners' point of view primary aim always remains minimizing the total cost based on achieving minimum emission requirements. But from the perspective of the public, maximum social benefits mean achieving a balance point between economy and environment [**34**] and therefore, the social cost of different emissions also needs consideration **[35]** The specific values of the social cost of different emissions which varies in turn w.r.to alternate fuel types are shown in **Table 4.4**. This study although shows distinctive advantage of lower social cost for Ammonia and Hydrogen as alternative fuels, nevertheless, total fuel cost figures are in-line with the majority of the studies as mentioned above with Methanol cost being lowest followed by LNG and Ammonia as shown in **Table 4.5.** The ship size specifications considered in this study is presented in **Table 4.6.**

Table 4.4 :Social Cost Factors of Different Exhaust Gases [34]

Exhaust Gas	Social Fost Factors ($/T)
CO_2	56.6
N_2O	15,000
CH_4	1,750
NO_x	34,700
PM	79,500
SO_2	24,900

Table 4.5: Private Cost, Social Cost and Total Cost of Different-Sized Containers under Different Options

Options	Ship Size	HFO	MGO	LNG	Methanol	Hydrogen	Ammonia
Private Cost ($/ton)	Small	242.428	255.715	426.684	363.499	570.582	710.792
	Medium	418.972	439.006	656.922	608.214	926.445	1134.741
	Large	721.060	762.957	1204.876	1119.719	1777.306	2217.026
	Ultra	954.981	1009.068	1583.638	1469.154	2313.693	2883.602
Social Cost($/ton)	Small	207.952	192.324	142.659	82.160	25.474	34.343
	Medium	328.540	308.196	233.315	142.097	56.629	70.001
	Large	675.522	592.227	435.626	244.859	66.118	94.085
	Ultra	848.155	785.155	582.993	336.725	105.981	142.084
Total Cost($/ton)	Small	450.380	448.039	569.343	445.659	596.056	745.135
	Medium	747.512	747.202	890.237	750.310	983.074	1204.742
	Large	1396.582	1355.184	1640.503	1364.578	1843.425	2311.111
	Ultra	1803.136	1794.223	2166.631	1805.879	2419.674	3025.687

Table 4.6 : Parameters of Sample Vessels and Engines Selected in Reference [6]

Size	Small	Medium	Large	Ultra

Builder	Hyundai Mipo	New Times SB	Hyundai HI (Ulsan)	Hudong Zhonghua
TEU	2,500	7,000	16,000	24,000
DWT	32,479	81,689	1,57,473	2,26,367
Speed (kn)	23	25	22	19
Price (m$)	36.1	75.13	129.75	152.44
Main Engine				
Attribute	**Small**	**Medium**	**Large**	**Ultra**
Type	2-stroke 7-cyl	2-stroke 7-cyl	2-stroke 8-cyl	2-stroke 11-cyl
Model	MAN B. & W. 7S60ME-C10.5	MAN B. & W. 7G80ME-C10.5	MAN B. & W. 8G95ME-C10.5	WinGD 11X92-B
Bore/Stroke	600 mm × 2400 mm	800 mm × 3720 mm	950 mm × 3460 mm	920 mm × 3468 mm
Power (kW)	17,430	26,280	54,960	70,950
Speed (rpm)	105	72	80	82
Auxiliary Engine				
Attribute	**Small**	**Medium**	**Large**	**Ultra**
Type	4-stroke 7-cyl	4-stroke 8-cyl	4-stroke 9-cyl	4-stroke 9-cyl
Model	HHI-EMD (HiMSEN) 8H21/32	HHI-EMD (HiMSEN) 8H32/40	HHI-EMD (HiMSEN) 9H32DF-LM	MAN Energy Solutions 9L32/40
Bore/Stroke	210 mm × 320 mm	320 mm × 400 mm	320 mm × 400 mm	320 mm × 400 mm
Power (kW)	1,760	3,200	4,500	4,500
RPM	900	720	420	750
Number	3	3	3	5

4.1.3 Alternative Fuels Life Cycle Analysis-Comparative Assessment

From an environmental perspective, it is worth noting that different fuel pathways can generate different amounts of emissions in the life cycle approach, although tail pipe emissions are similar. From this perspective, life cycle assessments (LCAs) for evaluating environmental impacts across the entire life cycle of a fuel is necessary. The inclusion of the upstream emission of ship fuels can help in conducting a more comprehensive assessment of emissions in this sector and prevent the miscalculation of overall emissions [**36**]

At the 76th session of MEPC held in 2021, the development of life cycle assessment GHG/Carbon intensity guidelines (LCA Guidelines) for all relevant types of fuels are discussed [**37**]. Life cycle emission of marine fuel are defined as Well-to-Wake emission, which is a sum of Well-to-Tank (from the production of the fuel to the bunkering of the fuel to a tank onboard) and Tank-to-Wake emission (from the fuel tank of the ship to an exhaust gas). Alternative fuels are relatively costly compared to conventional fuels, despite their positive effects in terms of GHG reduction in the maritime sector. Therefore, for the fuel transition from conventional fossil fuels to alternative fuels, emission reductions and related costs should be considered **[38].** Implementing LCAs of marine fuel can help quantify GHG emissions from the extraction of feedstock and conversion or synthesis and transportation of fuels, as well as their bunkering and onboard combustion. This would eventually help shipowners make decisions for the selection of environmentally viable marine fuels.

To facilitate the transition to alternative fuels and accordingly achieve emission reductions in the maritime sector, carbon pricing is gaining unprecedented momentum as one of the most important measures. As in the recently concluded MEPC 83 IMO has given green signal Net-Zero Framework, setting mandatory GHG Fuel Intensity Targets for all global ships > 5,000 GT. **The new rules include a tiered compliance system, which is not only penalties on CO2eq emission, but also rewards based on emission compliance of the ship as seen in Figure 4.9. Ships able to achieve emission targets earn Surplus Units (SUs) which can be traded, saved, or cancelled. Tier 1 (Direct Compliance) shortfalls need to purchase Remedial Units (RUs) at $100/tCO_2$ whereas, Tier 2(Base Compliance) shortfalls need to either pay $380/tCO_2$ or use Surplus Units (SUs)Use of Zero or Near-Zero (ZNZ) would qualify for rewards from the IMO Net-Zero Fund.**

All emission tracking will be performed using new IMO GHG Fuel Intensity (GFI) Registry. This will be formally adopted by October 2025 and with enforcement starting on 2028.

It seen from **Figure 4.9,** the Base as well as Direct Target trajectories are highly ambitious. **Figure**

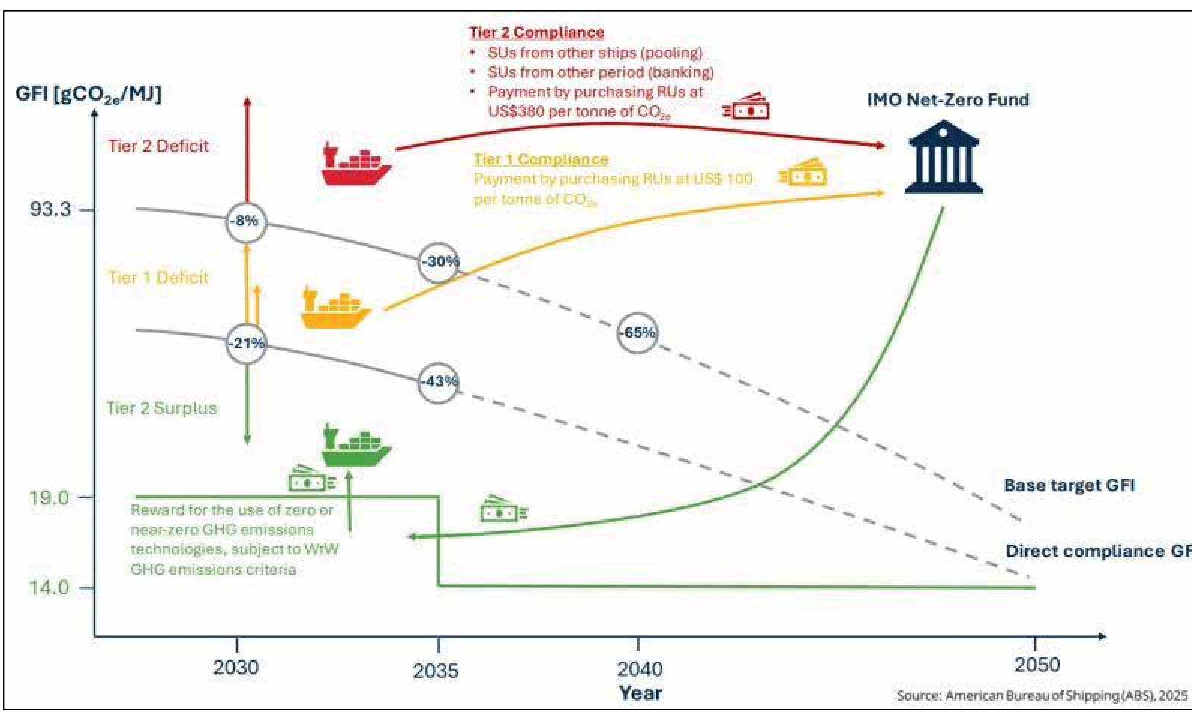


Figure 4.9 : MEPC 83 New Amendments in Emission Targets

4.10 shows MEPC 83's Base Target trajectory (in blue) versus the different proposals submitted by different countries at IMO. It is interesting to note that only the Fuel EU and Japanese proposal looks more stricter beyond 2040 compared to MEPC 83. Also it is worth highlighting that MEPC 83 trajectories fall short of reaching net zero target by 2050 which needs future readjustment of trajectories between 2035-2040 to reach near zero in 2050.

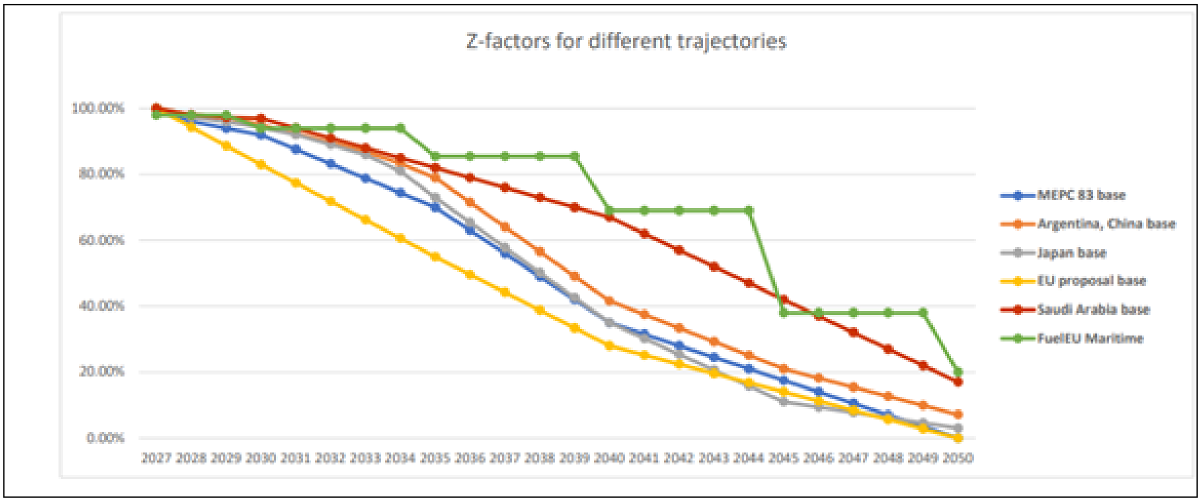


Figure 4.10: Base Trajectory of MEPC 83 (in blue) vs Different Country Proposals

When carbon pricing will be reinforced, it is expected to account for a large portion of fuel costs. Also, several financial institutions are signing onto the Poseidon Principles, established in 2019 in order to assess the climate alignment of ship finance portfolios. This is expected to expedite the process of shipping companies ensuring alignment with the IMO's GHG emission reduction targets **[42].**

In another noteworthy study, LCA of alternative fuels like LNG, Ammonia, Methanol, and Biofuel is conducted in conjunction with an economic analysis of ships using those fuels considering life cycle carbon pricing [**43**]**. It is important to highlight that in this study, the life cycle GHG emissions of the fuels are converted to carbon prices and incorporated in fuel cost values**.

As same fuels produced via different pathways can generate different degrees of emissions in spite of having same chemical properties, several pathways of multiple fuels are considered in this study including fossil LNG, Biomass-based Fischer–Tropsch (FT)-Diesel, Biodiesel, Natural gas (NG)-based Methanol, Biomass-based Methanol, e-Methanol, NG-based Ammonia, NG-based Ammonia plus CCS (Carbon Capture and Storage), and e-Ammonia. Fossil based marine fuels such as HFO (0.1% sulphur) and MGO (0.1% sulphur) are used as reference fuels. Interestingly, a Long Range 1 (LR1) tanker, ranging in size between 55,000 to 79,999 deadweights (DWT), is considered as a reference ship using alternative fuels aimed finding the fuel/s that would be commercially competitive over the next 25-year ship life cycle. Economic analysis results are expressed as fuel cost including carbon price with varying year and the net present value (NPV) of the ship. For the sensitivity study, the carbon prices are varied from the baseline scenario and is investigated the approximate years for when alternative fuels will become more cost-effective than conventional fossil fuels. In this study, also the effects of blending fuels those are produced through different pathways are assessed and compared. The fuel blending included HFO and biomass-based FT-Diesel, blend of NG-based Ammonia and NG-based Ammonia plus CCS, and blend of NG-based Methanol and biomass-based Methanol. The advantage of blend fuels is that these fuels are structurally identical; and therefore, capable of running the engine without any modification/retro fitment to the ship. **Figure 4.11 and Figure 4.12** present the life cycle emissions for each fuel in terms of CO2-eq/kWh, breaking it down into two stages: the Well-to-Tank stage and the Tank-to-Wake stage for main engine and auxiliary engine propulsion respectively.

It is evident that among the eleven fuels analysed, Natural Gas (NG)-based Ammonia shows the highest GHG emissions. When 1 kWh of output power in the main engine is generated from NG-based Ammonia, approximately 1025 g of CO2-eq is emitted, resulting in 48.7% more emissions relative to HFO. This study highlights those emissions from the Well-to-Tank stage account for 95.8% of the life cycle CO2-eq emissions, and the Tank-to-Wake stage emits just 42.63 g of CO2-eq, most of which results from pilot fuel combustion. **NG-based Methanol emits the second highest GHG emissions and has 3.2% more life cycle CO2-eq emissions compared to HFO. According to this study, from the Well-to-Wake perspective, Ammonia and Methanol from Natural gas is not a viable alternative fuel.**

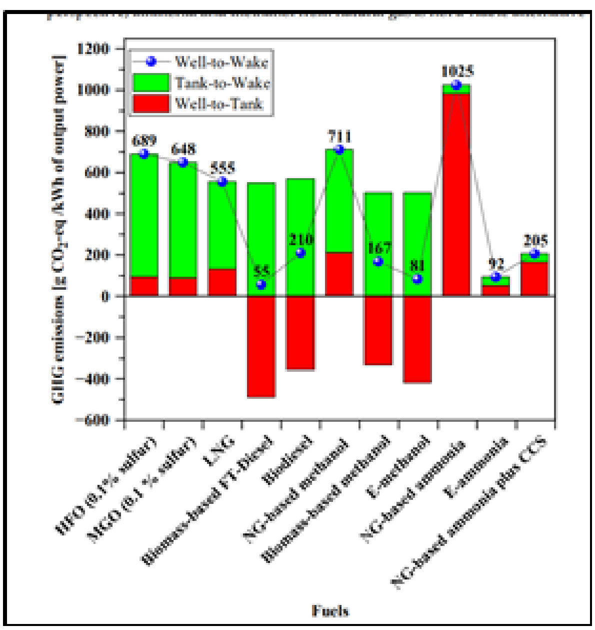


Figure 4.12: Life Cycle GHG Emissions per kWh of Main Engine Output Power

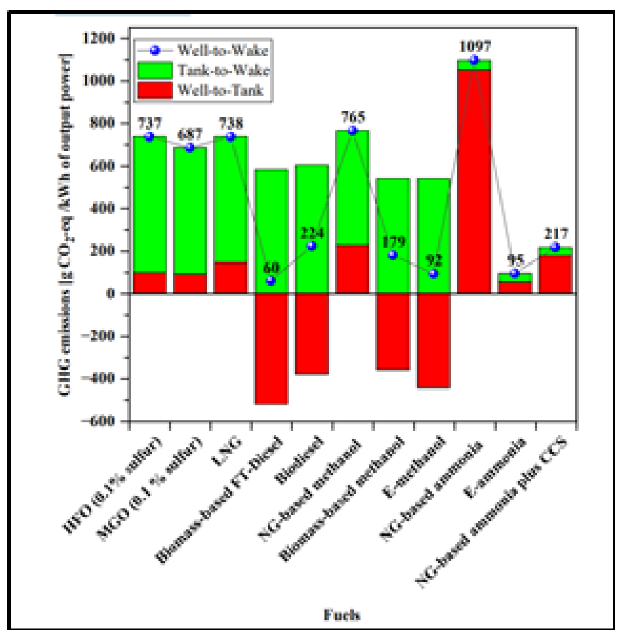


Figure 4.11: Life Cycle GHG Emissions per kWh of Auxiliary Engine Output Power

The GHG emission of e-Methanol in the Well-to-Tank stage is negative, as CO2 is directly captured from the air for the synthesis of Methanol. In the case of NG-based Ammonia plus CCS, while an 89.02% overall CO2 capture rate in the Ammonia plant was assumed, the CO2-eq reduction over its life cycle is 79.9%. This has resulted from the GWP effects of CH4 and N_2O, which are not captured in CCS, and CO2-eq emissions from pilot fuels combusted in the engine. In most cases, except for

Ammonia, the Tank-to-Wake stage accounts for the majority of the GHG emissions. Due to the efficiency difference between the main and auxiliary engines, slightly more emissions are generated in the auxiliary engine, as shown on Figure 4.12.

It is observed from this study that the following alternative fuels only have the potential to meet the IMO target of reducing the total GHG emissions by 50% by 2050, based on the level recorded in 2008: Bio-based fuels, E-Methanol, E-Ammonia, and CCS combined NG-based Ammonia; they have reduction potentials of 69–92%, 88%, 86%, and 70%, respectively.

For economic analysis, to calculate ship life cycle cost, annual carbon prices for each fuel type are derived by multiplying unit carbon price (USD/ton CO2-eq) and the annual power consumption of ships (kWh) by the Well-to-Wake CO2-eq emissions.

The ship life cycle fuel cost for each given Scenario is shown in Figure 4.13. Figure 4.14 represents the NPVs of ship life cycle cost, including the fuel production cost, carbon price, and CAPEX of the ships, whereas the NPVs of the ship life cycle costs for the blended fuels are shown Figure 4.15. The CAPEX assumptions, carbon pricing and NPV calculation details are given in Annexure.

E-Methanol shows the highest ship life cycle fuel cost, with 748.08 mUSD, followed by E-Ammonia at 621.71 mUSD. It is important to notice that fuel production cost for both fuels accounts for a majority of the ship life cycle fuel cost, while carbon prices take a small portion. The third and fourth higher costs were identified for NG-based Ammonia and NG-based Ammonia plus CCS, respectively. In this case, annual fuel production cost and carbon price are converted to present values and summed to CAPEX. **The NPVs of E-Methanol and E-Ammonia are 442.50 mUSD and 373.28 mUSD, respectively. For E-Methanol and E-Ammonia, these values are approximately 2.34 and 1.97 times that of HFO, respectively, showing a similar trend with ship life cycle fuel cost**

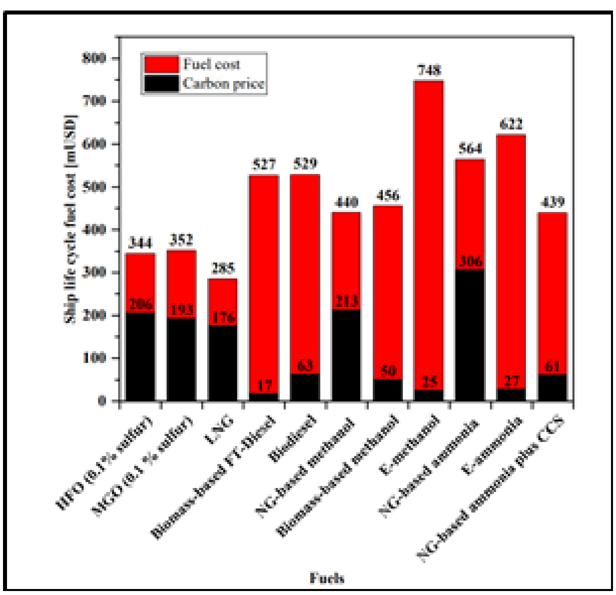


Figure 4.14: Ship Life Cycle Fuel Costs including Carbon Price

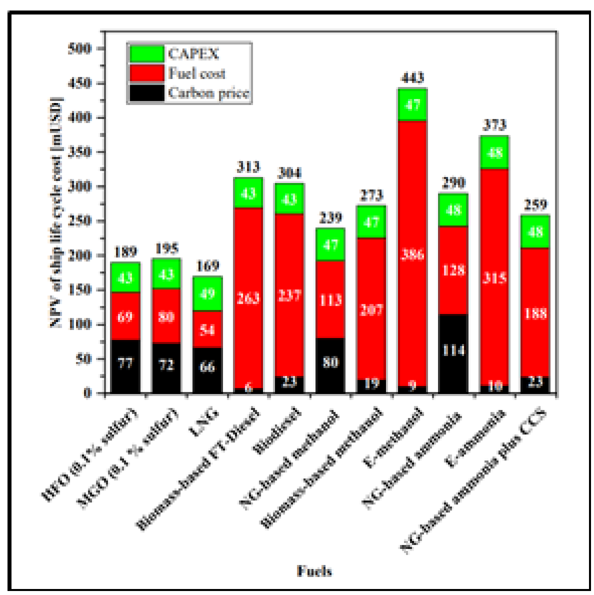


Figure 4.13: NPVs of Ship Life Cycle Fuel Costs including Carbon Price

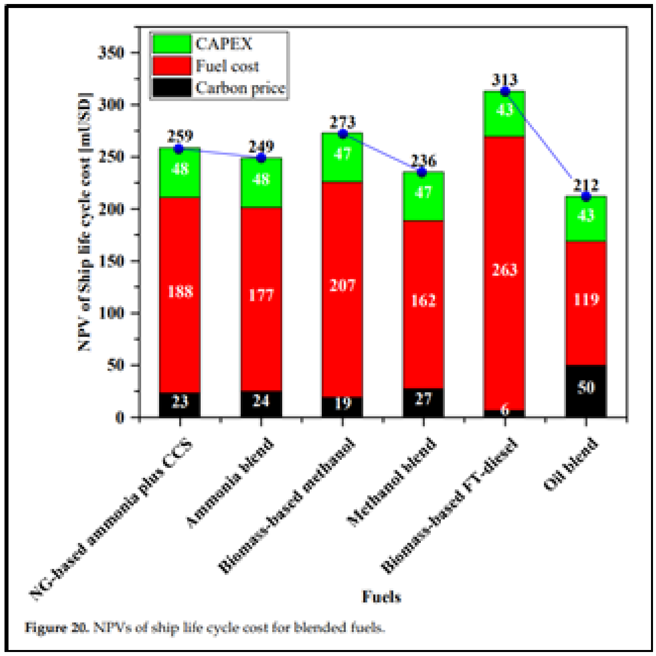


Figure 4.15 : NPVs of Ship Life Cycle Cost of Blended Fuels

The most cost-competitive option from a life cycle perspective involves using blended oil with a ship life cycle cost of 211.92 mUSD, which is 22.43 mUSD more than the cost of HFO. When blended Methanol and Ammonia are used, the NPVs of ship life cycle cost are approximately 235.58 mUSD and 248.9 mUSD, respectively, NPVs that are 11.17% and 17.45% higher than that in the mixed oil case, respectively. Among the three blended fuel cases, the Ammonia case has the lowest carbon price but the highest fuel production cost. It is opined that with the carbon capture ratio of NG-based Ammonia plus CCS (for which a 90% capture rate is assumed) adjustment, the result could be different.

The results show that using blended Ammonia, Methanol, and oil could save 9.7, 36.99, and 100.72 mUSD, respectively, compared to using NG-based Ammonia plus CCS, biomass-based FT-diesel, and biomass-based Methanol alone. None of the fuel blend cases are more cost-competitive than LNG from a life cycle perspective. However, it is important to note that LNG cannot meet the CO2-eq emission limit.

Additionally, it is estimated that In order to achieve the IMO's target of reducing total GHG emissions in the shipping sector by 50% by 2050, an estimated cumulative investment of USD 1–1.4 trillion is required between 2030 and 2050. Moreover, it is crucial to not only implement a carbon price but also reinvest the revenue from carbon pricing as subsidies which in turn could be used for stimulating the alternative fuel technology and infrastructure development efforts. This will ultimately contribute in reducing the alternative fuel cost [44].

A recent exhaustive LCA study by IFP Energies Nouvelles, commissioned by CMA CGM **[44]** has compared bio- E- blue fuel of both against VLSFO. The salient nature of this assessment is that for the first time (as per the PI's knowledge) the geographic variation in alternative fuel production considered across 17 region including India, China, Australia, Indonesia and South Africa estimating the GHG emission of the fuels for 2035 and 2050 Additionally in building fuel production Scenarios, difference energy integration strategies such as energy sources used for CO2 capture or auxiliary power consumption are considered.

It is also perceived that a functional unit shift from WtW (gCO2eq/MJ) to transport emission unit (gCO2eq/TEU.Km) is critical for accurate evaluation for the GHG reduction potential of the alternative marine fuels in different parts of the world. This is argued that proposed transport emission methodology/ unit would properly account onboard energy conversion efficiency, pilot fuel demand, impact of propulsion types and nature of fuels storage on container capacity which In turn invariably affect the real-world emission as the operational scale. Based on simulated consumption data for 23,000 TEU ships on a typical CMA and CGM route from Busan to Rotterdam, this study reports **Ammonia GHG emission reduction expressed in gCO2eq/MJ is greater than that of Methanol.**

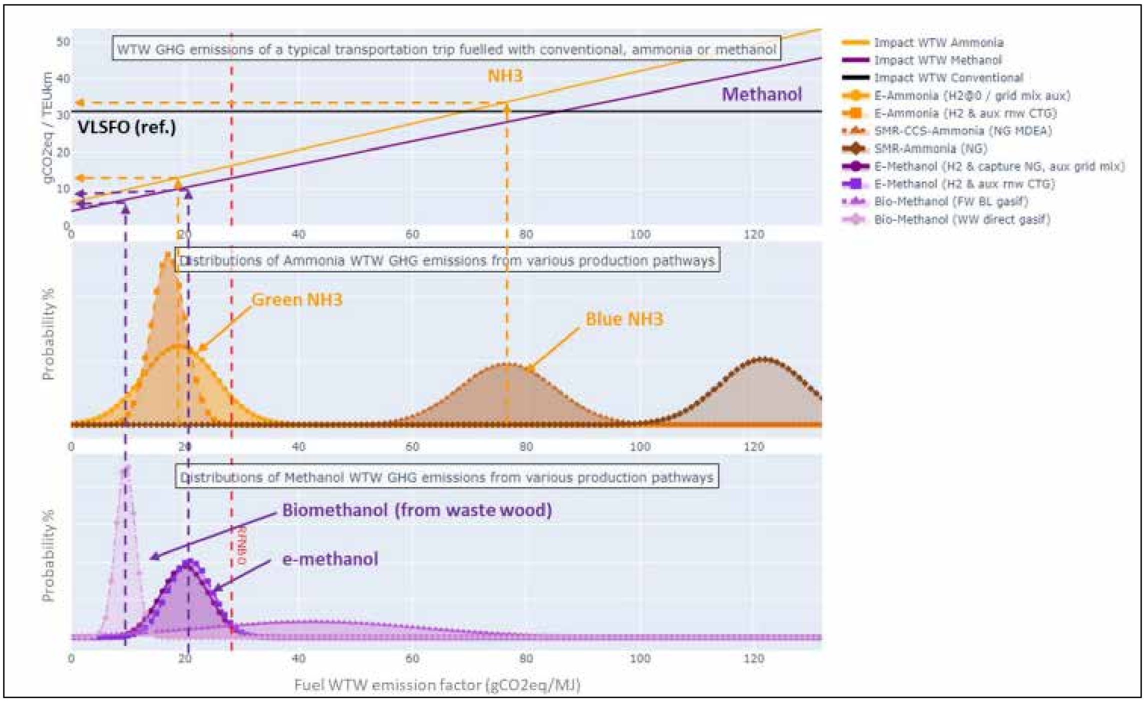


Figure 4.16: GHG Emissions from Transport Using Methanol or Ammonia – Relationship Between Fuel Well-to-Wake (WtW) GHG Intensity and Container Unit Transportation WtW GHG Intensity [44].

[The first graph presents fuel GHG intensity versus transportation work associated emissions, while the second and third graphs illustrate scenario sensitivity distributions for ammonia (NH_3) and methanol (MeOH), respectively. These distribution curves are derived from a global sensitivity analysis conducted using Monte Carlo simulations. The results are approximated as normal distributions, using mean values and standard deviations, to represent the most probable range of GHG emissions for each assessed fuel based on the defined parameter variations.]

However, it is interesting to note that Methanol achieves higher overall decarbonization as per gCO2eq/TEU.Km unit. This is attributed to Methanol's much higher engine efficiency, lower pilot fuel consumption and absence of Nitrous Oxide (NO) emission compared to Ammonia. This is represented in Figures 4.16.

4.1.4 Alternative Fuel from Ship Design Perspective – Comparative Assessment

A focused study **[45]** has analysed the engineering design aspect of storage of 3 alternative fuels, such as, Methanol, Ammonia and Hydrogen onboard on a large scale International sea water vessel. Comparing the performance of these hydrogen derived fuels, this study identifies the key engineering challenges for their ship integration especially from storage infrastructure and desired design range perspectives.

Based on exhaustive analysis of raw shipping data it is perceived that a maximum expected propulsion demand per voyage is 9270 MWh. This is taken as the basis for all estimation for fuel storage and design consideration in this study. The volume and mass requirement to deliver the 9270 MWh of energy are estimated for all the three fuels accounting for respective efficiency of each of the prolusion studied. **Table 4.7a** and **Table 4.7b** show the volume and mass comparison of these 3 selected fuels with and without storage system respectively. **Table 4.8** shows comparative design range of the ships for alternative fuel. It is noticed that the majority of these design ranges would not be large enough to be considered viable for global trade, therefore an increase in tank size to some extent would be unavoidable. The design range calculation details are given in Annexure.

Table 4.7 a: A Comparison of Volume and Mass (for fuel only without storage tank) to provide 9270MWh of Delivered Energy. The Upper Boundary for Efficiency used for Each Propulsion Type.

Fuel Type	Efficiency	Volumetric Energy Density (MWh/m^3)	Total Volume Required (m^3)	Mass Energy Density (MWh/kg)	Total Mass Required (tonnes)	40-ft Containers Equivalent	% of Cargo Volume	% Compared to Max HFO Volume	Energy Density (MWh/kg)	Total Storage Mass (tonnes)	% of Total Deadweight
LNG	58%	6.5	2459	32	1.82%	91%	58%	6.5	0.0159	1008	1.51%
Diesel (HFO)	20-40%	11.7	1981	26	1.47%	73%	40%	11.7	0.0116	1998	2.99%
Hydrogen (gas @700 bar)	40-60%	1.4	11,036	143	8.17%	409%	60%	1.4	0.0333	464	0.69%
Hydrogen (liquid)	40-60%	2.36	6547	85	4.85%	242%	60%	2.36	0.0333	464	0.69%
Metal Hydride	40-60%	3.18	4858	63	3.60%	180%	60%	3.18	0.0006	26,638	39.81%
Ammonia (-34°C)	30-60%	3.9	3962	51	2.93%	147%	60%	3.9	0.0052	2959	4.42%
Ammonia (10 bar)	30-60%	3.78	4062	53	3.03%	151%	60%	3.78	0.0063	2472	3.69%
Methanol	55-60%	4.99	3095	40	2.29%	115%	60%	4.99	0.0055	2792	4.17%
Batteries (Li-ion)	70- 95%	0.3	32,855	427	24.34%	1217%	95%	0.3	0.0002	44,354	66.30%

Table 4.7 b): A Comparison of Volume and Mass (for Fuel and Storage) to provide 9270 MWh of Delivered Energy. The Upper Boundary for Efficiency used for Each Propulsion Type

Fuel type	LNG	Diesel (HFO)	Hydrogen (gas)	Hydrogen (liquid)	Metal Hydride	Ammonia	Methanol	Batteries (Li-ion)
Efficiency	58%	20-40%	40-60%	40-60%	40-60%	30-60%	55-60%	70-95%
Volume								
Energy Density (MWh/m³)	3.3	7	0.9	1.2	0.8	2.22	3.97	0.27
Total Storage Size (m3)	4843	3311	17167	12875	19313	6963	3892	36140
40 ft Containers Equivalent	63	43	223	167	251	90	51	469
% of Cargo	35.9%	2.45%	12.72%	9.54%	143.1%	5.16%	2.88%	26.77%
% Compared to Max FO	179%	123%	636%	477%	715%	258%	144%	1339%
Mass								
Energy Density (MWh/kg)	0.0074	0.008	0.0018	0.002	0.0004	0.0028	0.0038	0.0002
Total Storage Mass (tonnes)	2160	2897	8583	7725	38625	5557	4014	65053
% of Total	3.2 %	4.3%	12.8%	11.5%	57.7%	8.3%	6%	97.2%

Table 4.8 : Theoretical Design Ranges based on a Fuel Volume of 2700 m3 Shown in Nautical Miles (nm) and Kilometres (km)

Fuel Option	Range (nm)	Range (km)
Diesel (HFO)	7155	13251
LNG	5764	10675
Compressed Hydrogen (700 bar)	1284	2378
Liquid Hydrogen	2165	4009
Ammonia	3578	6626
Methanol	4579	8480

Analyses of Table 4.7a, 4.7b and 4.8 shows Ammonia's high toxicity and corrosion, Hydrogen's complex storage requirements and Methanol's carbon content and subsequent CCS requirement making none of the fuels as ideal one.

Ships tend to operate with more fuel especially HFO storage onboard than what is required for a single voyage. This study has shown that reducing storage levels to closer to the expected output for single trip can reduce mass and volume requirements and hence make alternative fuels significantly more viable. In other words, till the alternative fuels become largely available in a cost-effective manner, it could be an argument for large design ranges (akin to those seen now). However once alternative fuel availability is more universal and price differential low then bunkering more frequently may be more viable and lower design ranges would be preferable.

4.2 Alternative Fuel- Mix Demand Scenarios for India

This Section evaluates the alternative fuel and fuel-mix demand for green transition in Indian maritime sector especially in Coastal and OGVs. This analysis further quantifies the green Hydrogen required for producing these alternative fuels specifically E-Fuels (E-Methanol, E-Ammonia and E-LNG). Additionally, it assesses the renewable energy (RE) demand which is necessary to make the required green Hydrogen ensuring a sustainable supply chain for alternative fuel. By understanding the fuel demand, Hydrogen supply, and energy requirements, this study provides valuable insights for strategic planning, infrastructure development, and policy recommendations aimed at decarbonizing the shipping sector using sustainable fuels (bio and E-fuels).

In order to estimate the Hydrogen requirement for producing sustainable alternative fuels the analysis has relied on established conversion factors and core chemical reactions. It is considered that, for example, synthesis of 1 tonne of Methanol requires 0.20 tonnes of green Hydrogen. Similarly, 1 tonne of Ammonia production requires 0.178 tonnes of green Hydrogen, while 1 tonne of E-Methane (or E-LNG) requires 0.50 tonnes of green Hydrogen. Also, producing Hydrogen through electrolysis requires a significant amount of renewable energy. On average, 1 kg of Hydrogen requires approximately 47 kWh of renewable electricity.

A thorough examination of the fuel mix for the Indian maritime industry has been done in order to meet these GFI targets. This analysis used fuel consumption data from the Marine Environmental Management Report 2023, which gave insights into the shipping industry's current fuel consumption for ocean-going and coastal vessels alone. As a result, it should be noted that fuel consumption for inland waterways is exclusive. Major portions of 0.65309 (42.4%) heavy fuel oil (HFO), 0.41026 (26.7%) diesel oil (DO), and 0.47527 (30.9%) light fuel oil (LFO) were consumed by Indian fleets in 2022, making up a total of 1.53862 (all in million tons).

The total consumption of these conventional fuels highlights the ongoing reliance on traditional energy sources in the Shipping sector alone. Based on this, the required amounts of alternative fuels are calculated to ensure that the Base and Direct compliance targets (as per MEPC 83 amendments) are met.

The existing GFI values for conventional fuels, such as Heavy Fuel Oil (HFO), Light Fuel Oil (LFO), and Diesel Oil (DO), are quite high, with GFI values of 90.6, 91, and 91 respectively. These values indicate the significant environmental impact associated with the use of these traditional fuels.

The fuel mix calculations consider the proportion of various alternative fuels required to achieve the emission targets to achieve net zero by 2050 while considering the well-to-wake emission pathways.

This calculation will guide the transition from conventional marine fuels to alternative fuels, such as Methanol, Ammonia, green Hydrogen, Biofuels, and other low- or zero-carbon options.

Amount of Alternative Fuels Required: Base and Direct Compliance

For the Base and Direct strategies, the fuel mix outlines specific quantities of alternative fuels and the quantity of conventional fuel required (also in%) for 2030 and 2035 for smooth and transition to more greener and sustainable fuel options of 612 vessels of <5000 GT and 236 vessels of >5000 GT category. Two cases are built here. Case A represents Diesel Oil and Alternative fuel mix for meeting Base and Direct Compliance targets, whereas Case B represents Diesel Oil and Alternative fuel mix with additional 20% Biodiesel. This is presented in **Table 4.10.**

4.2.1 Case A: Conventional Oil + Alternative fuel Mix Demand

In Case A, the fuel mix targets are calculated based on the existing fuel consumption patterns while ensuring compliance with GFI regulations. This scenario considers a blend of conventional fuels and alternative fuels to meet energy demands while reducing carbon emissions. The focus is on gradual integration of cleaner fuel sources while maintaining operational efficiency.

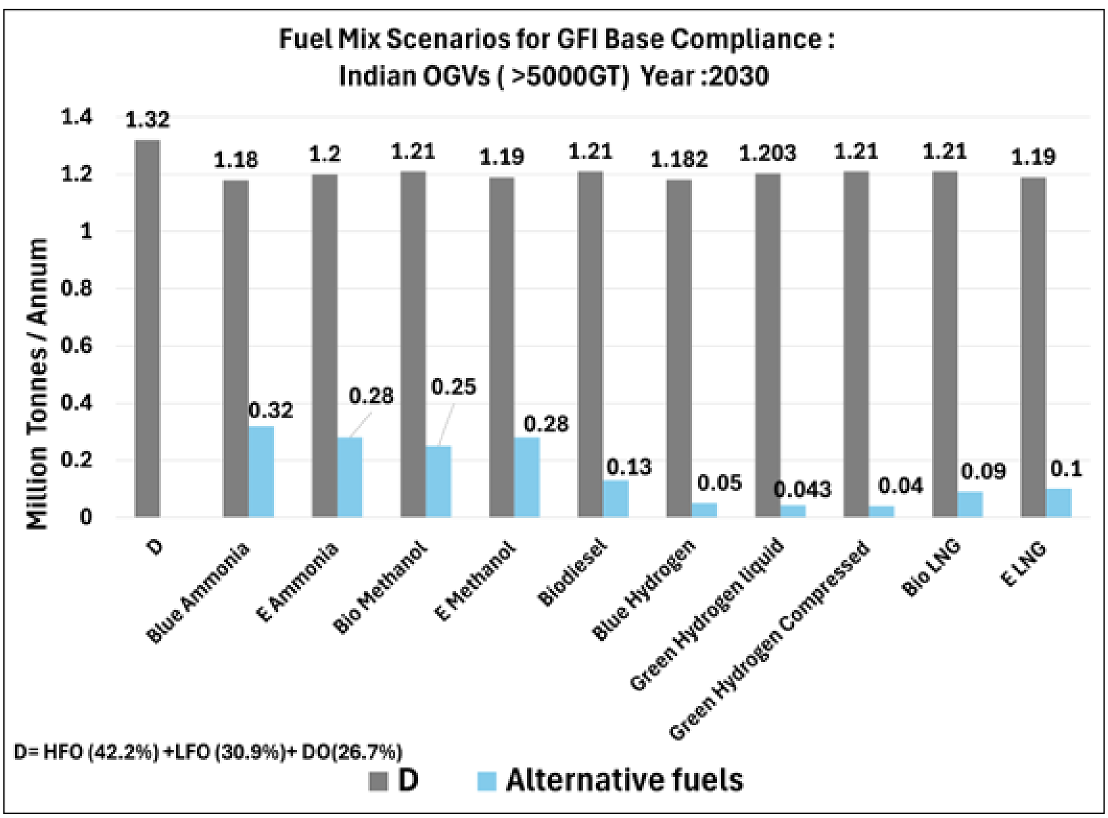


Figure 4.17 : Base GFI Compliance Fuel Mix Scenarios (OGVs >5000 GT Vessels) Year:2030

OGVs (>5000GT) Vessels

Table 4.9: Fuel Mix Demand for OGV’s (>5000GT) -Base and Direct Compliance (Conventional + Alternative Fuel)

In Million Tonnes								
	2030		2035		2030		2035	
	Base Compliance				Direct Compliance			
Fuel Type	**Conventional fuel**	**Alternative fuel**	**Conventional fuel**	**Alternative fuel**	**Conventional fuel**	**Alternative fuel**	**Conventional fuel**	**Alternative fuel**
Blue Ammonia	1.18	0.32	0.93	1.17	0.95	0.83	0.71	1.68
E Ammonia	1.20	0.28	1.02	0.98	1.00	0.72	0.83	1.40
Bio Methanol	1.21	0.25	1.01	0.94	1.01	0.65	0.82	1.34
E Methanol	1.19	0.28	1.02	0.92	0.98	0.73	0.83	1.31
Biodiesel	1.21	0.13	1.01	0.48	1.01	0.33	0.82	0.68
Blue Hydrogen	1.182	0.050	0.932	0.182	0.953	0.129	0.705	0.260
Green Hydrogen liquid	1.203	0.043	1.019	0.152	1.007	0.110	0.830	0.217
Green Hydrogen Compressed	1.21	0.04	1.02	0.15	1.03	0.10	0.83	0.22
Bio LNG	1.21	0.09	1.01	0.34	1.01	0.24	0.82	0.48
E LNG	1.19	0.10	1.02	0.33	0.98	0.26	0.83	0.47

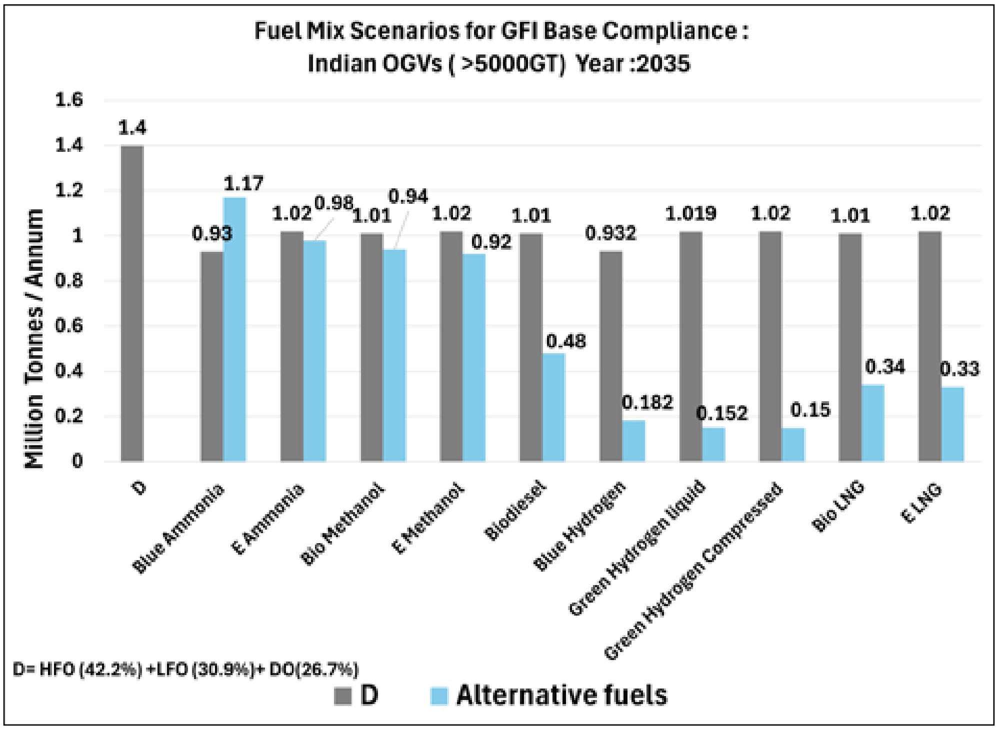


Figure 4.18: Base GFI Compliance Fuel Mix Scenarios (OGVs >5000 GT Vessels) Year:2035

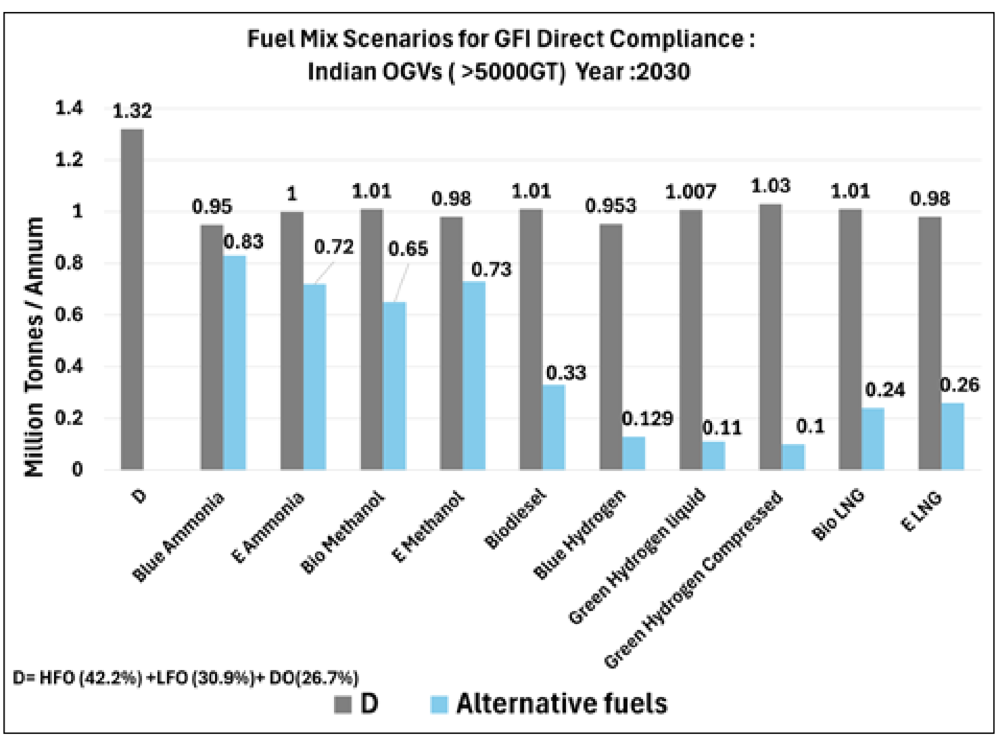


Figure 4.19: Direct GFI Compliance Fuel Mix Scenarios (OGVs >5000 GT Vessels) Year:2030

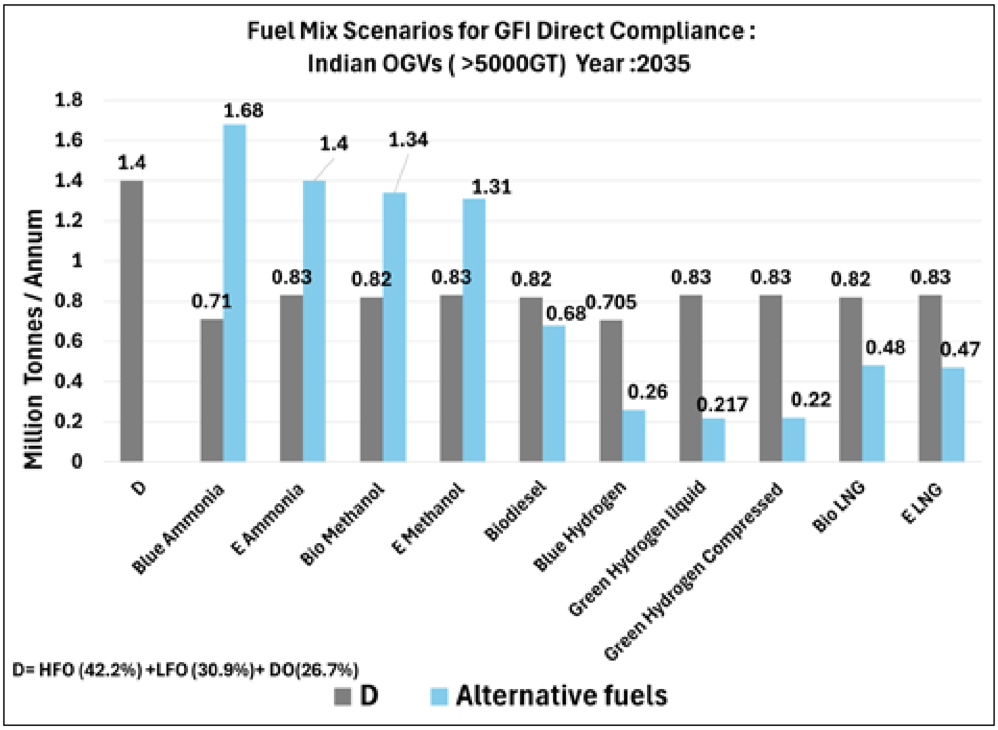


Figure 4.20: Direct GFI Compliance Fuel Mix Scenarios (OGVs >5000 GT Vessels) Year:2035

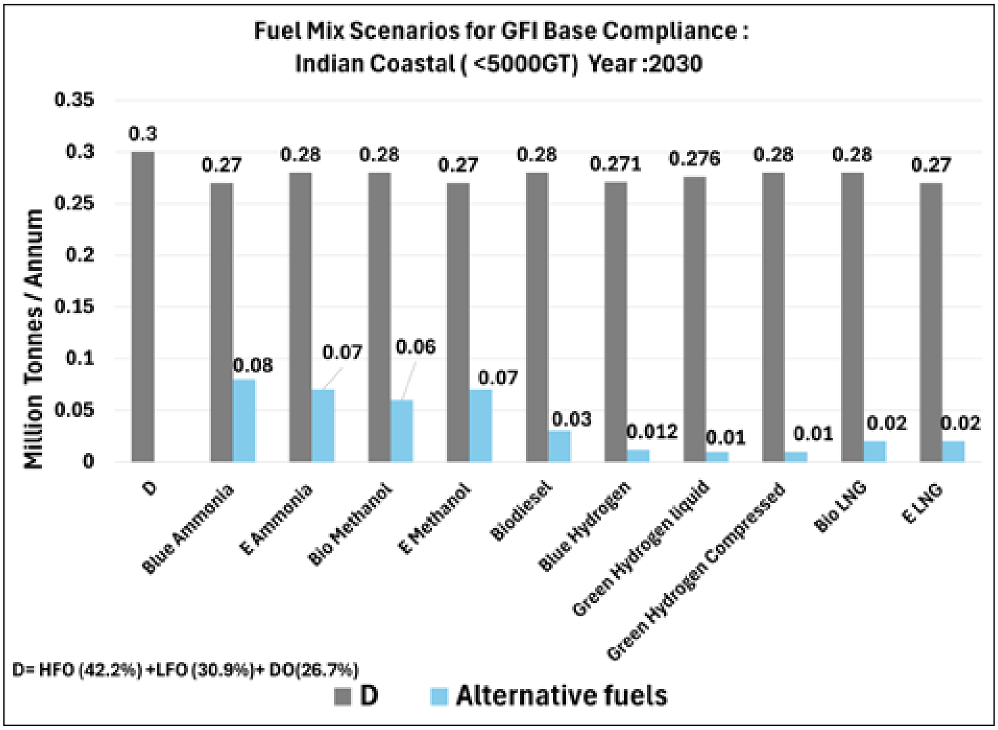


Figure 4.21: Base GFI Compliance Fuel Mix Scenarios (Coastal <5000 GT Vessels) Year:2030

Coastal Vessels (<5000 GT)

Table 4.10: Fuel Mix Demand for Coastal Vessels (<5000GT) -Base and Direct Compliance (Diesel + Alternative Fuel)

In Million tonnes								
	Base Compliance				Direct Compliance			
	2030		2035		2030		2035	
Fuel Type	Conventional fuel	Alternative fuel	Conventional fuel	Alternative fuel	Conventional fuel	Alternative fuel	Conventional fuel	Alternative fuel
Blue Ammonia	0.27	0.08	0.21	0.28	0.22	0.20	0.16	0.40
E Ammonia	0.28	0.07	0.23	0.24	0.23	0.17	0.19	0.34
Bio Methanol	0.28	0.06	0.23	0.23	0.23	0.16	0.19	0.32
E Methanol	0.27	0.07	0.23	0.22	0.22	0.18	0.19	0.31
Biodiesel	0.28	0.03	0.23	0.11	0.23	0.08	0.19	0.16
Blue Hydrogen	0.271	0.012	0.214	0.044	0.219	0.031	0.162	0.062
Green Hydrogen liquid	0.276	0.010	0.234	0.037	0.231	0.027	0.191	0.052
Green Hydrogen Compressed	0.28	0.01	0.23	0.04	0.24	0.02	0.19	0.05
Bio LNG	0.28	0.02	0.23	0.08	0.23	0.06	0.19	0.12
E LNG	0.27	0.02	0.23	0.08	0.22	0.06	0.19	0.11

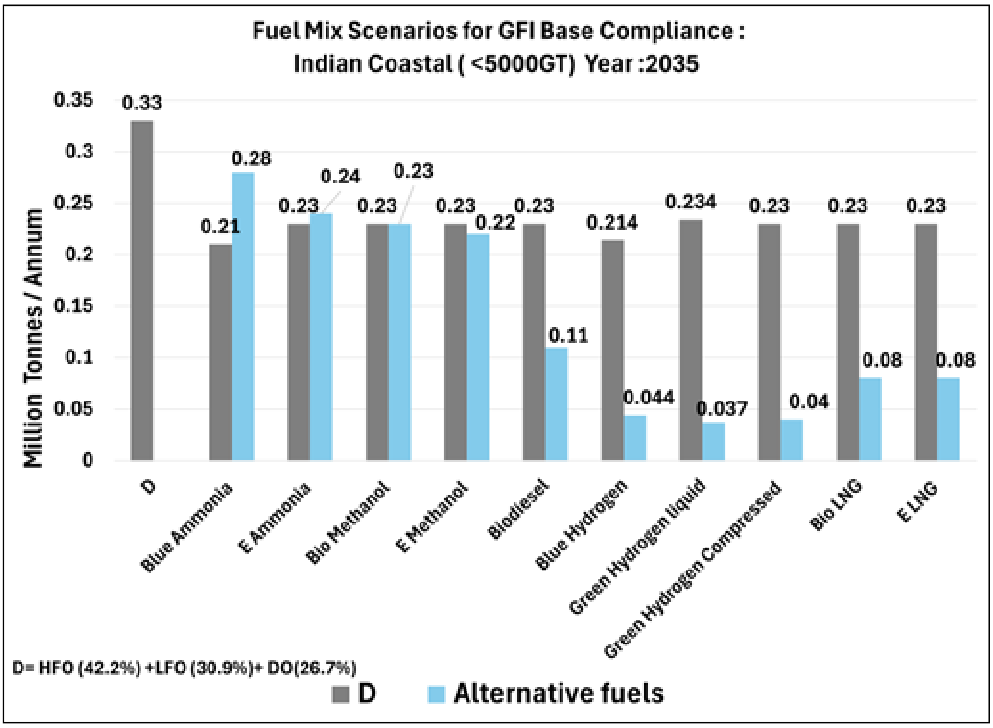


Figure 4.22: Base GFI Compliance Fuel Mix Scenarios (Coastal <5000 GT Vessels) Year:2035

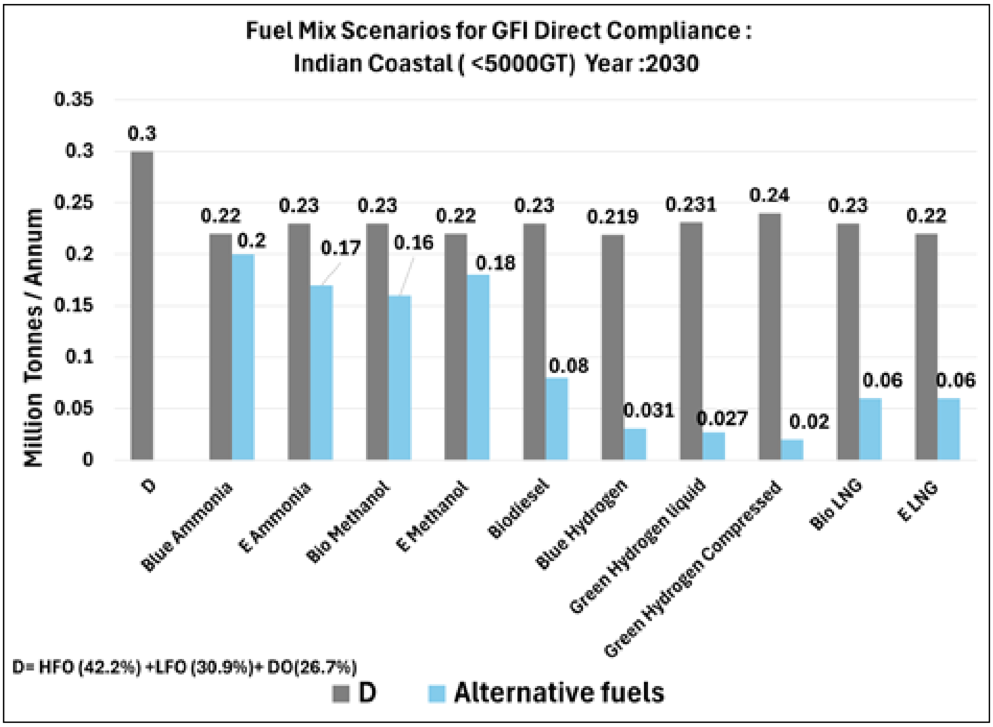


Figure 4.23: Direct GFI Compliance Fuel Mix Scenarios (Coastal <5000 GT Vessels) Year:2030

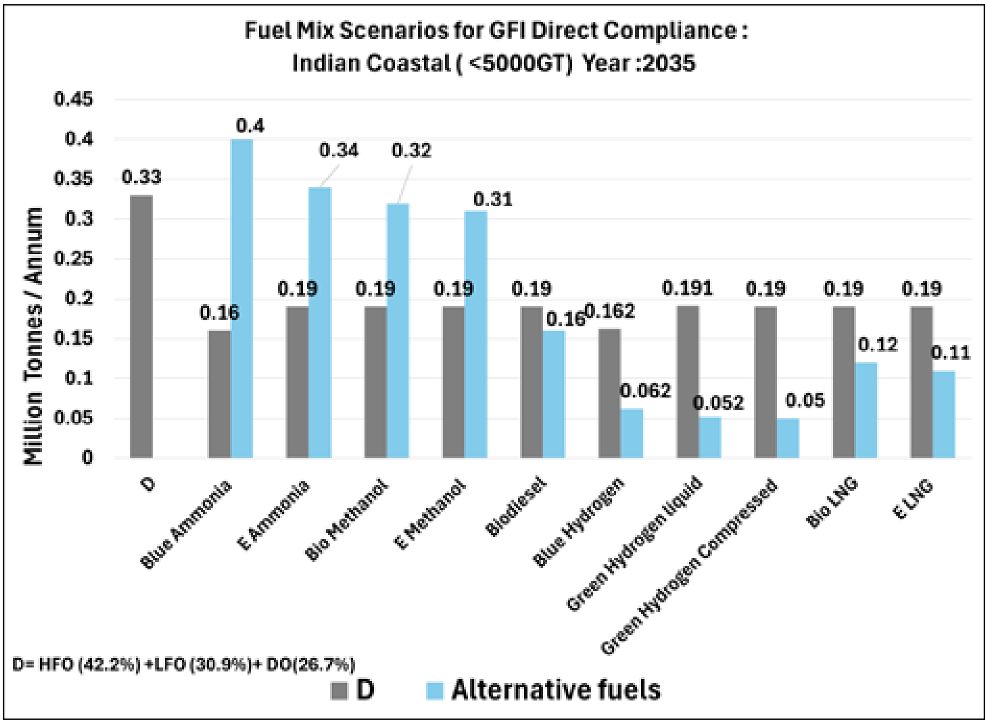


Figure 4.24: Direct GFI Compliance Fuel Mix Scenarios (Coastal <5000 GT Vessels) Year:2035

4.2.2 Case B: Conventional Fuel (CF)+ Alternative fuel (AF) Mix + 20% Biodiesel (BD) mix

In **Case B,** the fuel mix includes a **20% biodiesel blend,** along with **conventional fuels and alternative fuels.** This scenario enhances sustainability by **incorporating renewable fuel sources**, significantly lowering greenhouse gas emissions compared to pure fossil fuel reliance**.** The **20% biodiesel inclusion** ensures a balance between **fuel performance, regulatory compliance, and emissions reduction,** making it a viable approach for greener energy transitions.

OGV'S (>5000GT)

Table 4.11: Fuel Mix Demand for OGV's (>5000GT) -Base and Direct Compliance (Diesel + Alternative Fuel+20%Biodiesel)

	In Million Tonnes										
	2030						2035				
	Base Compliance			Direct Compliance			Base compliance			Direct Compliance	
Fuel Type	Conventional Fuel		Alternative Fuel	Conventional Fiel	20% Bio-diesel	Alternative Fuel	Conventional Fuel	20% Bio-diesel	Alternative Fuel	Conventional Fuel	20% Bio-diesel	Alternative Fuel
Blue Ammonia	0.95	0.26	0.32	0.76	0.21	0.83	0.75	0.21	1.17	0.56	0.16	1.68
E Ammonia	0.96	0.26	0.28	0.80	0.22	0.72	0.82	0.22	0.98	0.66	0.18	1.40
Bio Methanol	0.96	0.27	0.25	0.81	0.22	0.65	0.81	0.22	0.94	0.65	0.18	1.34
E Methanol	0.95	0.26	0.28	0.78	0.22	0.73	0.82	0.22	0.92	0.66	0.18	1.31
Blue Hydrogen	0.95	0.26	0.05	0.76	0.21	0.13	0.75	0.21	0.18	0.56	0.16	0.26
Green Hydrogen liquid	0.96	0.26	0.04	0.81	0.22	0.11	0.82	0.22	0.15	0.66	0.18	0.22
Green Hydrogen Compressed	0.97	0.27	0.04	0.83	0.23	0.10	0.82	0.22	0.15	0.66	0.18	0.22
Bio LNG	0.96	0.27	0.09	0.81	0.22	0.24	0.81	0.22	0.34	0.65	0.18	0.48
E LNG	0.95	0.26	0.10	0.78	0.22	0.26	0.82	0.22	0.33	0.66	0.18	0.47

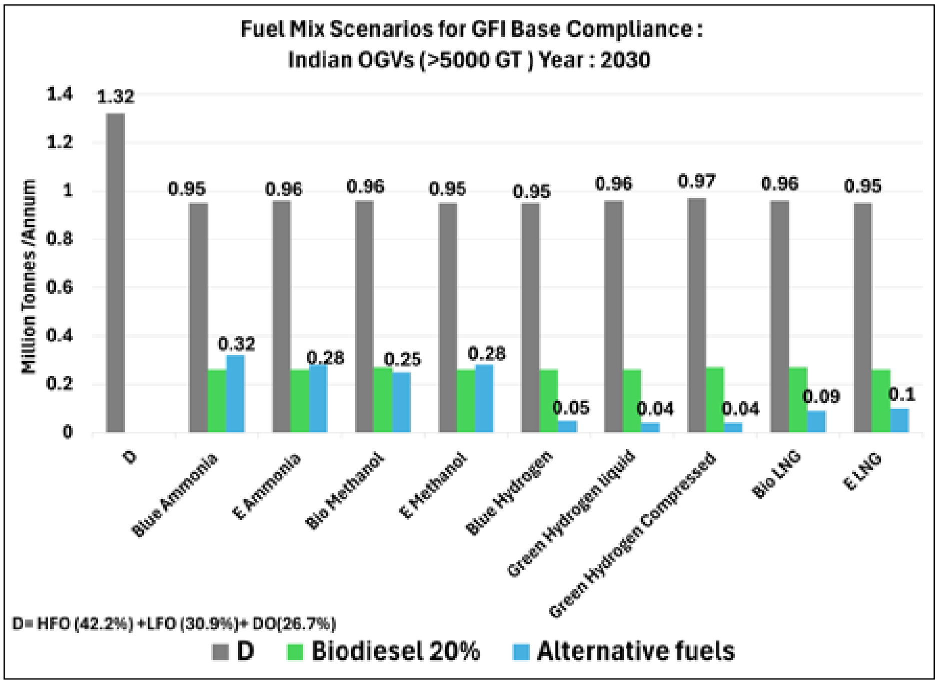


Figure 4.25: Base GFI Compliance Fuel Mix Scenarios (OGV'S >5000 GT Vessels) Year:2030(Conventional Fuel +Alternative Fuel+ 20% Biodiesel)

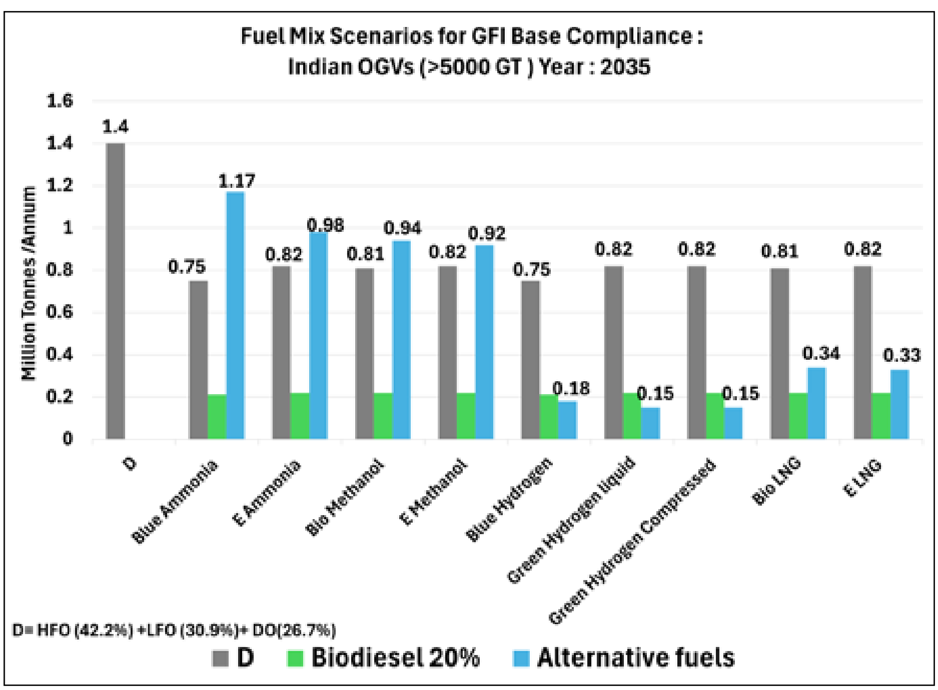


Figure 4.26: Base GFI Compliance Fuel Mix Scenarios (OGV'S >5000 GT Vessels) Year:2035(Conventional Fuel +Alternative Fuel+ 20% Biodiesel)

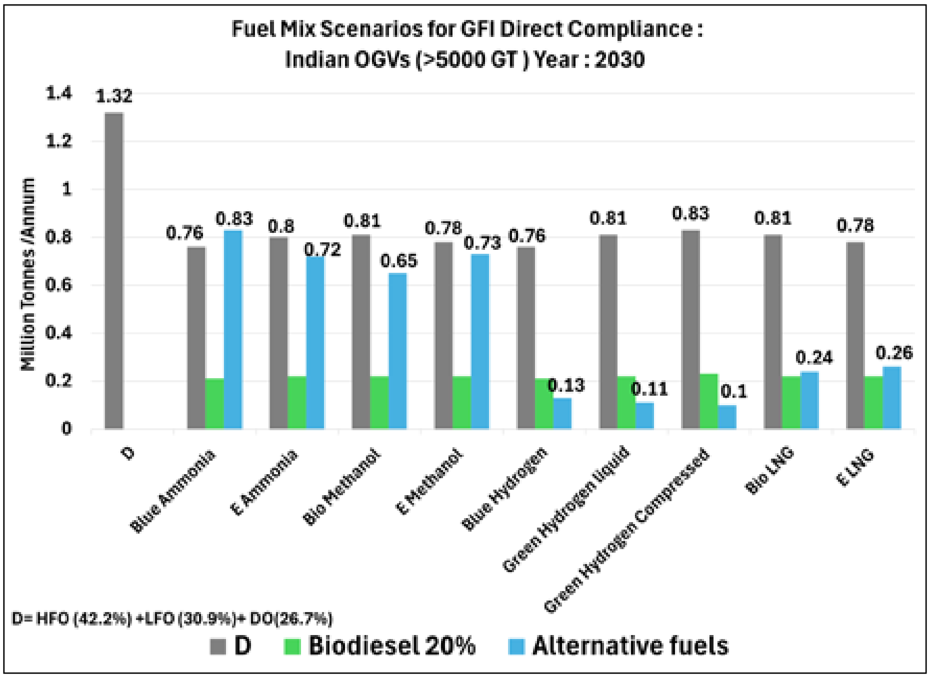


Figure 4.27: Direct GFI compliance fuel mix scenarios (OGV'S >5000 GT Vessels) Year:2030 (Conventional Fuel +Alternative Fuel+ 20% Biodiesel)

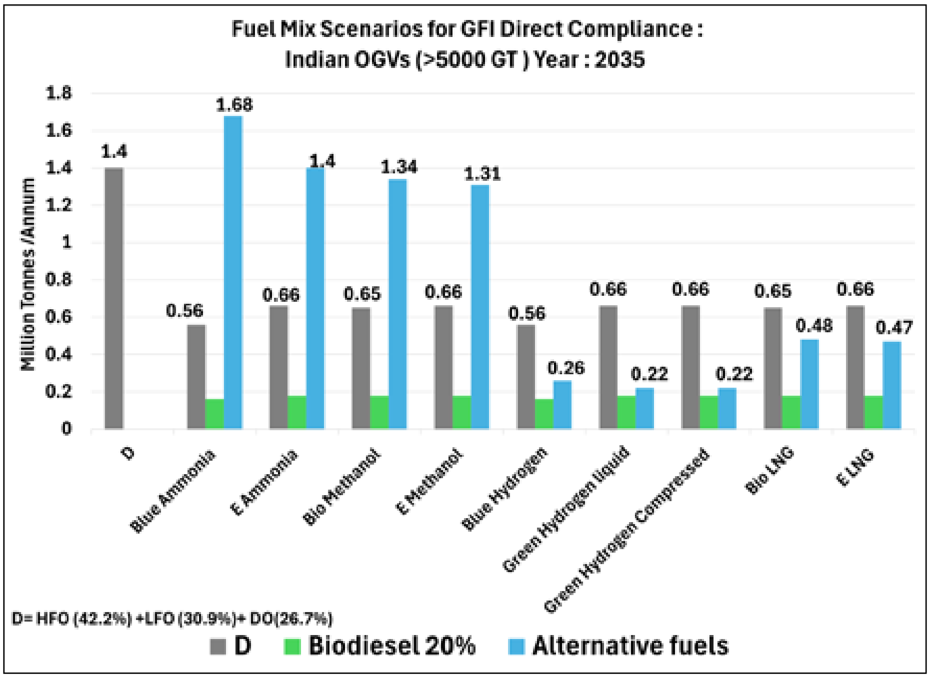


Figure 4.28: Direct GFI Compliance Fuel Mix Scenarios (OGV'S >5000 GT Vessels) Year:2035 (Conventional Fuel +Alternative Fuel+ 20% Biodiesel)

Coastal (<5000GT) Vessels

Table 4.12: Fuel Mix Demand for OGV's (>5000GT)-Base and Direct Compliance (Conventional Fuel + Alternative Fuel+ 20%Biodiesel)

	In Million Tonnes						In Million Tonnes					
	2030						2035					
	Base compliance			Direct Compliance			Base compliance			Direct Compliance		
Fuel Type	Conventional Fuel	20% Biodiesel	Alternative Fuel	Conventional Fuel	20% Biodiesel	Alternative Fuel	Conventional Fuel	20% Biodiesel	Alternativ Fuel	Conventional Fuel	20% Biodiesel	Alternative Fuel
Blue Ammonia	0.22	0.06	0.08	0.18	0.05	0.20	0.17	0.05	0.28	0.13	0.04	0.40
E Ammonia	0.22	0.06	0.07	0.18	0.05	0.17	0.19	0.05	0.24	0.15	0.04	0.34
Bio Methanol	0.22	0.06	0.06	0.19	0.05	0.16	0.19	0.05	0.23	0.15	0.04	0.32
E Methanol	0.22	0.06	0.07	0.18	0.05	0.18	0.19	0.05	0.22	0.15	0.04	0.31
Blue Hydrogen	0.22	0.06	0.01	0.18	0.05	0.03	0.17	0.05	0.04	0.13	0.04	0.06
Green Hydrogen liquid	0.22	0.06	0.01	0.19	0.05	0.03	0.19	0.05	0.04	0.15	0.04	0.05
Green Hydrogen Compressed	0.22	0.06	0.01	0.19	0.05	0.02	0.19	0.05	0.04	0.15	0.04	0.05
Bio LNG	0.22	0.06	0.02	0.19	0.05	0.06	0.19	0.05	0.08	0.15	0.04	0.12
E LNG	0.22	0.06	0.02	0.18	0.05	0.06	0.19	0.05	0.08	0.15	0.04	0.11

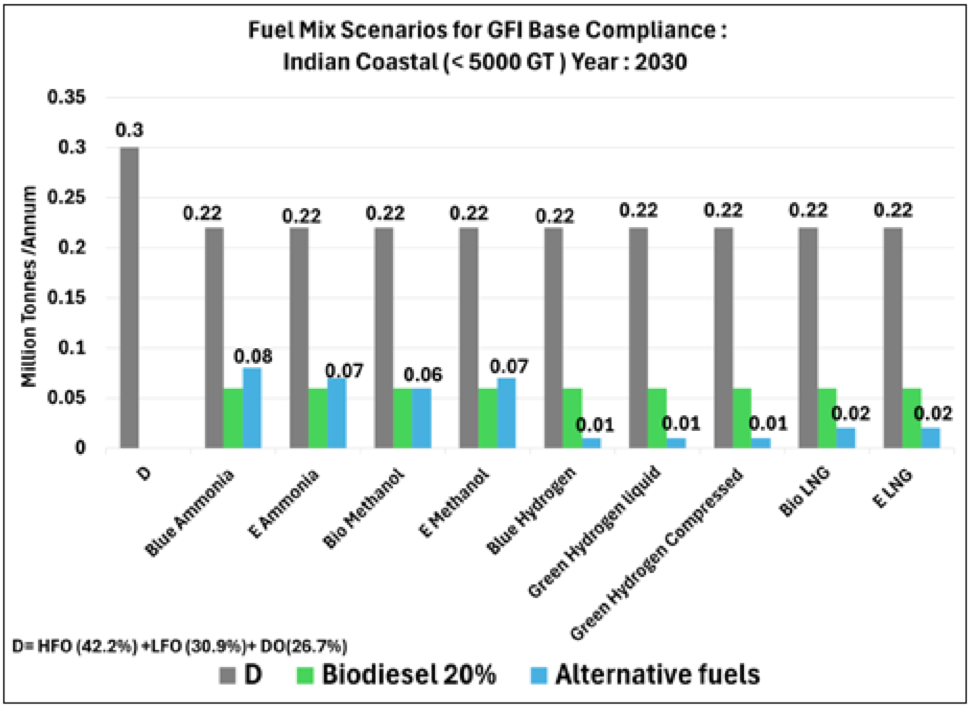


Figure 4.29: Base GFI Compliance Fuel Mix Scenarios (Coastal <5000 GT Vessels) Year:2030 (Diesel +Alternative Fuel+ 20% Biodiesel)

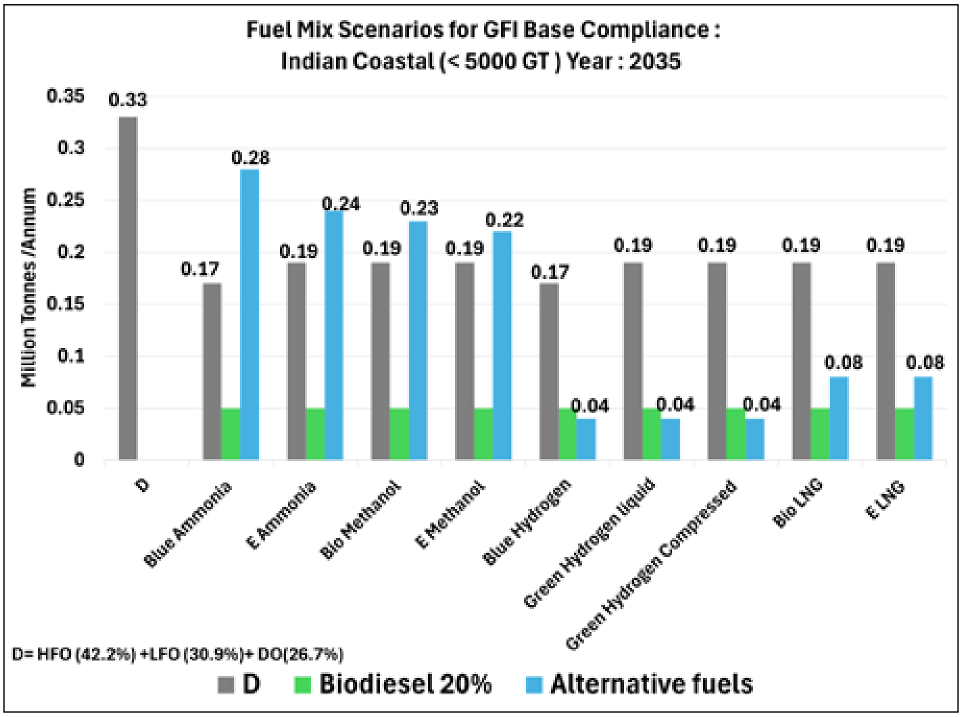


Figure 4.30: Base GFI Compliance Fuel Mix Scenarios (Coastal <5000 GT Vessels) Year:2035 (Conventional Fuel +Alternative Fuel+ 20% Biodiesel)

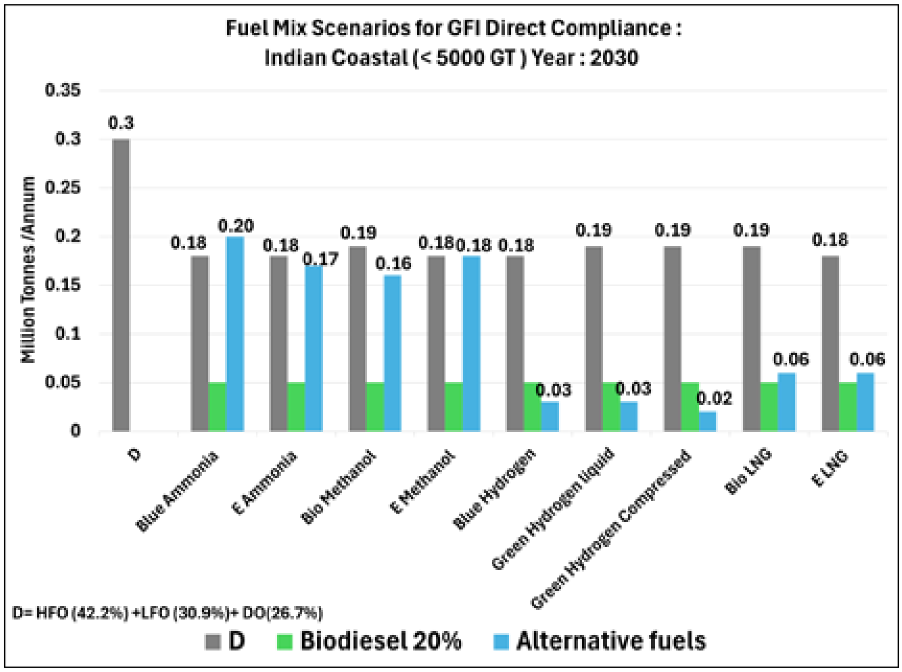


Figure 4.31: Direct GFI compliance fuel mix scenarios (Coastal <5000 GT Vessels) Year:2030(Diesel +Alternative Fuel+ 20% Biodiesel

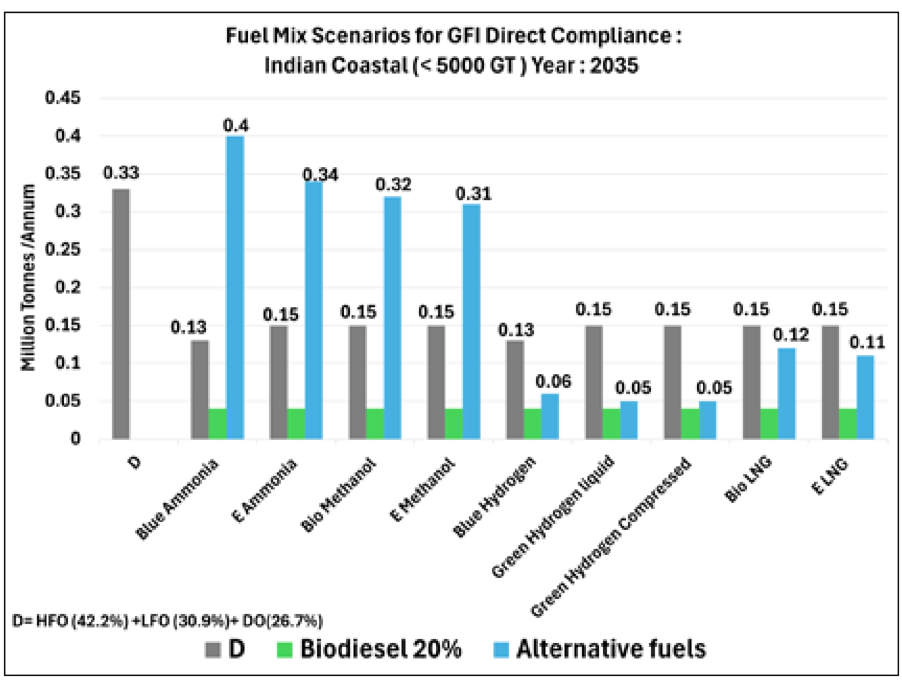


Figure 4.32: Direct GFI Compliance Fuel Mix Scenarios (Coastal <5000 GT Vessels) Year:2035(Diesel +Alternative Fuel+ 20% Biodiesel)

4.2.3 Estimation of Renewable Energy and Hydrogen Requirement

Scenario 1: India's Alternative Fuel-Mix Demand for GFI Compliance by 2030, 2035 (both Coastal and OGVs) with Green Electricity and Green Hydrogen Requirement

This Scenario aligns fuel transition strategies with Greenhouse gas Fuel Intensity (GFI) compliance, ensuring that the alternative fuel mix meets IMO's latest targets. It also provides the estimates for additional RE Power and green Hydrogen requirement to meet India's alternative fuel-mix demand scenarios both for OGVs considering **4 types of alternative fuels viz., Methanol (bio- and e-), Ammonia (blue and e-), Hydrogen (blue, green liquid & green compressed) & LNG (bio and e-).** Under Scenario 1 two cases are considered.

Case 1 represents the alternative fuel-mix demand and associated green Hydrogen and RE requirement under IMO's Base compliance category. Case 2 on the other hand represents the same under IMO's Direct Compliance category.

Table 4.13 and Figures 4.33, 4.34 display fuel and /fuel mix demand with Hydrogen and RE requirement for GFI Compliance of Indian OGV's > 5000GT for 2030 and 2035 under Base Compliance Category. Whereas, Table 4.14 and Figures 4.35, 4.36 display fuel and /fuel mix demand with Hydrogen and RE requirement for GFI Compliance of Indian OGV's > 5000GT for 2030 and 2035 under Direct Compliance Category

A) Scenario 1-Case 1: Base Compliance Category

Table 4.13: Alternative Fuel-Mix Demand for Indian OGVs (> 5000GT) for GFI Compliance with Green Electricity and Green Hydrogen Requirement (Base Compliance Category)

	(In Million Tonnes)				GWh x 10^3	
Fuel Type	GFI Compliance Fuel Mix Quantity		Amount of Hydrogen Required		Amount of Renewable Electricity needed to Produce Hydrogen	
	2030	2035	2030	2035	2030	2035
Blue Ammonia	0.32	1.17	0.06	0.21	2.68	9.79
E Ammonia	0.28	0.98	0.05	0.17	2.34	8.20
Bio Methanol	0.25	0.94	0.05	0.19	2.35	8.84
E Methanol	0.28	0.92	0.06	0.18	2.63	8.65
Blue Hydrogen	0.05	0.182	0.05	0.182	2.35	8.55
Green Hydrogen liquid	0.043	0.152	0.043	0.152	2.02	7.14
Green Hydrogen Compressed	0.04	0.15	0.04	0.15	1.88	7.05
Bio LNG	0.09	0.34	0.05	0.17	2.12	7.99
E LNG	0.1	0.33	0.05	0.17	2.35	7.76

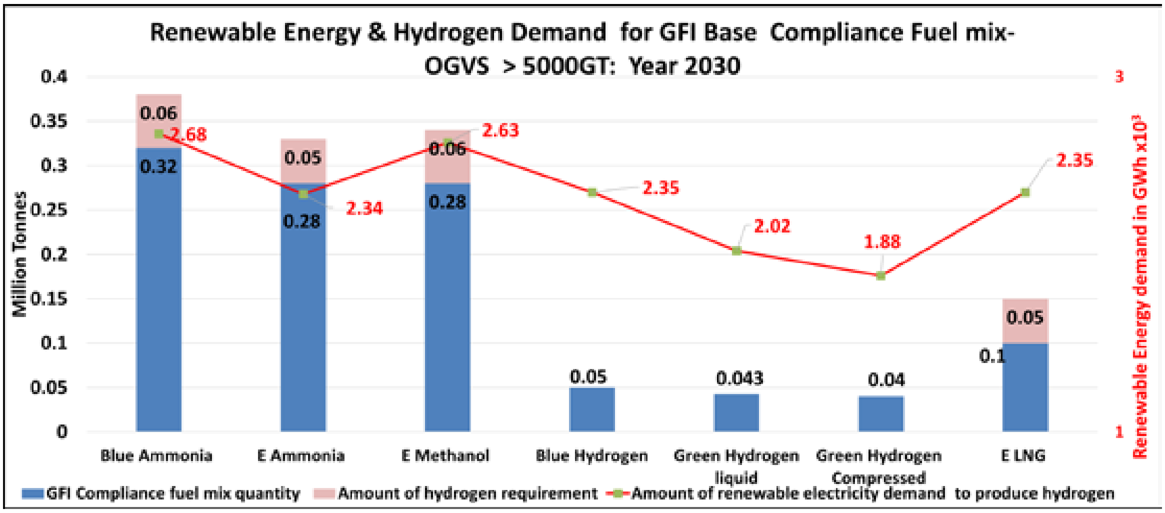


Figure 4.33: Alternative Fuel-Mix Demand with RE &Green Hydrogen Requirement for GFI-Compliance (>5000GT) Year 2030 (Base Compliance Category)

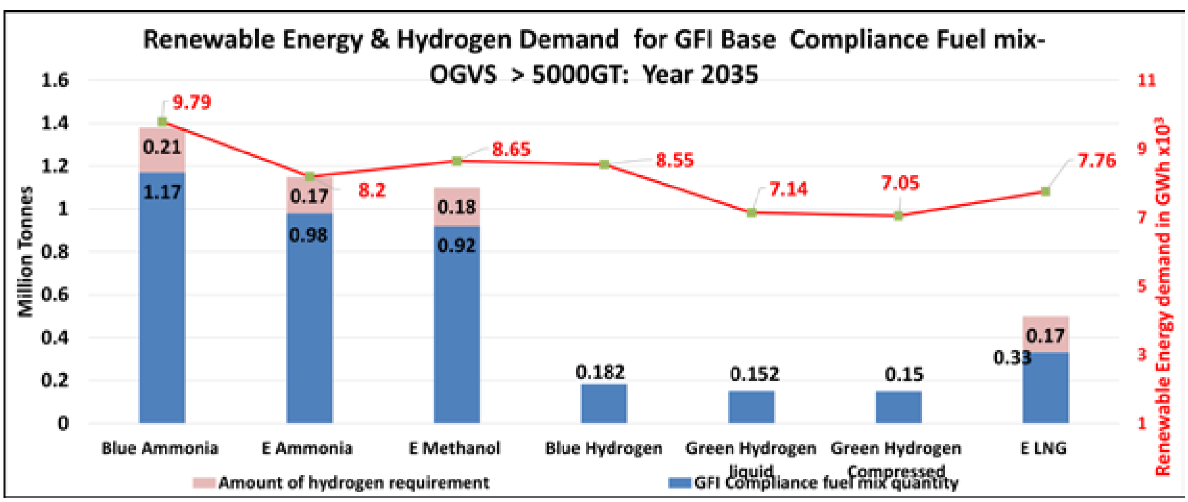


Figure 4.34: Alternative Fuel-Mix Demand with RE &Green Hydrogen Requirement for GFI-Compliance (>5000GT) Year 2035 (Base Compliance Category)

B) Scenario 1-Case 2: Direct Compliance Category

Table 4.14: Alternative Fuel-Mix Demand for Indian OGVs (> 5000GT) for GFI Compliance with Green Electricity and Green Hydrogen Requirement (Direct Compliance Category)

	(In Million Tonnes)				GWh x 10^3	
Fuel Type	**GFI Compliance Fuel Mix Quantity**		**Amount of Hydrogen Required**		**Amount of Renewable Electricity Needed to Produce Hydrogen**	
	2030	**2035**	**2030**	**2035**	**2030**	**2035**
Blue Ammonia	0.83	1.68	0.15	0.30	6.94	14.05
E Ammonia	0.72	1.4	0.13	0.25	6.02	11.71
Bio Methanol	0.65	1.34	0.13	0.27	6.11	12.60
E Methanol	0.73	1.31	0.15	0.26	6.86	12.31
Blue Hydrogen	0.129	0.26	0.129	0.26	6.06	12.22
Green Hydrogen liquid	0.11	0.217	0.11	0.217	5.17	10.20
Green Hydrogen Compressed	0.1	0.22	0.1	0.22	4.70	10.34
Bio LNG	0.24	0.48	0.12	0.24	5.64	11.28
E LNG	0.26	0.47	0.13	0.24	6.11	11.05

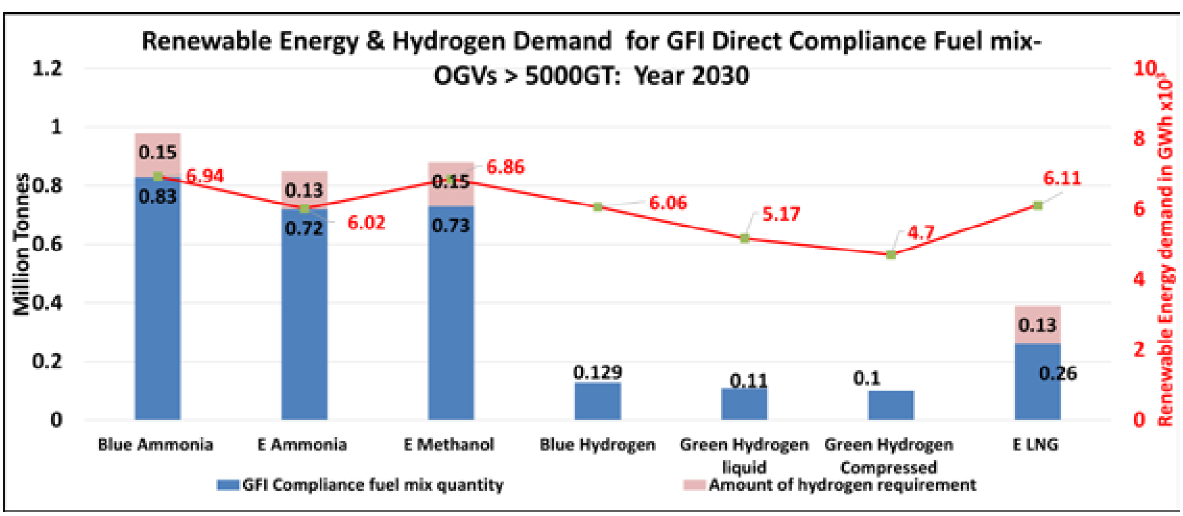


Figure 4.35: Alternative Fuel-Mix Demand with RE &Green Hydrogen Requirement for GFI-Compliance (>5000GT) Year 2030 (Direct Compliance Category)

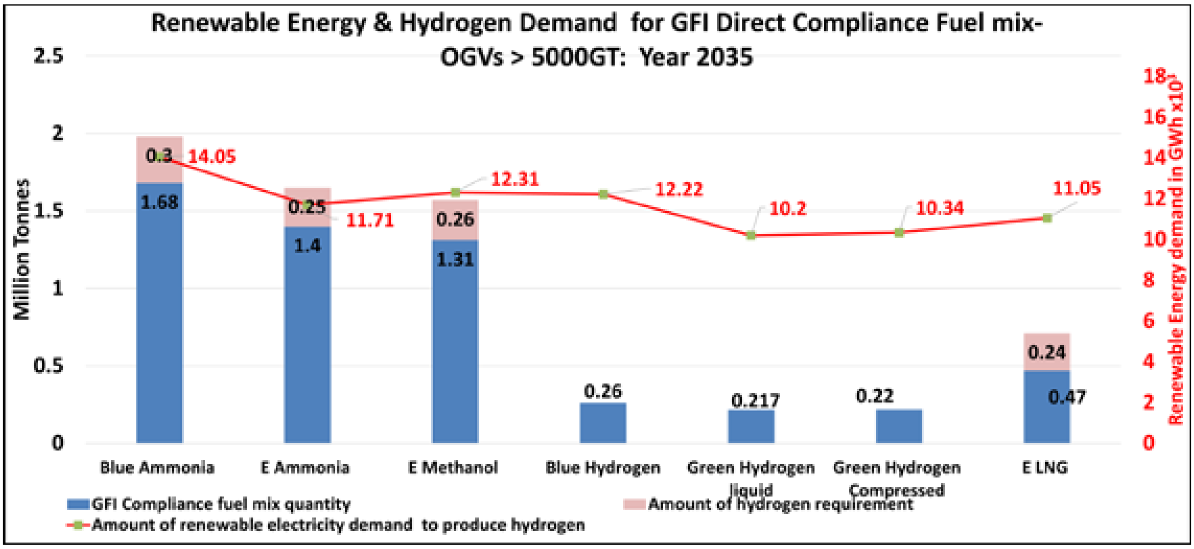


Figure 4.36: Alternative Fuel-Mix Demand with RE &Green Hydrogen Requirement for GFI-Compliance (>5000GT) Year 2035 (Direct Compliance Category)

4.2.4 Scenario 2: Blend Fuel Demand Scenarios with Emission Reduction by 2030 & 2035 (10 and 5 v/v % Methanol-Biodiesel-Diesel blend)

In this section two sets of blend fuel scenarios are built.

In Set 1, Blend fuel Scenarios with Diesel & Methanol 10 v/v % are made along with additional Diesel-Biodiesel blends of varying proportion (2%, 5%, 10%, 20%, 30 & 50% v/v). This demand scenarios are made both for Indian Coastal and OGVs.

In Set 2, Blend fuel Scenarios with Diesel & Methanol 5 v/v % are made along with additional Diesel-Biodiesel blends of varying proportion (2%, 5%, 10%, 20%, 30% & 50% v/v). Alike Set1, blend fuel demand estimation is made both Indian Coastal and OGVs for Set 2 also.

Under Set 1, The overall blend fuel volume requirement and subsequent GHG emission reduction profiles for OGVs (>5000 GT) are estimated and reported in **Figures 4.37, 4.38 for 2030 and in Figure 4.39 for year 2035. Figures 4.40, 4.41 and 4.42 are made for** blend fuel volume requirement and subsequent GHG emission reduction profiles for India Coastal vessels for year 2030 and 2035 (<5000 GT).

Similarly under Set 2, Figures 4.43, 4.44 and 4.45 represent OGVs and **Figures 4.46, 4.47 and 4.48 represent Coastal** respectively.

Set 1: OGVs for year 2030 & 2035

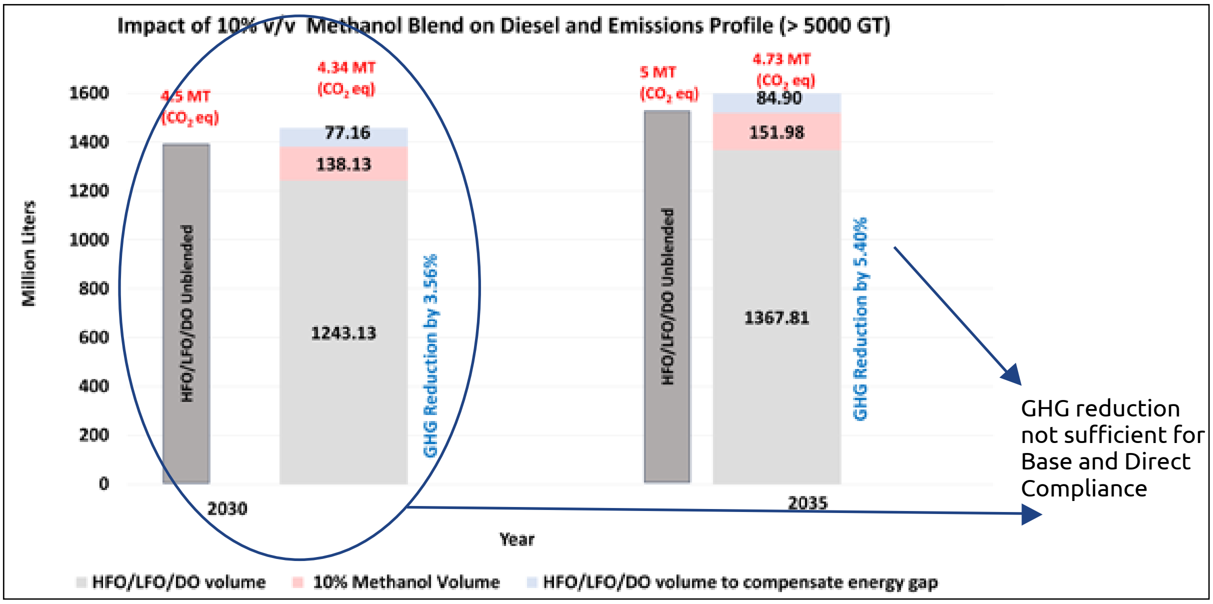


Figure 4.37: Dual Fuel Blend Scenarios (HFO/LFO/DO& Methanol 10 %v/v) with GHG Emission Reduction Profile (2030) for Indian OGVs

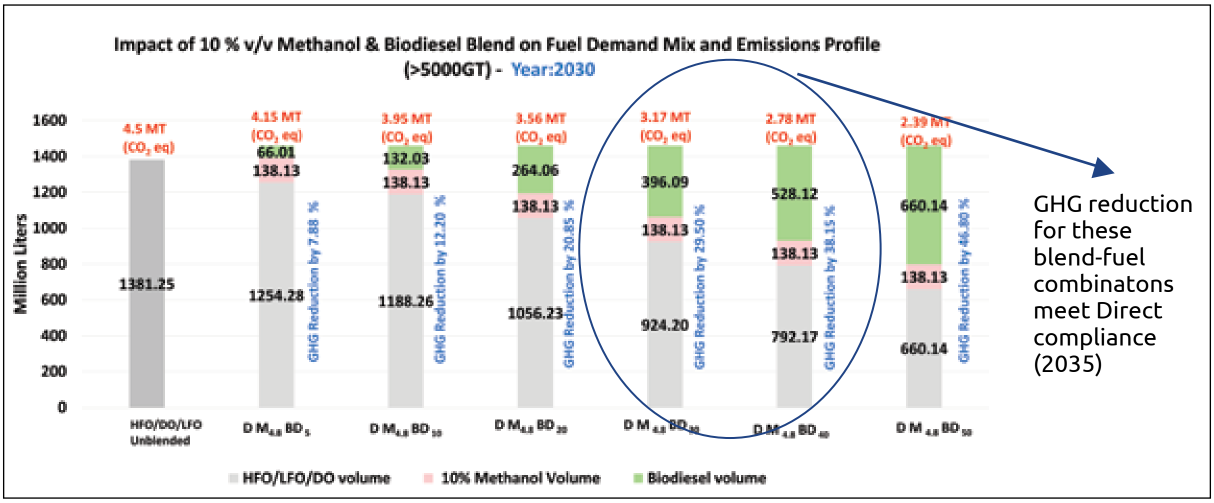


Figure 4.38: Multifuel Blend Scenarios (HFO/LFO/DO, Methanol 10 v/v %) & Biodiesel Blend (5%, 10%,20%, 30%, 40% & 50% v/v%) with GHG Emission Reduction Profile (2030) for Indian OGVs

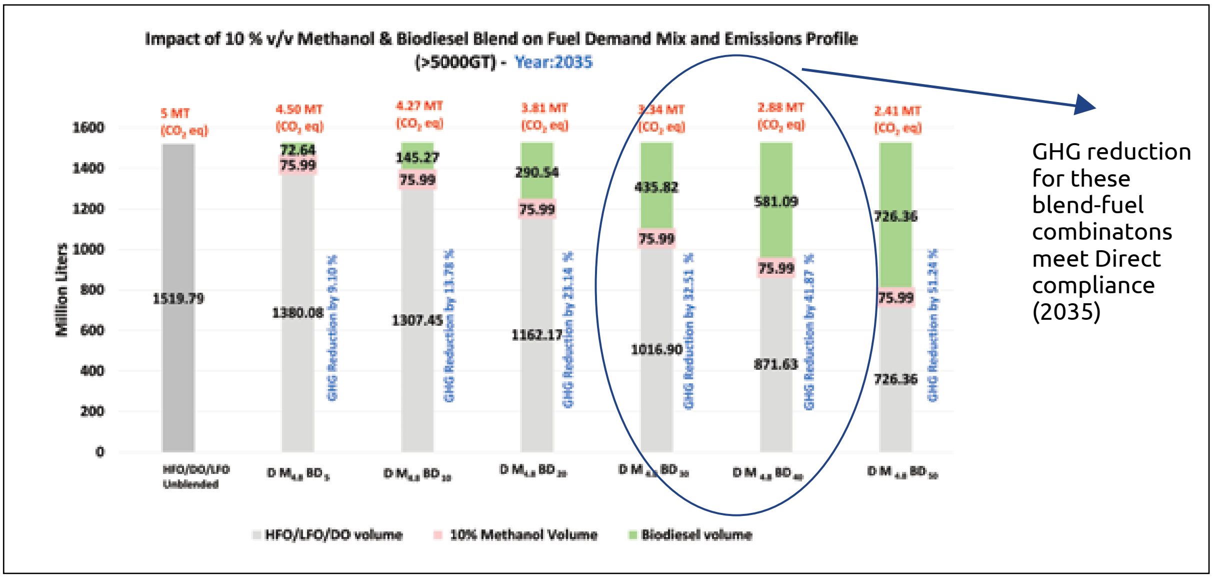


Figure 4.39: Multifuel Blend Scenarios (HFO/LFO/DO, Methanol 10 v/v %) & Biodiesel Blend (5%, 10%,20%, 30%, 40% & 50% v/v%) with GHG Emission Reduction Profile (2035) for Indian OGVs

Set1: Coastal for Year 2030 & 2035

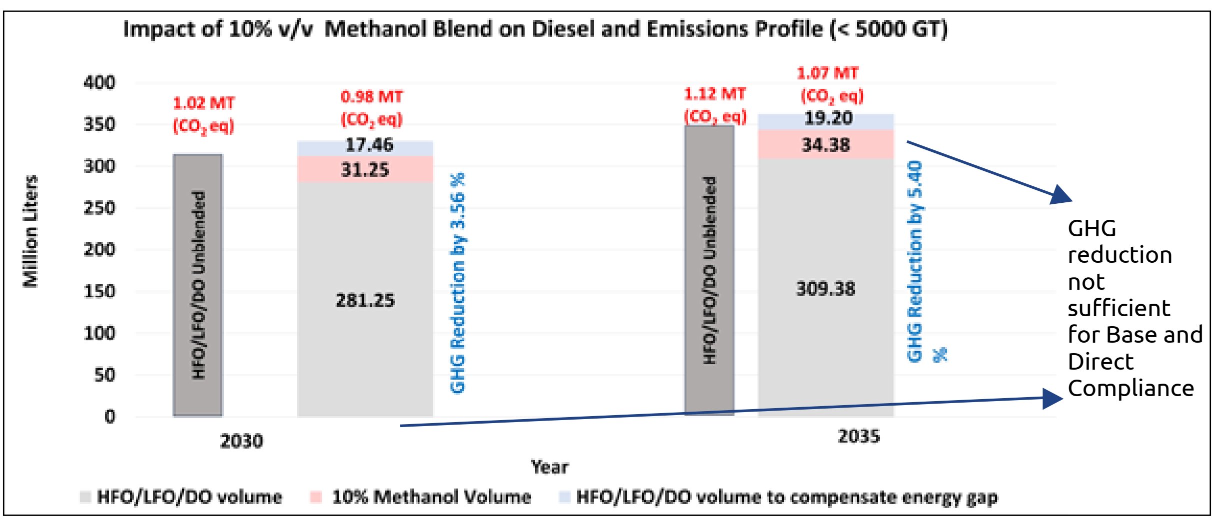
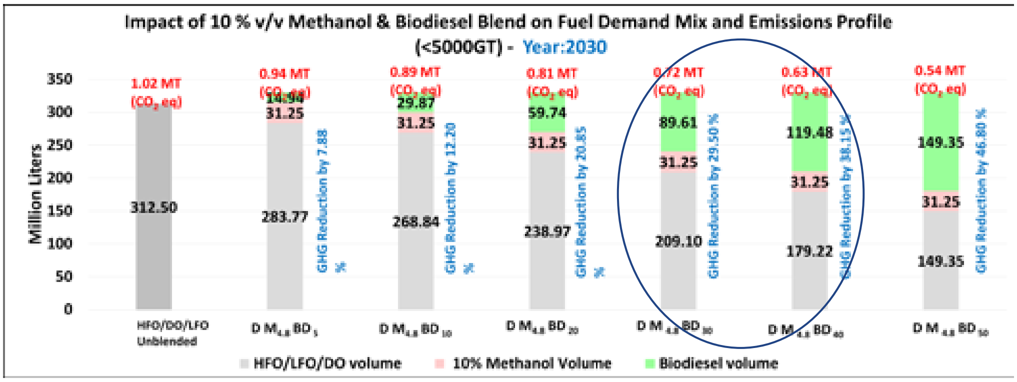


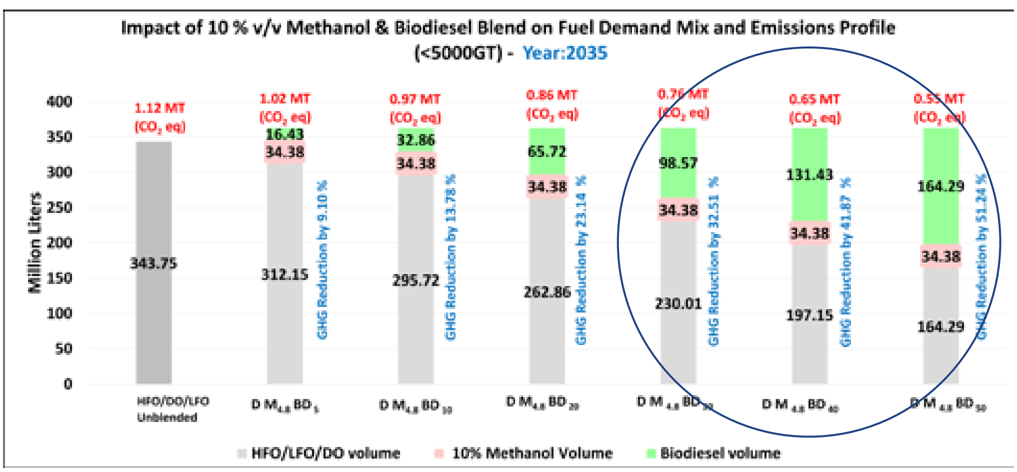
Figure 4.40: Dual Fuel Blend Scenarios (HFO/LFO/Diesel & Methanol 10 %v/v) with GHG Emission



GHG reduction for these blend-fuel combinatons meet Direct compliance (2035)

HFO(42.4)%+LFO(30.9%)+DO(26.7%)

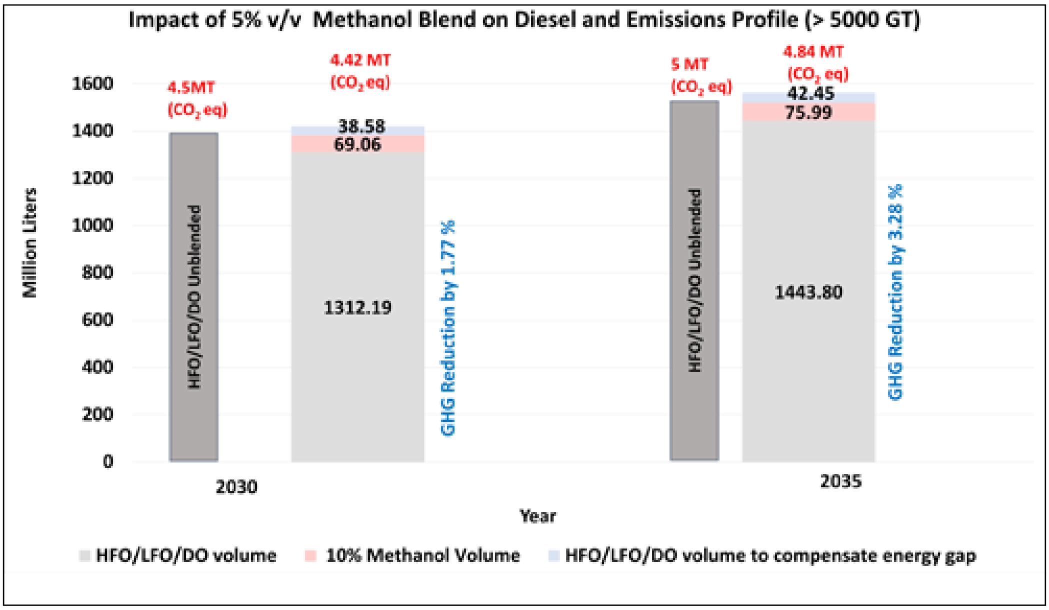
Figure 4.41: Multifuel Blend Scenarios (Diesel, Methanol 10 v/v %) & Biodiesel (5%, 10%,20%, 30%, 40% & 50% v/v%) with GHG Emission Reduction Profile (2030) for Coastal



GHG reduction for these blend-fuel combinatons meet Direct compliance (2035)

Figure 4.42: Multifuel Blend Scenarios (Diesel, Methanol 10 v/v %) & Biodiesel Blend (5%, 10%,20%, 30%, 40% & 50% v/v%) with GHG Emission Reduction Profile (2030) for Coastal

Set 2: OGVs for Year 2030 & 2035



HFO(42.4)%+LFO(30.9%)+DO(26.7%)

Figure 4.43: Dual Fuel Blend Scenarios (Diesel & Methanol 5 %v/v) with GHG Emission Reduction Profile (2030) for OGVs

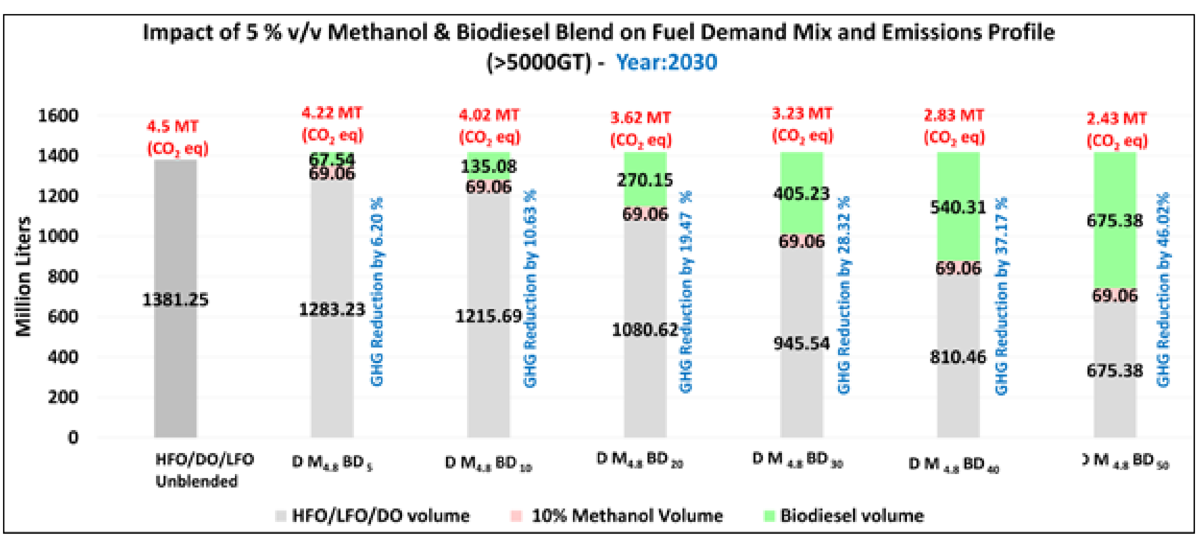
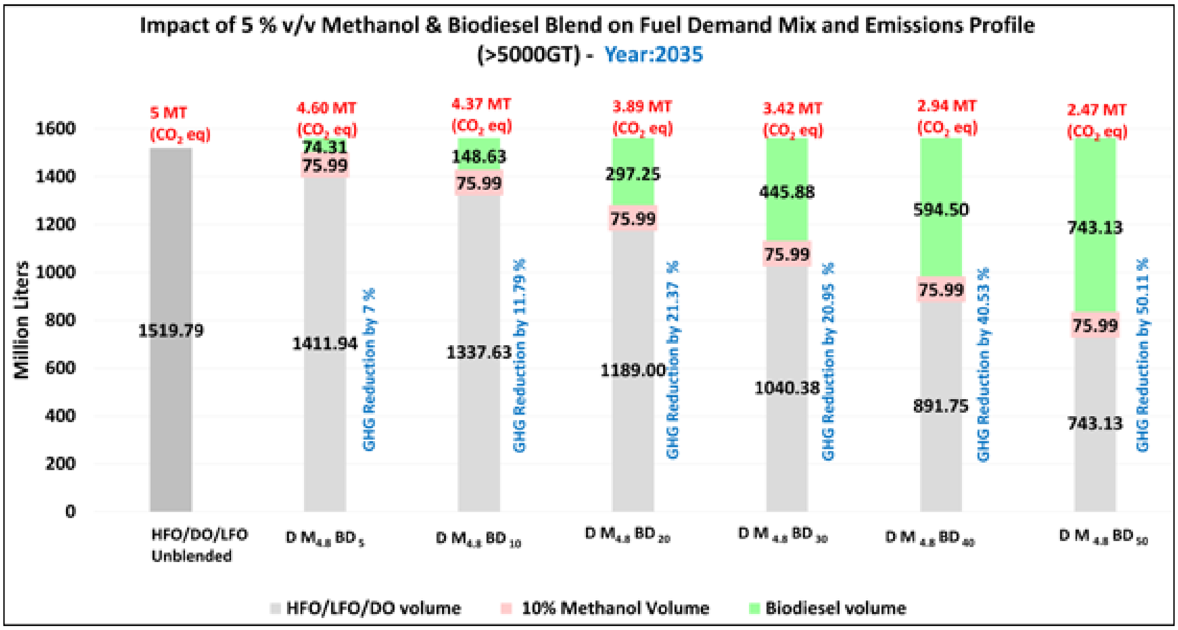


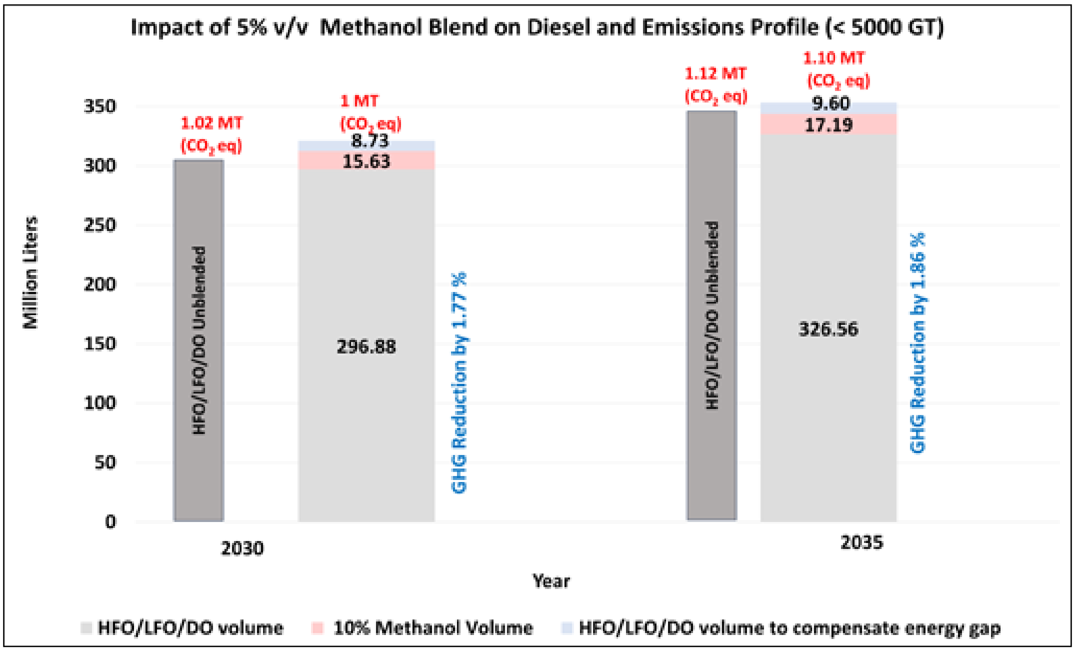
Figure 4.44: Multifuel Blend Scenarios (Diesel, Methanol 5 v/v %) & Biodiesel Blend (5%, 10%,20%, 30%, 40% & 50% v/v%) with GHG Emission Reduction Profile (2030) for OGVs



HFO(42.4)%+LFO(30.9%)+DO(26.7%)

Figure 4.45: Multifuel Blend Scenarios (Diesel, Methanol 5 v/v %) & Biodiesel Blend (5%, 10%,20%, 30%, 40% & 50% v/v%) with GHG Emission Reduction Profile (2035) for OGVs

Set 2: Coastal for Year 2030 & 2035



HFO(42.4)%+LFO(30.9%)+DO(26.7%)

Figure 4.46: Dual Fuel Blend Scenarios (Diesel & Methanol 5 %v/v) with GHG Emission Reduction Profile (2030) for Coastal

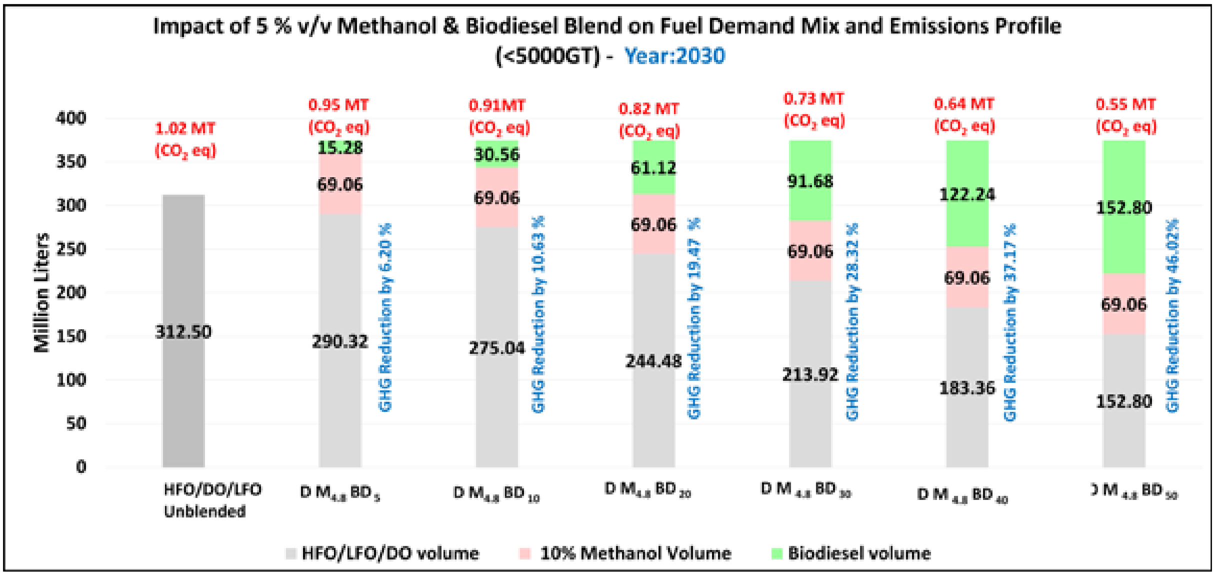


Figure 4.47: Multifuel Blend Scenarios (Diesel, Methanol 5 v/v %) & Biodiesel Blend (5%, 10%,20%, 30%, 40% & 50% v/v%) with GHG Emission Reduction Profile (2030) for Coastal

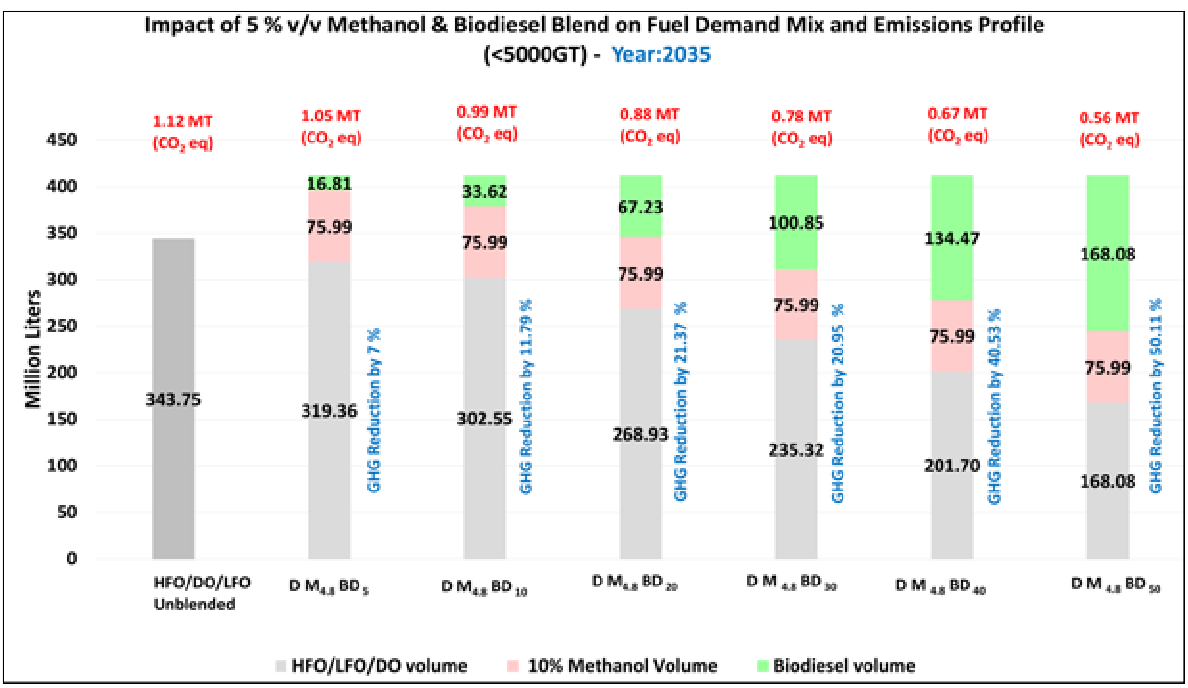


Figure 4.48: Multifuel Blend Scenarios (Diesel, Methanol 5 v/v %) & Biodiesel Blend (5%, 10%,20%, 30%, 40% & 50% v/v%) with GHG Emission Reduction Profile (2035) for Coastal

4.3 Alternative Fuel Feedstock and Supply (India and Global) Alternative Fuel Supply Chain (India)

The production capacities of Methanol, Hydrogen, and Ammonia are distributed across different project statuses, ranging from operational facilities to conceptual projects. The current and projected capacities are as follows: The total Methanol production capacity stands at 0.83 million tonnes per year (Mt/y) from operational projects, with additional potential from feasibility and concept-stage projects. While only a single project is under construction, feasibility studies indicate 800,000 t/y of additional capacity, with concept-stage projects contributing 27,886 t/y. The Hydrogen production capacity from operational projects is 4.25 Mt/y, with feasibility and concept-stage projects expected to contribute significantly. The conceptual projects alone represent a capacity of 4,065,925 t/y, showing a strong pipeline of future development. Feasibility studies account for 176,286.57 t/y, while a few projects are already under FID/construction, adding 8,015.16 t/y to the total capacity. Ammonia has the highest projected capacity, with an operational total of 20.40 Mt/y. Feasibility-stage projects account for 15.81 Mt/y, while concept-stage projects could add 4.35 Mt/y (excluding one project with an unknown capacity). A single project under construction is expected to contribute 2.5 MT/y.

Table 4.15: Overview of Methanol Plants in India

Fuel	Status	No of projects	Sub Total Capacity T MeOH /y	Total
Methanol	Operational	-	-	831,536 T/y Or 0.83 MT/y
	FID/Construction	1	3,650 T/y	
	Feasibility study	2	800,000 T/y	
	Concept	2	27,886 T/y	

Table 4.16: Overview of Ammonia Plants in India

Fuel	Status	No of projects	Sub Total Capacity T NH_3/y	Total
Ammonia	Operational	1	1825	20,40,000 T (Or) 20.40 MT
	FID/Construction	1	250,000	
	Feasibility study	14	15,816,000	
	Concept	12	4,350,000 (1-Unknown capacity)	

Table 4.17: Overview of Hydrogen Plants in India

Fuel	Status	No of Projects	Sub Total Capacity T Methanol/y	Total
Hydrogen	Operational	8	3384.29 T H_2/y	4,248,814.08 T H_2/y (Or) 4.25 MT H_2/y.
	FID/Construction	7	8,015.16 T H_2/y	
	Feasibility study	25	176,286.57 T H_2/y	
	Demo	4	203.06 T H_2/y.	
	Concept	17	4,065,925 T H_2/y.	

4.4 Bridging the Gap: Alternative Fuel-Mix Demand Scenarios Vs Supply Capacity (India Status)

This Section shows the alternative fuel demand-supply gap or fuel supply readiness level for all the fuel- mix and blend-fuel demand Scenarios considered for India towards 2030 collectively for Coastal and OGVs. This Section also evaluates the current bunker capacity of in 3 major Indian ports and their preparedness in transitioning to alternate fuel bunkering hub.

Case 1, represent the alternative fuel demand-supply gap for GFI Compliance Scenario, whereas Case 2 depict the fuel demand-supply gap for 10 and 5 v/v % blended Methanol Scenarios.

Case 1: Alternative Fuel Mix Demand Supply Gap for GFI Compliance Scenario (India Cumulative Costal and OGVs)

Figure 4.49, Figure 4.50 and Figure 4.51 represent Case 1 Scenario's demand supply gap

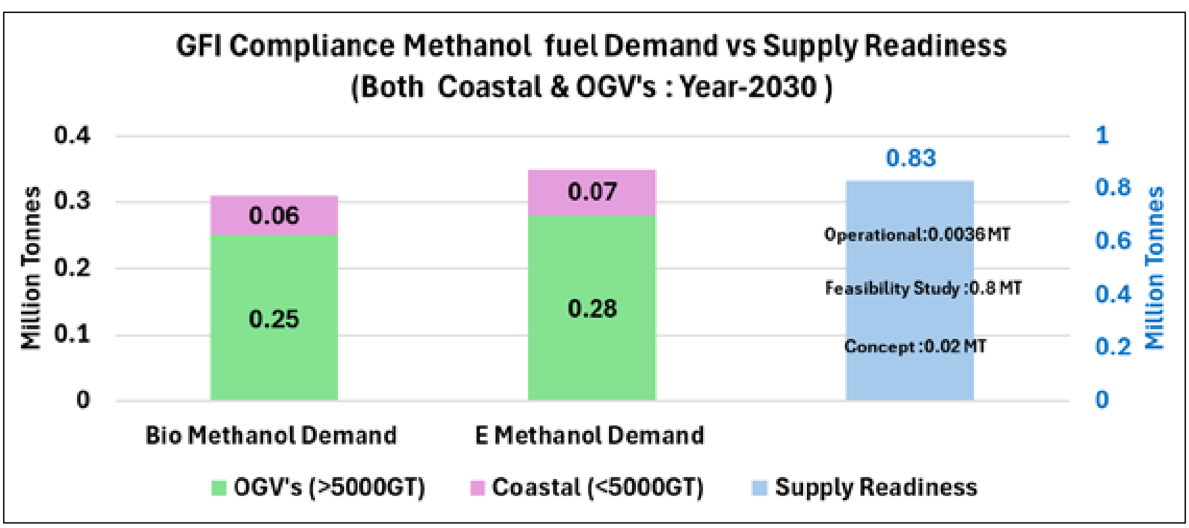


Figure 4.49: Alternative Fuel (Methanol) Mix Demand-Supply Gap for GFI Compliance Scenario (India)

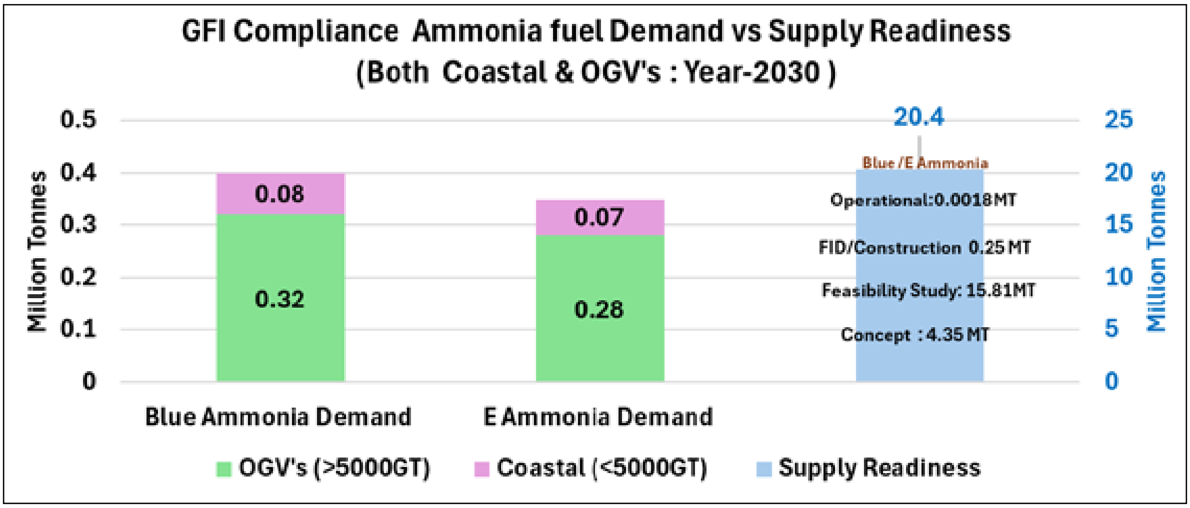


Figure 4.50: Alternative Fuel (Ammonia) Mix Demand-Supply Gap for GFI Compliance Scenario (India)

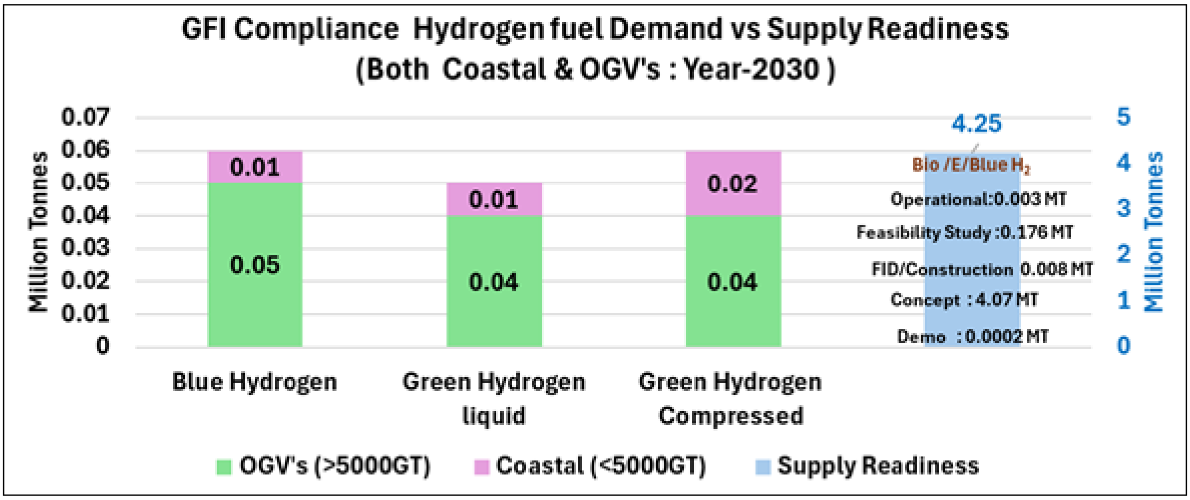


Figure 4.51: Alternative Fuel (Hydrogen) Mix Demand-Supply Gap for GFI Compliance Scenario (India)

Case 2: Alternative Fuel-Mix Demand Supply Gap for 10 & 5 v/v % Methanol Blending Scenarios (India Cumulative Costal and OGVs)

Following Figure 4.52 shows the projected Methanol blend fuel demand and the status of alternative fuels supply statistics in achieving this demand by 2030.

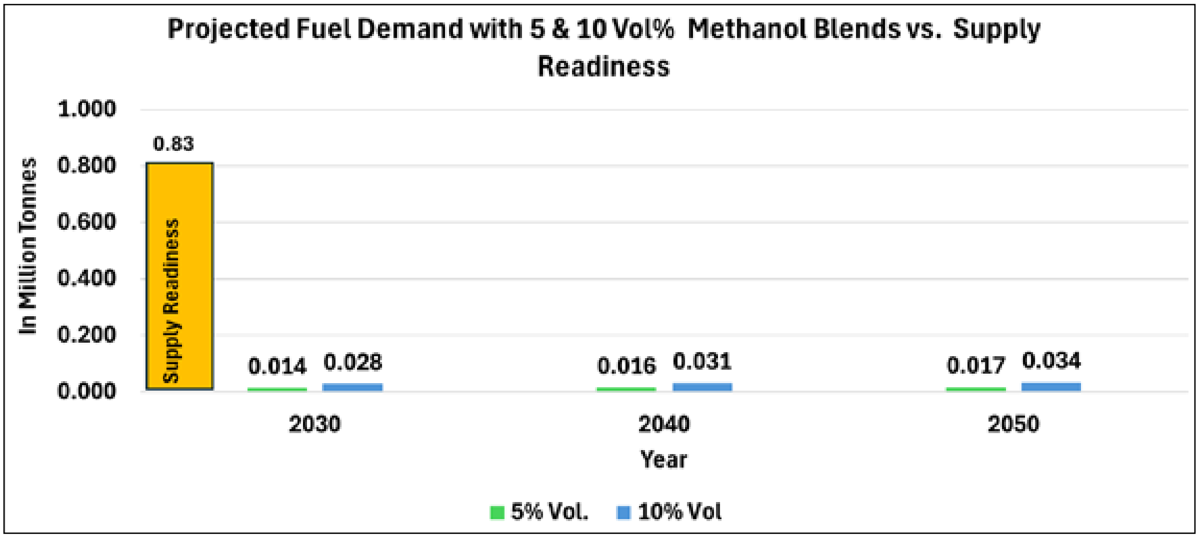


Figure 4.52: Alternative Fuel-Mix Demand-Supply Gap for 10 & 5 v/v % Methanol Blending Scenarios (India Cumulative Costal and OGVs)

Alternative Fuel Supply Status (Global) vs India

The global production capacities of Methanol, Hydrogen, and ammonia are distributed across different project statuses, ranging from operational facilities to conceptual projects. The estimated production capacities provided are specifically for projects in India.

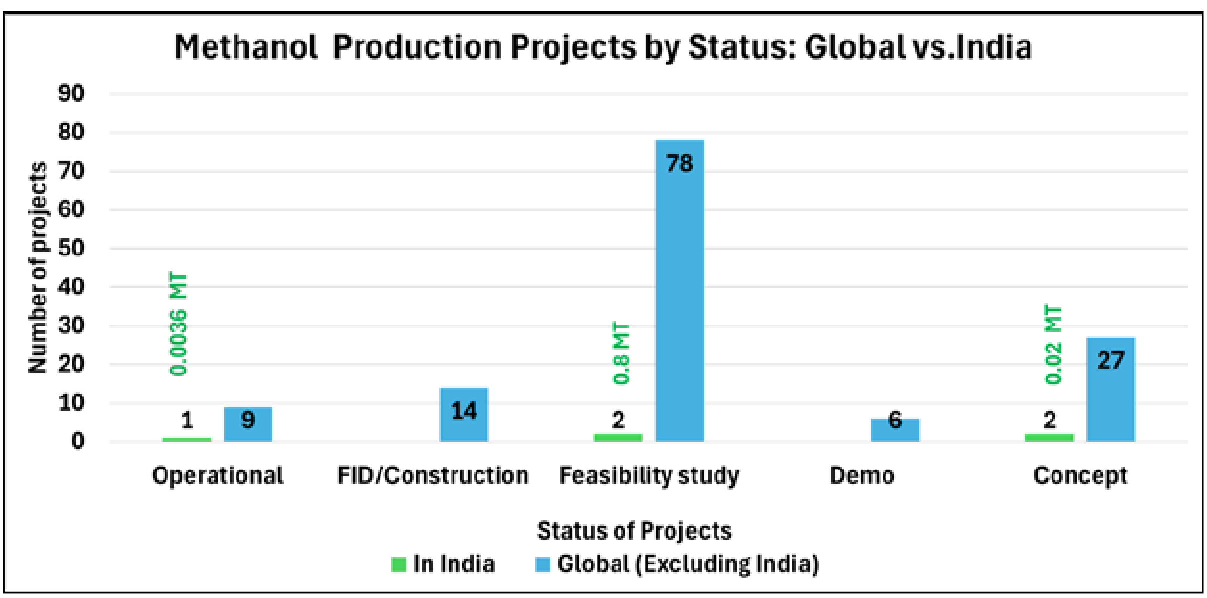


Figure 4.53: Methanol Production Projects Global vs India

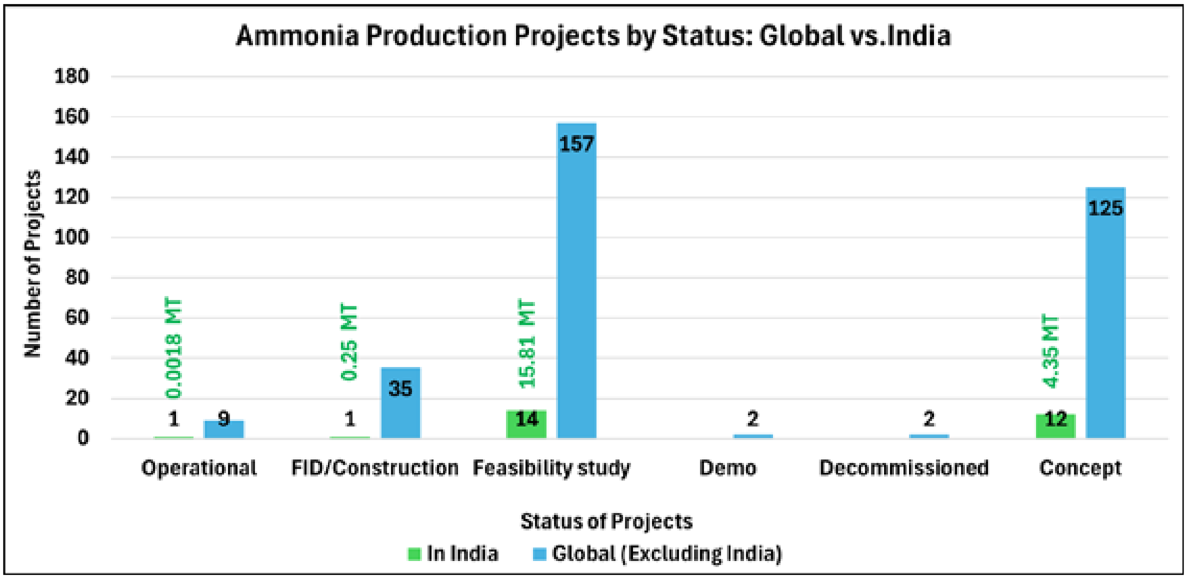


Figure 4.54: Ammonia Production Projects Global vs India

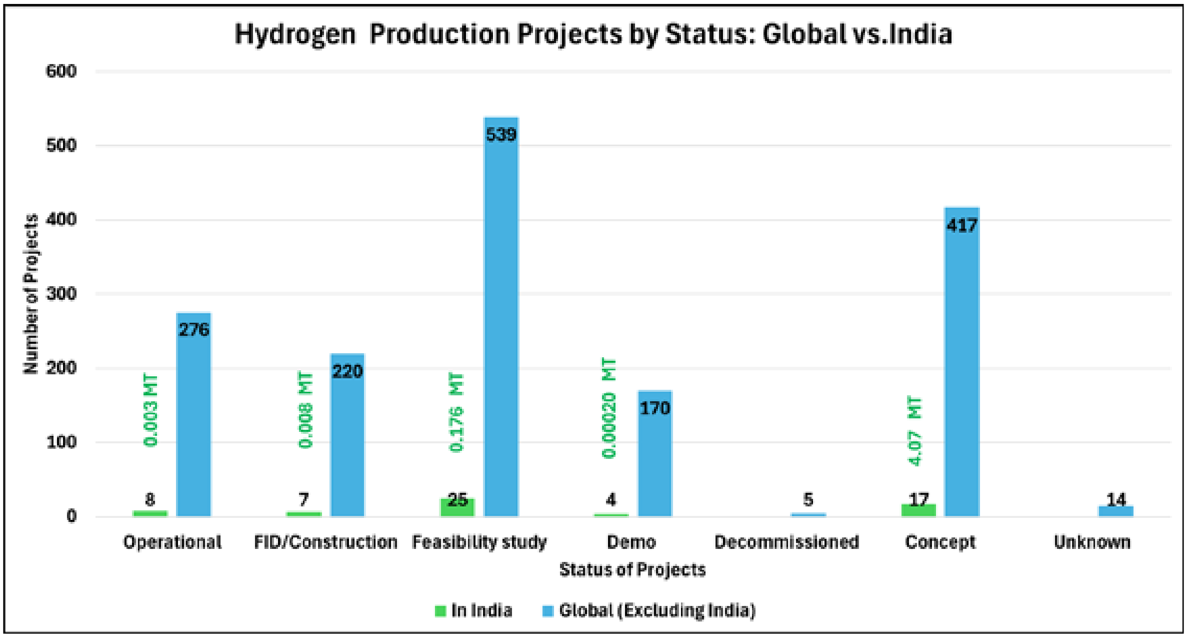


Figure 4.55: Hydrogen Production Projects Global vs India

Green Fuel Supply [46]

a) Methanol

As of November 2024,   status shows 113 e-Methanol plants and projects with total capacity of 18.7 Mt (+0.6 Mt), 77 bio Methanol plants and projects with total capacity of 13.1 Mt (+0.7 Mt), and 14 low-carbon Methanol plants and projects with total capacity of 8.1 Mt. Currently, 2.6 Mt of renewable Methanol facilities are either operational or under construction.

It is estimated that renewable Methanol capacity by 2030 could reach 7–14 Mt (22–44% of the project pipeline). However, a lack of long-term off-take agreements and insufficient state support may result in a lower capacity range of 3–7 Mt.

» 113 E-Methanol plants and projects with a total capacity of 18.7 Mt,

» 77 Bio-Methanol plants and projects with a total capacity of 13.1 Mt,

» 14 low-carbon Methanol plants and projects with a total capacity of 8.1 Mt.

» The Bio-Methanol project pipeline grew by 0.7 Mt in November due to two new projects being added.

» Total, the renewable Methanol (E-Methanol + Bio-Methanol) project pipeline has reached 31.8 Mt (+1.3 Mt).

b) Ammonia

The total capacity of low-carbon ammonia projects aimed to start up by 2030 stands at 33.5 MT. The total capacity of renewable ammonia projects by 2030 increased by 1.2 MT and reached 87.1 MT. The total clean ammonia project pipeline capacity has reached 35.7 MT by 2027, 120.6 MT by 2030, and 127.4 MT by 2032.One low-carbon ammonia project started FEED. Currently, about 12% of low-carbon ammonia projects are under construction, and 42% in engineering. Only about 6% of renewable ammonia projects have reached FID, while 10% are in engineering. The renewable ammonia project pipeline is almost three times larger than low-carbon ammonia. However, low-carbon projects have lower production costs, and a higher share of advanced-stage projects, which leads to a higher average expected success rate. Low-carbon ammonia capacity may reach about 18-22 Mt by 2030, while renewable ammonia capacity may reach 14-30 Mt. However, weak state support, slower demand growth, hesitation of consumers to sign off-take agreements, and rising costs could lead to a more conservative set of capacity scenarios in a range of 5-14 Mt for renewable ammonia and 4-18 Mt for low-carbon ammonia. As of November 2024, the clean ammonia project pipeline consists of 301 projects and operational facilities, with a total capacity of 35.7 Mt by 2027 and 120.6 Mt by 2030. The project pipeline includes:

» 261 renewable ammonia facilities with a total capacity of 87.1 Mt by 2030

» 40 low-carbon ammonia facilities with a total capacity of 33.5 Mt by 2030.

c) Hydrogen

Global Hydrogen demand surpassed 97 Mt in 2023 and is projected to reach 100 Mt in 2024, driven by economic trends rather than policies. Demand remains focused on refining and industry, with new applications like heavy industry, transport, and energy storage accounting for less than 1% despite 40% growth from 2022. Low-emissions Hydrogen grew 10% in 2023 but remains under 1 Mt. Policies and incentives could raise this to 6 Mtpa by 2030, just 10% of NZE Scenario needs. Firm offtake agreements are increasing, especially in chemicals, refining, and shipping, alongside tenders and aggregation initiatives. Large-scale projects for refining, chemicals, and steel could push demand for low-emissions Hydrogen to 1.5 Mtpa by 2030, 3 times today's levels.

Regional trends:

- China leads with 28 Mt (one-third of demand), followed by the US at 13 Mt (14%).
- Middle East (6%) and India (5%) posted strong growth in refining, Methanol, and steel.

4.5 Alternative Fuel Storage and Bunkering (India and Global)

4.5.1 Storage and Bunkering of Alternative Fuels: Present Global Status (Technology /Infrastructure)

The alternative fuels used in maritime sector widely differ in their chemical and physical properties from their fossil counterparts as shown in earlier Sections. Current global infrastructure for the supply, storage, delivery and bunkering of alternative fuels are at varying degree of maturity at ports, at terminals, and on ships. Global alternative flue bumkering readiness is presented in **Annexure II**. With regard to compliance with Annex VI of the International Convention for the Prevention of Pollution from Ships, fossil fuels too face capacity issues. Along with the IMO's emission targets, a large demand supply gap of sulfur scrubber technology offers an additional scope for alternative fuels to largely penetrate marine sector. However, establishment of new infrastructure stands critical in the way of its' adoption, in addition to technological readiness of sustainable alternative fuel and related economic factors **[47]**

Till date, scaling up Infrastructural ecosystem for alternative fuels is largely limited by economic considerations (i.e., price differentials) as well as persistence of a chicken-and-egg scenario in which ship operators have been hesitant in retrofitting ship engines and fueling systems. It is anticipated that high fuel costs will add-on to retrofit costs due to the inadequate supply of alternatives fuels at ports. In an alternate scenario of Flex fuel options, alternative fuel producers in turn become wary of investing in scaling up with low demand at ports and compatible engines and fueling infrastructure**.**

In order to avoid high stranded assets with the disruptive technological advancement, diversification of investments towards alternative fuel adoption and applying modular scale-up strategies appears strategically advantageous in derisking and mitigating path dependence. For example, the IMO has cited carbon lock-in as a potential side effect of building momentum for LNG or any other carbon-intensive infrastructure **[48].** Hence investing in LNG infrastructure in the short term, to comply with immediate sulfur and NOx regulations, may dissuade the build-out of alternatives and future divestment from gas as a maritime fuel. **The term modularity here represents the capability of a fueling system's cost-effective transition over time for its use with alternative fuels [47].**

Among all alternative options compared, Biofuels (Biodiesel) shows attractive infrastructural compatibility features with lower risk of stranded assets. While Methanol being liquid at ambient condition still able to use existing infrastructure to some degree; Ammonia and Hydrogen necessitate brand new or largely modified infrastructures.

It is worth mentioning that, the availability of standards for fuel quality and production along with presence of guidelines and regulations for safe storing, handling, transport and bunkering are of critical importance for fast paced adoption of alternative fuels. Fuel standards ensure that fuels are safe for purchase, and fuels that lack standardization may vary in quality and thus are less attractive to purchasers. Of particular importance to biofuels such as SVO, biocrude, pyrolysis and HTL bio-oil, a lack of standardization still presents significant barriers to adoption although these technologies show present economic attractiveness. ASTM, EU, and ISO authorities carry the responsibility to clarify potential barriers to and timelines for developing and disseminating alternative fuel quality standards. In concert with path dependence, fuels already standardized and those poised for quick standardization like Biodiesel and Methanol have started showing initial advantages in global markets.

Marine diesel fuel tanks are generally composed of Aluminium, high-carbon steel, fiberglass, plastic, or stainless steel. The presence of incompatible metals requires the costly process of stripping out and replacing fuelling and engine systems for most of the alternative fuels except Biodiesel.

Regarding alternative fuels energy density and storage volume are critical parameters as they impact vessel endurance range and bunkering frequency **[47].** The density of the fuel is expressed both in terms of a volumetric energy density (energy content per volumetric unit) and gravimetric energy density (energy content per mass unit). The energy density partially determines how suitable the fuel is for certain ship types and ship operations. Alternative fuels with lower volumetric energy density than HFO require larger volume of fuel in order to provide same amount of energy and additionally either reduce the cargo volume or reduce ship range between refuelling. Similarly, alternative fuels with a lower gravimetric energy density reduces ship's cargo capacity on a mass basis. Also, any increase in vessel's fuel storage capacity to accommodate less energy-dense fuel lead to additional cost and reduce the volume of space available for cargo transport. **Figure 4.56** demonstrates this trade-off of volumetric and gravimetric energy density for selected alternative fuels, relative to HFO**.** Relative volumetric energy densities greater than 1 indicate the fuel requires less storage volume relative to HFO, and fuels with values less than 1 require more storage volume.

The Figure 4.56 indicates that prominent fuel pathways such as Methanol, LNG, LPG, Pyrolysis oil and liquid-Ammonia have volumetric energy densities that are 0.36–0.61 that of HFO and thus would require up to a 2.77 X increase in fuel storage volume. **Liquified and compressed hydrogen having significantly lower volumetric energy densities than HFO leads to ~6–7 X increase in fuel storage capacity.** Several biofuels including Biodiesel, Pyrolytic biooil/biocrude, SVO, and HVO display volumetric energy densities that are competitive to HFO and existing marine distillate fuels like MGO, MDO.

The alternative fuel bunkering in ports along with their types, country it belongs to and status (active/ under construction/potential) for each of the alternative fuels are detailed below. The **Figures 4.57 (a, b, c, d, e, f)** gives the snapshot of alternative fuel bunkering readiness level in global ports in descending order w.r.to number of active ports under different fuel category. It is broken down by fuel type and by facility type, such as Terminals and Ship-to-Ship (STS) or Truck-to-Ship operations (TTS). These Figures clearly differentiate between projects that are active, those that are potential, and those still under construction, providing a perspective on where we stand now and what the future holds w.r.to clean marine fuel bunkering.

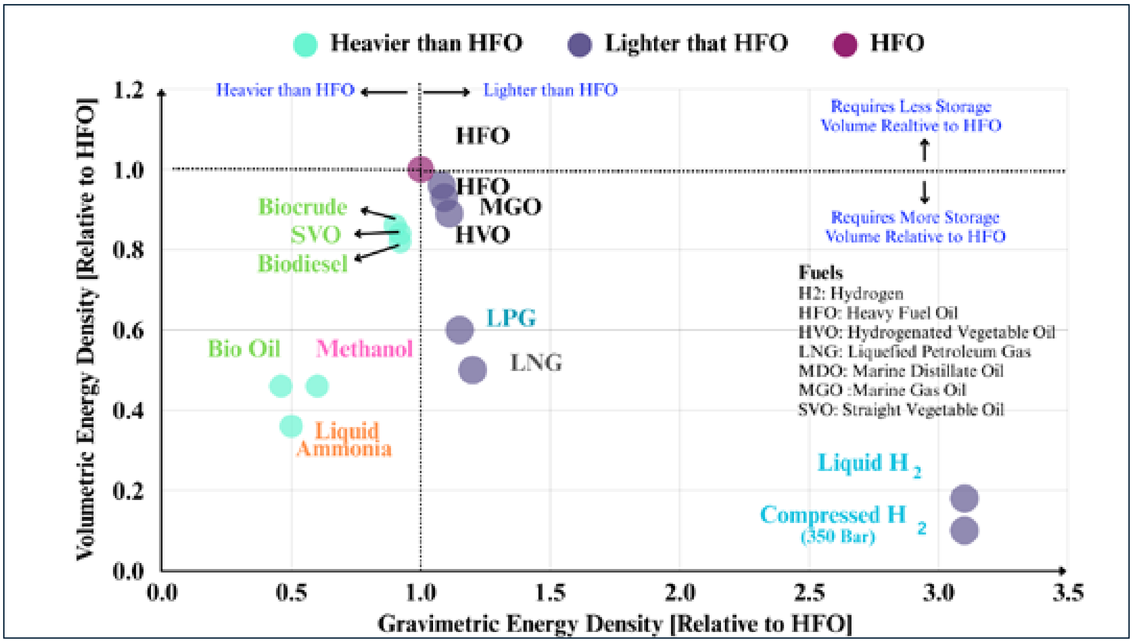


Figure 4.56: Volumetric Versus Gravimetric Energy Density [reproduced from 47]

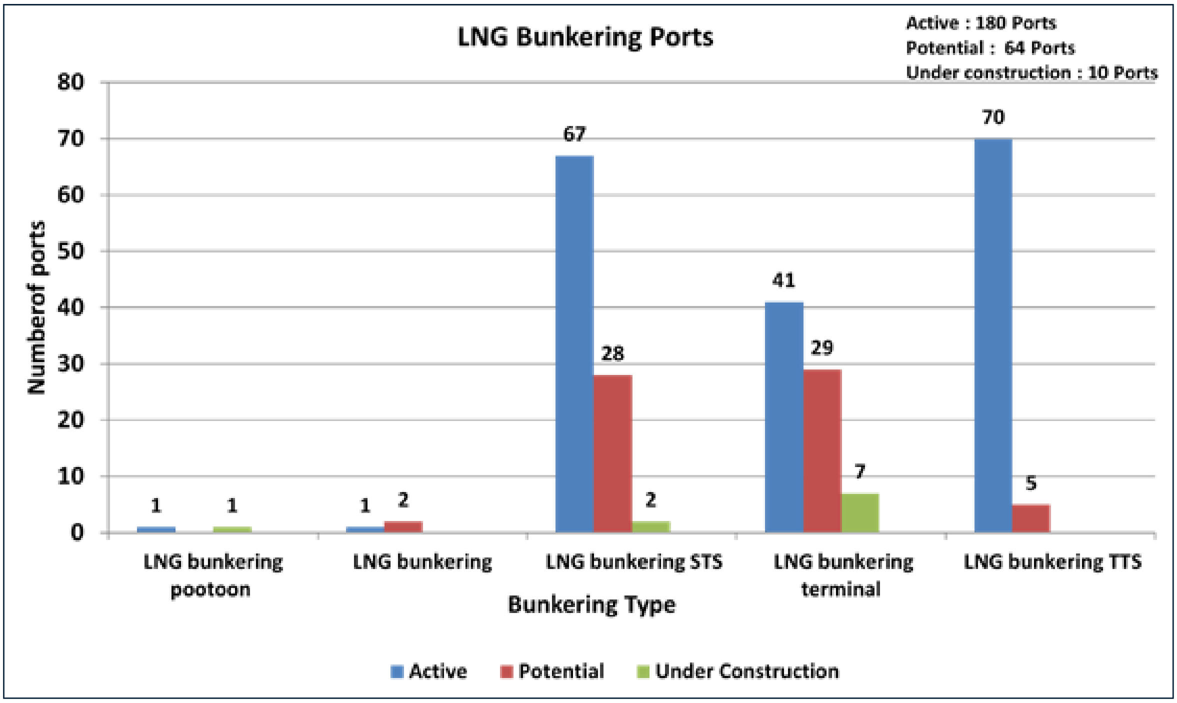


Figure 4.57 a: LNG Bunkering Capable Ports

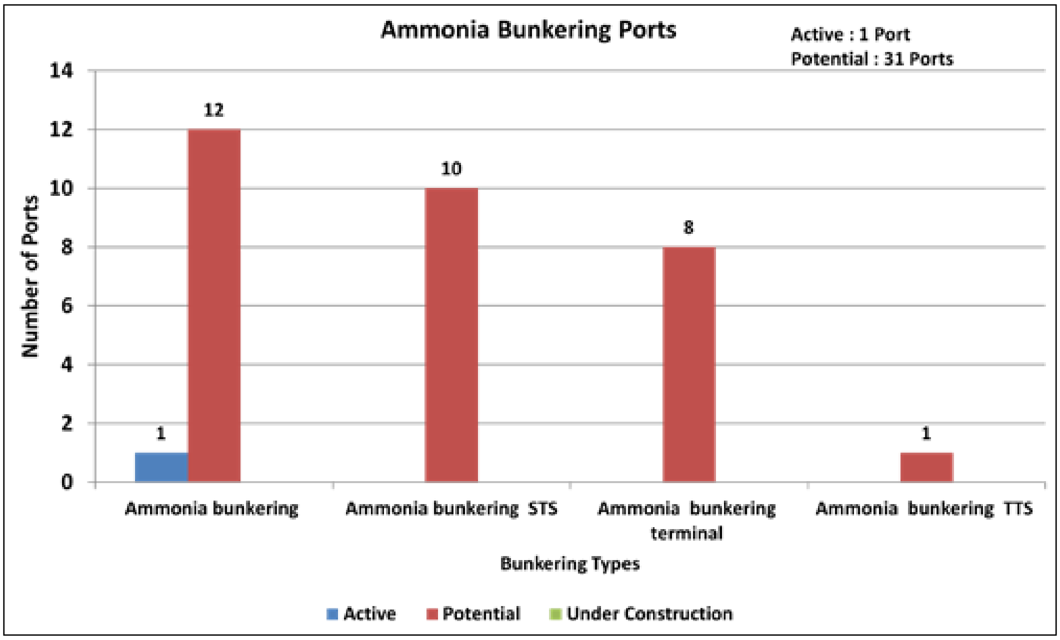


Figure 4.57 b: Biofuel (Biodiesel) Bunkering Capable Ports

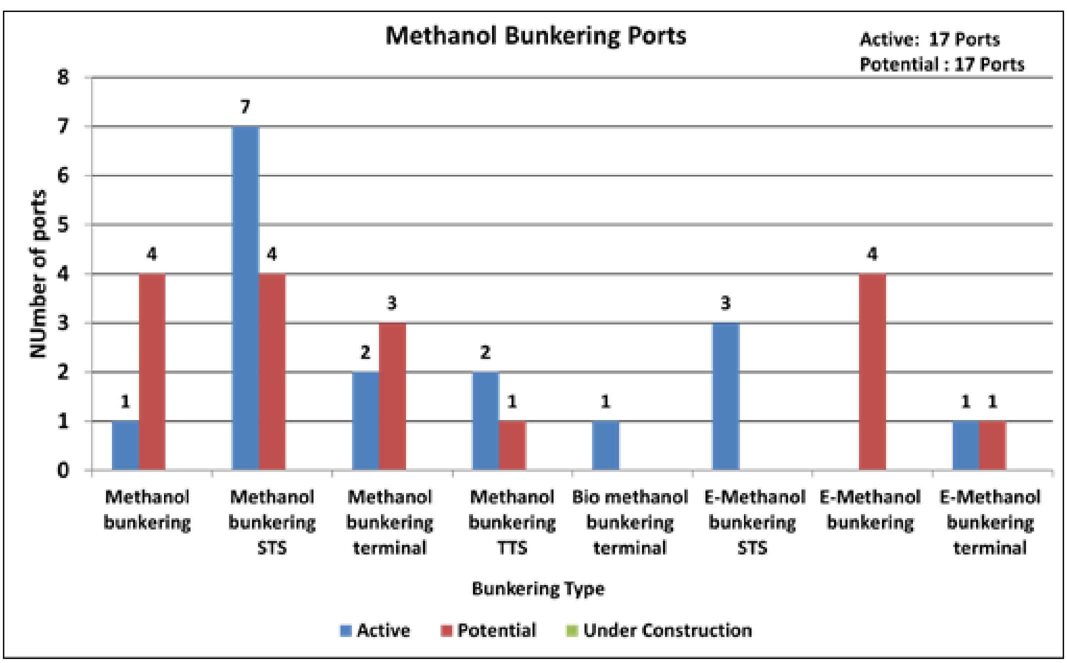


Figure 4.57 c: Methanol Bunkering Capable Ports

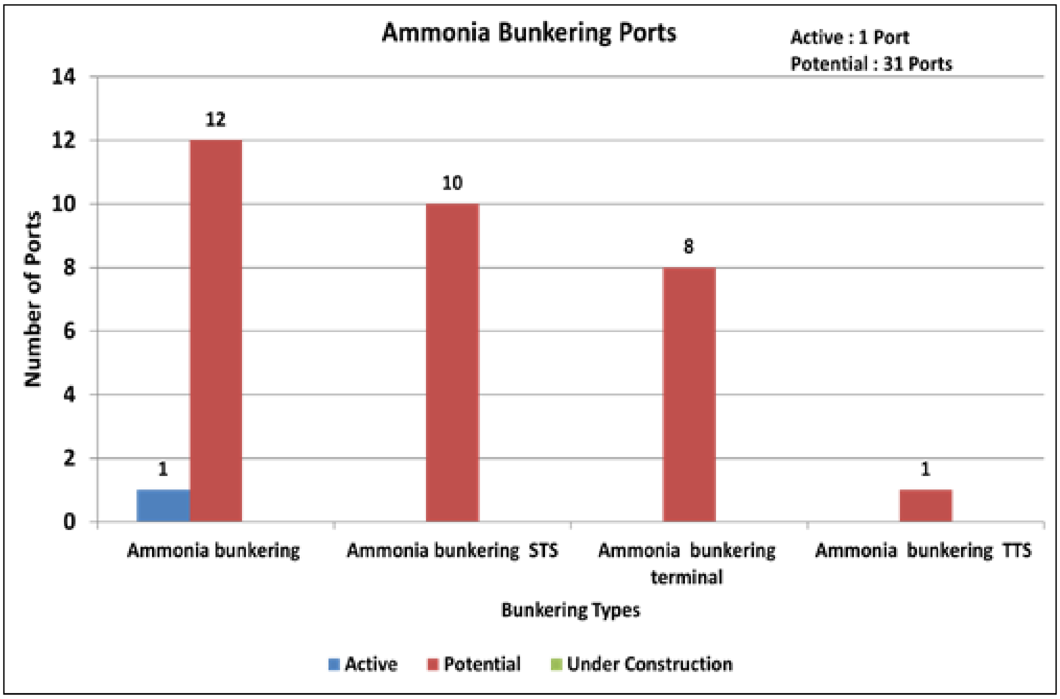


Figure 4.57 d: Ammonia Bunkering Capable Ports

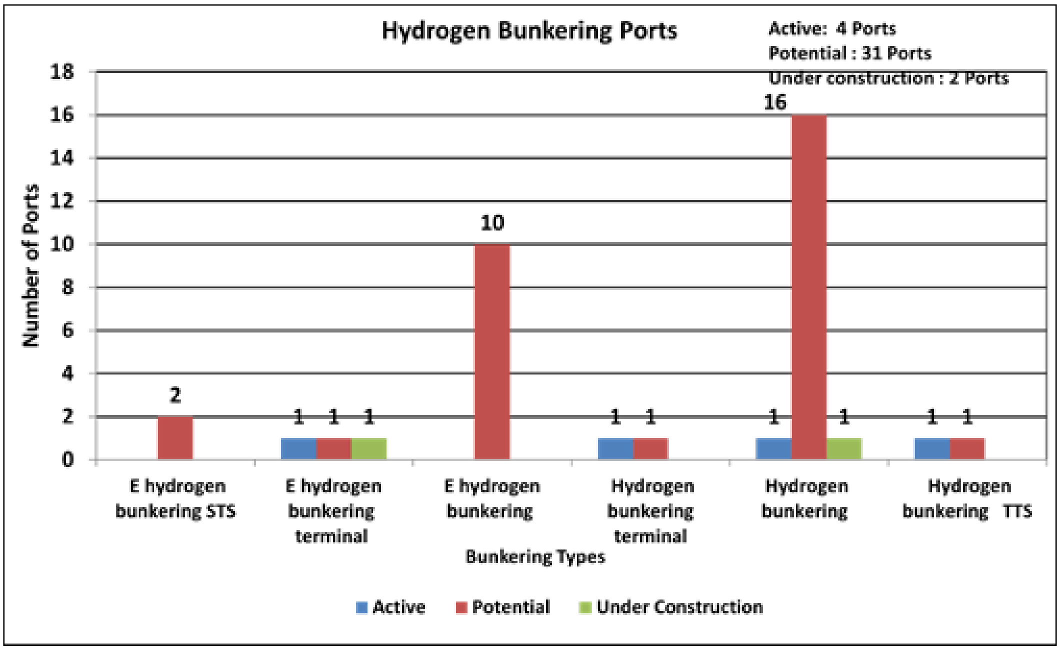


Figure 4.57 e: Hydrogen Bunkering Capable Ports

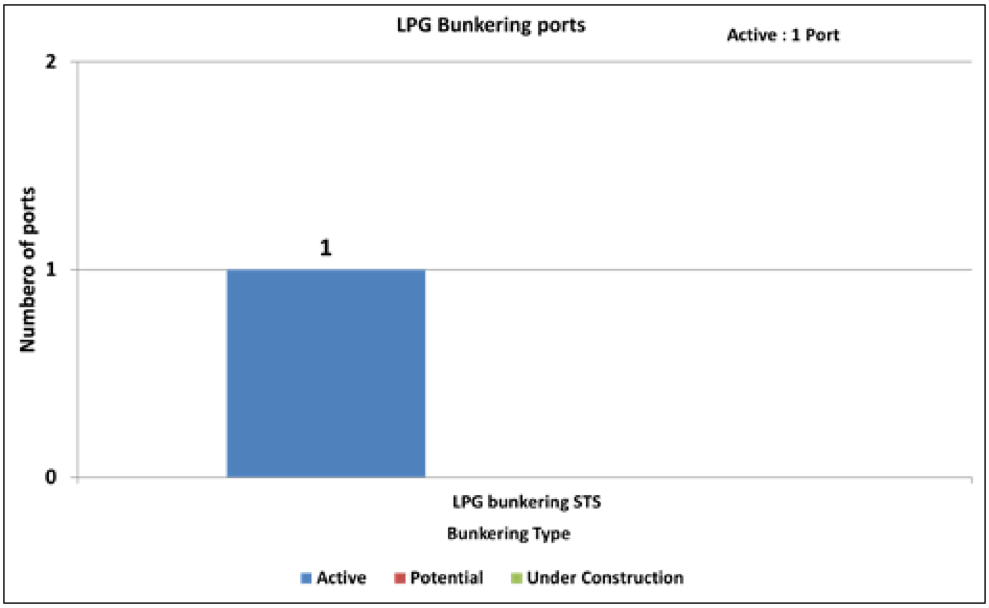


Figure 4.57 f: LPG Bunkering Capable Ports

Global Bunkering Status of Alternative Fuels

1. **LNG** is currently the frontrunner among alternative fuels, boasting over **254** bunkering setups in various formats. It's particularly strong in ship-to-ship (STS) operations, with 97 setups, and has 77 and 75 Terminals and TTS respectively in play.
2. **Methanol** is on the rise, with a total of **34** facilities—including **17 active and 17 potentials**—spread across 14 STS, 8 Terminals, and 3 Truck-to-ship (TTS) operations and rest bunkering type not known. This growth reflects a growing interest, thanks to its easy storage and compatibility with existing systems.
3. **Hydrogen** bunkering is just starting to take shape, with a total of **37** bunkers including **4 active and 31 in the planning** phase even though there are some high-pressure storage limitations.
4. **Ammonia** bunkering is still in its infancy but is showing solid progress, with **32 planned** sites across STS, Terminals, and TTS with only **1 active** sites.
5. Biofuels (Biodiesel) are having **21 active and 12 planned** bunkering facilities.
6. **E-Hydrogen** and **E-Methanol** are in the early stages, with only a handful of active pilot sites **1 and 4** respectively
7. **TTS bunkering remains quite limited** across all fuel types except for LNG with 75 ports likely due to concerns about volume capacity and safety.
8. **Ship-to-ship (STS)** bunkering appears most common across all alternative fuels owing to its flexibility and less reliance on port facilities.

Based on IEA's Hydrogen production and infrastructure projects database, infrastructure readiness level in ports for low emission Hydrogen and Hydrogen derived fuels are plotted in **Table 4.18**. **Figures 4.58 (a, b and c)** present the country wise distribution of Port Infrastructure Projects for Methanol, Ammonia and Hydrogen respectively.

It shows existing capacity of 2.76 MT for Methanol, 71.69 MT for Ammonia, and 1.18 MT for Hydrogen excluding the existing terminals and announced projects which are principally aimed at storing unabated fossil Ammonia and Methanol. However, the actual numbers could be much higher as some of the capacities are undisclosed [IEA Hydrogen Production and Infrastructure Projects Database]

Global Infrastructure Project and Readiness of Hydrogen Derived Fuels

» **For Methanol,** there are 9 projects identified, with a total capacity of 2.76 MT spread across 4 disclosed projects. Most of these (56%) are still in the concept stage, and only one is currently operational.

» **For Ammonia,** there are 97 projects with a combined capacity of 71.69 MT across 69 of them. Here, 42% are still in the concept phase, and 41% are in feasibility studies, while just 7% are actually under construction or close to it.

» **For Hydrogen**, there are 13 projects with a capacity of 1.18 MT across 7 projects. A significant 69% are in the feasibility stage, and only one is in the concept phase.

Table 4.18: Infrastructure Projects in Global Ports for Hydrogen and Hydrogen Derived Fuels

Fuel	Status	No of projects	Total
Methanol	Operational	1	2.76 MT for (For 4 out of 9 Projects)
	FID/Construction	1	
	Feasibility study	1	
	Under Construction	1	
	Concept	5	
Ammonia	Under Construction	4	71.69 MT for (For 69 out of 97 Projects)
	FID/Construction	3	
	FEED	7	
	Feasibility study	39	
	Decommissioned	1	
	Demo	1	
	Concept	40	
Hydrogen	Feasibility study	9	1.18 MT (For 7 out of 13 Projects)
	Demo	3	
	Concept	1	

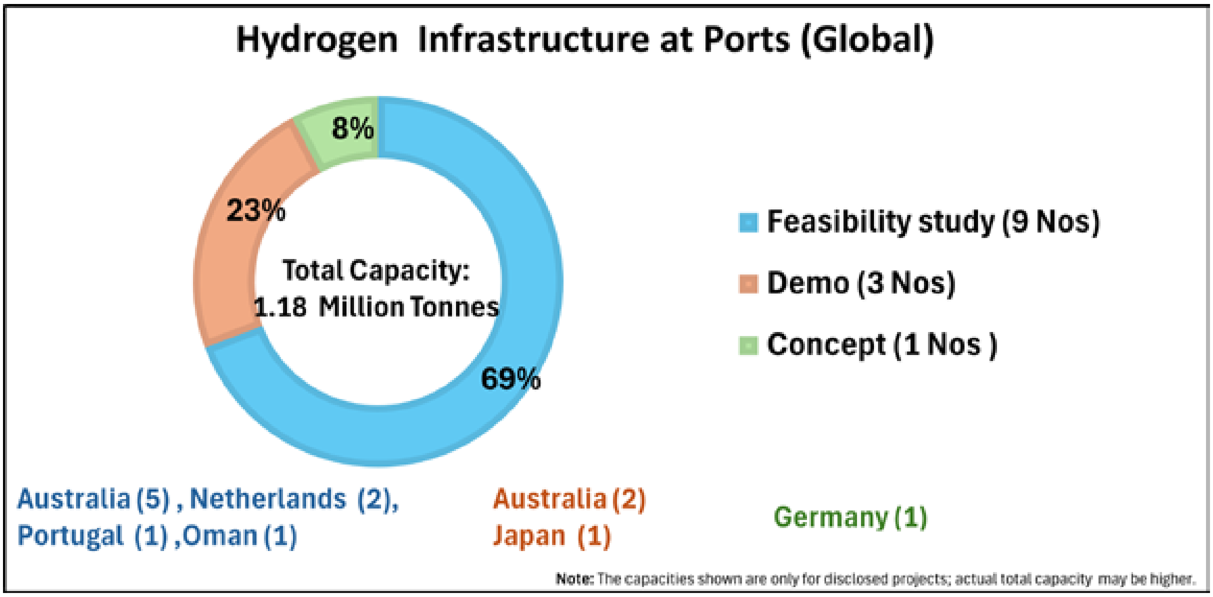


Figure 4.58 a: Low Emission Hydrogen Infrastructure at Global Port (Country-wise Distribution

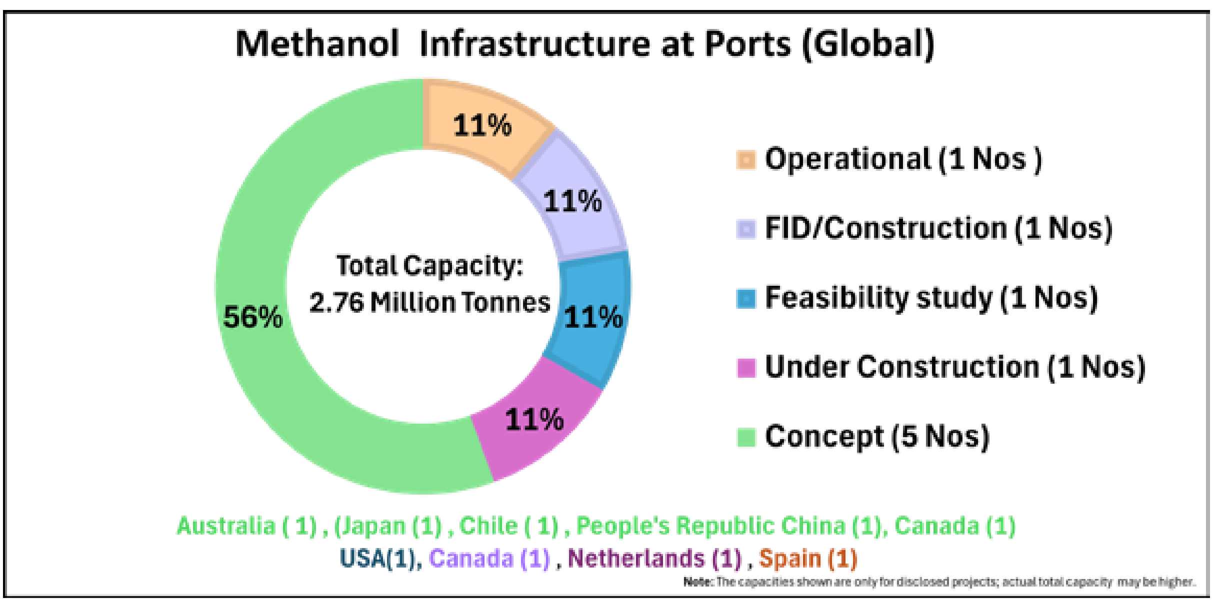


Figure 4.58 b: Low Emission Methanol Infrastructure at Global Port (Country-wise Distribution)

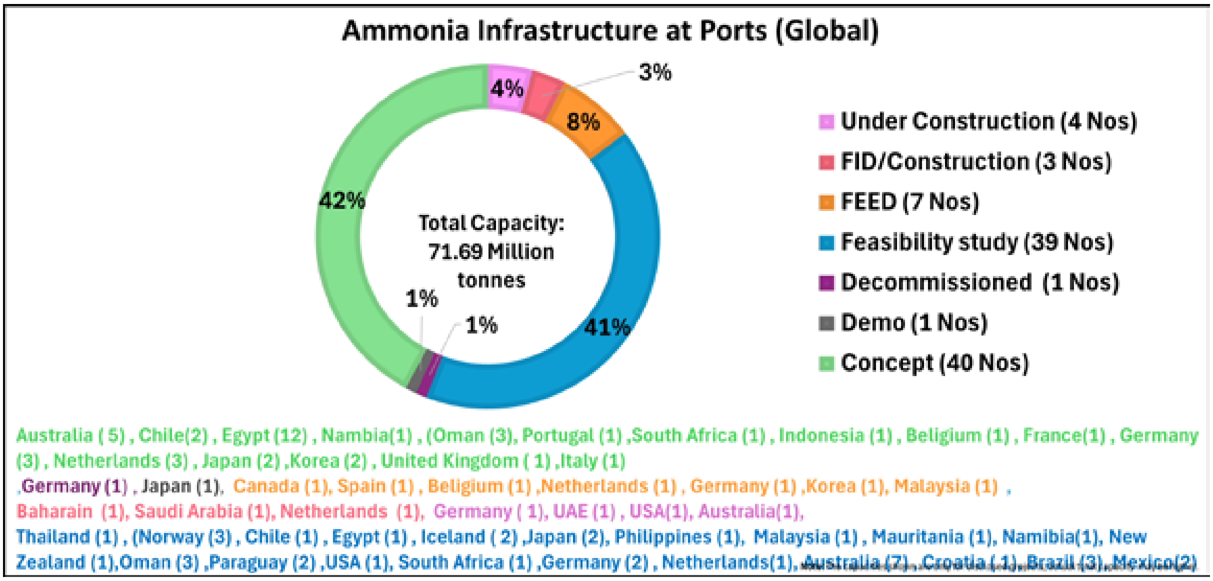


Figure 4.58 c : Low Emission Ammonia Infrastructure at Global Port (Country-wise Distribution)

4.5.2 Alternative Fuel for Bunkering (India)

The bunkering scenario of year 2022 as shown in **Figure 4.59** at major Indian ports is led by Vishakhapatnam, which tops the list with 4.64 MT bunkering capacity. Mangalore follows with 3.08 MT, and then there's Chennai at 2.14 MT. When it comes to how supplies are delivered, barges take the lead, making up 59% of the total, while trucks contribute 32%, and pipelines or terminals only account for 6%. This shows there's not much fixed infrastructure in place. Ports such as Paradip, Tuticorin, and Vizag are heavily reliant on barges, while Chennai, Cochin, and Mumbai use a combination of barges and trucks. All in all, the data highlights a strong reliance on barge and truck-based bunkering, with the development of infrastructure differing quite a bit from one port to another.

To support the shift to alternative marine fuels' bunkering hub, an analysis as show in **Figure 4.60** is conducted for three key ports—Kandla, Paradip, and VOC—based on their annual bunkering capacity. The study evaluates 5%, 10%, 20%, and 50% (on energy equivalence basis) bunker fuel replacement with for alternative fuels like Methanol, Ammonia, Biodiesel, LNG, and Hydrogen to assess feasibility and related infrastructure needs. By comparing energy content—Methanol (2.11x), Ammonia (2.26x), Biodiesel (1.11x), LNG (0.84x), and Hydrogen (0.35x) vs. conventional fuels—this analysis estimates the fuel quantities and infrastructure required for transition. It also explores supply-demand alignment and supports strategic planning for cleaner, sustainable maritime operations.

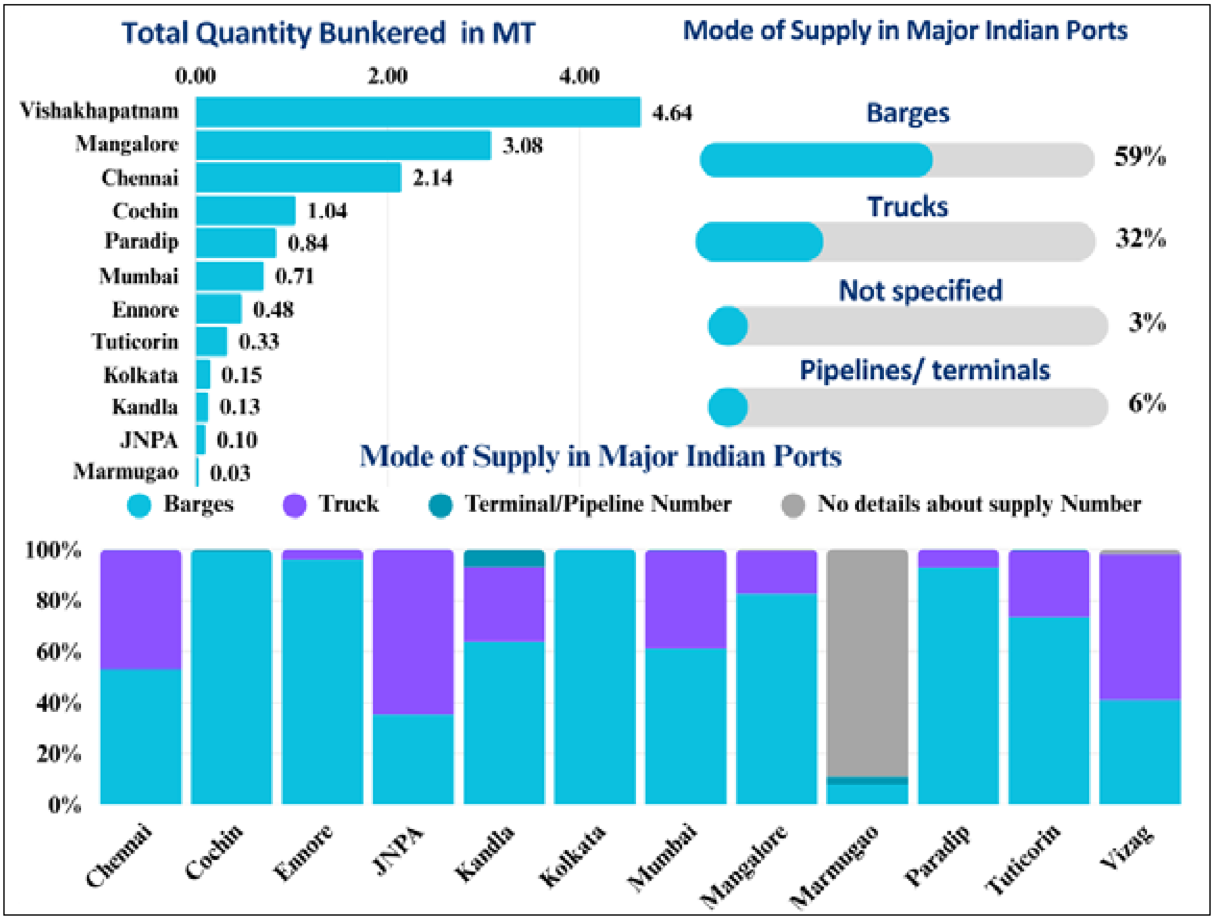
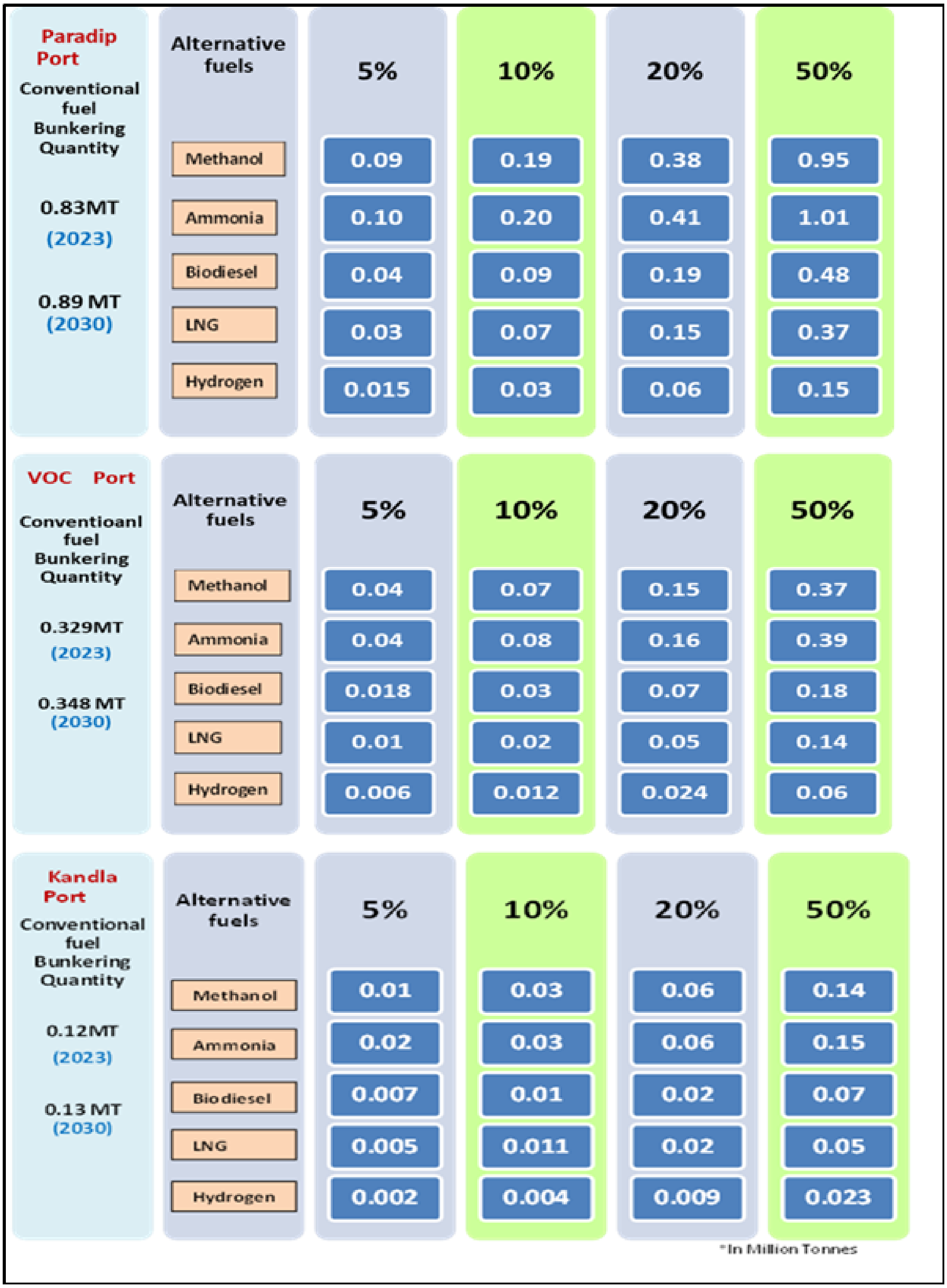


Figure 4.59: Bunkering Volume and Supply Modes at Major Indian Ports, Highlighting Total Fuel Bunkered (in Million Tonnes) and the Distribution of Supply Methods



Paradip Port	Alternative fuels	5%	10%	20%	50%
Conventional fuel Bunkering Quantity	Methanol	0.09	0.19	0.38	0.95
0.83MT (2023)	Ammonia	0.10	0.20	0.41	1.01
0.89 MT (2030)	Biodiesel	0.04	0.09	0.19	0.48
	LNG	0.03	0.07	0.15	0.37
	Hydrogen	0.015	0.03	0.06	0.15

VOC Port	Alternative fuels	5%	10%	20%	50%
Conventioanl fuel Bunkering Quantity	Methanol	0.04	0.07	0.15	0.37
0.329MT (2023)	Ammonia	0.04	0.08	0.16	0.39
0.348 MT (2030)	Biodiesel	0.018	0.03	0.07	0.18
	LNG	0.01	0.02	0.05	0.14
	Hydrogen	0.006	0.012	0.024	0.06

Kandla Port	Alternative fuels	5%	10%	20%	50%
Conventional fuel Bunkering Quantity	Methanol	0.01	0.03	0.06	0.14
0.12MT (2023)	Ammonia	0.02	0.03	0.06	0.15
0.13 MT (2030)	Biodiesel	0.007	0.01	0.02	0.07
	LNG	0.005	0.011	0.02	0.05
	Hydrogen	0.002	0.004	0.009	0.023

*In Million Tonnes

Figure 4.60: Energy Equivalence Analysis (5%, 10%, 20%, 50%) of Alternative Marine Fuels—Methanol, Ammonia, Biodiesel, LNG, and Hydrogen—at Kandla, Paradip, and VOC ports, based on their annual bunkering capacity, to assess feasibility and infrastructure requirement for fuel transition.

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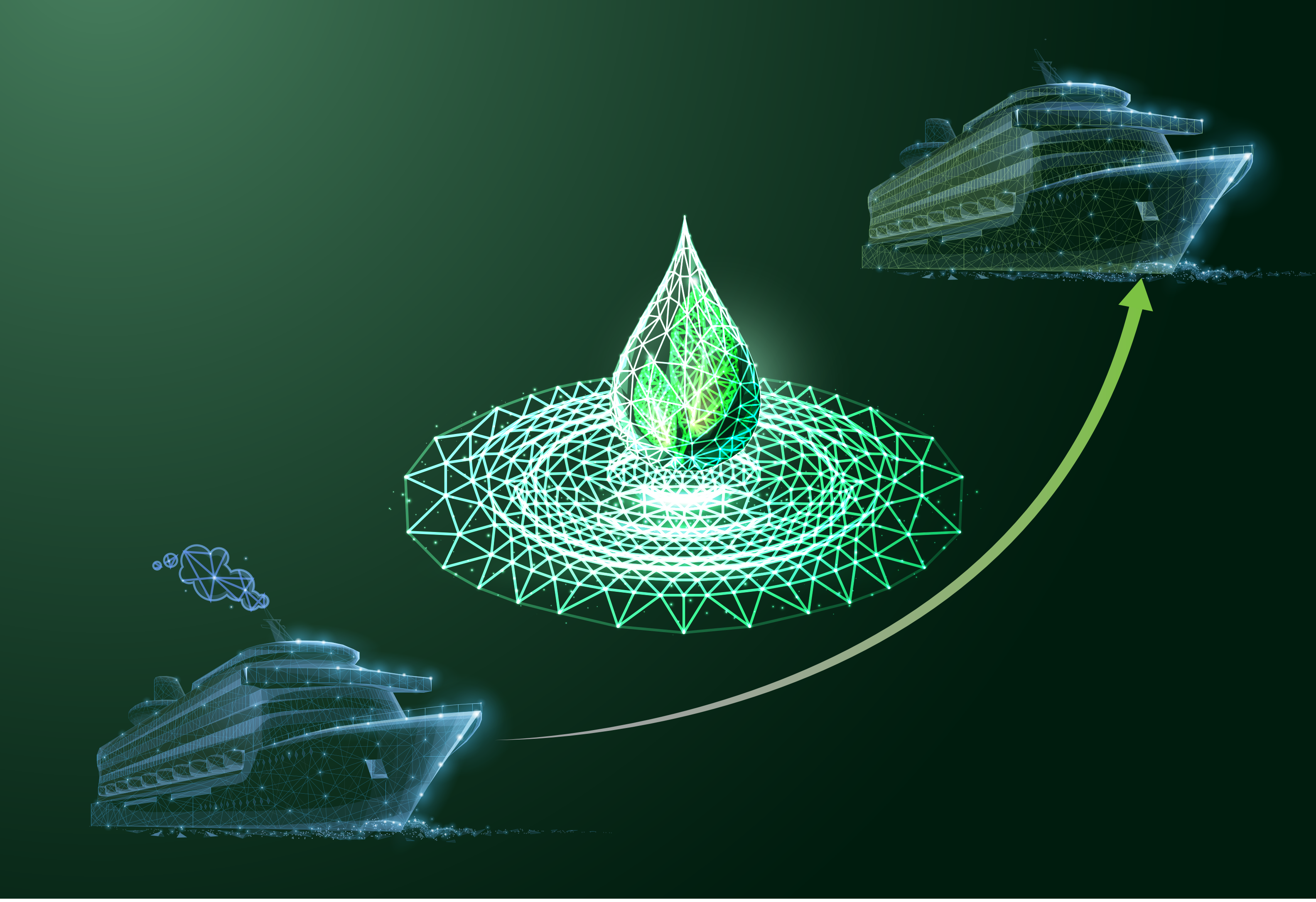

Chapter 5

Fuel Cell for Decarbonizing Maritime Sector and Prospects for India

Introduction

IMO has set the ambitious target to cut down the GHG emissions from international shipping to reach net zero by or around, i.e. close to, 2050. Fuel cells stand out to be one of the promising options with potential for both emission reduction and efficient energy use. By assessing the available Fuel Cell technologies, it is possible to identify the most viable path forward which will ensure that each checkpoint is meeting with the best approach. Although Fuel cells offer transformative technology for the reduction in the GHG emissions creating a shift from traditional fuel sources to green fuels such as Hydrogen, Methanol, Ammonia which sounds environmentally fit, but it comes with a unique operational, economic and technical con that the shipping industry must address.

This chapter offers a comprehensive overview of different types of Fuel cells in marine examining their adaptability, their present status, suitability, operational profiles and the prospects it holds for India. Each type of Fuel Cell has its unique characteristics in terms of efficiency, power density, durability and the operational temperatures. The infrastructure and logistics required for Fuel Cell adoption in the marine industry are another important area of study. The limited availability of green hydrogen and other clean fuels at marine hubs necessitates the development of extensive refueling infrastructure and onboard storage systems that meet both capacity and safety standards. The logistics of storing high-energy-density fuels, bunkering procedures, fuel availability, and the difficulties of on-board storage and safety regulations are evaluated.

The development of refueling infrastructure is crucial to the broad use of Fuel Cell s in marine applications. Hydrogen and Ammonia are two important marine fuel options for Fuel Cell s, and each one needs a different bunkering system. Both compressed and liquefied forms of Hydrogen have different logistical requirements; liquid hydrogen needs cryogenic storage at very low temperatures, while compressed Hydrogen is lighter but requires high-pressure tanks. Despite being more widely available and simpler to carry, Ammonia is dangerous and needs to be handled carefully. This chapter also illustrates the case studies and the progress of Fuel cell in the pilot/ demonstration projects which are currently operational and also in pipelines.

Although Fuel Cell s show great promise for use in marine applications, a number of issues still need to be resolved. Future research should focus on creating Fuel Cell stacks that are more affordable, extending stack life, and increasing efficiency. Therefore, by understanding these elements will help the maritime industry get closer to a sustainable future powered by technology that not only satisfies legal requirements but also promotes a more robust, efficient, and clean shipping sector.

Analysis of Clackson's research database shows that Fuel Cell s are being incorporated into more and more types of maritime vessels to satisfy a range of power requirements. Medium-sized ships, such as supply ships and ferries, use 320ekW to 1,200ekW of high-capacity Fuel Cell s, whereas large cruise ships use 4,000ekW to 6,000ekW. For auxiliary purposes, smaller ships use 30 ekW to 300 ekW Fuel Cell s, which offer efficiency without having extra capacity. The potential of Fuel Cell s as a pillar of the marine energy revolution will only be realized with sustained research, funding, and policy support.

Looking from India perspective the inland water vessels have great near-future prospects, whereas the adoption of Fuel Cell technology for coastal and especially for OGVs seems a little distant future.

5.1 Types of Fuel Cells for Shipping Application

5.1.1 Working of Fuel Cells

A Fuel Cell is a device that converts energy into electricity through a chemical reaction. Typically, it has two electrodes: the anode and the cathode, where the chemical reactions take place as shown **in Figure 5.1**. Every Fuel Cell also includes an electrolyte, which helps the transport of electrically charged particles between the electrodes along with catalyst, which speeds up the reactions. Unlike traditional mechanical systems, a Fuel Cell operates without any moving parts, allowing it to function quietly which makes them reliable and easy to maintain. The energy that is released during the process is in the form of heat and electricity. This is different from a battery, which also generates electricity but works in a different way. A battery stores chemical energy inside and converts it into electricity when it is connected to a load. Being a sealed unit battery keeps all its chemicals contained and has a limited energy supply. In contrast, Fuel Cell s are an open system continuously taking external fuel, like hydrogen from a tank and oxygen from the air, to keep generating energy. As long as there is a supply of fuel, the Fuel Cell can keep producing electricity. Fuel cells typically have higher efficiency than batteries. Fuel cells can operate at theoretical efficiencies more than 90% but the typical practical efficiencies are 30–55%. They come in various types, which differ in design, operating temperature, and the fuels they use. However, the fundamental operating principle is the same across all Fuel Cell types is discussed as shown in **Figure 5.1.**

Several types of Fuel Cell s are relevant for marine propulsion, each offering distinct characteristics and advantages based on specific marine applications. Below are the diverse ranges of Fuel Cell types and their suitability for different ship types. The comparative assessment of the Fuel Cell s with respect to their characteristics are illustrated in **Table 5.1.**

5.2 Comparison of Key Characteristics of Fuel Cells

This section dives into the main types of Fuel Cell s, each boasting its own unique traits that make them ideal for different uses. **Figure 5.2**, which gives a clear visual breakdown of the key differences among these Fuel Cell technologies along with a short brief, will shed light on how they vary in terms of electrolyte material, operating temperature, fuel flexibility, efficiency, power density, and common applications.

Proton Exchange Membrane Fuel Cells (PEMFCs): It uses a solid polymer electrolyte (e.g., Nafion), allowing proton transfer but blocking electrons. It operates at 80–120 °C with 50–60% efficiency and a power output between 50–250 kW. It requires high-purity hydrogen and platinum catalysts, increasing costs. The solid electrolyte is durable and leak-proof.

Solid Oxide Fuel Cells (SOFCs): It use solid ceramic electrolytes like Yttria-stabilized Zirconia (YSZ), operates at 600–1,000 °C with ~60% efficiency. Support various fuels including hydrogen, natural gas, biogas, and coal gas. Power outputs reach up to 100 kW. Two main types: SOFC-O^{2-} (high power but thermal issues) and SOFC-H^+ (lower temp, better hydrogen compatibility). Materials like $BaCeO_3$ (high conductivity, less stable) and $BaZrO_3$ (more stable, lower conductivity) are enhanced by doping. Waste heat can be reused, but units are bulky and prone to cracking.

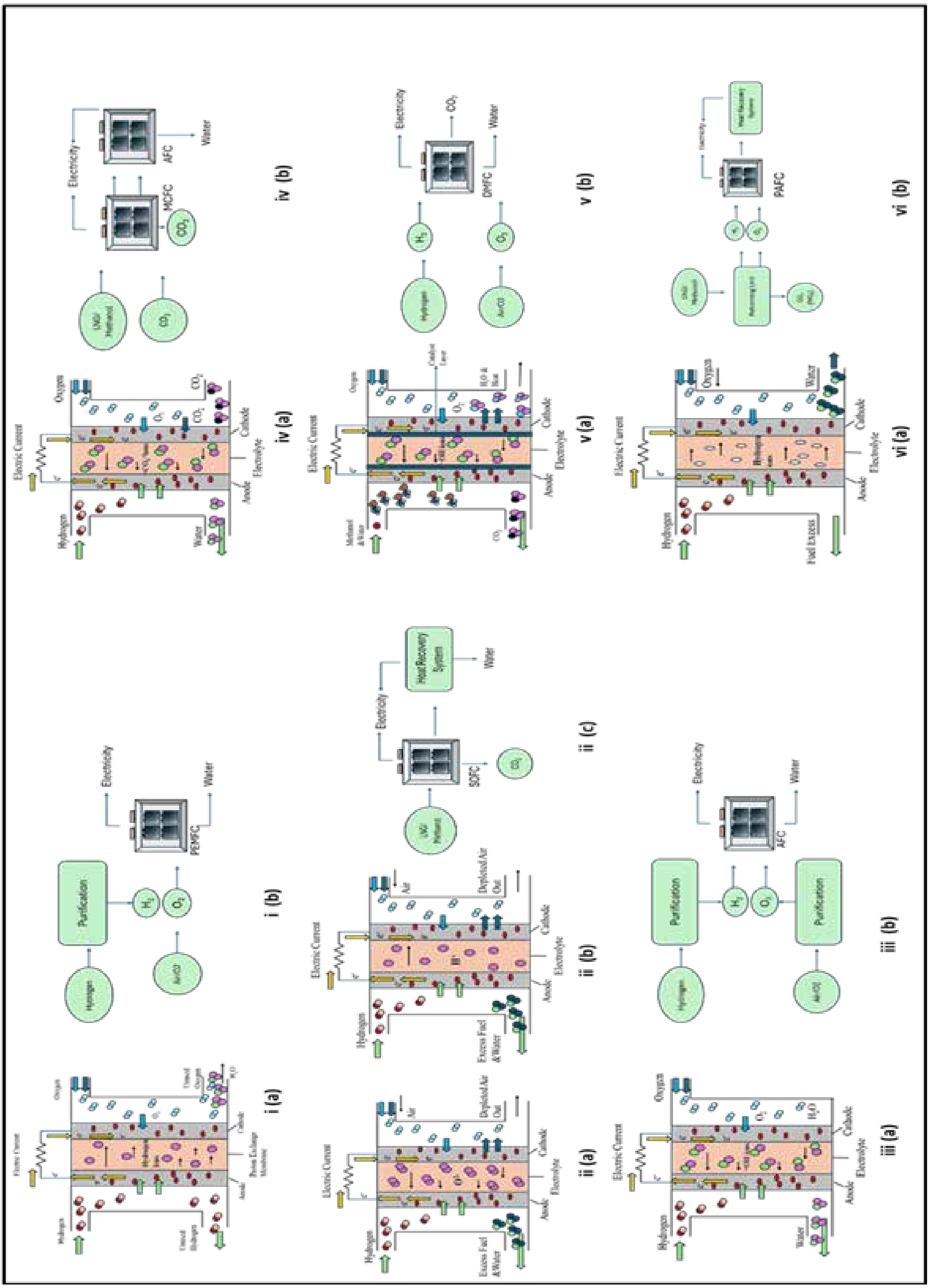

Figure 5.1:This Figure shows (a) schematic diagrams (b] process flows of six key Fuel Cell types used in maritime applications: i – PEMFC, ii – SOFC, iii – AFC, iv – MCFC, v – PAFC, and VI – AFC. (Represented from [12,13,&14)]

Alkaline Fuel Cells (AFCs): It uses compressed hydrogen and oxygen with a liquid potassium hydroxide (KOH) electrolyte. Typically operates at 60–250 °C and offers around 70% efficiency. Require high-purity hydrogen and use platinum catalysts. Risk of electrolyte leakage due to liquid nature.

Molten Carbonate Fuel Cells (MCFCs): It uses molten carbonate salts (e.g., Sodium or Lithium Carbonates) as electrolytes. It operates at ~650 °C with 60–80% efficiency, generating up to 2 MW (and some designs up to 100 MW). It needs inexpensive nickel-based catalysts and require CO_2 injection to maintain electrolyte balance. High temps limit material options and application flexibility.

Direct Methanol Fuel Cells (DMFCs): It directly feeds Methanol to the cell without a reformer. It operates at 60–250 °C with 40–50% efficiency and output below 5 kW using platinum-based catalysts. Methanol crossover through the membrane reduces efficiency and damages the

Phosphoric Acid Fuel Cells (PAFCs): It uses Phosphoric acid as the electrolyte, operates at 150–200 °C with 40–80% efficiency. Power output has reached 200 kW, with some systems tested up to 11 MW. It can tolerate up to 1.5% CO and uses Hydrogen or Methanol. It also requires Platinum catalysts and corrosion-resistant components due to acidic nature.

Fuel cell technologies provide a sustainable and efficient alternative to conventional power sources. This is particularly important for industries such as maritime transport, where these technologies play a crucial role in lowering emissions and enhancing performance. The table below outlines the main features of different Fuel Cell technologies, emphasizing their benefits, drawbacks, and potential uses, especially in the context of maritime decarbonization.

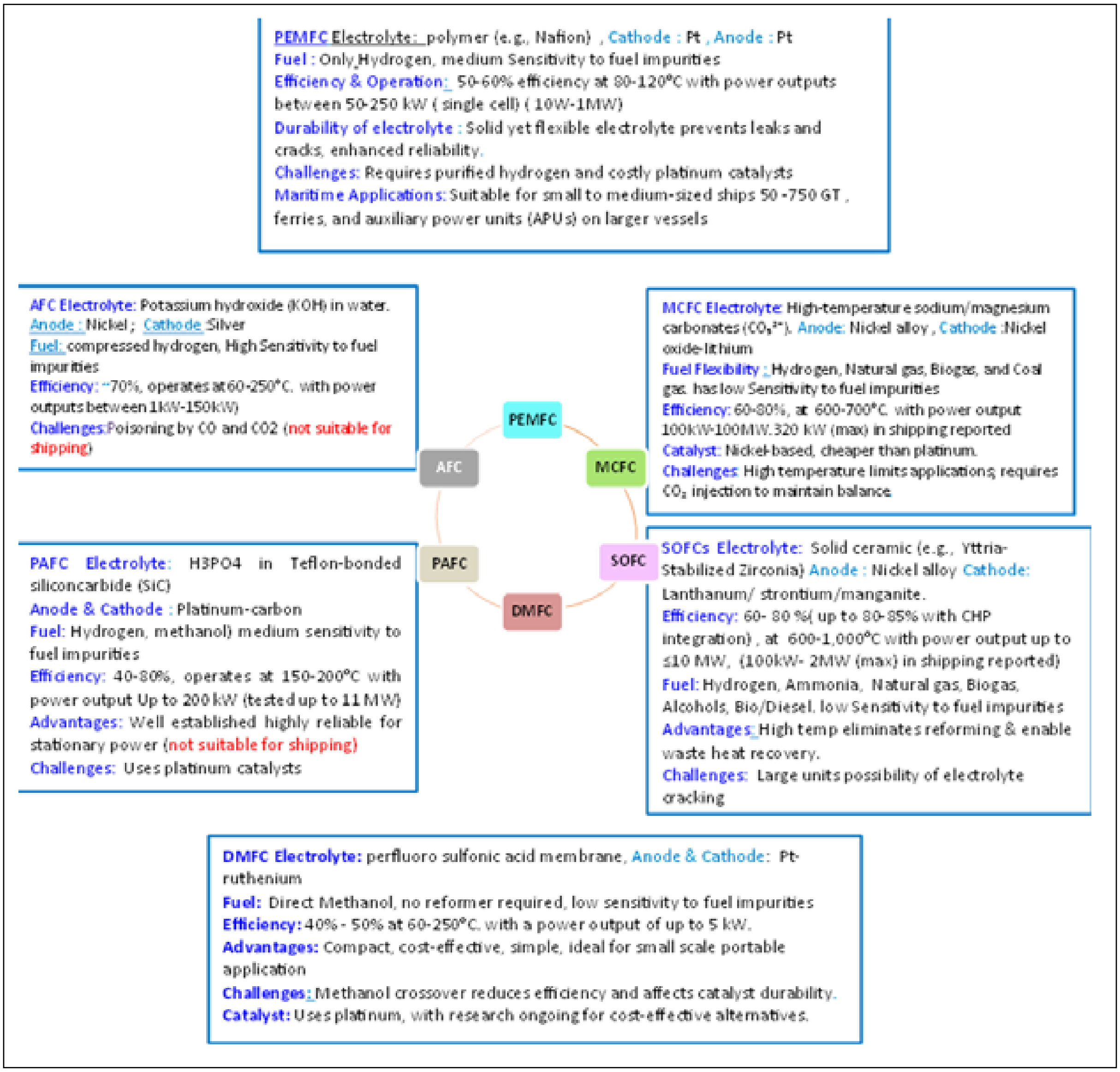

Figure 5.2: Overview of Different Fuel Cell Types and Their Key Characteristics.

Table 5.1: Characteristics of Different Types of Fuel Cells

Characteristics	Units	Alkaline Fuel Cells (AFCs)	Proton Exchange Membrane Fuel Cells (PEMFCs)	Solid Oxide Fuel Cells (SOFC)	Molten Carbonate Fuel Cells (MCFC)	Direct Methanol Fuel Cells (DMFC)	Phosphoric acid Fuel Cell s (PAFCs)
Efficiency	%	60-70	50-60	33-60	45-60	40-50	40-50
Operating Temperature	°C	60–250	80–120	600–1000	600–700	60–250	150-200
Fuel Flexibility		Hydrogen Ammonia	Hydrogen	Hydrogen, Ammonia, Natural gas, Biogas, Alcohols Bio/Diesel	Natural gas biogas coal gas	Methanol	Hydrogen Methanol
Energy density	(kW hr/ m^3)	172–462. 09	112.2–770	29.9–274	—	—	25–40
Power density	(W/cm^2)	0.05-1	>2	>0.5	0.15	0.1	0.16
Cell voltage	V	0.8-1.0	0.6-0.8	0.8-1.0	0.6-0.8	0.5-0.7	0.6-0.7
Nominal current density	A/cm^2	0.2-0.5	0.5-2	0.5-1.5	0.5 - 1.0	0.1-0.3	0.2-0.4
Electrolyte		Aqueous potassium hydroxide soaked in a porous matrix, or alkaline polymer membrane	Perfluoro sulfonic acid (Nafion membrane)	Yttria stabilized zirconia	Molten lithium, sodium, and/ or potassium carbonates, soaked in a porous matrix	Perfluoro sulfonic acid membrane, such as Nafion	Phosphoric acid soaked in a porous matrix or imbibed in a polymer membrane
Power Capacity	kW/MW	≤500kW	≤120kW	≤10 MW	120kW-10MW	≤5 kW	100-400kW
Start-up Time	min	<1	<1	~60	10	10	—

Table 5.1: Characteristics of Different Types of Fuel Cells

Characteristics	Units	Alkaline Fuel Cells (AFCs)	Proton Exchange Membrane Fuel Cells (PEMFCs)	Solid Oxide Fuel Cells (SOFC)	Molten Carbonate Fuel Cells (MCFC)	Direct Methanol Fuel Cells (DMFC)	Phosphoric acid Fuel Cell s (PAFCs)
Combined heat and power efficiency (%)	%	<90	70–90	80	>80	>85	>80
Anode reaction		$H_2 + 2OH^-$ → $2H_2O + 2e^-$	H_2 → $2H+ + 2e^-$	a) $H_2 + O^{2-}$ → $H_2O + 2e^-$ b) $CO + O_2$- → $CO_2 + 2e^-$	H2 + CO_3^{2-} → CO2 + H2O + $2e^-$	$CH_3OH + H_2O$ → CO_2 + 6H+ + $6e^-$	H_2 → $2H+ + 2e^-$
Cathode reaction:		$½O_2 + H_2O + 2e^-$ → $2OH^-$	$½O_2$ +2H+ + $2e^-$ → H_2O	$O_2 + 4e^-$ → $2O^{2-}$	$½O_2 + CO_2 + 2e^-$ → CO_3^{2-}	$3(½O_2)$ + 6H+ + $6e^-$ → $3H_2O$	$½O_2$ +2H+ + $2e^-$ → H_2O
Overall reaction:		$H_2 + ½O_2$ → H_2O	$H_2 + ½O_2$ → H_2O	$H_2 + O_2 + CO$ → $H_2O + CO_2$	$H_2 + ½O_2$ → H_2O	$CH_3OH + H_2O$+ $3(½O_2)$ → $CO_2 + 3H_2O$	$H_2 + ½O_2$ → H_2O
Size	-	Small	Small	Medium	Large	Small	Large
Lifetime		Not available	2,000-3,000 h	1,000 h	7,000-8,000 h	1,000 h	>50,000 h

Table 5.1: Characteristics of Different Types of Fuel Cells

Characteristics	Units	Alkaline Fuel Cells (AFCs)	Proton Exchange Membrane Fuel Cells (PEMFCs)	Solid Oxide Fuel Cells (SOFC)	Molten Carbonate Fuel Cells (MCFC)	Direct Methanol Fuel Cells (DMFC)	Phosphoric acid Fuel Cell s (PAFCs)
By products		Water, heat	Water	Water and heat	Carbon dioxide &Water	Waste heat, water vapor and a small amount of carbon dioxide	Water and Heat
Drawbacks		CO_2Poisioning	CO $_+$ Sulfur Poisoning	Sulfur, poisoning, cycling effects, mechanically fragile, Long start up times	Sulfur, poisoning, cycling effects, Long start up times	Methanol Crossover	CO $_+$ S Poisoning

5.3 Global Status and Trends in Fuel Cell Adoption in Shipping (In-service & Orderbook)

The present fleet of fuel-cell-equipped vessels are examined based on the data procured from Clarkson Research World Fleet Registar **[2],** which also highlights the in-service and orderly vessels that are spearheading the transition to more environmentally friendly marine transportation. **Table 5.2 and 5.3** provides the details of global Fuel Cell installed vessels in-service and orderbook respectively.

5.3.1 Inservice

The global fleet of fuel-cell vessels is on the rise, according to Clarkson Research, with more and more ship types embracing this technology. Hydrogen stands out as the most popular fuel, frequently used alongside batteries and diesel. Cruise ships are at the forefront of this trend, utilizing large-capacity systems that can reach up to 4,000ekW. Following closely are ferries, cargo ships, and inland vessels, which typically operate with smaller setups. Notable technology providers in this space include Ballard, Nedstack, and Proton Motor, all of which offer modular solutions that cater to a variety of vessel sizes and applications.

5.3.2 Orderbook

Hydrogen is the leading fuel in fuel-cell vessel propulsion, mainly in hybrid systems with batteries and diesel. Among the 20 vessels examined, the majority utilize hydrogen in conjunction with Fuel Cell s, batteries, and other fuels like LNG or biofuels.Cruise ships dominate adoption, with Fuel Cell capacities reaching up to 6,000 ekW, while smaller vessels use lower capacities. Key technology providers include PowerCell, Ballard, Alma Clean Power, and TECO 2030, reflecting a growing and diverse industry commitment to clean maritime solutions.

Table 5.2: Status of Fuel Cells Vessels In Service

Type	GT	Builder	Flag State	Main Engine Fuel Type	No. of Fuel Cells propulsion system /Fuel cell Type-capacity/ Technology provider	Registered Owner Company	Registered Owner Country/ Region	Power Type
Cruise Ship	2,48,663	Meyer Turku	Bahamas	LNG, VLS MGO	1 x Fuel Cell, Propulsion / PEMFC-4,000ekW /-	ICON OF THE SEAS LLC		Fuel Cell & Diesel
Cruise Ship	55,051	Meyer Werft	Bahamas	Hydrogen, LNG, VLS MDO	1 x Fuel Cell, Propulsion/ 4,000ekW/-	Silver Nova Shipping Co LLC	Liberia	Batteries, Diesel & Fuel Cell
Cruise Ship	47,878	Fincantieri Ancona	Norwegian Int'l	Hydrogen, IFO 380	1 x Fuel Cell, Propulsion /SOFC-100ekW /-	Viking Ocean Cruises Ship IX	Bermuda	Fuel Cell & Diesel
Cruise Ship	44,650	Meyer Werft	Bahamas	Hydrogen, LNG, VLS MDO	1 x Fuel Cell, Propulsion / -4,000ekW/-	Silversea Cruises Ltd.	Bahamas	Batteries, Diesel & Fuel Cell
PSV/ Supply 4,000 DWT+	6,111	Westcon	Norway	LNG, VLS MGO	1 x Fuel Cell, Propulsion /MCFC-320ekW/-	Eidesvik Shipping AS	Norway	Batteries, Diesel & Fuel Cell
PSV/ Supply 4,000 DWT+	5,073	Kleven Verft	Norway	Ammonia, LNG, VLS MGO	1 x Fuel Cell, Propulsion / SOFC-2,000ekW /Alma Clean Power	Eidesvik Shipping AS	Norway	Batteries, Diesel & Fuel Cell
Pass./Car Ferry	3,240	Armon (Vigo)	Spain	Hydrogen	1 x Fuel Cell, Propulsion /100ekW	Caixabank, SA	Spain	Batteries, Diesel & Fuel Cell
Container Ship (Inland)	3,041	Begej Shipyard	Netherlands	Hydrogen	3 x Fuel Cell, Propulsion /SOFC-825ekW/Nedstack	Zero Emission Shipping BV	Netherlands	Fuel Cell & Battery

Table 5.2: Status of Fuel Cells Vessels In Service

Type	GT	Builder	Flag State	Main Engine Fuel Type	No. of Fuel Cells propulsion system /Fuel cell Type-capacity/ Technology provider	Registered Owner Company	Registered Owner Country/ Region	Power Type
Pass./Car Ferry	2,699	Westcon	Norway	Hydrogen, VLS MGO	2 x Fuel Cell, Propulsion/ PEM-400ekW/ Ballard Power	Norled AS	Norway	Batteries, Diesel & Fuel Cell
General Cargo (Inland)	2,466	Concordia Damen JV	Netherlands	Hydrogen, VLS IFO	1 x Fuel Cell, Propulsion /PEM-/ Nedstack	Lenten Scheepvaart BV	Netherlands	Batteries, Diesel & Fuel Cell
Trailing Suction Hopper Dredger	1,742	Chantiers Piriou	France	Hydrogen	1 x Fuel Cell, Propulsion /100ekW /Helion	Region Occitanie	France	Batteries, Diesel & Fuel Cell
Container Ship (Inland)	1,676	Unknown/ Netherlands	Netherlands	Hydrogen	6 x Fuel Cell, Propulsion / PEMFC-1,200ekW/ Ballard Power			Fuel Cell & Battery
Patrol Vessel	749	Zhuhai Jianglong	China P.R.	Hydrogen	Fuel Cell, Propulsion -/-500ekW/ CSSC 712		China P.R.	Fuel Cell & Battery
Utility/ Workboat	328	Metz	Netherlands	Hydrogen, VLS MDO	1 x Fuel Cell, Propulsion /PEMFC-400ekW /Ballard Power	Coastal Shipping BV	Netherlands	Fuel Cell & Battery
Passenger Vessel	248	Hongawara Zosen	Japan	Biofuel, Hydrogen	2 x Fuel Cell, Propulsion / 480ekW /Yanmar Power Tech		Japan	Batteries, Diesel & Fuel Cell

Table 5.2: Status of Fuel Cells Vessels In Service

Type	GT	Builder	Flag State	Main Engine Fuel Type	No. of Fuel Cell s propulsion system /Fuel cell Type-capacity/ Technology provider	Registered Owner Company	Registered Owner Country/ Region	Power Type
Passenger Catamaran Vessel	200	Bay Ship & Yacht	United States	Hydrogen	3 x Fuel Cell, Propulsion / PEMFC- 1,020ekW/ Zero Emission Ind.	Switch E-Ferry #1 LLC	United States	Fuel Cell & Battery
Marine Research	160	Fincantieri Castell	Italy	Hydrogen, VLS MGO	2 x Fuel Cell, Propulsion -/PEMFC- 140ekW/ Proton Motor			Batteries, Diesel & Fuel Cell
Towing/ Pushing (Inland)	136	Hermann Barthel	Germany	Hydrogen	3 x Fuel Cell, Propulsion / PEMFC- 300ekW/ Ballard Power			Fuel Cell & Battery
Passenger (Inland)	50	Zhongqing Bochuang	China P.R.	Hydrogen	Fuel Cell, Propulsion / PEMFC- 30ekW/ Pearl Hydrogen			Fuel Cell & Battery
Passenger (Inland)		SSB Spezialschiffbau	Germany	Hydrogen	2 x Fuel Cell, Propulsion /PEMFC- 96ekW /Proton Motor			Fuel Cell & Battery

Table 5.2: Status of Fuel Cells Vessels In Service

Type	GT	Builder	Flag State	Main Engine Fuel Type	No. of Fuel Cell s propulsion system /Fuel cell Type-capacity/ Technology provider	Registered Owner Company	Registered Owner Country/ Region	Power Type
Passenger (Inland)		Bodewes Hasselt	Netherlands	Hydrogen	Fuel Cell, Propulsion / PEMFC 70ekW /Nedstack			Fuel Cell & Battery
Cruise (Inland)		Lux-Werft	Germany	Methanol, ULS MGO	7 x Fuel Cell, Propulsion / PEMFC-35ekW /Advent			Batteries, Diesel & Fuel Cell
General Cargo (Inland)		Shipyard ATG Giurgiu	France	Hydrogen, VLS MDO	2 x Fuel Cell, Propulsion /PEMFC-400ekW /Ballard Power			Batteries, Diesel & Fuel Cell
Passenger (Inland)		Unknown Yard	United Kingdom	Hydrogen	4 x Fuel Cell, Propulsion /PEMFC - / Auriga Energy			Fuel Cell Propulsion

Table 5.3: Status of Fuel Cells Vessels (Orderbook)

Type	GT	Builder	Flag State	Main Engine Fuel Type	No. of Fuel Cells propulsion system /Fuel cell Type-capacity/ Technology provider	Registered Owner Company	Registered Owner Country/ Region	Power Type
Cruise Ship	2,48,663	Meyer Turku	Bahamas	LNG, VLS MGO	1 x Fuel Cell, Propulsion / PEMFC-4,000ekW /-	ICON OF THE SEAS LLC		Fuel Cell & Diesel
Cruise Ship	55,051	Meyer Werft	Bahamas	Hydrogen, LNG, VLS MDO	1 x Fuel Cell, Propulsion/ 4,000ekW/-	Silver Nova Shipping Co LLC	Liberia	Batteries, Diesel & Fuel Cell
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Cruise Ship	44,650	Meyer Werft	Bahamas	Hydrogen, LNG, VLS MDO	1 x Fuel Cell, Propulsion / -4,000ekW/-	Silversea Cruises Ltd.	Bahamas	Batteries, Diesel & Fuel Cell
PSV/Supply 4,000 DWT+	6,111	Westcon	Norway	LNG, VLS MGO	1 x Fuel Cell, Propulsion /MCFC-320ekW/-	Eidesvik Shipping AS	Norway	Batteries, Diesel & Fuel Cell
PSV/Supply 4,000 DWT+	5,073	Kleven Verft	Norway	Ammonia, LNG, VLS MGO	1 x Fuel Cell, Propulsion / SOFC-2,000ekW /Alma Clean Power	Eidesvik Shipping AS	Norway	Batteries, Diesel & Fuel Cell
Pass./Car Ferry	3,240	Armon (Vigo)	Spain	Hydrogen	1 x Fuel Cell, Propulsion /100ekW	Caixabank, SA	Spain	Batteries, Diesel & Fuel Cell

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Container Ship (Inland)	1,676	Unknown/ Netherlands	Netherlands	Hydrogen	6 x Fuel Cell, Propulsion / PEMFC-1,200ekW/ Ballard Power	-	-	Fuel Cell & Battery
Patrol Vessel	749	Zhuhai Jianglong	China P.R.	Hydrogen	Fuel Cell, Propulsion -/-500ekW/ CSSC 712	-	China P.R.	Fuel Cell & Battery
Utility/ Workboat	328	Metz	Netherlands	Hydrogen, VLS MDO	1 x Fuel Cell, Propulsion /PEMFC-400ekW /Ballard Power	Coastal Shipping BV	Netherlands	Fuel Cell & Battery

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Passenger Vessel	248	Hongawara Zosen	Japan	Biofuel, Hydrogen	2 x Fuel Cell, Propulsion / 480ekW /Yanmar Power Tech	-	Japan	Batteries, Diesel & Fuel Cell
Passenger Catamaran Vessel	200	Bay Ship & Yacht	United States	Hydrogen	3 x Fuel Cell, Propulsion / PEMFC-1,020ekW/ Zero Emission Ind.	Switch E-Ferry LLC	United States	Fuel Cell & Battery
Marine Research	160	Fincantieri Castell	Italy	Hydrogen, VLS MGO	2 x Fuel Cell, Propulsion -/ PEMFC-140ekW/ Proton Motor	-	-	Batteries, Diesel & Fuel Cell
Towing/ Pushing (Inland)	136	Hermann Barthel	Germany	Hydrogen	3 x Fuel Cell, Propulsion / PEMFC-300ekW/ Ballard Power	-	-	Fuel Cell & Battery
Passenger (Inland)	50	Zhongqing Bochuang	China P.R.	Hydrogen	Fuel Cell, Propulsion / PEMFC-30ekW/ Pearl Hydrogen	-	-	Fuel Cell & Battery
Passenger (Inland)	-	SSB Spezialschiffbau	Germany	Hydrogen	2 x Fuel Cell, Propulsion /PEMFC-96ekW /Proton Motor	-	-	Fuel Cell & Battery

Table 5.3: Status of Fuel Cells Vessels (Orderbook)

Type	GT	Builder	Flag State	Main Engine Fuel Type	No. of Fuel Cells propulsion system /Fuel cell Type-capacity/ Technology provider	Registered Owner Company	Registered Owner Country/ Region	Power Type
Passenger (Inland)	-	Bodewes Hasselt	Netherlands	Hydrogen	Fuel Cell, Propulsion / PEMFC 70ekW /Nedstack	-	-	Fuel Cell & Battery
Cruise (Inland)	-	Lux-Werft	Germany	Methanol, ULS MGO	7 x Fuel Cell, Propulsion / PEMFC- 35ekW /Advent	-	-	Batteries, Diesel & Fuel Cell
General Cargo (Inland)	-	Shipyard ATG Giurgiu	France	Hydrogen, VLS MDO	2 x Fuel Cell, Propulsion /PEMFC- 400ekW /Ballard Power	-	-	Batteries, Diesel & Fuel Cell
Passenger (Inland)	-	Unknown Yard	United Kingdom	Hydrogen	4 x Fuel Cell, Propulsion /PEMFC - / Auriga Energy	-	-	Fuel Cell Propulsion

5.4 India Status for Fuel Cell Adoption in Shipping

The Table 5.4 showcases the upcoming projects of Cochin Shipyard Ltd (CSL) for alternative Fuel Cell vessels including hybrids, all designed to boost clean maritime transportation. It provides insights into the number of vessels, their propulsion capabilities, and its timeline of deployment. These projects really emphasize the increasing dedication and commitment to hydrogen technologies, which are key to cutting down emissions in both short and long-haul shipping.

CSL, the first premier greenfield shipyard in India, has designed and constructed 23 Nos of 100 Passenger capacity electric-hybrid ferries as part of the urban mobility infrastructure of the Kochi water metro project and completed the delivery of India's first indigenous Hydrogen Fuel Cell ferry for IWAI. CSL has also established a temporary Hydrogen dispensing facility based on pressure balancing system used for filling the cylinders onboard from shore which has managed by a professional agency for filling the H2 to the vessel.

Table 5.4: Status of Fuel Cells Adoption Indian Shipping

S. No.	Project	No of Vessels	Technology	Order Type	Year of completion (Tentative)
1	FCV PILOT 01	1	**Hydrogen Fuel based 50kW)**	Domestic	2024
2	Hydrogen Fuel Cell vessels	4	Hydrogen Fuel Cell based (2x 1600kw)	Domestic	2027-2028
3	Samskip feeder container vessel	2	Hydrogen Fuel Cell based	International	2025-2026

5.5 Comparative LCA between Fuel Cells & Other Alternative Options in Green Shipping

An unique study is reported evaluates the life cycle environmental and economic impacts of eight decarbonization solutions for shipping **[3]**. Using Prospective Life Cycle Assessment (pLCA) and Environmental Life Cycle Costing (eLCC), it examines energy use, emissions, and cost trade-offs. The solutions analyzed include e-Methanol, Hydrogen, Ammonia, and Battery-electric with reference to MGO systems in various propulsion technologies, providing a comprehensive comparison for future fossil-free shipping. The decarbonization solutions included are

1. **Case 1 (EMeOHICE):** Uses electro-Methanol with MGO pilot fuel in a dual-fuel ICE, equipped with SCR for NOx reduction.
2. **Case 2 (EMeOHICE w/PostCC):** Similar to Case 1 but includes Post-Combustion Carbon Capture (70% CO_2 capture).
3. **Case 3 (HyMethShip):** Uses pre-combustion CC (95% CO_2 capture) to separate H_2 from methanol for a spark-ignition ICE.
4. **Case 4 (ELH$_2$ICE):** Uses liquid hydrogen in a spark-ignition ICE with excess heat for heating.
5. **Case 5 (ENH$_3$ICE):** Uses electrolytic ammonia with H_2 pilot fuel, equipped with SCR for NOx reduction.
6. **Case 6 (ELH$_2$PEMFC):** Uses liquid hydrogen in a Fuel Cell , powering an electric motor, offering higher efficiency than ICE.

7. **Case 7 (ENH₃SOFC):** Uses ammonia in a solid oxide Fuel Cell (SOFC) to generate electricity for propulsion.
8. **Case 8 (BE):** Uses lithium-ion batteries for round-trip operation with a 30% reserve, charged at Gothenburg port.
9. **Case 9 (MGO ICE):** Uses marine gas oil (MGO) in a medium-speed diesel ICE, with SCR for NOx reduction.

LCA System Boundaries considered clear boundaries for this analysis by separating the foreground from the background processes. The foreground system encompasses the processes that are directly modelled, such as manufacturing components, producing fuel, operating the system, and handling the end-of-life (EOL) phase. On the other hand, the background system includes external factors like electricity generation, fuel infrastructure, and consumables that have an impact but aren't directly modelled. While fuel distribution and transport losses due to space limitations are considered during scenario analysis, they aren't part of the life cycle assessment (LCA). This boundary framework allows for a focused evaluation of fuel and propulsion options while also considering important external dependencies.

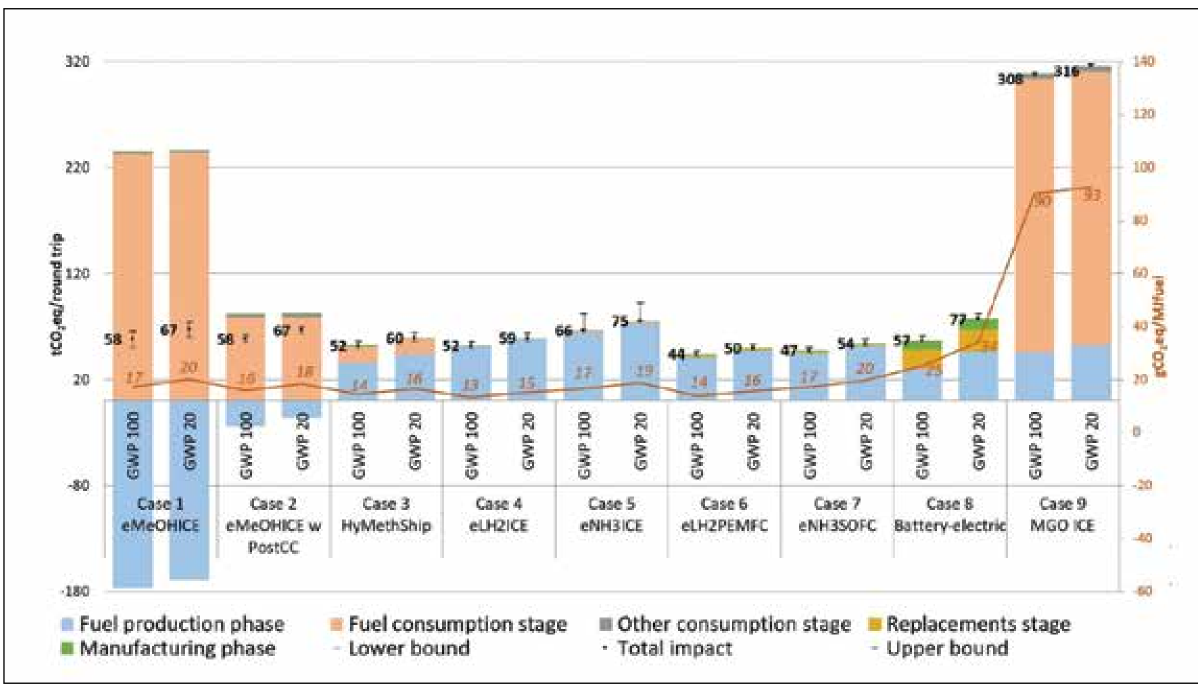

Figure 5.3: pLCA Results on Climate Change Potential (GWP20 and GWP100) for the Round Trip [3]

The pLCA results shown in the above Figure 5.3 reveal that all decarbonization pathways make a significant dent in climate impact. Among these, ELH₂-PEMFC, ENH₃-SOFC, and ELH₂-ICE stand out with the greatest potential for reduction. In contrast, for carbon-free fuels such as ENH₃, ELH₂, and BE, the production phase—especially the generation of electricity—plays a bigger role in emissions. The study also takes a closer look at battery-electric (BE) systems in a renewable electricity context, emphasizing how much they rely on energy sources. While manufacturing and replacing components generally have a minor impact on overall emissions, battery production does have a notably higher effect. The uncertainty analysis indicates that eNH_3-ICE experiences a significant variation (+25%) due to uncertainties surrounding N_2O emissions, which have a GWP factor of 273. Meanwhile, other pathways stay within a ±8% uncertainty range, reinforcing their strong potential for GHG reduction when powered by wind energy.

LCA Study of decarbonizing pathways using different energy carriers (E-H_2, E-NH_3,E-MeOH, Battery, Electricity in different propulsions systems (IC Engine, Fuel cell & CC technology)

GHG Reduction Across different Pathways (GWP100)

- **ELH_2- PEMFC (Hydrogen Fuel Cell):** Lowest Emissions ~**44 tCO_2**-eq/round trip
- **ENH_3- SOFC (Ammonia Fuel Cell) :** Emissions ~**50 tCO_2**-eq/round trip
- **ELH_2- ICE (Hydrogen IC Engine):** Emissions ~**52 tCO_2**-eq/round trip
- **Battery-electric (BE) Propulsion:** Emissions ~**57 tCO_2**-eq/round trip including replacement impact (**34 tCO_2**-eq/round trip)
- **EMeOH- ICE with Post CC:** Emissions **56 tCO_2**-eq/round trip
- **EMeOH- ICE :** Emissions ~ ***58 tCO_2**-eq/round trip

*It is achieved through C negative production via CO_2 capture use of RE, and circular C -cycle despite combustion emissions **(-180 tCO_2** eq/round trip)

- **ENH3- ICE (Ammonia Fuel Cell):** Emissions ~**66 tCO_2**-eq/round trip
- **MGO- ICE (Marine Gas Oil Internal Combustion Engine):** Emissions ~**316 tCO_2**-eq/round trip

Overall, Hydrogen Fuel Cell s (eLH_2-PEMFC) provide the greatest climate benefit, while Ammonia and Methanol pathways show moderate reductions. The study highlights that the energy source and production method significantly impact GWP, making renewable electricity crucial for true decarbonization.

Figure 5.4 illustrates the energy conversion efficiencies across different decarbonization pathways, highlighting how electricity and MGO transform into usable energy. The key observations highlight that battery-electric (BE) systems exhibit the highest energy conversion efficiency (~78%), as they utilize electricity directly, avoiding fuel conversion losses. In contrast, electrolytic fuels such as eLH_2, eNH_3, and eMeOH experience significant conversion losses during both upstream fuel production and downstream energy conversion, resulting in lower efficiencies. Among these options, eNH_3 and eMeOH struggle the most with round-trip efficiency due to significant upstream losses. The HyMethShip concept demonstrates slightly higher efficiency (~26%) compared to Post-Combustion Capture (PostCC) systems (~25%), as it benefits from better heat utilization in pre-combustion carbon capture. In terms of energy requirements, fuels used in internal combustion engines (ICEs) demand about 2 to 2.5 times more energy than MGO, while in Fuel Cell s (FCs), this need drops to roughly 1.5 times more energy. On the other side, battery-electric (BE) systems are much more efficient, requiring 40% less energy than MGO since they utilize electrical energy directly without going through multiple conversion steps. The study assesses energy conversion using intermediate energy carriers like electricity and fossil fuels, which can be used directly (for instance, MGO or battery electricity) or further transformed into fuels for ships.

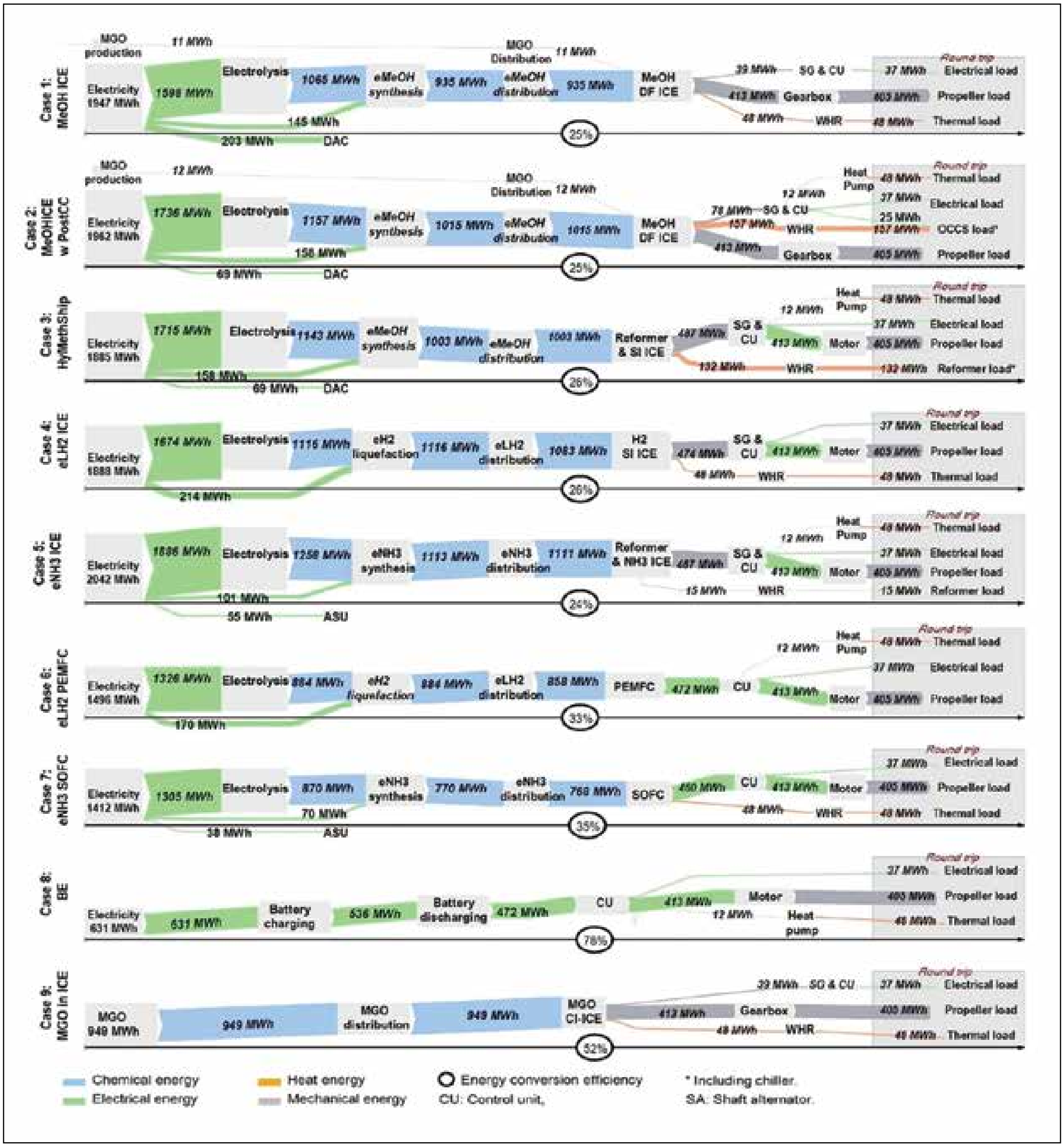

Figure 5.4 : Energy Conversion Efficiency for the Major Conversion Processes from Pathways Starting from the Base Energy Carrier [3].

Global Standards and Regulations for Fuel Cells

The IMO has issued interim guidelines regarding Fuel Cell onboard ships. Different classification societies/flag states continuously adding newer guidelines appropriate to their specific need. Guidelines specific to the use of alternative fuels including hydrogen and its derivatives are covered in the International Code of Safety for ships using gases or other low flashpoint fuels (IGF Code) and International Code for the Construction and Equipment of ships carrying liquified gases in bulk (IGC Code). The above two guidelines are recognized by IMO which came into effect in January 2017. This provides overall guidance from installation to monitoring and derisk the ship crew and environment from the related safety concerns **[4].** This decision to accommodate Fuel Cell under IGF Code with a separate section dealing with the other gas and low flammability is made over the existing codes for natural gas. Interim safety guidelines for other emerging fuels such as methyl and ethyl alcohol are added under IGF Code **[4].** The IGC Code is pivotal for the safe transport of liquified gases by sea ensuring protection of human life, environment and the vessels through strict measures for gas carriers and operations among other mention worthy guidelines, the International Convention for the Safety of Life at Sea (SOLAS-1974) defines the safety standards for ships in general although it does not specify anything to Fuel Cell , nevertheless all Fuel Cell systems and associated components needs compliance with SOLAS standards when mounted on ship. In line with the IGF Code American Bureau of Shipping (ABS) has published comprehensive guidelines for ships and offshore equipment. The specific feature of this code is testing and monitoring protocols to be adhered during construction phase the special feature of this code **[5].**

Among Asian countries Japan has developed Fuel Cell guidelines in 2018 specific to smaller ships which covers aspects like layout of Fuel Cell s and storage systems, leakage preventions, ships ventilation, fuel pipelines, safety monitoring and firefighting facilities. Among the rules and standards introduced by the International Electrochemical Commission (IEC) and international organization for standardization (ISO) in particular IEC 62281 & ISO 16110 have relevance to use of use of Fuel Cell s in marine use.

The following **Table 5.5** outlines important guidelines from leading classification societies concerning Fuel Cell systems and liquefied hydrogen carriers in maritime settings **[6,7,8,9,&10]** The American Bureau of Shipping (ABS) sets forth requirements for Fuel Cell power systems and liquefied hydrogen carriers to guarantee safety, reliability, and performance in marine and offshore environments. Bureau Veritas (BV) establishes standards for vessels utilizing Fuel Cell s, with a focus on safety and environmental compliance. Det Norske Veritas (DNV) offers comprehensive rules for Fuel Cell installations and specific instructions for handling hydrogen cargo in liquefied hydrogen carriers. The Korean Register (KR) emphasizes the safe design and integration of Fuel Cell systems on ships, while Nippon Kaiji Kyokai (NK) provides guidelines for the secure transportation of liquefied hydrogen. Lloyd's Register (LR**) [6]** has been issuing guidance notes on the installation of Fuel Cell s on ships since 2006, addressing both performance and prescriptive requirements for Fuel Cell s in the marine context. Türk Loydu (TL) **[7]** also plays a role by providing specific regulations for the deployment of Fuel Cell systems on ships, ensuring their safe and effective use. Together, these standards aim to improve safety, efficiency, and sustainability in the adoption of advanced maritime technologies.

Table 5.5: Standards and Regulations on Fuel Cells

S. No.	Standard No.	Standard Name	Remarks
1.	NFPA 2 - 2011 Edition	Hydrogen Technologies Code	Establishes safety standards for hydrogen technologies and their applications.
2.	IMO IGF Code	International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels	Mandatory safety code for ships using gases or low-flashpoint fuels to ensure safety and environmental protection.
3.	IMO IGC Code	International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk	Specifies design, construction, and equipment standards for ships transporting liquefied gases in bulk.
4.	IMO CCC5/3	Amendments to the IGF Code and Development of Guidelines for Low-Flashpoint Fuels	Provides updates and guidelines related to the use of low-flashpoint fuels under the IGF Code.
5.	Annex to MSC.1/ Circ.1455	Guidelines for the Approval of Alternatives and Equivalents as Provided for in Various IMO Instruments	Details of the approval process for alternative designs and equipment under IMO regulations.
6.	IEC/ISO 31010	Risk Management – Risk Assessment Techniques	Offers techniques for risk assessment to support decision-making and enhance safety.
7.	IEC 62282–1:2012	Terminology	Fuel cell-related terms.
8.	IEC 62282–2:2012	Fuel Cell Modules	Minimum requirements for safety and performance of Fuel Cell modules with or without enclosure.
9.	IEC 62282–3-100:2012	Stationary Fuel Cell Power Systems - Safety	Stationary Fuel Cell power system for ship auxiliary power.
10.	IEC 62282–3-200:2015	Stationary Fuel Cell Power Systems - Performance Test Methods	Operational and environmental aspects of stationary Fuel Cell power systems with electrical output exceeding 10 kW.
11.	IEC 62282–3-300:2012	Stationary Fuel Cell Power Systems - Installations	Minimum safety requirements for the installation of indoor and outdoor stationary Fuel Cell power systems per IEC 62282–3-100.

Table 5.5: Standards and Regulations on Fuel Cells

S. No.	Standard No.	Standard Name	Remarks
12.	IEC 60079-10	Explosive atmospheres - Part 10-1: Classification of areas - Explosive gas atmospheres	Explosive Atmospheres – Part 10-1: Classification of Areas – Explosive Gas Atmospheres: Focuses on classifying areas where flammable gases or vapors may occur.
13.	IEC 60079-14	Explosive atmospheres - Part 14: Electrical installation design, selection and installation of equipment, including initial inspection	Electrical Apparatus for Explosive Gas Atmospheres – Part 14: Electrical Installations in Hazardous Areas (Other than Mines): Details requirements for safe electric installations.
14.	IEC 60092-504	Electrical installations in ships - Part 504: Automation, control and instrumentation	Electrical Installations in Ships, Automation, Control, and Instrumentation: Specifies requirements for automation, control, monitoring, and safety protection systems in ships.
15.	ISO 16110–1:2007	Hydrogen Generators using Fuel Processing Technologies - Safety	Covers significant hazardous situations and events associated with hydrogen generators, except environmental compatibility.
16.	ISO/DIS 14687–3	Hydrogen Fuel – Product Specification — Part 3: PEMFC Applications	——
18.	ISO 15649	Petroleum and Natural Gas Industries — Piping	Specifies standards for piping systems in petroleum and natural gas industries, including hydrogen piping.
19.	ISO 15649:2001	Petroleum and Natural Gas Industries — Piping	Hydrogen piping network standards.
20.	ISO 17268:2012	Gaseous Hydrogen Land Vehicle Refueling Connection Devices	——
21.	ISO/TR 15916	Basic Considerations for the Safety of Hydrogen Systems	——
22.	ISO 26142:2010	Hydrogen Detection Apparatus - Stationary Applications	Detection of leaks related to hydrogen systems.

Table 5.5: Standards and Regulations on Fuel Cells

S. No.	Standard No.	Standard Name	Remarks
23.	ISO/TS 19880–1:2016	Gaseous Hydrogen – Fueling Stations – Part 1: General Requirements	——
24.	ISO/TS 18683	Guidelines for Systems and Installations for Supply of LNG as Fuel to Ships	Guidance on design and operation of LNG refueling facilities, including LNG refueling of ships.
25.	DNV-GL Rules Part 6, Chapter 2, Section 3	Study on the use of Fuel Cell s in shipping	Fuel Cell Installations: Covers safety and operational requirements for Fuel Cell power installations, including fuel supply, reformers, and exhaust systems.
26.	ASME B31.12	Hydrogen Piping and Pipelines	Provides requirements for the design, construction, and maintenance of hydrogen piping and pipelines.

The main regulatory gaps arise from the lack of internationally accepted standards. The Maritime sector in general follows in the footsteps of the automotive sector in terms of technology. Therefore, wherever applicable the Fuel Cell standards in automotive sectors can be considered. The existing regulations for hydrogen and Fuel Cell s in the maritime sector still lack sufficient safety, quality, performance and minimum retirement standards. The standards defined under IGF Code **[3]** primarily focus on liquefied natural gas and although hydrogen is considered a reference point for Fuel Cell s, its inherent nature necessitates different selection standards. However, due to the absence of a correlation between hydrogen and natural gas among marine diesel engines and Fuel Cell s, entirely different and innovative approaches are required. The current regulations are unable to establish a reference standard for Fuel Cell s and remain at the IMO Guideline level **[3].** In this context possible regulations can be categorized under 3 subtitles namely: Safety, design and operational and they should provide enough knowledge about these topics. These contents can be summarized as shown in **Table 5.6**

Table 5.6: Possible Different Levels of the Considered Fuel Cell Regulations for Ships (ref [8])

Safety	Design	Operational
System Installation	Material and Installation	Periodical Inspections
Room Ventilation	Fuel Cell Unit	System Maintenance
Protective Equipment	Onboard Hydrogen Storage	Fault Diagnostics
Fire and Explosion Protection	Fuel Supply and Bunkering	System Testing
Fire Detection	Fuel Transfer	Commissioning Procedure
Surveillance	Port Facilities	Fuel Bunkering Procedure
Electrical Safety		Energy Management System

Conclusions

- » Critical factors for larger deployment of Fuel cells in shipping are power density, size, reliability, cost, fuel flexibility and durability
- » Present power capacity from kW to few MW scale limits Fuel Cell s the application to inland water and sort sea/coastal shipping
- » Hybrid power systems combining Diesel engines, batteries, and Fuel Cell s significantly help to reduce emissions (CO_2, NO_x, SO_x), improve fuel efficiency, and enhance vessel maneuverability.
- » Batteries and Fuel Cell s complement each other, with Fuel Cell s addressing battery range limitations and batteries enabling immediate power for short-distance operations.
- » Fuel Cell (FC) systems with ICE/GT in hybrid propulsion appear as most practical solutions for deep sea applications/OGVs
- » Energy management optimization is key factor for FC/Battery hybrid while power distribution optimization is most crucial for FC &ICE /GT hybrid systems
- » Towards commercialization of Fuel Cell system in shipping –size standardization is most critical
- » Size standardization is the focus of the ongoing projects like STASHH (Standard Sized FC Module for Heavy Duty Applications) which is primarily aimed at developing open size standard for FC modules extendable for integration with ship.
- » 8 FC suppliers codeveloping standard sizes for FC under STASHH project. This is expected to develop sizes and drive the cost down significantly to make it highly competitive for engines and batteries
- » Capex reduction possible through market demand and economy of scale, selection FC using less expensive materials, integration of fuel reforming technology in order to use syngas, hydrocarbon or alcohols as feedstock instead of direct use of green Hydrogen.
- » As far as durability is concerned, the degradation of electrolytes, electrode, and bipolar plates are significant impact on Fuel Cell stack lifetime in terms of catalyst performance decline, loss of electrolyte conductivity cracking and corrosion. The prevention of sea water mist entry to cathode air is important to maintain Fuel Cell efficiency.
- » Fuel price is linked to supply of green hydrogen, infrastructure, especially the storage for hydrogen and bunkering for hydrogen derivatives in ports and terminals are absolute necessity
- » Fuel cell reliability is largely impacted by the cycling effect and load variation especially for SOFC and MCFC (high temperature FC). Battery integration is the most practical solution to dampen Fuel Cell load variation for ship power.
- » Available system in the market w.r.to gravimetric and volumetric density underscores PEMFC as most preferred option for shipping in smaller vessel (< 500 GT) and power range
- » Analysis of Global Research Projects on FC System onboard ships spanning over 22 years shows the following **[11].**

Fuel Cell in Marine Snapshot:

- **PEMFCs** lead with **76%** (28 projects), mostly using Hydrogen; 3 use Diesel/Methanol reforming.
- **SOFCs** make up **13%** (5 projects), using LNG, Diesel, Methanol, and Ammonia.
- **MCFCs** account for **11%** (4 projects).

Recommendations for India

- Instead of targeting C-free operation, use of renewable/e-/green fuels with high efficiency over whole life cycle should be the focus for ship operation using Fuel Cell s
- Towards zero emission, Fuel Cell should be considered a promising option for Inland water and shortsea/coastal shipping
- For very small vessel <100eKW (Inland water) DMFC could be worth investing for India. However, as DMFC relies on Methanol which produces CO2 as a byproduct, this technology will be considered carbon neutral/green only when Methanol is sourced from greener means. Thus, while complete adoption of DMFC could be a medium to long term option, the LT-PEMFC could make the technology adoption immediate and completely green in short to medium term. India should also develop small to mid-sized (100-500ekW) LTMFC Fuel Cell ships (PSV, Ferries, RO-RO & Cargo) till storage and safety challenges of compressed or liquified hydrogen (LH2) as fuel persist. In long term once LH2 overcome the become viable technological and safety challenges, larger ships can be integrated too.
- India should develop small to mid-sized (100-500ekW) LTMFC Fuel Cell ships (PSV, Ferries, RO-RO & Cargo) due to persisting storage and safety challenges of compressed or liquified hydrogen as fuel
- In order to avoid the challenge of hydrogen storage at high pressure or cryogenic temperature on board, PEMFC reforming technology using Biodiesel and/Methanol could be worth investing to especially >500 eKW
- Global trend shows very limited research on Fuel Cell adoption in Tugs and Dredgers and also not recommended for India
- For cruise, and long-haul vessels, pilot projects needs to be initiated with SOFC –Battery hybrid (immediate) and SOFC/ICE hybrid with alternative fuel options like Methanol and Ammonia (medium to long term) especially for auxiliary power units (AMUs).
- SOFC technology should leverage its high fuel flexibility especially Ammonia & Methanol
- Establishing bunkering for alternate fuels especially renewable /E/green Methanol and Ammonia is of absolute necessity to accelerate Fuel Cell adoption in shipping

- The drawbacks of low power density, short lifetime and high capital costs are surmountable by sustained innovation, high efficiency of integrated SOFC-CHP system &and drastic GHG emission reduction which could be made favorable with emission tax
- Research should be encouraged in terms of hydrogen storage solutions, high performance membranes, reducing operating temperature of SOFC in order to use cheaper materials, easier assembling methods and use of off the shelf components

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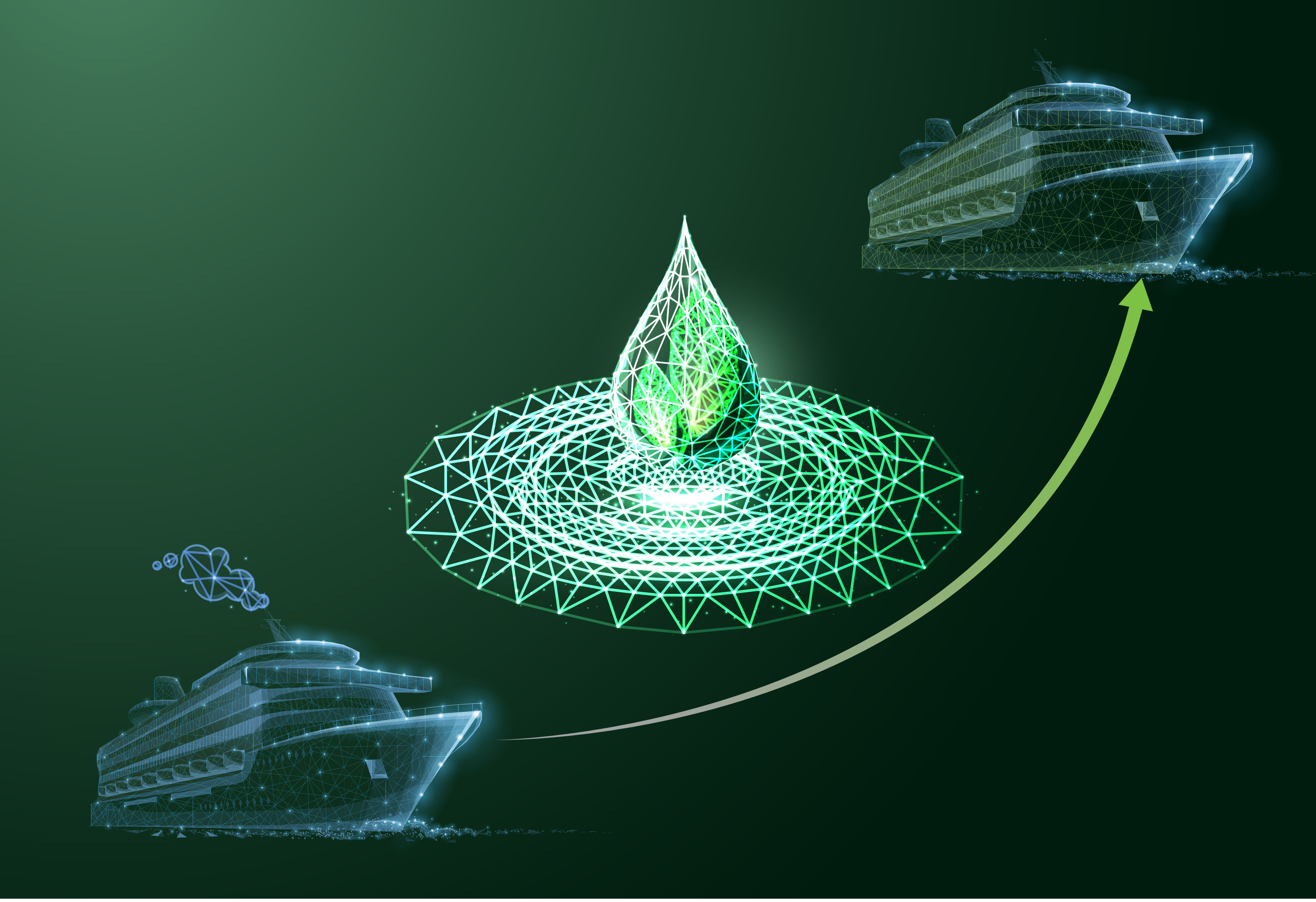

Chapter 6

Shipping Fuels and Possibility of On-Board Carbon Capture

Globally Marine sector is moving towards LNG (near and medium term though fossil-based but later can be shifted to CBG), Methanol (immediate), and Hydrogen & Ammonia (long term) as dual fuel & retrofitting options for marine engines. From medium term perspective in the timeline between2027 to 2035 **[1]**, among the various bio/green fuel options, bio/e-methanol, bio-DME, bio/e-LNG, and pyrolysis bio-oil appears well suited for the marine sector owing to their potential for scale-up, global advanced production status, and low costs. These options are close to each other in their overall fitness.

Nevertheless, on board Carbon Capture Storage and Utilisation (OCCUS) as priority for deep decarbonization option in synergy with broader green energy sector will accrue long term benefit. Each of these fuels have intrinsic strengths and limitations that could favour that fuel under specific circumstances. In a recent study as shown in Table 6.1, a critical assessment is also made on the possibility of integrating deployment of these low carbon bio/green fuels in combination with CCS for ambitious emission reduction in marine sector [2]. This awareness though presently is lacking among industrial stakeholders but likely to be enhanced in future.

Table 6.1: Scores for the fuels [2]

	Weight	Bio-Methanol			Bio-DME			Bio-LNG			Bio-oil		
		A	B	C	A	B	C	A	B	C	A	B	C
Present technology status	0.08	3.5	3.8	1.8	3	3.2	1.5	4	3.7	1.8	3.5	3.3	1.6
Potential availability (EJ/y)	0.2	3	3.3	4.0	3	2.9	3.5	3	3.3	4.0	3.5	3.4	4.1
GHG mitigation potential (%)	0.2	4	3.9	4.7	4	3.7	4.4	3	3.4	4.1	3.5	3.7	4.4
Cost (€/GJ)	0.31	3.5	3.5	6.5	3.5	3	5.6	2	2.7	5.0	3	3.3	6.1
Infrastructure compatibility	0.16	3	3.4	3.3	3.5	3.6	3.5	3.5	3.3	3.2	3	3.7	3.6
CCS compatibility	0.05	3	3.2	1.0	3	2.9	0.9	4	2.7	0.8	2	2.7	0.8
Sum		20.0		21.2	20.0		19.4	19.5		18.8	18.5		20.6

** A: Score allotted to fuel for criterion based on literature study; B: Score allotted to fuel criterion by stakeholders; C: Weighted score of fuel for criterion (C=Weight*B*6, as 6 criteria used; rounded to one decimal place)*

In a comparison between Hydrothermal Liquefaction (HTL) derived bio crude (Technology mostly deployed for wet feedstock like algal biomass, organic food wastes etc.) and pyrolysis oil derived biocrude (dry biomass including forestry, wood and agro-residues), it is argued that though the former is favourably considered as drop-in fuel for heavy marine engines owing to its lower moisture content, higher calorific value and higher H: C ratio, the later, being a near-commercial technology, with a higher TRL level deserves closer attention as well. Nevertheless, the simplicity, maturity, applicability for dry wastes and low cost of pyrolysis bio-oil production could be balanced against the present cost of its downstream upgrading. Another critical study is conducted on OCC as part of the Green Fuels Optionality Project (GFOP) at the Mærsk McKinney Møller Centre for Zero Carbon Shipping (MMMCZCS). To gain a better understanding of the role of OCC in maritime decarbonization and assess OCC's business case for different vessel types and sizes, the applicability of OCC to the largest shipping segments (container, bulk, and tanker), main carbon-based fuels and full and partial application as part of a retrofit or newbuild is analysed. Based on the case studies completed, it is inferred that among OCC technologies the one with chemical absorption is technically feasible and expected to reach commercial availability by 2030. Potential application of OCC shows the most promise for newbuilds as retrofits are costly and can require major modifications. A detailed techno-economical study [3] reveals that retrofitted CO2 capture plant on-board scenario is technically feasible and economically competitive. This study also reveals that the transport of liquid CO2 is a major safety concern due to its instability at the triple phase point. However, at ambient pressure, gaseous CO2 requires large space available on-board, which would make this option infeasible even for a week trip.

As it is unrealistic to achieve a complete replacement of fossil fuels in the maritime sector due to lack of both fuel supply chain and alternate engines there is a need to increasingly implement CO2 capture on-board and switch over to bio/ synthetic e-Fuels from HFO with the advancement of alternate fuel engines. This could even lead to achieving negative emissions in the next generation of container fleets. However, there is an urgent need of larger number of Pilot demonstration of CCUS projects through valorization of adsorbed CO2 especially for the countries like India with lack of geological CO2 storage sites along with innovation in sustainable CO2 adsorption material production.

6.1 Onboard Carbon Capture Technologies

The IMO has initiated discussions towards creating a regulatory framework for Onboard Carbon Capture and Storage (OCCS), with the Marine Environment Protection Committee (MEPC) planning to review progress this year in 2025. Meanwhile, the European Union (EU) has woven shipping emissions into its climate policy, which includes the EU Emissions Trading System (EU ETS) and the FuelEU Maritime Regulation, though OCCS isn't yet included in these regulations. The Intergovernmental Panel on Climate Change (IPCC), in its special report on carbon capture and storage (CCS), identifies three primary methods for capturing CO_2 emissions from fossil fuel sources, as illustrated in **Figure 6.1.** Regarding OCC technology, CO2 can be separated or captured both pre- and post-combustion.

6.1.1 CCS Technology Pathways

A detailed techno-economical study [3] reveals that retrofitted CO2 capture plant on-board scenario is technically feasible and economically competitive. This study also reveals that the transport of liquid CO2 is a major safety concern due to its instability at the triple phase point as shown in Figure 6. However, at ambient pressure, gaseous CO2 requires large space available on-board, which would make this option infeasible even for a week trip.

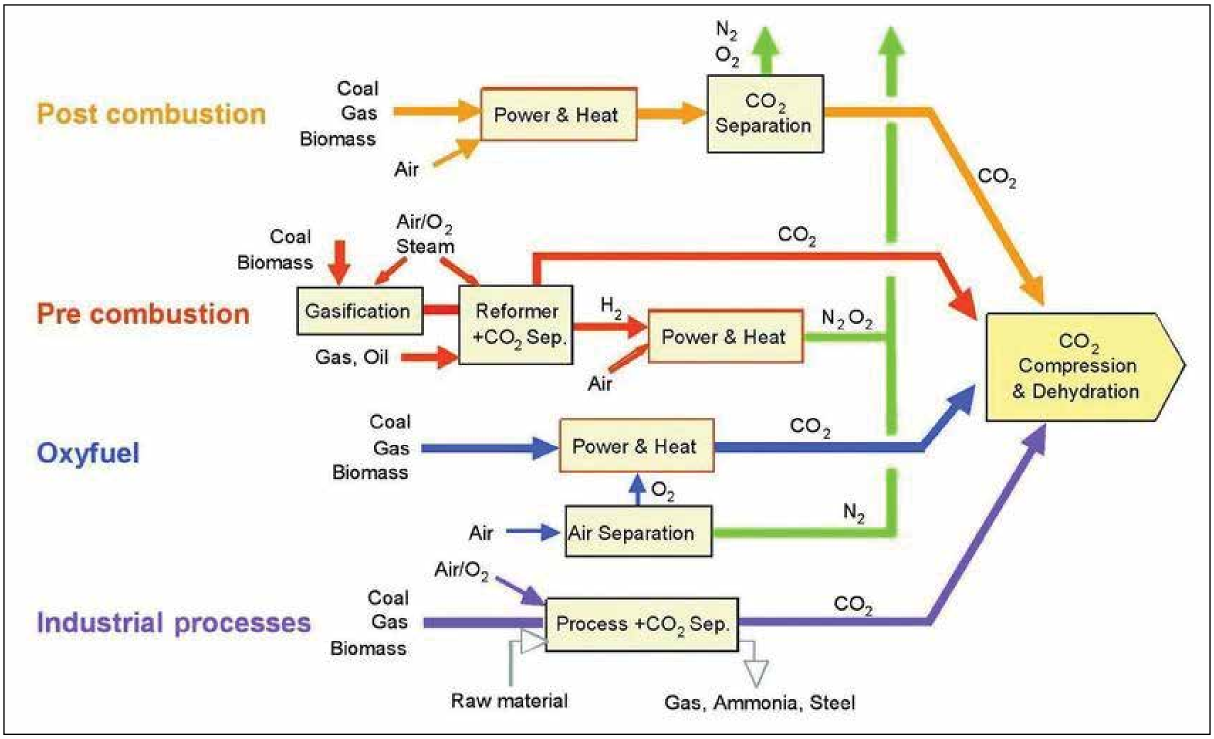

Figure 6.1: Different Pathways of OCCS (Inspired by [4])

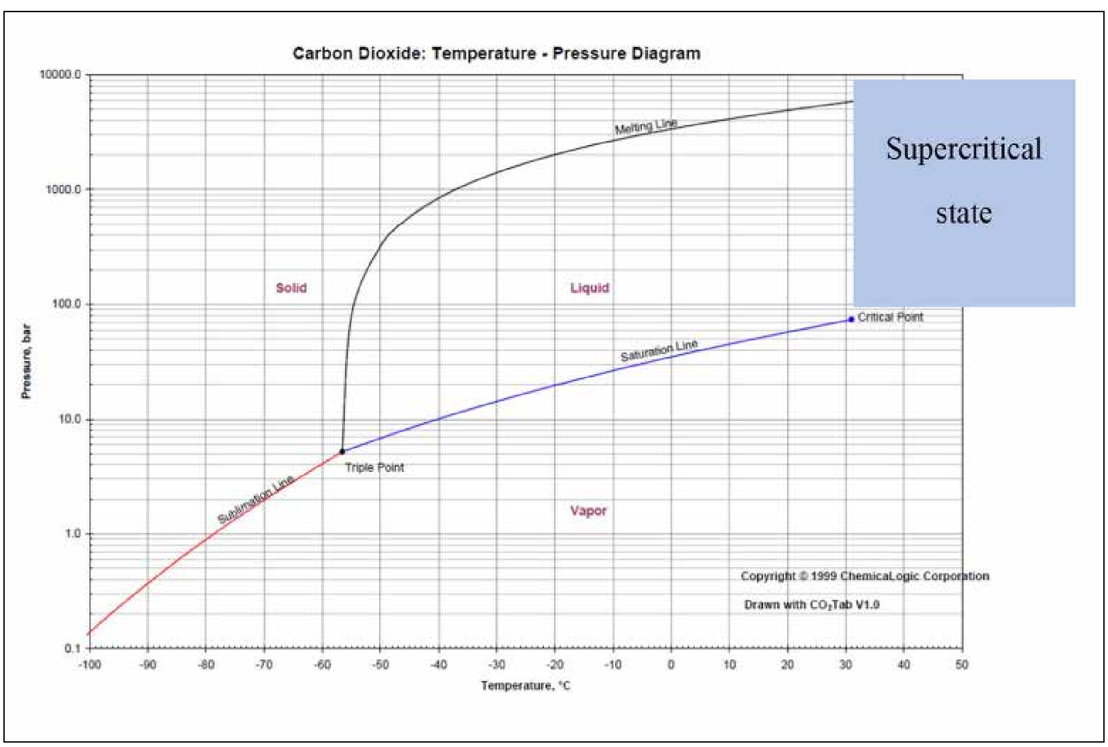

Figure 6.2: Phase Diagram of CO_2 [5]

6.1.2 Viable Options for Onboard CO_2 Storage

The viable options for storing CO2 onboard include a gaseous state, supercritical state, solid state, or liquid state. Large number of studies **[6]** have shown the gas phase storage of CO2 impractical owing to the significant volume it would occupy, despite its pressurization and cooling requirement been much lower in comparison to other phases. In addition, gaseous CO2 has lowest density among other forms. **In gaseous state CO2 has a density of 172 kg/m3 at 30 °C and 60 bar <density of supercritical CO2 757 kg/m3 at 35 °C and 125 bar < the density of liquid CO2 1011 kg/m3 at–15 °C and 30 bar < and the density of solid CO2 1562 kg/ m3 at–80 °C and 1 bar [7]**. It is therefore not used for the transport of large quantities of CO2 in gaseous form.

The supercritical phase is attained by compressing CO2 above 73 bar (critical pressure) and beyond 31.1 °C (critical temperature), as illustrated in Figure 6.2. Supercritical fluid phase is the favoured state for pipeline transportation due to its higher density compared to compressed gas where the typical operating pressure is >96 bars and it is cost-effective. Pressures < 96 bars are preferably avoided due to the possibility of two-phase flows as shown in Figure 6.2.

There are two methods in which CO_2 can be solidified. In one method, it is cooled to −78 °C at atmospheric pressure, requiring an enthalpy of sublimation of 573 kJ/kg. This means, beyond cooling, an additional 573 kJ/kg must be extracted for CO2 solidification, demanding significant amount of energy. Another method of CO_2 solidification involves chemically binding it to another substance. Although solid stage is promising shipboard storage **[8]**, it remains in the lab stage and has not yet been mature enough for widespread commercial application. Additionally, this also requires onboard materials for binding process, therefore increasing ship weight. Both refrigeration and chemical sequestration demand a robust system to manage solid CO_2 effectively on ships. For refrigerated CO_2, a closed system is crucial to prevent sublimation, which could pose asphyxiation risks due to the air escaping out from the engine room, making implementation a complex maritime challenge.

Storing CO2 in liquid form is advantageous because it is easy to handle with pumps. In addition, the volume required to store CO2 is significantly lower due to the density of the liquid form. There are several strategies for this, each differing in the temperature and pressure at which storage takes place. The triple point of CO2, which is 5.18 bar and–56.6 °C, indicates that CO2 only exists as a gas or solid at atmospheric pressure. To keep it in liquid form, a pressure of at least 5.18 bar is required. However, storing CO2 near its triple point carries the risk of solid CO2 formation, which could clog pipelines and be difficult to remove from storage tanks. It is therefore recommended to store CO2 well above its triple point. Another critical study reviews optimal temperature and pressure for onboard liquid CO_2 storage by analyzing ship-based CCS chains at pressures from 5.18 to 73.8 bar, assessing life cycle cost (LCC) across five modules (liquefaction system, storage tanks, CO2 carrier, intermediate storage tanks and pumping system **[5].** Results show 15 bar as optimal, balancing liquefaction, storage, and transport costs.

To effectively manage captured carbon on ships, as on today, liquefaction stands out as the best storage option. The liquefied CO_2 must be kept under cryogenic conditions in pressurized and insulated tanks to stop it from turning back into gas. These tanks are usually built following the guidelines set by the International Code for the Construction and Equipment of Ships Carrying

Liquefied Gases in Bulk (IGC Code) **[9].** In particular, Type C liquefied gas tanks are the go-to choose for storing pressurized CO_2, due to their proven safety, durability, and ability to handle liquefied gases even in tough maritime environments **[10].**

Captured CO_2 needs to be periodically offloaded at ports, either at the end of a journey or transferred to vessels designed for carrying CO_2. After that, it gets transported to reception facilities using ships, pipelines, trucks, or trains for either storage or utilization. As on 2024, there are 35 carbon storage projects in operation with a capacity of 37 Mtpa. Looking ahead, projections suggest that by 2050, there could be up to 8,400 $MTCO_2$ stored annually, which would be a significant boost for CO_2 management in shipping **[9].**

6.2 OCCS Demonstration Projects

Onboard Carbon Capture and Storage (OCCS) demonstration projects play a vital role in assessing how practical, effective, and economically feasible OCCS technologies really are. These initiatives put various systems and components to the test, including CO_2 capture, onboard liquefaction, storage, and offloading, all in real maritime environments. By tackling important operational hurdles and ensuring they meet regulatory standards, these projects are designed to promote the adoption of OCCS and help achieve maritime decarbonization goals. Table 6.2 provides a list of significant OCCS demonstration projects, highlighting their objectives, the country, stakeholders involved, and their status.

Table 6.2: Some significant OCCS demonstration projects, detailing their objectives, the country, stakeholders involved, and their current status

S. No	Project	Objective	Vessel Type	Technology Used/ Technology Provider	CO_2 Capture Target/Scale of Capture	Key Features and Progress	Country	Ref.
1	CC-Ocean Project (2020)	Validate onboard CO_2 capture systems	88,000-tonne bulk carrier	Post-combustion chemical absorption / Mitsubishi Heavy Industries (MHI)	Achieved CO_2 purity > 99.9% / 200 CO2-ton/day	6 months of operation met targets for CO_2 quantity, ratio, and purity. Supported by Japan's Ministry of Land, Infrastructure, Transport, and Tourism.	Japan	[11,12]
2	EverLoNG Project	Advance Ship-Based Carbon Capture (SBCC) technology	LNG-powered carrier	CO_2 capture prototype /-	Capture 10 tonnes CO_2 over 3000 hours / 250 kg of CO2 per day	Aiming for 70% reduction in CO_2 emissions. Further testing planned on other vessels.	16 partners from 5 countries: Germany, Netherlands, Norway, the UK, and the USA	[13,14]
3	Decarbon ICE Project (2019)	Develop cryogenic CCS system (CO_2 stored as dry ice)	Not specified	Cryogenic CO_2 capture and dry ice storage / DecarbonICE	Not specified	Targeting carbon-negative shipping by storing CO_2 in seafloor sediments.	Copenhagen N	[15]

Table 6.2: Some significant OCCS demonstration projects, detailing their objectives, the country, stakeholders involved, and their current status

S. No	Project	Objective	Vessel Type	Technology Used/ Technology Provider	CO_2 Capture Target/Scale of Capture	Key Features and Progress	Country	Ref.
4	Green Marine Project	Retrofit ships with emission control technologies	Passenger ferry (MV Coruisk)	Emission control retrofits, including CCS	Ca/Mg–alkali solvent capture process is capable of removing 75% of CO2 from flue gases	Develop protocols for retrofitting engines and integrating CCS systems. Supported by Horizon Europe.	European Union	[16]
5	Bulk Carrier Carbon Capture Project	Develop CCS for bulk carriers	Bulk carriers (Tianjin Venture, CSSC Wan Mei)	Organic amine solution for CO_2 absorption	Over 85% CO_2 capture rate	Approved by Bureau Veritas (BV). CO_2 capture system uses chemical absorption.	-	[17]
6	REMARCCABLE Project	Evaluate CCS performance during sea trials	Medium-range tanker (Stena Bulk)	CO_2 capture via chemical absorption	Continuous CO_2 capture during deep-sea voyages	Approved by American Bureau of Shipping (ABS). Planned two-year sea trials with potential for long-term CCS integration.	23 Study Partners and 2 Observers. This includes Shell, Woodside Energy, Alfa Laval, Panasia, Maritime and Port Authority of Singapore, Port of Rotterdam Authority	[18,19]

Table 6.2: Some significant OCCS demonstration projects, detailing their objectives, the country, stakeholders involved, and their current status

S. No	Project	Objective	Vessel Type	Technology Used/ Technology Provider	CO_2 Capture Target/Scale of Capture	Key Features and Progress	Country	Ref.
7	HyMethShip	Develop OCCS with simultaneous elimination of CO_2, SOx, and PM emissions	Not specified	Pre-combustion capture	Closed CO_2 cycle	EU-funded under Horizon 2020; explores pre-combustion capture and closed fuel cycle		[20]
8	Deltamarin	Analyze OCCS system feasibility for RoPax ferries	RoPax ferries	Pre-combustion capture	Closed methane cycle	Found OCCS more suitable for LNG than HFO; integrates CO_2 capture with methane fuel production	Finland	[21]
9	Value Maritime (2022)	Store CO_2 in a rechargeable onboard "battery"	13,000-GT container ship Nordica	Exhaust gas CO_2 capture	Not specified	World's first OCCS installed on operating vessel; approved by ABS in 2023	Dutch	[22]
10	CO2ASTS (2020)	Analyze OCCS effects on LNG-powered ships	LNG-fueled ships	MEA solvent-based capture	75%, 54%, and 69% capture rates	Demonstrated cost efficiency by integrating heat from exhaust gas and cold from LNG vaporization	Germany, the Netherlands and the EU	[23]

Table 6.2: Some significant OCCS demonstration projects, detailing their objectives, the country, stakeholders involved, and their current status

S. No	Project	Objective	Vessel Type	Technology Used/ Technology Provider	CO_2 Capture Target/Scale of Capture	Key Features and Progress	Country	Ref.
11	Daewoo Shipbuilding (2022)	Verify OCCS performance on large LNG vessel	LNG vessel	Not specified	Low-energy consumption system	Achieved relatively low CO_2 emissions from equipment operation	South Korean (Daewoo Shipbuilding , Marine Engineering (DSME) and GasLog)	[24]
12	SMDERI (2022)	Real-vessel OCCS application tests	Bulk carriers	Post-combustion capture	86.3% capture rate	Issued AIP certificate by China Classification Society; conducted real-vessel tests with Bureau Veritas	China Classification Society	[25]
13	Headway Technology (2022)	Develop OCCS system and obtain certification	Ferries	Not specified	Not specified	Obtained AIP certificates from DNV and RINA; scheduled for ferry-based testing	China	[26]

6.3 OCCS Readiness Level

The readiness assessment for carbon capture technologies evaluates their technology Readiness Level (TRL), Investment Readiness Level (IRL), and Commercial Readiness Level (CRL). These metrics help gauge the feasibility, economic viability, safety, and scalability of carbon capture solutions across maritime and industrial applications.

Value Maritime's post-combustion CO_2 capture system, currently deployed on vessels like the M/T Pacific Cobalt (targeting 40% emissions capture), has reached TRL 6, indicating early operational success. However, its IRL remains at 2 due to economic concerns, high costs, and cargo space impact. The CRL is at 3, reflecting unresolved safety, regulatory, and carbon accounting issues **[27]**. MARPOL lacks clear guidelines for onboard CO_2 handling, and real-world validation is limited. Port infrastructure for CO_2 transport is emerging, with early developments in Antwerp, Gdansk, Gothenburg, Dunkirk, and Germany. **Value Maritime is currently testing its innovative "CO2 battery" in a containerized format, while global CO_2 pipelines, such as the Mid-west Carbon Express, are on the rise.** The technology readiness level (TRL) is at 5 as prototypes for offloading continue to develop **[27]. However, both the IRL and CRL are sitting at a level 2, mainly because there are still limited commercial trials, early-stage port pilots, and ongoing safety and regulatory issues related to large-scale CO_2 management and pipeline risks**. Permanent CO_2 storage needs to be reliable over geological timescales, but there are still some regulatory and logistical challenges to tackle. Recent changes to the London Protocol now permit the movement of CO_2 for offshore storage, but these changes aren't fully implemented yet, which restricts transboundary CO_2 transport to just bilateral agreements, like the one between Denmark and Flanders. While storage technology has reached a TRL of 8, the current capacity of 10 million tons of CO_2 per year falls significantly short of the global shipping industry's requirements, which are around 1,050 million tons **[28]**.

While global expansion efforts are underway—including the North Sea storage licensing round—the real-world Investment Readiness Level (IRL) remains at 3, constrained by limited storage capacity and low shipping sector engagement. The Commercial Readiness Level (CRL) is at 2, due to unresolved issues around long-term liability. Additionally, the CO_2 commodity market remains small, costly, and focused on niche sectors such as food, agriculture, and construction. Scaling up will require regulatory updates and greater public and stakeholder awareness.

6.4 Advantages and Disadvantages of OCCS Technologies

Implementing carbon capture technologies onboard ships presents opportunities and challenges that influence their feasibility, efficiency, and overall impact on maritime operations. The advantages and disadvantages vary significantly based on the type of carbon capture technology utilized—pre-combustion capture, oxy-fuel combustion capture, or post-combustion capture are presented in **Figure 6.4- 6.6**.

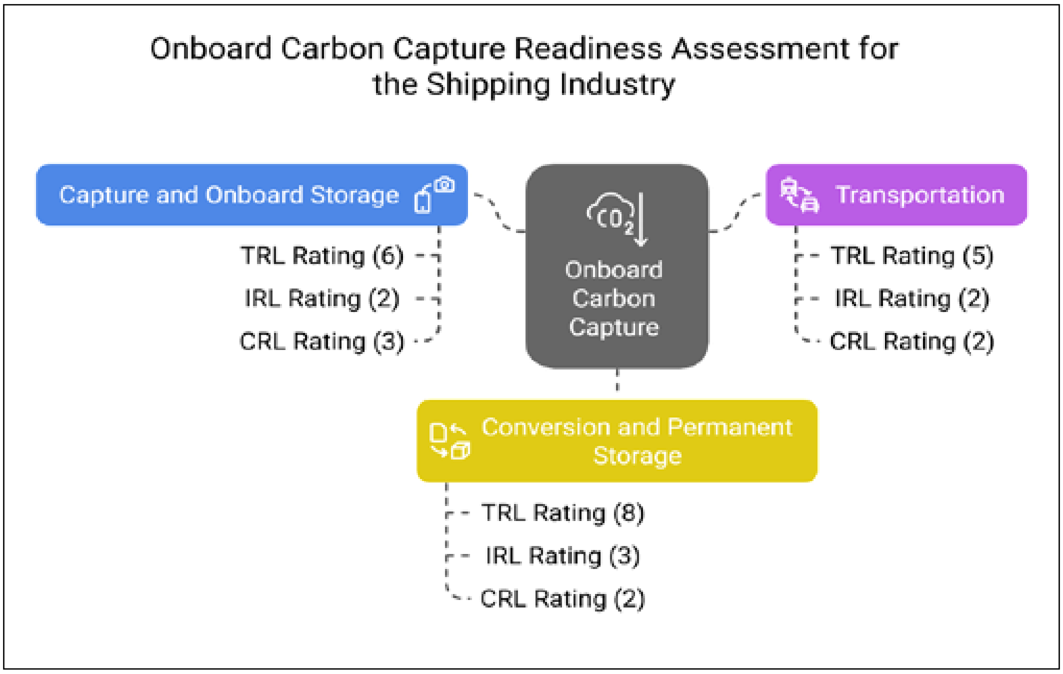

Figure 6.3: Readiness Levels of Onboard Carbon Capture

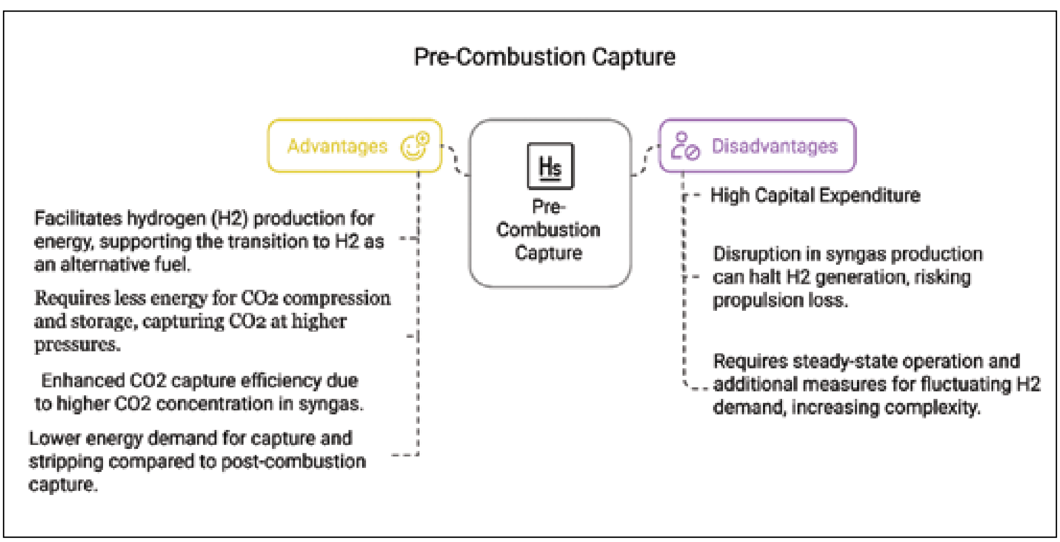

Figure 6.4: Advantages and Disadvantages of Pre Combustion Capture

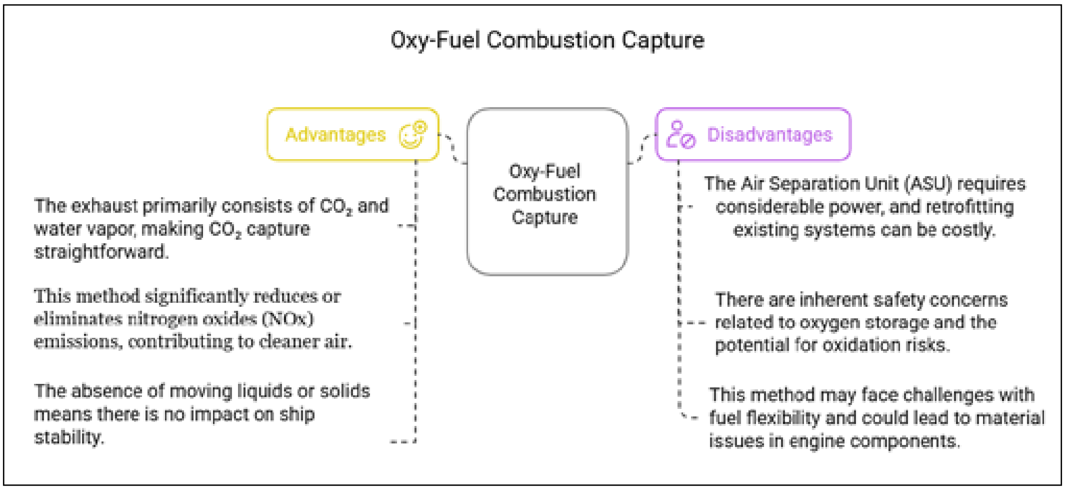

Figure 6.5: Advantages and Disadvantages of Oxy Fuel Combustion Capture

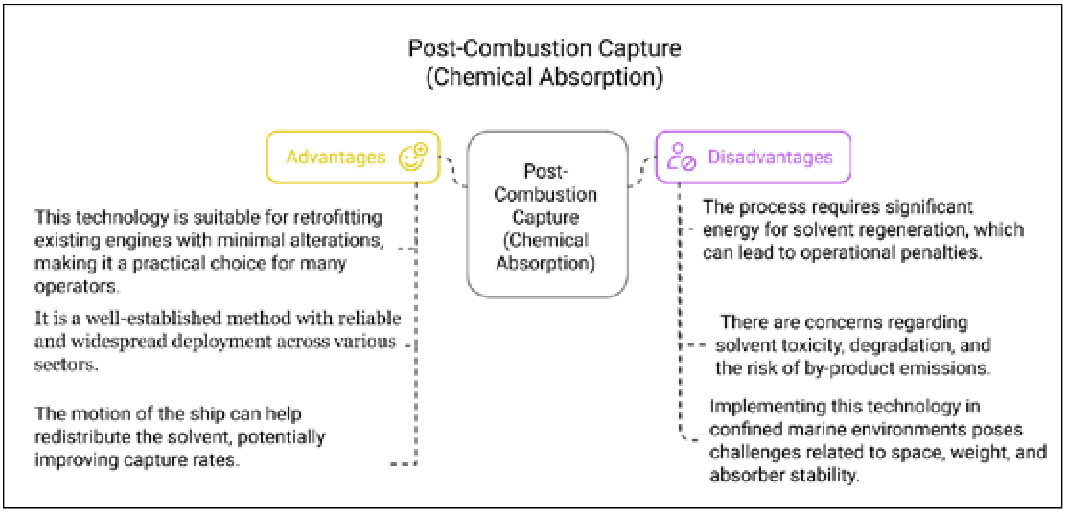

Figure 6.6: Advantages and Disadvantages of Post Combustion Capture Chemical Absorption

6.5 Key Parameters for OCCS

The following diagram **Figure 6.7** provides a clear overview of the essential factors to consider when setting up onboard carbon capture systems (OCCS) for ships. It points out crucial elements like how these systems affect engine performance, the power needed for auxiliary systems, and overall energy efficiency. The diagram stresses the importance of thoughtful design to tackle challenges such as CO_2 treatment and storage, ensuring fuel system compatibility, and addressing safety issues like the risk of asphyxiation. Moreover, it points the need to optimize space, weight, and storage capacities to make sure operations are feasible and meet emissions regulations.

Two highest, one high and one moderate potential, making it the most deserving candidate for the next stage of the analysis. This is closely followed by membrane technology with one highest, one high, one moderate and one lowest potential. Although it has the lowest potential in removing exhaust pollution, the implementation of successive pre-treatments could mitigate this challenge, albeit with an additional energy input. The third candidate to move up to the next stage of the comparison is chemical absorption, which has one high and three moderate potentials to overcome the challenges mentioned.

A recent paper **[29]** provides an in-depth review of CC technologies and analyses their process flows, advantages, disadvantages, and recent advances through a literature review. A particular focus is placed on assessing the suitability of these technologies for use on-board ships, considering the particular challenges posed by the shipboard environment. A comprehensive comparative assessment is conducted, analysing each technology based on factors such as economic feasibility, capture rates, maturity, energy requirements, space requirements and other relevant considerations.

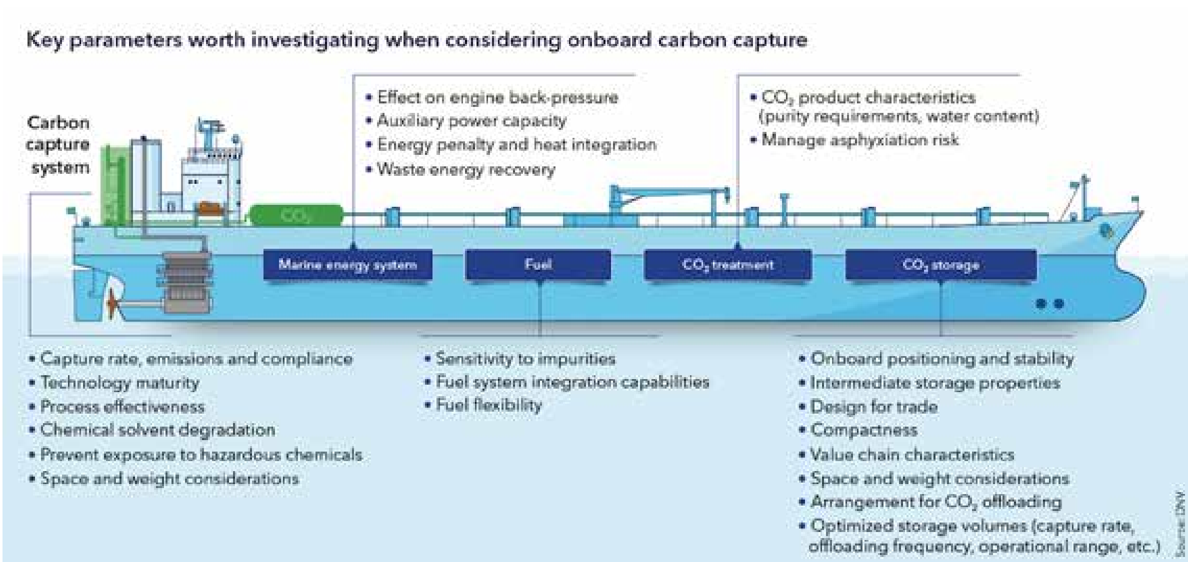

Figure 6.7: Key Parameters Worth Investigating when Considering Onboard Carbon Capture Source (DNV 2024)

Conclusions

Present Technological status of Onboard Carbon Capture and Storage (OCCS) are poised to cut CO_2 emissions from ships by as much as 20% each year, while keeping the fuel consumption penalty below 10%. Projects like EverLoNG and various pilot studies have established the feasibility of OCCS, although rolling it out on larger scale comes with its intrinsic set of economic, technical, and regulatory hurdles. For instance, retrofitting a vessel like the Stena Imperio is expected to cost around $13.6 million, with an abatement cost of $769 for every ton of CO_2 captured [**19**]. Ongoing research and development are focused on driving these costs down and boosting efficiency, which would make OCCS a more attractive option for decarbonization. Among all carbon capture technologies, chemical absorption stands out as the most developed and commercially viable choice today, owing to its impressive capture efficiency and the wealth of research backing it. Nevertheless, alternatives like membrane separation and cryogenic capture are being considered for ships that have limited space and energy resources. The feasible method for storing captured CO_2 onboard is liquid storage at 15 bar and −27°C, which helps optimize handling and lifecycle costs. While storing CO_2 in gaseous form lacks practical viability due to space limitations, solid-state storage too in early development stage although hold future potential. The global capacity for CCS is expected to grow from the current 37 million tonnes per year (Mtpa) to between 4,000 and 8,400 Mtpa by 2050, with a substantial portion of that potentially dedicated to maritime uses. Most importantly, for larger adoption, OCCS needs carbon pricing strategies, government incentives, and the development of CCS clusters to support CO_2 storage and utilization. While OCCS boasts a high technology readiness level (TRL) for capturing and storing carbon, its Investment readiness level (IRL) and Commercial readiness level (CRL) are still lagging, indicating a need for clearer regulations and operational and pilot level experience.

As it is unrealistic to achieve a complete replacement of fossil fuels in the maritime sector due to lack of both fuel supply chain and alternate engines, there is a need to increasingly implement CO2 capture on-board and switch over to Bio/ synthetic E-fuels from HFO with the advancement of alternate fuel engines. This could even lead to achieving negative emissions in the next generation of container fleets. However, there is an urgent need of larger number of Pilot demonstration of CCUS projects through valorization of adsorbed CO2 especially for the countries like India with lack of geological CO2 storage sites along with innovation in sustainable CO2 adsorption material production.

Recommendation for India

1. Sustainable production of amine-based compound (similar to mono Ethanol Amine) from specific renewable feedstock, especially marine algae and other biomass-based resources for CO2 Adsorption (short to medium term)
2. In addition to Amine based CCS, India should focus (through timebound innovative R&D) for cryogenic & solid-state storage technology upscaling and adoption in shipping (short to medium term projects to undertake)

3. In order to minimize CO_2 transport and enable larger adoption of OCC, policy support is needed in developing CCU units in ports along India's coastal belt for frequent offloading of captured CO_2 (short to medium term)
4. Among CCU options, onboard captured CO_2 utilization for E-Methanol synthesis could be given priority for leveraging twin benefit of CO_2 capture and E-Methanol supply sustainability to maritime application (short to medium term)
5. Developing Collaborative (National/Cross National) Pilot scale project for Indian Marine Coastal Vessel's CCUS project with LCA analysis over the whole value chain (short-medium term)
6. Other promising CCU options such as captured CO_2 utilization especially via direct epoxide/CO2 copolymerization for CO_2-based copolymers, like poly (Propylene Carbonate) (PPC) should be encouraged for supporting local economy. PPC occupies a unique place among plastics by virtue of its biodegradability and unparallel CO_2 utilization. (medium to long term)
7. Commercially viable biorefinery plants through onboard captured CO_2 utilization for largescale marine algae cultivations in coastal/port area should be undertaken for long term sustainability (Medium to long term)

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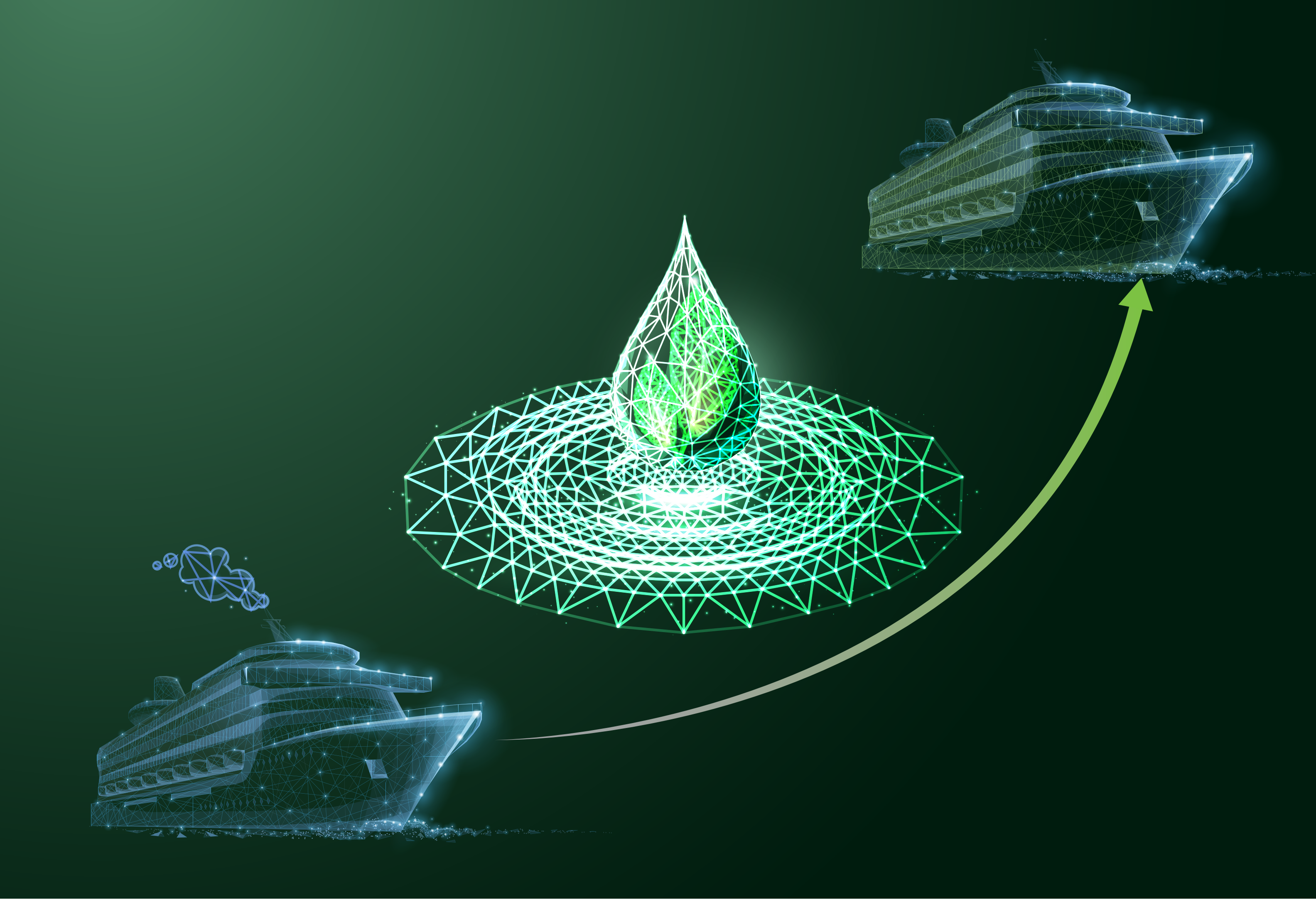

Chapter 7

Standards, Regulations and Policies

Table7.1 presents the overview of the IMO's ongoing initiatives through the MEPC aimed at tackling greenhouse gas (GHG) emissions from international shipping. It tracks tracks significant progress from MEPC 76 up to the anticipated adoption of new amendments at MEPC 83 in 2025. More detailed Amendments and Measurses of MEPC can be asscessed through **[1-3].**

Table 7.1: Timeline and Key Milestones of IMO MEPC Actions Toward Maritime Decarbonization

Timeline / Meeting	Event / Measure	Key Actions / Outcomes
MEPC 76 (2021)	Adoption of short-term measures	- Amendments **to MARPOL Annex** VI - Target: ≥40% carbon intensity reduction by 2030 - Introduction **of** CII (operational) **&** EEXI (technical) measures
ISWG-GHG 10	Start of mid-/long-term strategy	- Initiation of discussions **on technical and economic mid-term** measures
MEPC 78 (2022)	Approval of mid-term measure development	- "Basket of candidate mid-term measures" approved Includes: • Fuel/energy standards • Carbon pricing/taxation
MEPC 80 (2023)	Comparative analysis	- Identified **commonalities** in proposed technical & economic elements - Supported **a goal-based fuel** standard: • 20% GHG reduction by 2030 • 70% by 2040 • 100% by 2050 - Sulphur limit in fuel: Reduced from 3.5% to 0.5%
MEPC 81 (2024)	Adoption of LCA Guidelines	- **Resolution MEPC.391(**81) on **revised LCA** guidelines - Establishment **of GESAMP-LCA** WG to review scientific/technical LCA issues
MEPC 82 (2024)	Progress review	- Assessment of mid-term measures - Consideration of: • IMO GHG intensity registry • IMO GHG reduction fund
MEPC 83 (Scheduled Apr 2025)**	Finalization phase	- Review and refine the **IMO Net-Zero Framework** draft - Based on **inputs from** 107 parties (97.3% of world merchant fleet) - Aim: Approval of MARPOL amendments
Autumn 2025	Adoption of amendments	- Special MEPC session **to** adopt approved measures
2027 (Expected Entry into Force)	Implementation	- Mid-term measures from **2025 enter into** force

The maritime industry is leading the charge in the global effort to decarbonize, with regulatory frameworks playing a crucial role in the shift towards cleaner fuels and more sustainable practices. Key players, including international organizations like the International Maritime Organization (IMO) and regional authorities such as the European Union (EU), are implementing ambitious policies aimed at reaching net-zero greenhouse gas (GHG) emissions by 2050.

In this chapter, a closer look is taken at the main regulatory tools that are currently shaping the maritime decarbonization agenda. The global initiatives are led by the IMO—like efficiency indices and lifecycle GHG emission targets—as well as regional EU strategies, including the EU Emissions Trading System (EU ETS), FuelEU Maritime, and Renewable Energy Directive III (RED III). These frameworks not only are setting the emission limits and fuel requirements but also providing market incentives, such as double-counting for renewable fuels and tax breaks, to encourage the adoption of low- and zero-carbon alternatives.

Additionally, this chapter delves into the status of marine fuel standards, which are crucial for the safe, certified, and widespread use of alternative fuels. Regulatory definitions, GHG performance thresholds, and certification criteria for fuels like e-methanol, e-ammonia, hydrogen, and advanced biofuels are being established through delegated acts and fuel classification systems. As the industry transitions from setting targets to actual implementation, it's important to grasp these regulatory frameworks—and what they mean for fuel production, supply chains, vessel technology, and port infrastructure. This chapter aims to provides a thorough understanding of the current and future regulatory landscape that will guide the shift towards a sustainable maritime fuel ecosystem.

Following Table 7.2 presents the European Union regulations and directives that lay the groundwork for the EU's maritime decarbonization efforts, especially under the European Green Deal and the Fit-for-55 package. These initiatives set mandatory renewable energy goals, outline sustainability and greenhouse gas (GHG) performance standards, and create a framework for alternative fuels like e-methanol and e-ammonia.

Table 7.2: EU-level Regulations and Directives [4,5,6]

Regulation/Directive	Scope	Targets and Main Requirements	Sustainability and GHG Savings Criteria
EU GHG regulatory framework			
EU Renewable Energy Directive (REDIII) DIRECTIVE (EU) 2023/2413	WtT	• **Overall binding RES target:** at least 42.5% by 2030 in • **Advanced biofuels (AB) and RFNBOs:** Combined 5.5% Advanced biofuels and RFNBO (min. 1%) target in 2030. Incentive for AB and RFNBOs (double counting) and their use in aviation and maritime (1,2 x for AB and x1,5 for RFNBOs). Indicative target of 1.2% for RFNBOs in shipping • **Waste G Residues:** Capped to 1.7% • **Food and feed crops:** capped to 7% or 2020 share +1% (all transport), limit to high-ILUC risk except if certified Low-ILUC risk biomass	Defines sustainability criteria and minimum GHG savings for renewable fuels brought to EU market and sets a GHG emissions reduction threshold compared to reference fossil (94 gCO_2eq/MJ): · **biofuels** requiring at least **50- 65%** (depending on the date of facility installation) · **RFNBO and RCFs at least 70%**

Table 7.2: EU-level Regulations and Directives [4,5,6]

Regulation/Directive	Scope	Targets and Main Requirements	Sustainability and GHG Savings Criteria
RFNBO Delegated act under Art.27(3) of the 2018/2001 directive (REDII) - (EU) 2023/1184 RFNBO Delegated act under Art.28(5) of the 2018/2001 directive (REDII) - (EU) 2023/1185		• Requirements have been set out for when hydrogen produced from electricity can be considered zero-emission, and how to account for captured carbon reused in the fuel. • Methodology for determining GHG emissions of RFNBOs	Defines the conditions under which the **electricity** used for hydrogen production is considered **fully renewable: temporal correlation, geographical correlation and additionality**.
FuelEU Maritime Régulation (EU) 2024/2031	WtW	• Aims to increase demand for renewable and low- carbon fuels by establishing limits on the annual average GHG intensity of the energy used on-board (reference value 91.16 g CO2eq/MJ) every 5 years starting in 2025: -2%; -6%; -14.5%; -31%; -62%; -80% • Ships above 5000 GT, cover 100% of energy used on intra-EU voyages and 50% of the energy on extra-EU voyages.	**Refers to RED II Directive:** · RED compliant : use actual certified GHG intensity values for well-to-tank emissions · RED compliant : considered as having GHG emissions equal to the least favourable fossil
EU Emissions Trading System Directive (EU ETS) 2003/87/EC consolidated text	TtW	Since 2024, the EU ETS has been extended to cover the maritime sector. Regulate GHG emissions in the EU/ EEA through cap and trade of emission allowances. Ships of 5000 GT and above to be included in the EU ETS from 2023. Applicable to all intra-EEA voyages and 50% of voyages to/from countries outside the EEA.	EU-ETS allows for a zero CO2 emissions factor for biofuels, RFNBOs and RCFs that meet specific sustainability and GHG savings criteria defined by the RED.
Alternative Fuels Infrastructure Regulation (AFIR) (EU) 2023/1804		Main EU ports are required to provide a minimum shore power supply for container ships and passenger ships over 5,000 GT by 2030. Mandates LNG refuelling infrastructure at major ports by 2025.	

Table 7.2: EU-level Regulations and Directives [4,5,6]

Regulation/Directive	Scope	Targets and Main Requirements	Sustainability and GHG Savings Criteria
Revision of Energy Taxation Directive (ETD) 2003/96/EC		Aims to modify the way energy products are taxed in EU. The proposal introduces a new structure of tax rates based on energy content and environmental performance of the fuels and electricity. Removes tax exemptions for conventional maritime fuels; introduces €10.75/GJ tax for fossil fuels while advanced biofuels, biogas, and RFNBOs have a reduced rate of €0.15/GJ.	

Table 7.3: Key Regulatory Mechanisms Introduced by the IMO [4,8,9]

Regulation/Directive	Scope	Targets and Main Requirements
2023 IMO GHG Strategy	WtW	• The 2023 revised IMO GHG Strategy strengthens the ambitions for international shipping to achieve net zero emissions by 2050: • To reduce CO2 emissions per transport work by at least 40% by 2030 (baseline2008) • To reduce total annual GHG emissions by at least 20%, striving for 30%, by 2030 and by 70% (striving for 80%) in 2040 (baseline 2008). • To uptake Zero or Near-Zero GHG emission fuels and/or energy sources that should represent at least 5 % of the energy used in shipping in 2030. • To adopt Life cycle GHG assessment guidelines (LCA Guidelines) using a well-to-wake GHG emissions approach • Interim guidance on the use of biofuels under DCS and CII
EEDI/EEXI (Energy Efficiency Design/ Existing Ship Index)	TtW	EEDI (2013) applies to new ships, mandating design efficiency improvements; EEXI (2023) extends efficiency standards to existing ships, requiring compliance by 2023.

Table 7.3: Key Regulatory Mechanisms Introduced by the IMO [4,8,9]

Regulation/Directive	Scope	Targets and Main Requirements	
CII (Carbon Intensity Indicator)	TtW	• Carbon Intensity Indicator (starting 2023), vessels must collect emissions and be rated A-E for annual efficiency of all ships above 5000 GT. The use of biofuels under IMO DCS and CII regulations	• Biofuels that have been certified as sustainable through an international certification system (ISCC, RSB,etc.) should be promoted. • Biofuels that are not certified as sustainable or do not meet the emissions reduction criterion will be assigned a Cf equal to that of the equivalent fossil fuel type

Alternative Marine Fuels: Regulatory Mapping

Table 7.4 provides regulatory mapping and insights into how fuel oil is defined across various regulatory frameworks, identifying potential inconsistencies or gaps **[7]** . This effort aims to assist IMO Member States and maritime stakeholders in understanding and addressing regulatory challenges associated with the adoption of alternative fuels.

This regulatory mapping exercise is carried out by the Alternative Fuels Workstream of the Low Carbon Global Industry Alliance to Support Low Carbon Shipping (Low Carbon GIA). Significant contributions from the International Chamber of Shipping (ICS) and valuable input from the IMO Marine Environment and Maritime Safety Divisions are provided. The main goal of this exercise is to help IMO Member States, and the broader maritime community understand, and tackle potential regulatory challenges linked to alternative fuels. The work takes a close look at the current regulatory landscape surrounding various alternative marine fuels and energy converters. It points out that, while there are safety guidelines in place for using Methanol and Ethanol as marine fuels, there are still some significant gaps regarding safety requirements for low-flashpoint and toxic fuels. In order to resolve this, the IMO is actively working on developing regulations for fuels like Ammonia, Hydrogen, and low-flashpoint Diesel. This suggests there is a need to update regulations in future related to these fuels. The following Table uses a color-coded system based on the availability and maturity of relevant standards, regulations, and guidelines as follows.

High: Indicates the availability of related marine standards, adopted regulations and/or adopted interim/final guidelines
Medium: Indicates the availability of work in progress or approved (waiting for adoption) related marine standards, regulations and/or approved interim/final guidelinesTop of Form
Low: Indicates the absence of related marine standards, regulations and/or interim/final guidelines with required work yet to start

Table 7.4: Comparative Overview of Fuel Regulations in External Standards and IMO Frameworks

Fuel	External Standards	IMO Safety-SOLAS	IMO Environment - MARPOL
Conventional fuels (Diesel/ Gas Oil/Fuel Oil)	ISO 8217:2017 "Petroleum products – Fuels (class F) – Specifications of marine fuels" ISO PAS 23263:2019 "Considerations for fuel suppliers and users regarding marine fuel quality in view of the implementation of maximum 0.50 % sulfur in 2020"		MARPOL Annex I regulates spills and discharges MARPOL Annex VI regulates emissions of CO_2, NO_x, SO_x and PM
Bio/Synthetic Liquid Diesel Fuels	ISO is currently engaged in incorporating HVO (Hydrotreated Vegetable Oil) and FAME (Fatty Acid Methyl Ester) into the upcoming revision of **ISO 8217**, which specifies the requirements for marine fuels. Specifically, the revision allows for the inclusion of up to 7% FAME in distillate marine fuels of DF grade. This indicates a move towards accommodating alternative and renewable fuels in the marine industry's specifications and standards, reflecting a broader trend towards sustainability and environmental responsibility in maritime fuel usage.	SOLAS Chapter I regulates oil fuels with flashpoint > 60°C SOLAS Chapter II regulates low-flashpoint fuels (< 60°C) through SOLAS Ch II-1 Part G (low-flashpoint liquid fuel or gas) and IGF Code; alternatively SOLAS Ch II-1 Part F (Alternative design and arrangement) –MSC.1/Circ.1212/ Rev.1 and MSC.1/Circ.1455 The IGF Code does not cover low flashpoint fuel oil. Development of draft interim guidelines for the use of oil fuels with a flashpoint between 52°C and 60°C are currently under consideration.	1. MARPOL Annex VI regulates emissions of CO2, NOx, and PM from ships. 2. According to a Unified Interpretation (MEPC.1/Circ.795/Rev.6): • Fuel oil blends with 30% or less of biofuel or synthetic fuel are considered marine fuel oil derived from petroleum refining (Regulation 18.3.1). NOx testing is not required for such blends. 3. Fuel oil blends with over 30% of biofuel or synthetic fuel can be used if: • The engine can operate without modifications to its NOx critical components or settings. • Compliance is maintained with the engine's approved Technical File. 4. This interpretation facilitates the use of alternative fuels while ensuring compliance with NOx emission standards.

Table 7.4: Comparative Overview of Fuel Regulations in External Standards and IMO Frameworks

Fuel	External Standards	IMO Safety-SOLAS	IMO Environment - MARPOL
	EN 14214:2012 "Liquid petroleum products – Fatty acid methyl esters (FAME) for use in diesel engines and heating applications – Requirements and test methods"		
	EN 15940:2016 "Automotive fuels – Paraffinic diesel fuel from synthesis or hydro treatment – Requirements and test methods"		
	Both EN 14214:2012 and EN 15940:2016 are road transport standards, which have also been used in the marine industry.		
Methyl Alcohol (Methanol)	The development of ISO/AWI 6583, titled "Specification of methanol as a fuel for marine applications," indicates an effort to establish specific standards for the use of methanol as a marine fuel. Currently, when specifying methanol quality for marine applications, industry stakeholders commonly refer to existing standards such as the IMPCA (International Methanol Producers and Consumers Association) Methanol reference specification and the ASTM (American Society for Testing and Materials) D1152 standard.	SOLAS Chapter II regulates low-flashpoint fuels (those with a flashpoint below 60°C) through two main avenues: SOLAS Ch II-1 Part G and IGF Code: This part of SOLAS addresses the use of low-flashpoint liquid fuel or gas and is supplemented by the International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code). However, it's important to note that the IGF Code currently does not cover methanol as a fuel. SOLAS Ch II-1 Part F and MSC.1/Circ.1212/Rev.1, MSC.1/Circ.1455: Alternatively, SOLAS Chapter II-1 Part F, along with circulars MSC.1/Circ.1212/Rev.1 and MSC.1/Circ.1455, deals with alternative design and arrangement considerations. These provisions offer guidance for ships employing alternative fuels or propulsion systems.	Methanol is categorized as Category Y under the IBC Code, indicating that it presents a hazard to either marine resources or human health. Despite this classification, the spill and discharge requirements outlined in MARPOL Annex II do not apply specifically to methanol used as fuel. This suggests that while methanol is recognized as potentially hazardous under the IBC Code, its regulation regarding spills and discharges as a fuel differs from those outlined in MARPOL Annex II for other substances. MARPOL Annex VI regulates emissions of CO2 and NOx

Table 7.4: Comparative Overview of Fuel Regulations in External Standards and IMO Frameworks

Fuel	External Standards	IMO Safety-SOLAS	IMO Environment - MARPOL
	IMPCA Methanol Reference Specification: Developed by the International Methanol Producers and Consumers Association, this reference specification provides detailed guidelines for the quality requirements of methanol intended for various applications, including marine use. It covers parameters such as purity, water content, acidity, and trace impurities, ensuring that methanol meets certain standards suitable for its intended use.	Despite the IGF Code's lack of coverage for Methanol/ Ethanol as fuel, interim measures have been developed. Specifically, MSC.1/ Circ.1621 provides interim guidelines for the safety of ships utilizing methyl or ethyl alcohol as fuel. These guidelines aim to ensure the safe operation of ships using alcohol-based fuels until formal regulations or standards are established within the IGF Code or other relevant SOLAS provisions.	
	ASTM D1152 Standard: This ASTM standard, titled "Standard Specification for Methanol (Methyl Alcohol) for Industrial Use," provides comprehensive requirements for the quality of methanol intended for industrial applications. It specifies parameters related to purity, water content, acidity, color, and other impurities, ensuring that methanol meets certain quality standards.		
	These existing standards serve as reference points for specifying the quality of methanol used in marine applications. However, the development of ISO/AWI 6583 indicates a recognized need for more specific standards tailored to the unique requirements of methanol as a marine fuel. This forthcoming ISO standard will likely provide more detailed and comprehensive specifications to ensure the safe and efficient use of methanol in marine propulsion systems.		

Table 7.4: Comparative Overview of Fuel Regulations in External Standards and IMO Frameworks

Fuel	External Standards	IMO Safety-SOLAS	IMO Environment - MARPOL
Ethyl Alcohol (Ethanol)	No marine standards available		Ethanol is categorized as presenting a minor hazard under the IBC Code (Category Z), implying limited risk to marine resources or human health. Despite this classification, the spill and discharge requirements outlined in MARPOL Annex II do not specifically apply to ethanol used as fuel. This exemption suggests that ethanol fuel, while recognized as posing some level of hazard, is subject to different regulations compared to more hazardous substances, reflecting a nuanced approach to environmental regulation. MARPOL Annex VI regulates emissions of CO2 and NOx
Dimethyl Ether (DME)	No marine standards available	SOLAS Chapter II regulates low-flashpoint fuels (< 60°C) through No specific requirements or guidelines available for dimethyl ether (DME) as fuel. The IGC Code identifies DME as a toxic product and prohibits toxic cargo to be used as a fuel	MARPOL Annex VI regulates emissions of CO_2 and NO_x
Propane/ Butane (LPG)	No marine standards available	SOLAS Chapter II regulates low-flashpoint fuels (< 60°C) through • SOLAS Ch II-1 Part G (low-flashpoint liquid fuel or gas) and IGF Code; alternatively • SOLAS Ch II-1 Part F (Alternative design and arrangement) –MSC.1/Circ.1212/ Rev.1 and MSC.1/Circ.1455 The IGF Code does not cover LPG as fuel. Draft interim guidelines for the safety of ships using LPG fuels have been finalized and are adopted by MSC 107 in June 2023.	MARPOL Annex VI regulates emissions of CO_2 and NO_x

Table 7.4: Comparative Overview of Fuel Regulations in External Standards and IMO Frameworks

Fuel	External Standards	IMO Safety-SOLAS	IMO Environment - MARPOL
Methane (LNG)	ISO 23306:2020 provides comprehensive specifications for liquefied natural gas (LNG) as a marine fuel. It outlines quality requirements, testing methods, and safety considerations to ensure the efficient and safe utilization of LNG in marine engines and propulsion systems. The standard sets standards for LNG composition, purity, energy content, and potential contaminants, with specified testing procedures to verify compliance. Additionally, ISO 23306 addresses safety aspects associated with LNG handling, storage, and use onboard ships, providing guidelines for risk assessment and emergency response. Overall, the standard serves as a vital framework for the effective implementation of LNG as a sustainable and environmentally friendly fuel in maritime applications.	SOLAS Chapter II regulates methane (LNG) as fuel primarily through SOLAS Chapter II-1 Part G (low-flashpoint liquid fuel or gas) and the International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code). These provisions outline safety standards and requirements for the arrangement, installation, control, and monitoring of machinery, equipment, and systems utilizing low-flashpoint fuels, including LNG. Compliance with these regulations ensures the safe handling and use of LNG as a fuel in marine applications, promoting maritime safety and environmental protection.	MARPOL Annex VI regulates emissions of CO_2 and NO_x Fugitive emissions of methane are not currently regulated under MARPOL Annex VI.
Ethane	No marine standards available	SOLAS Chapter II regulates low-flashpoint fuels (< 60°C) through SOLAS Ch II-1 Part G (low-flashpoint liquid fuel or gas) and IGF Code; alternatively SOLAS Ch II-1 Part F (Alternative design and arrangement) –MSC.1/Circ.1212/Rev.1 and MSC.1/Circ.1455 No specific requirements or guidelines available for ethane as fuel.	MARPOL Annex VI regulates emissions of CO_2 and NO_x

Table 7.4: Comparative Overview of Fuel Regulations in External Standards and IMO Frameworks

Fuel	External Standards	IMO Safety-SOLAS	IMO Environment - MARPOL
Ammonia	No marine standards available ISO/AWI 23397 Ships and marine technology Ammonia fuel systems for ships is under development	SOLAS Chapter II regulates low-flashpoint fuels (< 60°C) through SOLAS Ch II-1 Part G (low-flashpoint liquid fuel or gas) and IGF Code; alternatively SOLAS Ch II-1 Part F (Alternative design and arrangement) –MSC.1/Circ.1212/Rev.1 and MSC.1/Circ.1455 IGC Code identifies ammonia as a toxic product and prohibits toxic cargo to be used as a fuel. The IGF Code does not cover ammonia as fuel. Draft interim guidelines for the safety of ships using ammonia as fuel are currently under development.	Ammonia aqueous" is assigned category Y as per the IBC Code, meaning it presents a hazard to either marine resources or human health. MARPOL Annex II requirements do not apply for spill and discharges of ammonia as fuel. MARPOL Annex VI regulates emissions of CO_2 and NO_x Other combustion products e.g., N_2O are not currently regulated under MARPOL Annex VI.
Hydrogen	ISO 14687:2019 "Hydrogen fuel quality – Product specification" No marine standards available	The IGF Code does not currently cover hydrogen as fuel. Resolution MSC.420(97) provides interim recommendations for the safe carriage of liquid hydrogen in bulk on ships. Additionally, draft interim guidelines are being developed to ensure the safety of ships using hydrogen as fuel. These measures aim to address the gap in regulations and promote the safe adoption of hydrogen as a maritime fuel.	MARPOL Annex VI regulates emissions of CO_2 and NO_x

Source: https://greenvoyage2050.imo.org/alternative-marine-fuels-regulatory-mapping/

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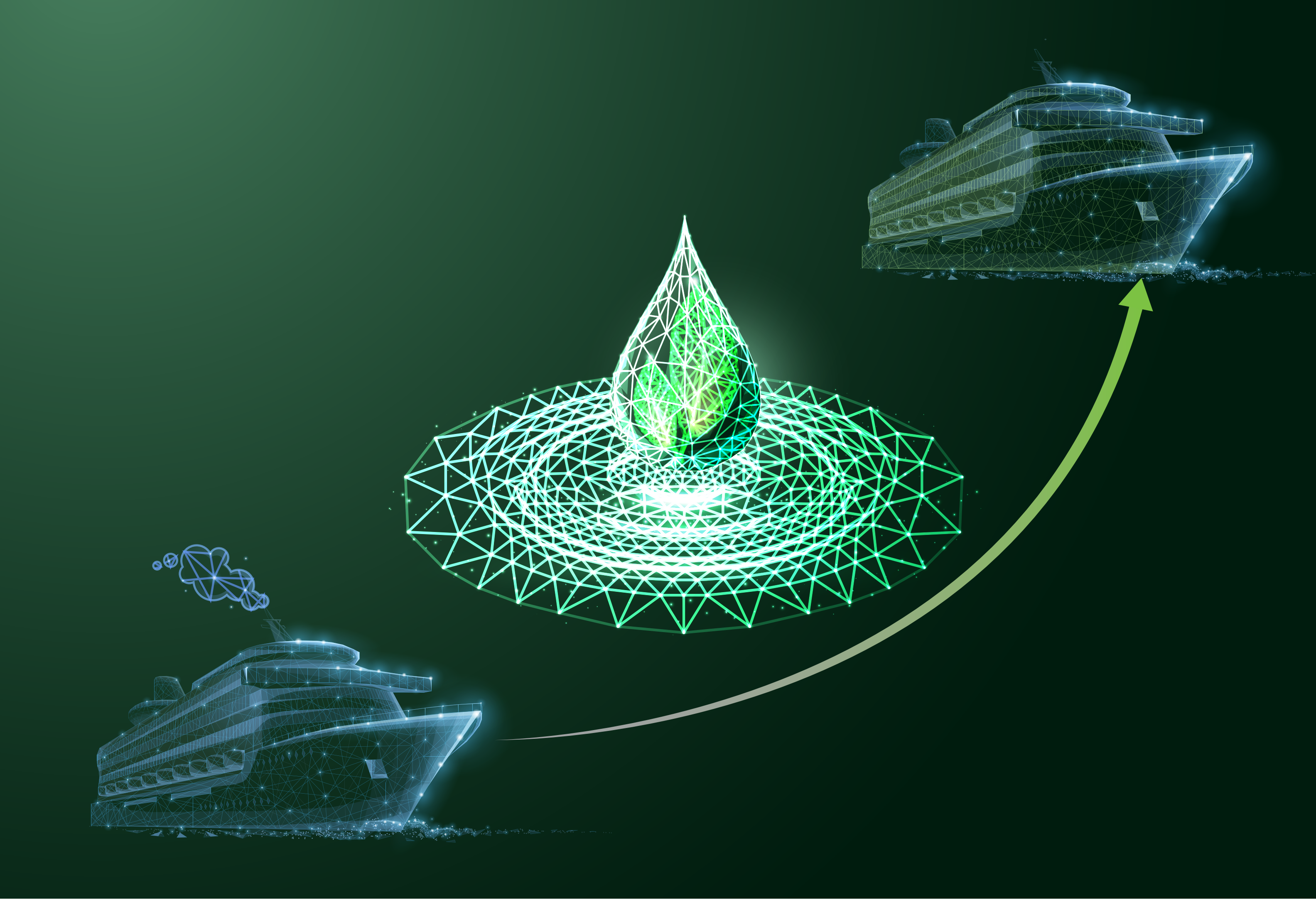


Annexures

Annexure I

IMO LCA Methodological Guidance

The Life Cycle Assessment (LCA) is considered by the IMO as the methodological approach to comprehensively assess the environmental impact of an energy carrier for maritime transport, from its production phase to its end of-life/combustion phase. This methodology is based on rigorous principles aimed at quantifying greenhouse gas emissions, resource and energy consumption, as well as other environmental impacts. According to the recommendations adopted in July 2023 (MEPC.376(80)) by the IMO, the calculation of GHG emissions from marine fuels is detailed below.

Scope

The scope of these guidelines is to address well-to-tank (WtT), tank-to wake (TtW), and well-to-wake (WtW) greenhouse gases (GHG) intensity and sustainability themes/aspects related to marine fuels/energy carriers (e.g. electricity for shore power) used for ship propulsion and power generation onboard. The relevant GHGs included are carbon dioxide (CO2), methane (CH4) and nitrous oxide (N2O). These guidelines are not intended to provide guidance for a complete IMO GHG inventory for international shipping. Emissions from cargo (e.g. volatile organic compounds (VOC)), or use of refrigerants are not included; other short-lived climate forcers and precursors such as non-methane volatile organic compounds (NMVOC), sulphur oxides (SOx), carbon monoxide (CO), particulate matter (PM) and Black Carbon are not part of the scope of these LCA guidelines.

The system boundaries of the WtW GHG emission factors calculation, in the context of these guidelines span the life cycle of fuels from their sourcing to production, conversion, transport, distribution, and eventually their use on board ships based on an attributional approach.1 The possibility to expand the system boundaries for specific pathways in which the feedstock is displaced from present use(s) will be assessed on a case-by-case basis.2 As such, emissions associated with the following life cycle stages of the fuel life cycle chain will be accounted for:

1. feedstock extraction/cultivation/acquisition/recovery;
2. feedstock (early) processing/ transformation at source;
3. feedstock transport to conversion site;
4. feedstock conversion to product fuel;
5. product fuel transport/storage/delivery/retail storage/bunkering; and
6. fuel utilization on board a ship.

Consistently with the attributional approach and using best available scientific evidence, the WtT emissions calculations (i.e. emissions related to the fuel sourcing, production, conversion, transport and delivery) are assessed regardless of the final use of fuels/energy carriers, and the TtW emissions (i.e. emissions related to the fuel use) are quantified regardless of the sourcing/production/ conversion/transport and delivery steps of the fuel/energy carrier. WtW emissions are given by the sum of the two parts, providing the full emission performance associated with the fuel production and use of a certain fuel/energy in a specific converter onboard.

The GHG emissions are calculated as CO2-equivalent (CO2eq), using the Global Warming Potential over a 100-year time-horizon (GWP100) to convert emissions of other gases than CO2, as given in the fifth IPCC Assessment Report,3 for CO2, CH4 and N2O, as follows:

» $gCO2eg(100y) = GWPCO2(100y) \times gCO2 + GWPCH4(100y) \times gCH4 + GWPN2O\ (100y) \times gN2O$

(CO2 1; CH4 28; N2O 265), this would read as:

» $gCO2eg(100y) = 1 \times gCO2 + 28 \times gCH4 + 265 \times gN2O)$

These GWP100 values should be used for the purpose of quantifying the GHG intensity in accordance with these guidelines.

A calculation using a Global Warming Potential over a 20-year horizon (GWP20) may be provided as information for comparative purposes, as follows:

» $gCO2eg(20y) = GWPCO2(20y) \times gCO2 + GWPCH4(20y) \times gCH4 + GWPN2O\ (20y) \times gN2O$

(CO2 1; CH4 84; N2O 264), this would read as:

» $gCO2eg(20y) = 1 \times gCO2 + 84 \times gCH4 + 264 \times gN2O$

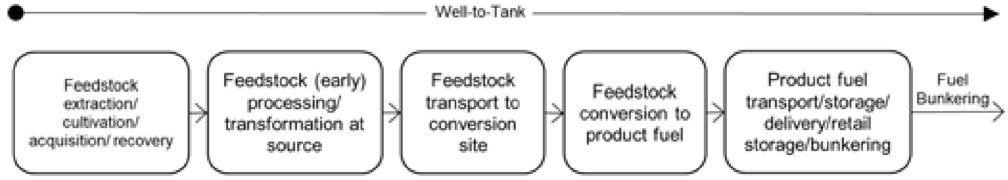
These guidelines provide:

- WtW GHG emission factors based on a life cycle attributional methodology, expressing the GHG profile of each representative fuel using on Global Warming Potential (GWP) values over a 100-year time-horizon of included GHG (CO2, CH4 and N2O);
- WtT GHG emission factors (CO2, CH4 and N2O) quantified consistently with the attributional approach;
- TtW GHG emission factors (CO2, CH4 and N2O); and
- sustainability themes/aspects for marine fuels.

These guidelines define a FLL that carries information about fuel type, feedstock used, fuel production pathway, GHG emission factors, information on fuel blends and sustainability themes/aspects.

a) WELL-TO-TANK (WtT)

The pathway of each relevant marine fuel should be clearly described and the GHG emissions during each step of the fuel pathway should be calculated. Specific GHG emissions of a specific non-conventional and non-fossil fuel's pathway may take into account different characteristics across geographic regions, where feedstock production and/or conversion occurs, as appropriate.



The WtT GHG emission factor ($gCO_{2eq}/MJ_{(LCV)}$ fuel or electricity) is calculated according to **Equation (1).**

$$GHG_{WtT} = e_{fecu} + e_l + e_p + e_{td} - e_{sca} - e_{ccs} \text{ ....(1)}$$

Table 1: Terms to consider according to IMO guidelines for calculating Well-to-Tank GHG emissions

Term	Units	Explanation
e_{fecu}	gCO2eq /MJ(LCV)	Emissions associated with the feedstock extraction/ cultivation/ acquisition/ recovery
e_l	gCO2eq /MJ(LCV)	Emissions (annualized emissions (over 20 years) from carbon stock changes caused by direct land-use change)[5]
e_p	gCO2eq / MJ(LCV)	Emissions associated with the feedstock processing and/or transformation at source and emissions associated with the conversion of the feedstock to the final fuel product, including electricity generation
e_{td}	gCO2eq / MJ(LCV)	Emissions associated with the feedstock transport to conversion plant, and the emissions associated with the finished fuel transport and storage, local delivery, retail storage and bunkering
e_{sca}	gCO2eq / MJ(LCV)	Emissions (annualized emission savings (over 20 years) from soil carbon accumulation via improved agricultural management)[6]
e_{ccs}	gCO_{2eq}/ $MJ_{(LCV)}$	Emissions credit from carbon capture and storage (e_{ccs}), that have not already been accounted for in e_p. This should properly account the avoided emissions through the capture and sequestration of emitted CO_2, related to the extraction, transport, processing and distribution of fuel (c_{sc}). From the above-mentioned emission credit, all the emissions resulting from the process of capturing (e_{cc}) and transporting (e_t) the CO_2 up to the final storage (including the emissions related to the injection, etc.) need to be deducted. This element should be calculated with the following formula: $e_{CCS} = c_{SC} - e_{cc} - e_t - e_{st} - e_x$
c_{sc}	g CO_2 stored / $MJ_{(LCV)}$	Emissions credit equivalent to the net CO_2 captured and stored (long-term: 100 years)
e_{cc}	gCO_{2eq} /$MJ_{(LCV)}$	Emissions associated with the process of capturing, compression and/or cooling and temporary storage of the CO_2
e_t	gCO_{2eq} /$MJ_{(LCV)}$	Emissions associated with transport to a long-term storage site
e_{st}	gCO_{2eq}/ $MJ_{(LCV)}$	Any emissions associated with the process of storing (long- term: 100 years) the captured CO_2 (including fugitive emissions that may happen during long-term storage and/or the injection of CO_2 into the storage)
e_x	gCO_{2eq} /$MJ_{(LCV)}$	Any additional emissions related to the CCS

**Pending further methodological guidance to be developed by OMI, the value of parameter should be set to 0.*

b) TANK-TO-WAKE (TtW)

The TtW GHG emission factors should be calculated using Equation (2):

$$GHG\ TtW = 1/LCV((1-1/100(C_{slip\_ship} + C_{fug}))x\ (Cf_{CO2}\ x\ GWP_{CO2} + Cf_{CH4}\ x\ GWP_{CH4} + Cf_{N20}\ x\ GWP_{N20}) + 1/100(C_{slip\_ship} + C_{fug})\ x\ C_{sf}x\ x\ GWP_{fuelx}) - SF_{c}\ x\ e_{c} - SF_{ccu}\ x\ e_{ccu} - eO_{ccs}) \ldots\ldots \textbf{(2)}$$

Table 2: Terms to consider according to IMO guidelines for calculating Tank-to-Wake GHG emissions

Term	Units	Explanation
Cslip_ship	% of total fuel mass	Factor accounting for fuel (expressed in % of total fuel mass delivered to the ship) which escapes from the energy converter without being oxidized (including fuel that escapes from combustion chamber/ oxidation process and from crankcase, as appropriate) $C_{slip\_ship} = C_{slip} * (1 - C_{fug}/100)$
Cslip	% of total fuel mass	Factor accounting for fuel (expressed in % of total fuel mass consumed in the energy converter) which escapes from the energy converter without being oxidized (including fuel that escapes from combustion chamber/oxidation process and from crankcase, as appropriate)
Cfug	% of fuel mass	Factor accounting for the fuel (expressed in % of mass of the fuel delivered to the ship) which escapes between the tanks up to the energy converter which is leaked, vented or otherwise lost in the system[7]
Csfx	gGHG/g fuel	Factor accounting for the share of GHG in the components of the fuel (expressed in g GHG/g fuel) Example: for LNG this value is 1
CfCO2	gCO2/g fuel	CO2 emission conversion factor (gCO2/g fuel completely combusted) for emissions of the combustion and/or oxidation process of the fuel used by the ship
CfCH4	gCH4/g fuel	CH4 emission conversion factor (gCH4/g fuel delivered to the ship) for emissions of the combustion and/or oxidation process of the fuel used by the ship[8]
CfN2O	gN2O/g fuel	N2O emission conversion factor (gN2O/g fuel delivered to the ship) for emissions of the combustion and/or oxidation process of the fuel used by the ship
GWPCH4	gCO2eq/g CH4	Global Warming Potential of CH4 over 100 years (based on the fifth IPCC Assessment Report 5)[9] Definition as per https://www.ipcc.ch/assessment-report/ar5/
GWPN2O	gCO2eq/g N2O	Global Warming Potential of N2O over 100 years (based on the fifth IPCC Assessment Report 5).[10] Definition as per https://www.ipcc.ch/assessment-report/ar5/
GWP_{fuelx}	gCO2eq/g GHG	Global Warming Potential of GHG in the components of the fuel over 100 years (based on the fifth IPCC scientific Assessment Report)

Table 2: Terms to consider according to IMO guidelines for calculating Tank-to-Wake GHG emissions

Term	Units	Explanation
S_{Fc}	0 or 1	Carbon source factor to determine whether the emissions credits generated by biomass growth are accounted for in the calculation of the TtW value
ec	gCO2eq/g fuel	Emissions credits generated by biomass growth
$eccu$	gCO2eq/g fuel	Emission credits from the used captured CO_2 as carbon stock to produce synthetic fuels in the fuel production process and utilization (that was not accounted under e_{fecu} and e_p)
$SFccu$	0 or 1	Carbon source factor to determine whether the emissions credits from the used captured CO_2 as carbon stock to produce synthetic fuels in the fuel production process are accounted for in the calculation of the TtW value
$eoccs$	gCO2eq / g fuel	Emission credit from carbon capture and storage (e_{occs}), where capture of CO_2 occurs onboard. This should properly account for the emissions avoided through the capture and sequestration of emitted CO_2, if CCS occurs on board. From the above-mentioned emission credit, all the emissions resulting from the process of capturing (e_{cc}), and transporting (e_t) the CO_2 up to the final storage (including the emissions related to the injection, etc.) need to be deducted. This element should be calculated with the following formula: $e_{OCCS} = c_{SC} - e_{cc} - e_t - e_{st} - e_x$
csc	gCO2 / g fuel	Credit equivalent to the CO_2 captured and stored (long- term: 100 years)
ecc	gCO2eq / g fuel	Any emission associated with the process of capturing, compress and temporarily store on board the CO_2
et	gCO2eq / g fuel	Emissions associated with transport to long-term storage site
est	gCO2eq / g fuel	Any emission associated with the process of storing (long- term: 100 years) the captured CO_2 (including fugitive emissions that may happen during long-term storage and/or the injection of CO_2 into the storage)
ex	gCO2eq / g fuel	Any additional emission related to the CCS
LCV	MJ/g	Lower Calorific Value is the amount of heat that would be released by the complete combustion of a specified fuel

- *Pending further methodological guidance to be developed by the Organization, the value of the multiplication $SFccu \times eccu$ should be set to zero.*
- *Pending further methodological guidance to be developed by the Organization, the value of the multiplication $SFccu \times eccu$ should be set to zero.*
- *Pending further methodological guidance to be developed by the Organization, the value of $eoccs$ should be set to zero.*

c) WELL-TO-WAKE (WtW)

The aim of the WtW methodology is to integrate WtT and TtW parts, to quantify the full life cycle emissions related to the production and use of a fuel.

The WtW GHG emission factor (gCO_{2eq}/MJ_{LCV} fuel or electricity) is calculated as follows

$GHG_{WtW} = GHG_{WtT} + GHG_{TtW}$ **…………………(3)**

Term	Units	Explanation
GHGWtW	gCO2eq/ MJ(LCV)	Total well-to-wake GHG emissions per energy unit from the use of the fuel or electricity in a consumer on board the ship
GHGWtT	gCO2eq/ MJ(LCV)	Total well-to-tank GHG upstream emissions per energy unit of the fuel provided to the ship
GHGTtW	gCO2eq/ MJ(LCV)	Total tank-to-wake GHG downstream emissions per energy unit from the use of fuel or electricity in a consumer on board the ship

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Annexure II

Alternative Fuel Bunkering Readiness At Global Ports

1. Ammonia Bunkering

Active	Potential	Under construction

S. No.	Port Name	Port Country	Port Operator
		Ammonia Bunkering	
	Singapore	Singapore	MPA Singapore
	Algeciras	Spain	APBA
	Houston	United States	Port of Houston
	Hamburg	Germany	Hamburg Port Auth
	Khalifa	U.A.E.	Abu Dhabi Ports
	Salalah	Oman	Salalah Port Service
	Gdynia	Poland	Port of Gdynia
	Amsterdam	Netherlands	Amsterdam Port
	Aarhus	Denmark	Port of Aarhus
	Ngqura	South Africa	Transnet
	Ain Sokhna	Egypt	Suez Canal Zone
	Duqm	Oman	Port of Duqm
	Sauda	Norway	Sauda Port Authority
		Ammonia Bunkering STS	
	Singapore	Singapore	MPA Singapore
	Rotterdam	Netherlands	Port of Rotterdam
	Antwerp	Belgium	Port Antwerp-Bruges
	Port Hedland	Australia	Pilbara Ports
	Savannah	United States	Georgia Ports Auth
	Dampier	Australia	Pilbara Ports
	Oakland	United States	Port of Oakland
	Amsterdam	Netherlands	Amsterdam Port
	Jacksonville	United States	JAXPORT
	Benicia	United States	AMPORTS

S. No.	Port Name	Port Country	Port Operator
Ammonia Terminals			
	Singapore	Singapore	South East Asia
	Dampier	Australia	Australasia
	Ulsan	South Korea	East Asia
	Newcastle	Australia	Australasia
	Jacksonville	United States	East Coast North America
	Ronne	Denmark	United Kingdom/Continent
	Tokuyama	Japan	East Asia
	Floro	Norway	United Kingdom/Continent
Ammonia Bunkering TTS			
	Yokohama	Japan	Yokohama Port

2. Biofuel Bunkering

S. No.	Port Name	Port Country	Port Operator
Biofuel Bunkering			
	Singapore	Singapore	MPA Singapore
	Rotterdam	Netherlands	Port of Rotterdam
	Antwerp	Belgium	Port Antwerp-Bruges
	Barcelona	Spain	Barcelona Port Auth
	Amsterdam	Netherlands	Amsterdam Port
	Busan	South Korea	BPA
	Vancouver	Canada	Port of Vancouver
	Rio De Janeiro	Brazil	Porto do Rio
	Brisbane	Australia	Brisbane Port
	Colon	Panama	Colon Port Terminal
	Vlissingen-Oost	Netherlands	North Sea Port
	Ghent	Belgium	North Sea Port
	Caleta Coloso	Chile	
Biofuel Bunkering STS			
	Singapore	Singapore	MPA Singapore
	Rotterdam	Netherlands	Port of Rotterdam
	Hong Kong	Hong Kong	Hong Kong Port Board
	Fujairah	U.A.E.	Abu Dhabi Ports
	Zhoushan	China P.R.	Ningbo Zhoushan Port
	Dalian	China P.R.	Dalian Port Group
	Yantian	China P.R.	Shenzhen Port Group
	Nansha	China P.R.	Guangzhou Port Grp

S. No.	Port Name	Port Country	Port Operator
	Nagoya	Japan	Nagoya Port
	Gibraltar	Gibraltar	Gibraltar Port
	Gothenburg	Sweden	Gothenburg Port
	Xinsha	China P.R.	Guangzhou Port Grp
	Mina Khalid	U.A.E.	Sharjah Ports
	Shekou	China P.R.	CMPort
	Khor Fakkan	U.A.E.	Khor Fakkan Port
	Wellington	New Zealand	Centreport Ltd.
	Kinuura	Japan	Kinuura Port Authori
Biofuel Bunkering TTS			
	Le Havre	France	Haropa Port
	Toulon	France	
	Aarhus	Denmark	Port of Aarhus

3. Hydrogen bunkering

S. No.	Port Name	Port Country	Port Operator
E- Hydrogen Bunkering			
	Poole Harbor	United Kingdom	
	Rouen	France	Haropa Port
E-Hydrogen Bunkering Terminal			
	Antwerp	Belgium	Port Antwerp-Bruges
	Newcastle	Australia	Newcastle Port Corp.
	Oostende	Belgium	Port Oostende
E hydrogen Bunkering			
	Hamburg	Germany	Hamburg Port Auth
	Long Beach	United States	Port of Long Beach
	Gdynia	Poland	Port of Gdynia
	Hirtshals	Denmark	Port of Hirtshals
	Halifax	Canada	Halifax Port Authori
	Kristiansand	Norway	Kristiansand Harbour
	Esbjerg	Denmark	Port of Esbjerg
	Tanjung Langsat	Malaysia	TLP, Malaysia
	Portland	United Kingdom	Portland Port UK
	Sandnessjoen	Norway	Helgeland Havn

S. No.	Port Name	Port Country	Port Operator
Hydrogen Bunkering Terminal			
	Antwerp	Belgium	Port Antwerp-Bruges
	Shanghai	China P.R.	SIPG
Hydrogen Bunkering			
	San Francisco	United States	Port of San Fran.
	Singapore	Singapore	MPA Singapore
	Rotterdam	Netherlands	Port of Rotterdam
	Busan	South Korea	BPA
	Port Hedland	Australia	Pilbara Ports
	Yokohama	Japan	Yokohama Port
	Tallinn	Estonia	Port of Tallinn
	Los Angeles	United States	Port of Los Angeles
	Klaipeda	Lithuania	Klaipeda Seaport
	Amsterdam	Netherlands	Amsterdam Port
	Saldanha Bay	South Africa	Port of Saldanha Bay
	Ngqura	South Africa	Transnet
	Ijmuiden	Netherlands	Port of Ijmuiden
	Aberdeen	United Kingdom	Port of Aberdeen
	Stockholm Norvik	Sweden	Ports of Stockholm
	Fredericia	Denmark	Danish Ports AS-ADP
	Rorvik	Norway	Nord-Trondelag Havn
	Walvis Bay	Namibia	Namport
Hydrogen Bunkering TTS			
	Bellingham	United States	Port of Bellingham
	Osaka	Japan	Osaka Port Corporation

4. LNG bunkering

Sl no.	Port name	Port country	Port operator
LNG Bunkering Pontoon			
	Nanjing	China P.R.	Nanjing Port
	Zhenjiang	China P.R.	Zhenjiang Port
LNG Bunkering			
	Stockholm	United Kingdom/Continent	Ports of Stockholm
	Frederikshavn	United Kingdom/Continent	Port Frederikshavn
	Huelva	United Kingdom/Continent	Port of Huelva

Sl no.	Port name	Port country	Port operator
		LNG Bunkering STS	
	Yangshan	China P.R.	SIPG
	Algeciras	Spain	APBA
	Port Klang	Malaysia	Port Klang Auth
	Gwangyang	South Korea	Yeosu Gwangyang Port
	Zhoushan	China P.R.	Ningbo Zhoushan Port
	Antwerp	Belgium	Port Antwerp-Bruges
	Yantian	China P.R.	Shenzhen Port Group
	Barcelona	Spain	Barcelona Port Auth
	Jebel Ali	U.A.E.	Port of Jebel Ali
	Tanjung Pelepas	Malaysia	Port Tanjung Pelepas
	Yokohama	Japan	Yokohama Port
	Meishan	China P.R.	Ningbo Zhoushan Port
	Hamburg	Germany	Hamburg Port Auth
	Nagoya	Japan	Nagoya Port
	Zeebrugge	Belgium	Port Antwerp-Bruges
	Helsinki	Finland	Port of Helsinki
	Le Havre	France	Haropa Port
	Tallinn	Estonia	Port of Tallinn
	Gibraltar	Gibraltar	Gibraltar Port
	Gothenburg	Sweden	Gothenburg Port
	Miami	United States	PortMiami
	Bremerhaven	Germany	Bremerhaven Port
	Dunkirk	France	Port de Dunkerque
	Marseille	France	Marseille Fos Port
	Kiel	Germany	Port of Kiel
	Port Canaveral	United States	Canaveral Port
	Rostock	Germany	Rostock Port
	Ust-Luga	Russia	Ust-Luga Company JSC
	Santa Cruz De Tenerife	Canary Islands	Puertos de Tenerife
	Fos	France	Marseille Fos Port
	Stockholm	Sweden	Ports of Stockholm
	Brunsbuttel	Germany	Brunsbuttel Ports
	Klaipeda	Lithuania	Klaipeda Seaport
	Kingston	Jamaica	
	La Spezia	Italy	La Spezia Port Autho
	Pengerang	Malaysia	

Sl no.	Port name	Port country	Port operator
	Jacksonville	United States	JAXPORT
	Bilbao	Spain	Bilbao Port
	Pasir Gudang	Malaysia	JPB
	St Petersburg	Russia	StPetersburg Seaport
	Bergen	Norway	Bergen Havn
	Visby	Sweden	
	Vlissingen-Oost	Netherlands	North Sea Port
	Toyohashi	Japan	Mikawa Port Office
	Huangpu	China P.R.	Guangzhou Port Grp
	Malmo	Sweden	CopenhagenMalmo Port
	Naantali	Finland	Port of Naantali
	Cadiz	Spain	Cadiz
	Hiroshima	Japan	HPPA
	Huelva	Spain	Port of Huelva
	Nynashamn	Sweden	Ports of Stockholm
	Ghent	Belgium	North Sea Port
	Ronne	Denmark	Ronne Havn
	Emden	Germany	Niedersachsen Ports
	Reykjavik	Iceland	Icelandic Ports
	Brofjorden	Sweden	Port of Brofjorden
	Eemshaven	Netherlands	Groningen Seaports
	Gongdan	South Korea	
	Okpo	South Korea	Gyeongsangnam-do PMO
	Kaliningrad	Russia	
	Lindo	Denmark	
	Sodertalje	Sweden	
	Oxelosund	Sweden	Oxelosunds Hamn AB
	Agotnes	Norway	Coast Center Base
	Vyborg	Russia	Vyborg Port
	Backviken	Sweden	
	Blang Lancang	Indonesia	Blang Lancang Port
	Singapore	Singapore	MPA Singapore
	Rotterdam	Netherlands	Port of Rotterdam
	Hong Kong	Hong Kong	Hong Kong Port Board
	West Port Said	Egypt	Suez Canal Zone
	Port Hedland	Australia	Pilbara Ports
	Piraeus	Greece	Piraeus Port Auth

Sl no.	Port name	Port country	Port operator
	Suez	Egypt	Red Sea Port Auth.
	Laem Chabang	Thailand	Laem Chabang Port
	Napoli	Italy	PSA Tyrrhenian Sea
	Dampier	Australia	Dampier Office
	Ulsan	South Korea	Ulsan Port Auth
	Osaka	Japan	Osaka Port Corporati
	Colon	Panama	Colon Port Terminal
	Swinoujscie	Poland	Szczecin Port Auth.
	Panama City	Panama	Panama Maritime
	Galveston	United States	Port of Galveston
	Amsterdam	Netherlands	Amsterdam Port
	Portsmouth	United Kingdom	Portsmouth Port
	Kochi	India	Cochin Port Auth.
	Tacoma	United States	Northwest Seaport
	Mokpo	South Korea	Mokpo MOF
	Heraklion	Greece	Heraklion Port Auth
	Ngqura	South Africa	Transnet
	Limassol	Cyprus	Cyprus Ports Auth.
	Fraser Mills	Canada	Port of Vancouver
	Labuan	Malaysia	Labuan Port Auth
	Kemaman	Malaysia	KPK
	Helsingborg	Sweden	
	Vancouver	Canada	Port of Vancouver
	Port Elizabeth	South Africa	Transnet
LNG Bunkering Terminal			
	Rotterdam	Netherlands	Port of Rotterdam
	Barcelona	Spain	Barcelona Port Auth
	Jebel Ali	U.A.E.	Port of Jebel Ali
	Livorno	Italy	AdSP MTS
	Gothenburg	Sweden	Gothenburg Port
	Fos	France	Marseille Fos Port
	Zhenjiang	China P.R.	Zhenjiang Port
	Klaipeda	Lithuania	Klaipeda Seaport
	Pengerang	Malaysia	
	Hirtshals	Denmark	Port of Hirtshals
	Wilhelmshaven	Germany	Niedersachsen Ports

Sl no.	Port name	Port country	Port operator
	Kochi	India	Cochin Port Auth.
	Jacksonville	United States	JAXPORT
	Bilbao	Spain	Bilbao Port
	Tacoma	United States	Northwest Seaport
	Caucedo	Dominican Rep.	Caucedo Port
	Bergen	Norway	Bergen Havn
	Mongstad	Norway	Port of Mongstad
	Cristobal	Panama	Hutchison Ports PPC
	Ravenna	Italy	
	Escombreras	Spain	Puerto de Cartagena
	Teesport	United Kingdom	PD Ports
	Risavika	Norway	
	Santander	Spain	Port of Santander
	Puerto De Sagunto	Spain	Valenciaport
	Sungai Udang	Malaysia	MISC
	Changzhou	China P.R.	Jiangsu Port Grp
	Brofjorden	Sweden	Port of Brofjorden
	Gongdan	South Korea	
	Tobata	Japan	Kitakyushu Seaport
	Hammerfest	Norway	
	Kristiansund	Norway	
	Montego Bay	Jamaica	
	Floro	Norway	Flora Hamn
	Lodingen	Norway	
	Avaldsnes	Norway	
	Borg Harbour	Norway	
	Agotnes	Norway	Coast Center Base
	Hamina	Finland	Port HaminaKotka
	Roytta	Finland	
	Tahkoluoto	Finland	Port of Pori Ltd
	Singapore	Singapore	MPA Singapore
	Shanghai	China P.R.	SIPG
	Busan	South Korea	BPA
	Fujairah	U.A.E.	Abu Dhabi Ports
	Incheon	South Korea	Incheon Port Auth
	Dunkirk	France	Port de Dunkerque

Sl no.	Port name	Port country	Port operator
	Jakarta	Indonesia	Pelindo
	Napoli	Italy	PSA Tyrrhenian Sea
	Jiangyin	China P.R.	Jiangyin Port
	Sohar	Oman	Sohar Port
	Gdansk	Poland	Port of Gdansk
	Tomakomai	Japan	JPTMK
	Brunsbuttel	Germany	Brunsbuttel Ports
	Port Louis	Mauritius	CHCL
	Galveston	United States	Port of Galveston
	Zhuhai	China P.R.	Zhuhai Port Holdings
	Constantza	Romania	Constantza Port
	Freeport	United States	Port Freeport
	Taizhou	China P.R.	Taizhou Port
	Dangjin	South Korea	Pyeongtaek MOF
	Dapeng	China P.R.	Unknown
	Shanghai Nangang	China P.R.	Lingang Industrial
	Paldiski	Estonia	Port of Tallinn
	Texas City	United States	
	Blang Lancang	Indonesia	Blang Lancang Port
	Oxelosund	Sweden	Oxelosunds Hamn AB
	Isle Of Grain	United Kingdom	GrainLNG
	Taixing	China P.R.	Taixing Port
	Sundsvall	Sweden	Sundsvalls Hamn
	Algeciras	Spain	APBA
	Gwangyang	South Korea	Yeosu Gwangyang Port
	Huelva	Spain	Port of Huelva
	Limassol	Cyprus	Cyprus Ports Auth.
	Boryeong	South Korea	
	Laowei	China P.R.	Unknown
	Swinoujscie	Poland	Szczecin Port Auth.
LNG Bunkering TTS			
	Singapore	Singapore	MPA Singapore
	Rotterdam	Netherlands	Port of Rotterdam
	Beilun	China P.R.	Ningbo Zhoushan Port
	Algeciras	Spain	APBA
	Antwerp	Belgium	Port Antwerp-Bruges

Sl no.	Port name	Port country	Port operator
	Barcelona	Spain	Barcelona Port Auth
	Nansha	China P.R.	Guangzhou Port Grp
	Yokohama	Japan	Yokohama Port
	Valencia	Spain	Valenciaport
	Hamburg	Germany	Hamburg Port Auth
	Nagoya	Japan	Nagoya Port
	Zeebrugge	Belgium	Port Antwerp-Bruges
	Helsinki	Finland	Port of Helsinki
	Le Havre	France	Haropa Port
	Tallinn	Estonia	Port of Tallinn
	Long Beach	United States	Port of Long Beach
	Gothenburg	Sweden	Gothenburg Port
	Bremerhaven	Germany	Bremerhaven Port
	Incheon	South Korea	Incheon Port Auth
	Kobe	Japan	Kobe Port Promotion
	Dunkirk	France	Port de Dunkerque
	Marseille	France	Marseille Fos Port
	Civitavecchia	Italy	Civitavecchia Port
	Southampton	United Kingdom	Port of Southampton
	Rostock	Germany	Rostock Port
	Dampier	Australia	Dampier Office
	Pyeongtaek	South Korea	Pyeongtaek MOF
	Melbourne	Australia	Melbourne Port Corp.
	Stockholm	Sweden	Ports of Stockholm
	Sines	Portugal	Port of Sines
	Gdansk	Poland	Port of Gdansk
	Tomakomai	Japan	JPTMK
	Brunsbuttel	Germany	Brunsbuttel Ports
	Immingham	United Kingdom	Port of Immingham
	Klaipeda	Lithuania	Klaipeda Seaport
	Gdynia	Poland	Port of Gdynia
	Buenos Aires	Argentina	Port of Buenos Aires
	Longkou	China P.R.	Longkou Port Group
	Amsterdam	Netherlands	Amsterdam Port
	Sakai-Semboku	Japan	Sakai Semboku Port
	Jacksonville	United States	JAXPORT

Sl no.	Port name	Port country	Port operator
	Yangpu	China P.R.	SDIC Jurong
	Bilbao	Spain	Bilbao Port
	Malaga	Spain	Port of Malaga
	Montreal	Canada	Montreal Port Auth
	Fremantle	Australia	Fremantle Ports
	Malmo	Sweden	CopenhagenMalmo Port
	Ijmuiden	Netherlands	Port of Ijmuiden
	Huelva	Spain	Port of Huelva
	Escombreras	Spain	Puerto de Cartagena
	Risavika	Norway	
	Santander	Spain	Port of Santander
	Fraser Mills	Canada	Port of Vancouver
	Puerto De Sagunto	Spain	Valenciaport
	Esbjerg	Denmark	Port of Esbjerg
	Devonport	Australia	
	Gijon	Spain	Port of Gijon
	Bodo	Norway	
	Cuxhaven	Germany	Niedersachsen Ports
	Eemshaven	Netherlands	Groningen Seaports
	Gongdan	South Korea	
	Vaasa	Finland	
	Szczecin	Poland	Port Szczecin
	Brest	France	Port of Brest
	Hamilton	Canada	Hamilton Oshawa Port
	Blang Lancang	Indonesia	Blang Lancang Port
	Brownsville	United States	
	Kokkola	Finland	
	Kitakyushu	Japan	Kitakyushu Seaport
	Honfleur	France	
	Galveston	United States	Port of Galveston
	Corpus Christi	United States	Corpus Christi Port
	Ibaraki	Japan	Ibaraki port authori
	New Orleans	United States	Port of New Orleans
	Port Arthur	United States	

5. LPG Bunkering

S. No.	Port Name	Port Country	Port Operator
LPG Bunkering STS			
	Portland	United Kingdom	Portland Port UK

6. Methanol Bunkering

S. No.	Port Name	Port Country	Port Operator
Methanol Bunkering			
	Ulsan	East Asia	Ulsan Port Auth
	Yokohama	East Asia	Yokohama Port
	Klaipeda	United Kingdom/Continent	Klaipeda Seaport
	Gdynia	United Kingdom/Continent	Port of Gdynia
	Amsterdam	United Kingdom/Continent	Amsterdam Port
Methanol Bunkering STS			
	Singapore	Singapore	MPA Singapore
	Rotterdam	Netherlands	Port of Rotterdam
	Yangshan	China P.R.	SIPG
	West Port Said	Egypt	Suez Canal Zone
	Antwerp	Belgium	Port Antwerp-Bruges
	Houston	United States	Port of Houston
	Ulsan	South Korea	Ulsan Port Auth
	Shanghai	China P.R.	SIPG
	Tianjin	China P.R.	Tianjin Port Group
	Zhoushan	China P.R.	Ningbo Zhoushan Port
	Yantian	China P.R.	Shenzhen Port Group
Methanol Bunkering Terminal			
	Savannah	United States	Georgia Ports Auth
	Frederikshavn	Denmark	Port Frederikshavn
	Gothenburg	Sweden	Gothenburg Port
	Melbourne	Australia	Melbourne Port Corp.
	Townsville	Australia	Port of Townsville
Methanol Bunkering TTS			
	Nansha	China P.R.	Guangzhou Port Grp
	Gothenburg	Sweden	Gothenburg Port
	Antwerp	Belgium	Port Antwerp-Bruges

S. No.	Port Name	Port Country	Port Operator
Bio Methanol Bunkering Terminal			
	Geismar	United States	
E Methanol Bunkering STS			
	Singapore	Singapore	MPA Singapore
	Gothenburg	Sweden	Gothenburg Port
	East Port Said	Egypt	Suez Canal Zone
E Methanol Bunkering Terminal			
	Onsan	South Korea	Ulsan Port Authority
	Ronne	Denmark	Ronne Havn
E Methanol Bunkering			
	Salalah	Middle East	Salalah Port Service
	East Port Said	Mediterranean / Black Sea	Suez Canal Zone
	Ain Sokhna	Middle East	Suez Canal Zone
	Duqm	Middle East	Port of Duqm

Annexure III

Alternative Fuel Feedstock and Supply (India)

A) Ammonia

S. No.	Project Name	Date	Status	Technology Details	Capacity		Technology Partners	Ref.
					Production Rate	Normalized Production Rate (Tonnes)		
1	Anil urea plant	2030	Concept	wind + solar	2 GW	5,600,000 t/y	Total Energies + Adani	1
2	ABC Cleantech H2	2027	Concept	Unknown	1275MW	5,000,000 NH_3/t/y	ABC Cleantech+ Axis Energy Group	3
3	Greenko green ammonia project	2026	Concept	Unknown	3440MW	-	-	
4	Hydreen HLC Green Energy Himachal Pradesh H2	2027	Concept	Unknown	300 kt H2/y production	1,500,000 t/y		4
5	Karnataka Acme H2	2027	Concept	Unknown	200 kt H2/y production	1,100,000 t/y		6
6	Ammonia plant Deendayal Port - Site Kandla in Gujarat	2027	Concept	Unknown	133 kt NH3/y production	133,000 t NH_3/y		11
7	Ammonia plant Kota - Rajasthan state - phase 1	2025	Concept	Unknown	15 kt NH3/y capacity	15,000 t NH_3/y		11

S. No.	Project Name	Date	Status	Technology Details	Capacity		Technology Partners	Ref.
					Production Rate	Normalized Production Rate (Tonnes)		
8	ReNew-Jera plant in Odisha		Concept	Unknown	100kt NH3/y production	100,000 t NH_3/y		11
9	ReNew Power Kerala plant, phase 2		Concept	Unknown	500kt NH3/y production	5,000,000 t NH_3/y		11
10	ReNew Power Kerala plant, phase 3		Concept	Unknown	500kt NH3/y production	5,000,000 t NH_3/y		11
11	INOX Air Products - Maharashtra government MoU		Concept		500kt NH3/y capacity	5,000,000 t NH_3/y		11
12	Torrent ammonia plant	2027	Concept	Solar PV	100 kt NH3/y production	1,000,000 t NH_3/y		11
13	ACME Tamil Nadu plant - Chidambaranar port	2030	Feasibility study	Solar PV	1.5GW - 3300 t NH3/d	1,204,500 t NH_3/y		11
14	ACME Odisha Plant	2028	Feasibility study	Solar PV	1.5GW - 3300 t NH3/d	1,204,500 t y		11
15	JSW Karnataka H2	2027	Feasibility study	Unknown	3.8 kt H2/y production	1,000,000 NH_3/t/y		5
16	Ocior Energy Andhra Pradesh H2	2030	Feasibility study	Unknown	46.68 t H2/y production	1,000,000 NH_3/t/y		7
17	Ocior Energy Gujarat H2	2030	Feasibility study	Unknown	2628 t H2/y production	1,000,000 NH_3/t/y		7
18	POSCO H2	2027	Feasibility study	Unknown	10 t H2/y production	5,000,000 NH_3/t/y		8
19	Renew Efuels Odisha Green H2	2027	Feasibility study	Unknown	365 t H2/y production	1,200,000 NH_3/t/y		9

S. No.	Project Name	Date	Status	Technology Details	Capacity		Technology Partners	Ref.
					Production Rate	Normalized Production Rate (Tonnes)		
20	Ammonia project Avaada Odisha		Feasibility study	Unknown	500 kt NH_3/y production	500,000 t NH_3/y		11
21	Waaree Odisha plant		Feasibility study	Unknown	1.2Mt NH_3/y production	1,200,000 NH_3/t/y		11
22	EG Solwin Hybrid - Enfinity Global ammonia plant in Tata Steel Special Economic Zone		Feasibility study	Unknown	300kt NH_3/y production	300,000 t NH_3/y		11
23	Sembcorp Gopalpur project		Feasibility study		720kt NH_3/y production	720,000 t NH_3/y		11
24	Hygenco Gopalpur GNH3 Plant- Tata Steel Special Economic Zone MoU, phase 1	2026	Feasibility study	Others/ Various	600 t NH_3/day production	219,000 t NH_3/y		11
25	Hygenco Gopalpur GNH3 Plant - Tata Steel Special Economic Zone MoU, phase 2		Feasibility study	Others/ Various	3.2 kt NH_3/day production	1,168,000 t NH_3/y		11
26	ReNew Power Kerala plant, phase 1	2027	Feasibility study	Unknown	100kt NH_3/y production	1,000,000 t NH_3/y		11
27	Greenko ZeroC - Kakinada city	2027	FID/ Construction	Others/ Various	1.3GW	250,000 t NH_3/y		2
28	Rajasthan pilot plant	2021	Operational	Solar PV	5t NH_3/day - 2.1MW	**1,825 t NH_3/y**		11

B) Methanol

S.No.	Project Name	Date	Status	Technology Details	Capacity		Other Details	Ref.
					Given Production Rate (Source: IEA & GENA)	Normalized Production rate (Tonnes/ y)		
	NTPC-Technip-L&T MeOH project, Vindhyachal	2024	FID/ Construction	PEM	10 TPD	3,650 t/y	NTPC is also working to setup two other units along with Hydrogen generation. Firstly, a CO2 capture facility that captures CO2 from flue gas stream of the Coal-fired power plant. Secondly, a Methanol unit that uses the captured CO2 and Hydrogen through a PEM electrolyzer to convert it into green Methanol.	11
	ReNew E-Fuels Private Limited green Methanol plant - Malkangiri	-	Concept	Other Electrolysis	500 kt MeOH/y production	500,000 t/y		11
	ReNew E-Fuels Private Limited green Methanol plant - Rayagada	-	Concept	Other Electrolysis	300 kt MeOH/y production	300,000 t/y		11

B) Methanol

S.No.	Project Name	Date	Status	Technology Details	Capacity		Other Details	Ref.
					Given Production Rate (Source: IEA & GENA)	Normalized Production rate (Tonnes/ y)		
	Thermax + IIT Delhi (CO2 to Methanol)	-	Feasibility or pre feasibility	CO2-to-Methanol	1.4 t/day	511 t/y	Designed to account for CO_2 emissions from power plants, cement, steel, fertilizer, and refineries.	10
	(NTPC REL) & Gujarat Alkalies Chemicals Ltd (GACL)	2029	Feasibility or pre feasibility		75 t/day	27,375 t/y		10

C) Hydrogen

S. No.	Project Name	Date	Status	Technology Details	Technology Electricity Eetails	Capacity		Ref.
						Given Production Rate (Source: IEA)	Converted production rate (tonnes/ y)	
1	Dalstur Energy Coal India coal Hydrogen		Concept	Coal w CCUS		-	-	11
2	Carbon Governance green Hydrogen project, phase 1	2026	Concept	Other Electrolysis	Solar PV	30 t H2/d (production)	10,950 t H_2/y	11
3	Carbon Governance green Hydrogen project, phase 2	2028	Concept	Other Electrolysis	Solar PV	60 t H2/d (production)	21,900 t H_2/y	11
4	Carbon Governance green Hydrogen project, phase 3	2033	Concept	Other Electrolysis	Solar PV	115 t H2/d (production)	41,975 t H_2/y	11
5	Adani H2	2030	Concept	Other Electrolysis	Unknown	1000 kt H2/y production	1,000,000 t H_2/y	11
6	Chitrakoot H2	2026	Concept	Other Electrolysis	Unknown	129.3 kt H2/y production	1,293,000 t H_2/y	11
7	Larsen & Toubro/ReNew Power Project	2025	Concept	Other Electrolysis	Unknown	21.9 kt H2/y production	21,900 t H_2/y	11
8	Maharashtra H2	2025	Concept	Other Electrolysis	Unknown	50 kt H2/y production	50,000 t H_2/y	11
9	NTPC NETRA Campus	2030	Concept	PEM	Unknown	547.5 kt H2/y production	547,500 t H_2/y	11
10	Indian Oil Corporation IOCL refinery	2030	Concept	Biomass		350 kt H2/y production	350,000 t H_2/y	11
11	Chennai Petroleum Corporation (CPCL) - phase 1	2027	Concept	Other Electrolysis	Unknown	1 kt H2/y production	1,000 t H_2/y	11
12	Chennai Petroleum Corporation (CPCL) - phase 2	2030	Concept	Other Electrolysis	Unknown	5 kt H2/y production	5,000 t H_2/y	11
13	MRPL Mangalore Refinery - phase 1	2025	Concept	Other Electrolysis	Unknown	0.5 kt H2/y production	500 t H_2/y	11

S. No.	Project Name	Date	Status	Technology Details	Technology Electricity Eetails	Capacity		Ref.
						Given Production Rate (Source: IEA)	Converted production rate (tonnes/ y)	
14	MRPL Mangalore Refinery - phase 2	2030	Concept	Other Electrolysis	Unknown	5 kt H_2/y production	5,000 t H_2/y	11
15	Essar-Gujarat MoU		Concept	Other Electrolysis		1GW	175,200 t H_2/y	11
16	Pudimadaka Green Hydrogen hub		Concept	Other Electrolysis		1.2 kt H_2/d production	438,000 t H_2/y	11
17	Welspun ammonia project	2029	Concept	Other Electrolysis		170 kt H_2/y production -	170,000 t H_2/y	11
18	Savli wind-Hydrogen demo project	2013	DEMO	Other Electrolysis		0.005MW	0.88 t H_2/y	11
19	MCRC bio-Hydrogen facility Chennai	2015	DEMO	Biomass		12m3 H_2/h	9.46 t H_2/y	11
20	Hygenco Demonstration Plant	2022	DEMO	ALK	Solar PV	100kW	17.52 t H_2/y	11
21	Chochin Airport Hydrogen project		DEMO	Other Electrolysis		1000 kW	175.2 t H_2/y	11
22	Sonam Nurboo Memorial Hopsital		Feasibility study	Other Electrolysis	Unknown	25MW	4,380 t H_2/y	11
23	Panipat refinery	2028	Feasibility study	Other Electrolysis	Unknown	10 kt H_2/y production	10,000 t H_2/y	11
24	Tamil Nadu project	2024	Feasibility study	PEM	Solar PV	-	-	11
25	Indian Oil Corporation Koyali refinery	2026	Feasibility study	NG w CCUS		0.7Mt CO_2/y (part for CCU)	72,500 t H_2/y	15
26	JSW Steel	2025	Feasibility study	ALK	Unknown	12MW	2,102.4 t H_2/y	11
27	Aranayak Mirzapur H2	2025	Feasibility study	Biomass		365 t H_2/y production	365 t H_2/y	11

S. No.	Project Name	Date	Status	Technology Details	Technology Electricity Eetails	Capacity		Ref.
						Given Production Rate (Source: IEA)	Converted production rate (tonnes/ y)	
28	Badarpur New Delhi H2	2027	Feasibility study	Other Electrolysis	Unknown	94.9 t H2/y production	94.9 t H_2/y	11
29	Bellary-Nellore H2	2027	Feasibility study	Other Electrolysis	Unknown	5 kt H2/y production	5,000 t H_2/y	11
30	Bina Refinery	2025	Feasibility study	Other Electrolysis	Unknown	3232.47 t H2/y production	3,232.47 t H_2/y	11
31	Chamba H2	2026	Feasibility study	Other Electrolysis	Unknown	7.3 t H2/y production	7.3 t H_2/y	11
32	Indore Waste to H2	2026	Feasibility study	Biomass		52.56 kt H2/y production	52,560 t H_2/y	11
33	JSW green Hydrogen	2026	Feasibility study	Other Electrolysis	Unknown	3.65 t H2/y production	3.65 t H_2/y	11
34	Kochi Green Hydrogen (KGH2) Hub	2027	Feasibility study	Other Electrolysis	Unknown	0.73 t H2/y production	0.73 t H_2/y	11
35	Leh H2	2027	Feasibility study	Other Electrolysis	Unknown	5 kt H2/y production	5,000 t H_2/y	11
36	L&T Hazira Phase II	2025	Feasibility study	PEM	Unknown	1 MW	175.2 t H_2/y	11
37	Madhya Pradesh H2	2040	Feasibility study	Other Electrolysis	Unknown	16.43 t H2/y production	16.43 t H_2/y	11
38	MAHAPREIT	2027	Feasibility study	Other Electrolysis	Unknown	64.02 t H2/y production	64.02 t H_2/y	11
39	NMC Green Hydrogen	2026	Feasibility study	Biomass		808.12 t H2/y production	808.12 t H_2/y	11
40	Numaligarh Refinery Green H2	2027	Feasibility study	Other Electrolysis	Unknown	10 kt H2/y production	10,000 t H_2/y	11
41	Pune-Mumbai	2030	Feasibility study	Other Electrolysis	Unknown	3650 t H2/y production	3,650 t H_2/y	11

S. No.	Project Name	Date	Status	Technology Details	Technology Electricity Eetails	Capacity		Ref.
						Given Production Rate (Source: IEA)	Converted production rate (tonnes/ y)	
42	SOEC demonstrator Bangalore	2025	Feasibility study	SOEC	Unknown	0.85 t H2/y production	0.85 t H_2/y	11
43	Swaraj Green Power H2	2026	Feasibility study	Biomass		36.5 t H2/y production	36.5 t H_2/y	11
44	Visakhapatnam H2	2025	Feasibility study	Other Electrolysis	Unknown	1569 t H2/y production	1,569 t H_2/y	11
45	Waaree Renewable Technologies H2	2024	Feasibility study	Other Electrolysis	Unknown	720 t H2/y production	720 t H_2/y	11
46	WBPDCL Durgapur H2	2027	Feasibility study	Other Electrolysis	Unknown	4 kt H2/y production	4,000 t H_2/y	11
47	Mathura refinery		FID/ Construction	Other Electrolysis	Onshore wind	5 kt H2/y	5,000 t H_2/y	11
48	NTPC green Hydrogen mobiity project - Ladakh	2024	FID/ Construction	ALK	Solar PV	0.8MW	140.16 t H_2/y	11
49	NTPC Green Hydrogen Mobility Project - Delhi	2024	FID/ Construction	ALK	Unknown	1.6 MW	280.32 t H_2/y	11
50	Chusul Project	2025	FID/ Construction	PEM	Solar PV	1 MW	175.2 t H_2/y	11
51	HPCL Vizag Refinery H2	2024	FID/ Construction	Other Electrolysis	Unknown	2.4MW	420.48 t H_2/y	11
52	PMC Waste to H2 Phase I	2024	FID/ Construction	Biomass		2 kt H2/y production	2,000 t H_2/y	11
53	Hygenco Sterlite GH2 Plant		FID/ Construction	ALK	Others/ Various	1.8 Mwel	170 t H_2/y	14
54	Hazira, Reliance, back-up Hydrogen supply	2005	Operational	ALK		-	536 t H_2/y	13
55	Centre of Fuel Cell Technology, Chennai	2012	Operational	PEM		2 Nm3/h	1.6 t H_2/y	13

S. No.	Project Name	Date	Status	Technology Details	Technology Electricity Eetails	Capacity		Ref.
						Given Production Rate (Source: IEA)	Converted production rate (tonnes/ y)	
56	Dahej, Reliance, back-up Hydrogen supply	2014	Operational	ALK		444 Nm3 H2/h	350 t H_2/y	13
57	Gwalpahari Solar-Hydrogen demonstration	2015	Operational	Other Electrolysis	Solar PV	0.12MW	21 t H_2/y	13
58	Solar Energy Centre SmartFuel Hydrogen station	2015	Operational	Other Electrolysis	Solar PV	-	-	11
59	GAIL Vijaipur project	2024	Operational	PEM	Unknown	10 MW	1,752 t H_2/y	11
60	NTPC Green Hydrogen Blending Project (Kawas, Surat)	2023	Operational	PEM	Unknown	6.5 kW	1.14 t H_2/y	11
61	Hygenco JSL Plant	2024	Operational	ALK	Solar PV	1.8 Mwel -78 t H2/y production	78 t H_2/y	11
62	Hydrogen Based Microgrid at NETRA	2024	Operational	PEM	Unknown	0.34 MW	59.59 t H_2/y	11
63	Gwalpahari Solar-Hydrogen demonstration	2015	Operational	Other Electrolysis	Unknown	19.4 t H2/y production	19.4 t H_2/y	11
64	Jindal Hygenco India	2024	Operational	ALK	Solar PV	1.8 MW	315.36 t H_2/y	11
65	Jorhat H2	2022	Operational	Other Electrolysis	Unknown	75 t H2/y production	75 t H_2/y	11
66	L&T Hazira Phase I	2024	Operational	PEM	Unknown	1 MW	175.2 t H_2/y	11

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