A Route to Reducing Maritime Emissions

A 2024 ClimateCAP Project

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About Myself

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2014-2018: United States Naval Academy

- B.S. Mechanical Engineering
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- 2018-2019 Naval Nuclear Power School and Prototype
- 2020-2023 Submarine Officer, USS OHIO (GOLD)

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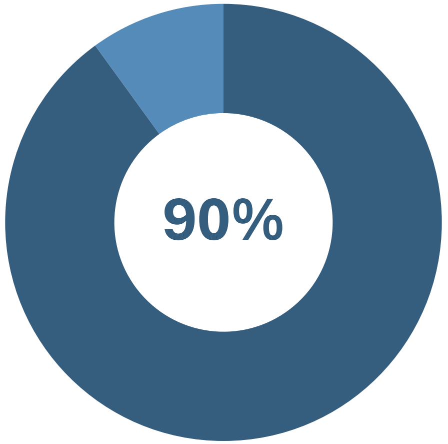
Executive Summary

- Maritime shipping is a vital sector of the global economy that requires prompt action to meet climate-related goals
- Shipping's international nature and need for energy-dense fuels complicate efforts to reduce greenhouse gas emissions
- Successfully reducing maritime emissions will require significant uptake in energy efficient solutions and a shift to alternative fuels supported by key pillars of partnerships, policy, and infrastructure development
  - While reducing shipping consumption and energy efficiency solutions can have a material impact, shifting to alternative fuels will be necessary to completely eliminate greenhouse gas emissions
  - While there is no clear winner amongst alternative fuels to be adopted by the maritime community, LNG offers one of the best near-term options for shipowners to begin to reduce their emissions
  - Regardless of the fuel pathway chosen, partnerships, the right policy, and scaling up fluid and power transmission quickly can catalyze the development and adoption of alternative fuels by reducing and, or sharing risks associated with them

Maritime shipping is projected to remain an important part of the global economy

The State of Maritime Trade in 2023

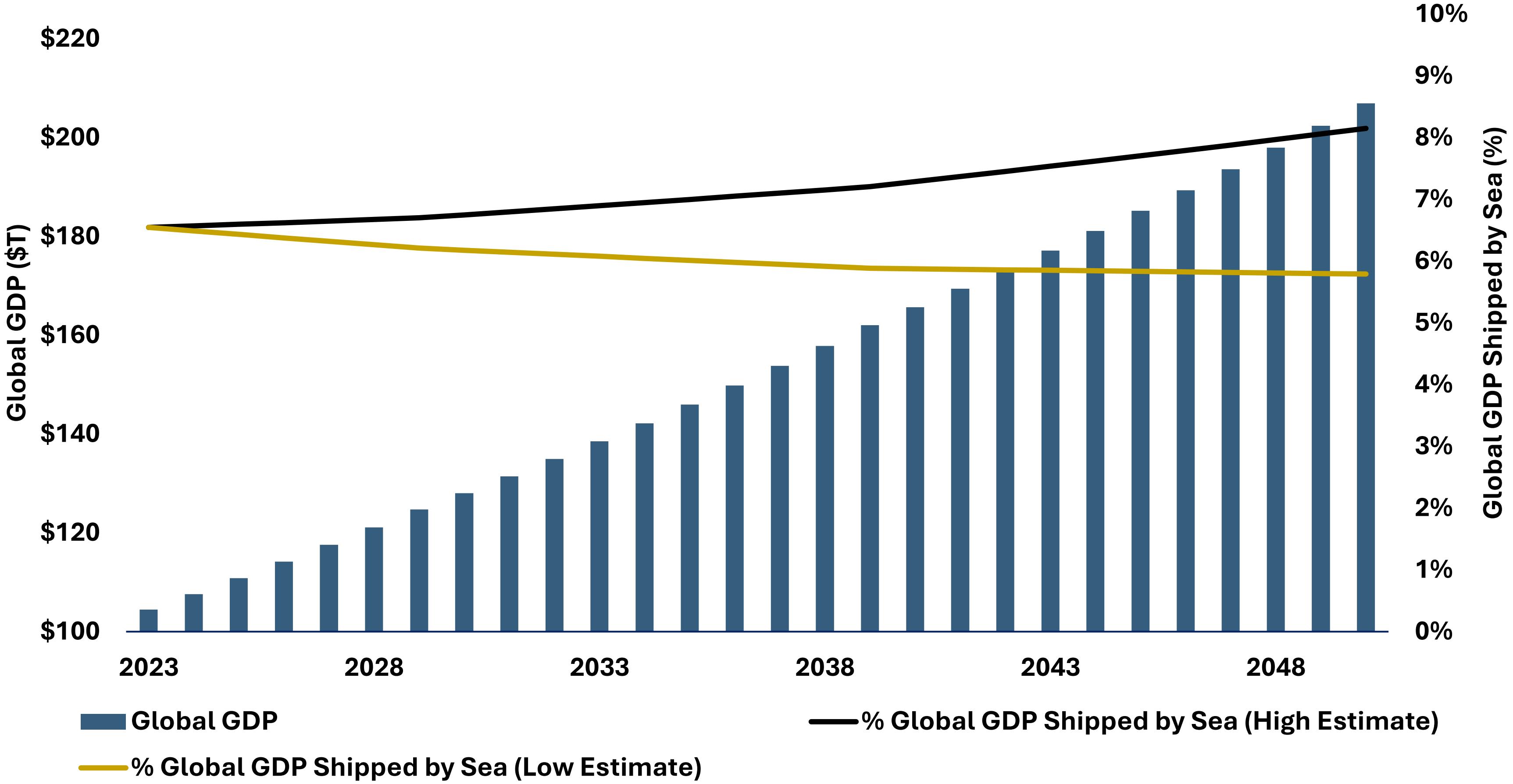


Percentage of Global Trade Traveling By Sea

$380 Billion

In Global Freight Revenues

Figure 1: Forecasted Global GDP Shipped by Sea (2023-2050)



Note: Low estimate assumes a 2.1% shipping growth rate; High estimate assumes 3.4% shipping growth rate; GDP growth rate assumed to be 3% 2024-2029, 2.65% 2030-2039, and 2.25% 2040-2049

Sources: Goldman Sachs, Global Economics Paper The Path to 2075; Maritime Executive, Global Freight Demand to Triple by 2050; UNCTAD Review of Maritime Transport 2023; International Chamber of Shipping: Shipping and World Trade: World Seaborne Trade

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Maritime shipping is a significant contributor to overall global greenhouse gas emissions and without prompt and drastic action, 2050 net-zero goals will not be met

A sizeable GHG footprint

Current Status:

2.8%

Maritime Shipping's 2023 contribution to global greenhouse gas (GHG) emissions

Results from Inaction:

50%

The potential increase from 2008 carbon dioxide (CO_2) emission levels experienced by 2050

17%

Potential global CO_2 emissions coming from shipping by 2050

An immediate turn-around strategy would be needed to meet climate-related targets

- The International Energy Agency (IEA) recognizes that shipping decarbonization trends are *"either in the wrong direction or substantially insufficient to get in line by 2030 with the Net Zero by 2050 Scenario trajectory"*
- Design changes will take time to be adopted throughout the global fleet
  - Ships are durable goods with effective lifespans reaching over 25 years
- Regulatory bodies such as the European Union (EU) and International Maritime Organization (IMO) have recognized the need for aggressive decarbonization policy

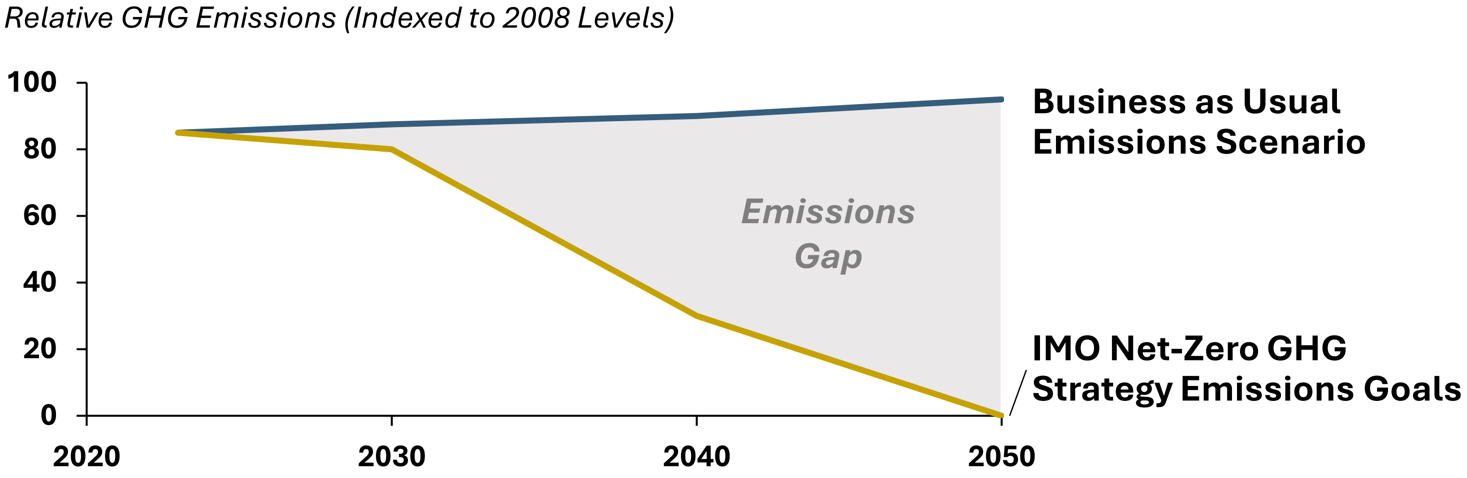


Figure 2: IMO GHG Strategy Ambitions and Checkpoints

Sources: UNCTAD Review of Maritime Transport 2023; 2023 DNV Maritime Forecast 2050 (Figure 2); Energy.gov, Ammonia as a Maritime Fuel; IEA, Tracking Clean Energy Progress – Global Shipping

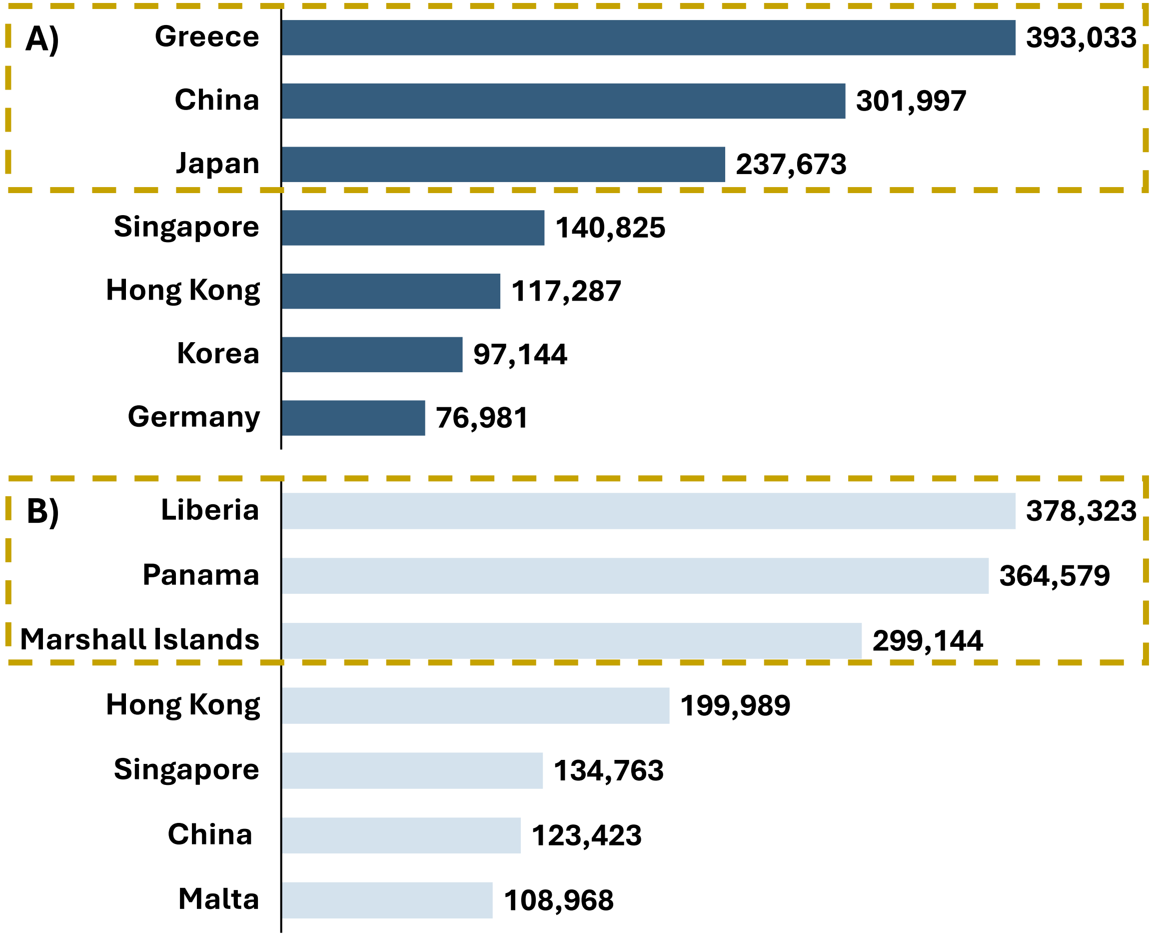
Reaching net-zero in maritime shipping requires overcoming challenges posed by a multinational environment…

Policymakers must overcome key obstacles in the way of promoting good behavior for shipping decarbonization:

- **Alignment of stakeholders across many different nations**
  - The nations where ships are registered, are owned, and travel between are generally not the same (*see figure 3)*
  - Disagreement may arise in several areas
    - The priority of reaching climate-friendly shipping emissions goals
    - How emissions controls are enforced
    - What is fair and equitable to developing nations (ex. Liberia and Panama)

- **Enforcement of regulations**
  - Routine monitoring of all vessels while sailing in international waters is likely infeasible
  - Work-arounds could occur
    - *Example: A maritime trade route is altered from one country with stringent shipping emissions controls to a neighbor with looser controls. Freight is then moved over land to the originally intended destination, avoiding emissions fines*

Figure 3: Top Maritime Shipping Countries (in Deadweight Tons) A) Country of Ownership and B) Country of Registration



Sources: Clarkson's Research via UNCTAD Review of Maritime Transport 2023 (Figure 3)

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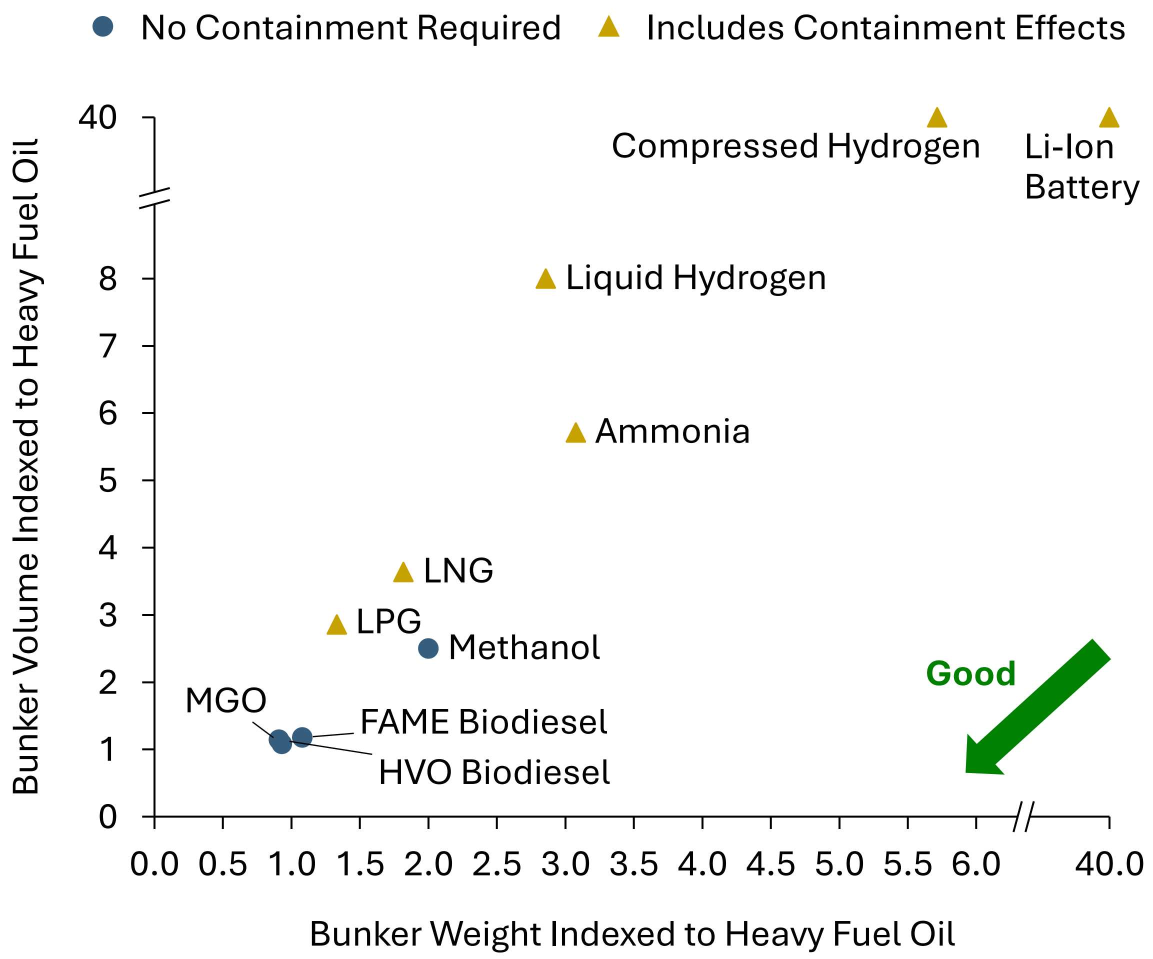
…as well as the need for an energy dense, scalable, low-carbon fuel solution

Energy dense, low-carbon transportation energy sources do not exist at the required scale to bring shipping to net-zero

- **Well-developed, low-carbon technologies such as Li-ion batteries with electric motors are not feasible options for large ocean-going vessels due to low energy density**
  - Ocean going vessels have significant spatial constraints
  - Containerships need immense amounts of power over routes which can last up to 45 days long
  - *The largest utility-scale battery storage plant in the US would fail to power a small containership (5000 TEU) operating at slow speeds for greater than 5 days*[i]

- **The remaining solution is to decarbonize through use of energy-dense liquids or gas-based fuels**
  - Mature "drop-in" alternative fuels lack the scale and carbon abatement required to be a complete solution:
    - Global biodiesel production stands at ~10% of global shipping fuel demand
    - On average, biodiesel pathways offer around only a 50% overall lifecycle emissions reduction compared to traditional fuels

Figure 4: Energy Density of Potential Maritime Fuels



i) Note: Considers Moss Landing Battery Storage Plant (750 MW, 4 hours of storage) and a small containership (5000 TEU) requiring 30 MW continuously at 19 kts

Sources: EIA.gov; Maersk, Sea Freight Guide; The Geography of Transport Systems – Chapter 4, Fuel Consumption by Containerships; Energy.gov, PNNL, Ammonia as a Maritime Fuel (Figure 4); TotalEnergies, The Drive for Cleaner Maritime Fuels, ResearchandMarkets.com (Through Businesswire) Global Biodiesel Market Analysis to 2030; LCFS Certified Pathways – California Air Resources Board

Eliminating maritime GHG emissions requires uptake in energy efficient solutions and shifting to alternative fuels supported by key pillars of partnerships, policy, and infrastructure deployment[i]

Bringing the global shipping fleet to net-zero will require a phased and flexible transition involving energy efficient solutions and alternative bunker fuels such as low-carbon LNG, methanol, and ammonia variants

- Energy-efficient design and operational solutions can help facilitate the transition to alternative maritime fuels
- While multiple alternative fuel options are available, no single solution exists to easily transition maritime shipping off fossil fuels, creating uncertainty and a need for optionality and flexibility
- LNG offers an immediate, partial decarbonization solution today as other less carbon intense fuel pathways develop
- Without rapid development, alternative low-carbon maritime fuels could be supply constrained in the near-term
- Transitioning to low-carbon fuels will result in a green premium that will need to be addressed through regulations or incentives
- Dual-fuel and conversion ready ships, fuel mixes, and carbon capture offsets can provide flexible cost and emissions solutions during the early stages of the transition to cleaner fuels

Key Supporting Factors Necessary to Catalyze the Development and Adoption of Alternative Maritime Fuels:

Strategic Partnerships

- Long term offtake agreements and shipping contracts, joint ventures, and technology sharing alliances are ways to share and reduce risk associated with alternative fuel adoption
- Examples of these partnerships exist across all fuel pathways

Policy and Regulation

- Through emissions restrictions and incentives, regulators can promote clean fuel adoption with minimal effect on the global economy
- Green Shipping Corridor Agreements can help reduce uncertainty around supporting infrastructure

Deploying Fluid and Power Transmission

- Greater amounts of fluid and power transmission will be necessary regardless of the fuel pathway chosen
- Several solutions exist to overcome challenges and opposition to deployment including reusing existing rights of way and optimal project siting

i) Note: Another potential solution is to reduce the overall amount of global shipping (i.e. nearshoring). This solution was not a part of this project's analysis as it has other, more complex supply chain and political implications which would need to be considered.

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Many energy efficiency solutions available today have potential to reduce maritime shipping fuel consumption by 2050, offsetting potential increases from growth in shipping demand

A variety of energy efficiency options exist for shipowners and builders to choose from

Maintenance and Operations

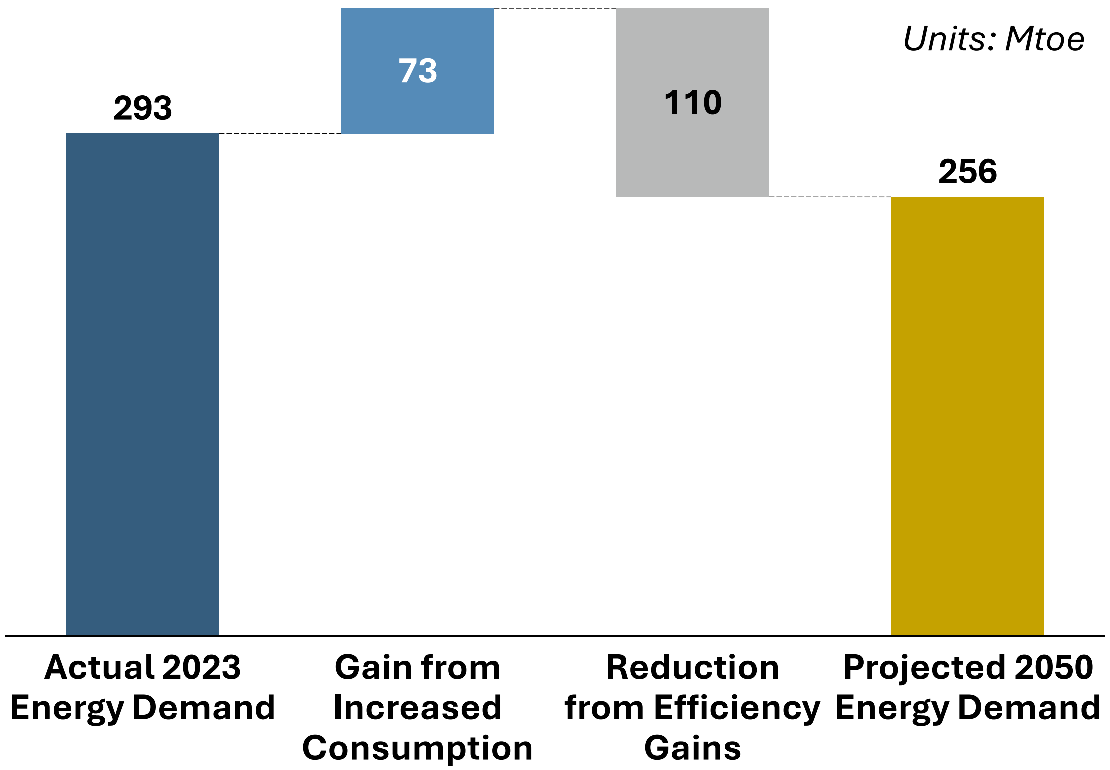
- Slow steaming
- Weather routing
- Hull and propellor maintenance
- Just-in-time operations
- Autopilot adjustment
- Steam plant operational Improvements
- Cold ironing
- Fully-loading ships

Technology and Design

- Hull coating and design improvements
- Propellor and engine improvements
- Reduced auxiliary loads
- Waste heat recovery
- Air lubrication
- Wind-assisted Propulsion
- Solar Panel Add-ons
- Fuel economies of scale with larger ships

Max Potential Emissions Reduction through Improved Fuel Economy: 30-40%

Figure 5: Maritime Shipping Fuel Consumption 2023-2050[(i)]



Energy efficiency is not a 100% solution; the remainder of emissions will need to be eliminated by transitioning to alternative, low-carbon fuels

(i) Note: See Appendix – Energy Demand an average between estimates provided by DNV and TotalEnergies
Sources: BCG, Voyaging Towards a Greener Maritime Future; 2023 DNV Maritime Forecast 2050; TotalEnergies, The Drive for Cleaner Maritime Fuels;

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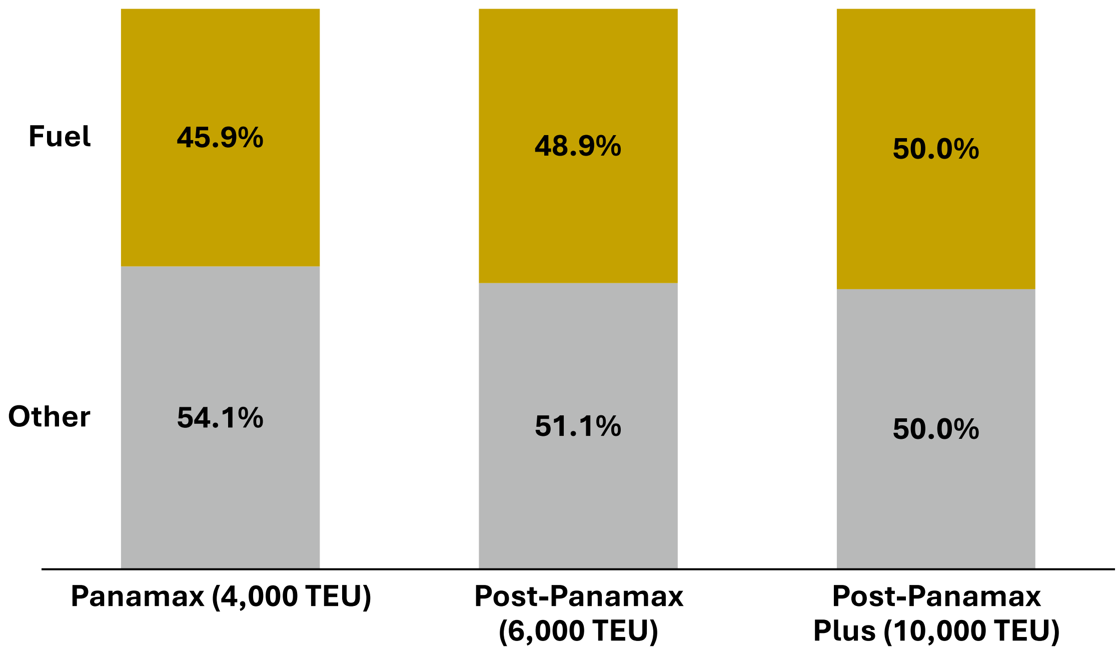
Energy efficiency can also help facilitate the long-term adoption of alternative fuels

Energy efficiency complements the adoption of low-carbon alternative fuels in several ways

- Mitigating supply shortages for nascent alternative fuels by suppressing fuel demand
- Easing tensions created by the need for greater onboard bunker capacity to accommodate lower energy density alternative fuels(i)
- Reducing total additional costs borne by shipping companies and, or customers (figure 6)

Figure 6: Typical Fuel Contributions to Maritime Shipping OpEx(ii)



- *Fuel is a major maritime shipping expense, ranging from 20% to 60% of OpEx depending on shipowner efficiency and scale*
- *Any green premium paid for low-carbon alternative shipping fuel will have a large impact on either shipping company margins or prices paid by shipping customers*

(i) Note: See Appendix
(ii) Note: TEU – Twenty Foot Equivalent Unit, a standard sized shipping container
Sources: Maersk Annual Financial Reports 2019-2023; Dewry Shipping Consultants via The Geography of Transport Systems (Rodrigue); Maritime Economics (Stopford) via Journal of Ocean Engineering and Science Vol 1 Issue 2 (2016); MoreThanShipping.com

Each alternative fuel must overcome its own unique challenges to decarbonize the global fleet

Fuel Attribute Overview	Traditional Biofuels Bio | Electro[i]		LNG Fossil | Bio | Electro			Methanol Bio | Electro		Ammonia Blue/Turquoise | Electro	
	Bio	Electro	Fossil	Bio	Electro	Bio	Electro	Blue/Turquoise	Electro
GHG Abatement	◑	●	◔	◕	●	◕	●	◕	●
Readiness for Fleet Adoption[ii]	●	●	◕	◕	◕	◑	◑	◔	◔
Existing Supply	◑	○	●	◔	○	○	○	○	○
Scalability	◔	◑	●	◔	◑	◔	◑	●	◕
Low Green Premium by 2050	◕	○	●	●	◑	◕	◔	◕	◕

● **Most Favorable** ○ **Least Favorable**

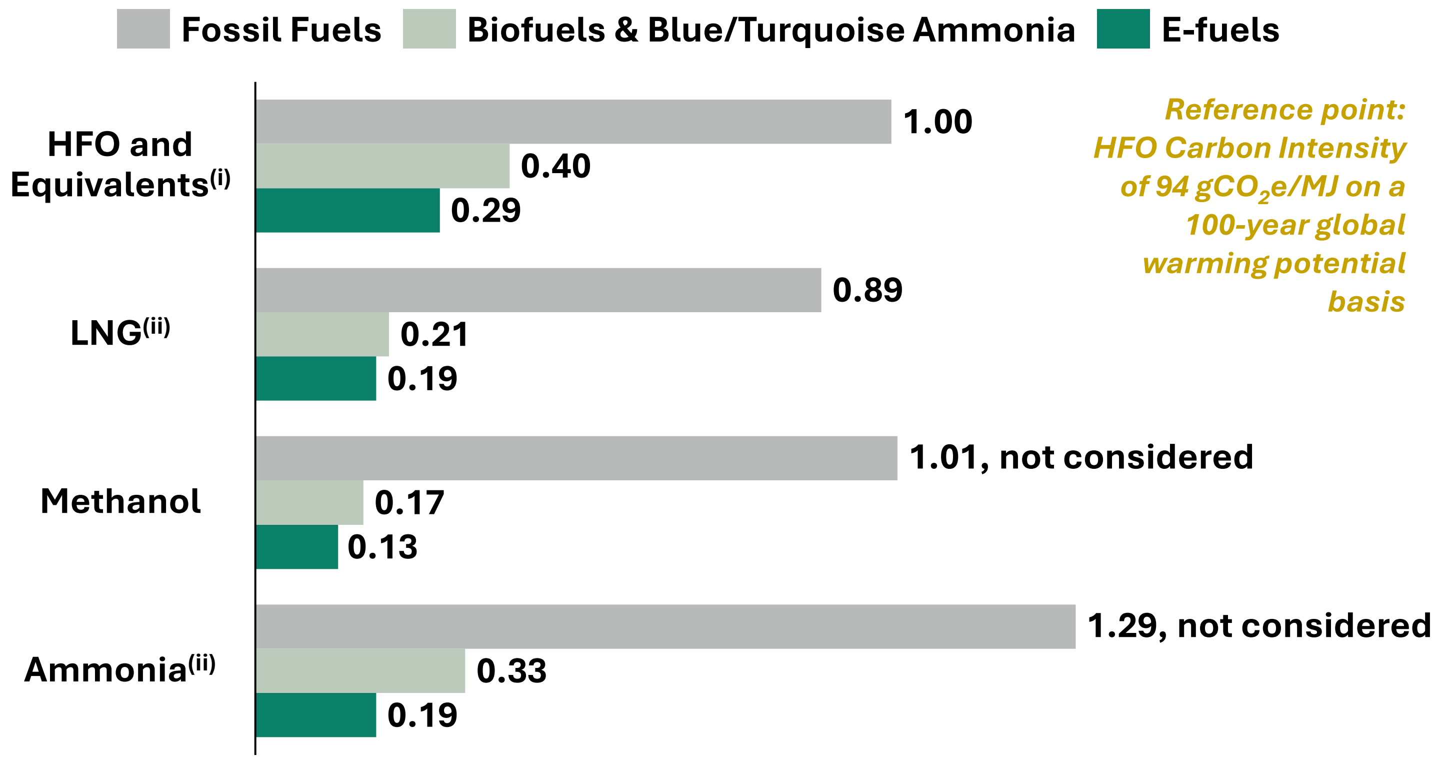
There is no "silver bullet" to decarbonizing maritime shipping; readily-available, partial solutions like fossil fuel LNG should be used today as less-carbon intense alternatives are developed and tested for large-scale commercialization

i) Note: While traditional biofuels are a viable short-term solution as the only true "drop-in" fuel, restricted biofeedstock supply and electrofuel price will prevent them from becoming a long-term pathway to helping shipping reach net-zero by 2050 and are therefore not considered in the following analysis.

ii) Note: "Readiness for Fleet Adoption" encompasses factors such as compatibility with existing ships and bunkering infrastructure, whether the fuel is allowed by existing regulation, and industry experience handling.

The next generation of maritime fuels has great potential to reduce GHG emissions

Figure 7: Average Alternative Fuel Lifecycle Carbon Intensity Relative to Heavy Fuel Oil (HFO)



- *No fuel completely eliminates lifecycle GHG emissions, requiring upstream segments of fuel value chains to decarbonize or offsets generated using carbon capture be used for shipping to reach net-zero*

Key Aspects to Consider

- **GHG emissions evaluated on a well-to-wake basis using gCO_2e/MJ as the functional unit, accounting for**
  - Emissions created and captured throughout fuel lifecycle
  - Differences in GHG warming effects
  - Difference in fuel energy density
- **Unintentional GHG releases**
  - Methane (CH_4) Slip: CH_4 not combusted, escaping in exhaust
    - ~25x 100-year GHG warming potential compared to CO_2
  - Nitrous oxide (N_2O) emissions as an ammonia combustion by-product
    - ~300x 100-year GHG warming potential compared to CO_2
- **Non-GHG emission reduction benefits**
  - Enhanced air-quality in coastal communities
  - Reduction in acid-rain contributors (sulfur and nitrogen-based emissions)

i) Note: Equivalents include renewable/biodiesel for biofuels and synthetic diesel for e-fuels
ii) Note: Effects of methane slip, nitrous oxide emissions, and imperfect carbon capture. Emissions performance can improve with better mitigation measures put in place
Sources: Methanol.org, Carbon Footprint of Methanol (2022), Marine Methanol Report (2023); Maersk McKinney Moller, LNG and Methane-based Marine Fuels (2021); California Air Resource Board, LCFS Pathways…; IRENA, Innovation Outlook – Renewable Ammonia (2022), Innovation Outlook – Renewable Methanol (2021)

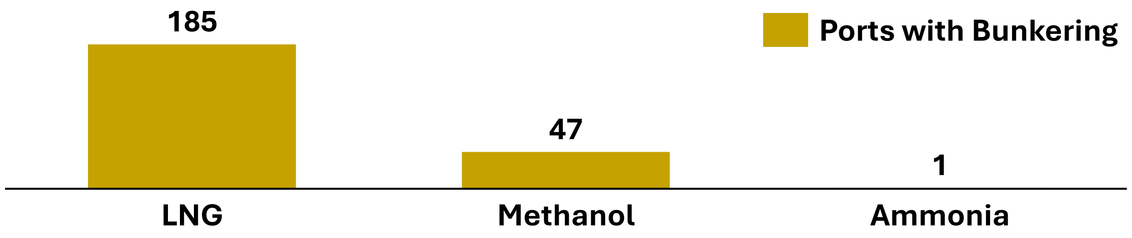
Existing bunkering experience, infrastructure compatibility, and recent book orders point to LNG variants as the most readily-deployable alternative shipping fuels

LNG and methanol fuels are currently ready to be used as bunker fuel alternatives

	LNG	Methanol	Ammonia
Allowed by IGC/IGF Regulation	Allowed	Allowed	Not Allowed[(i)]
Compatible Shipboard Bunkering And Engines *(See Appendix)*	Over 420 ships bunker LNG, including large containerships *(i.e. CMA CGM's Jacques Saade)*	20+ tankers bunker MeOH; containerships slowly adopting *(i.e. Maersk's Ane Maersk)*	No compatible ships exist outside of pilot projects *(i.e. Fortescue's Green Pioneer)*
Widespread Experience Safely Bunkering *(See Appendix)*	20+ years of industry-wide experience	Experience concentrated amongst MeOH traders only	No experience bunkering, but widely-traded internationally

Global port bunkering infrastructure is best positioned to support growth in LNG as an alternative bunker fuel

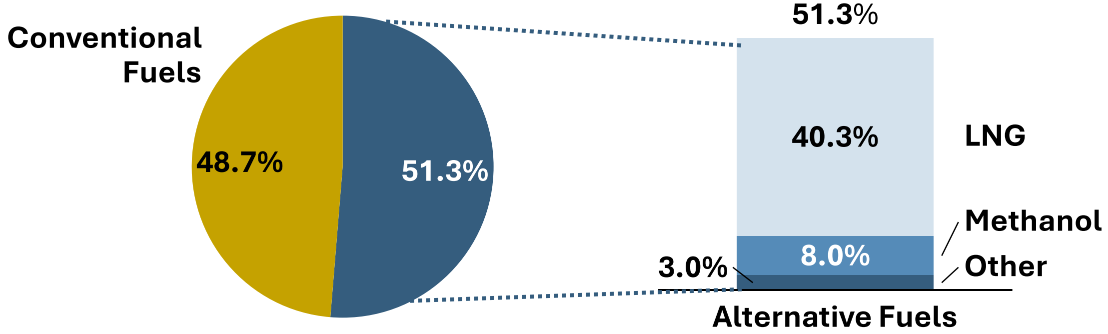
Figure 8: Global Ports with Bunkering Capabilities



- *100+ methanol and 200+ ammonia existing port terminals could be used as a foundation to expand current bunkering capacity*

Current ship book order supports using LNG fuel pathways over alternatives

Figure 9: World Fleet Alternative Fuel Uptake by Gross Tonnage

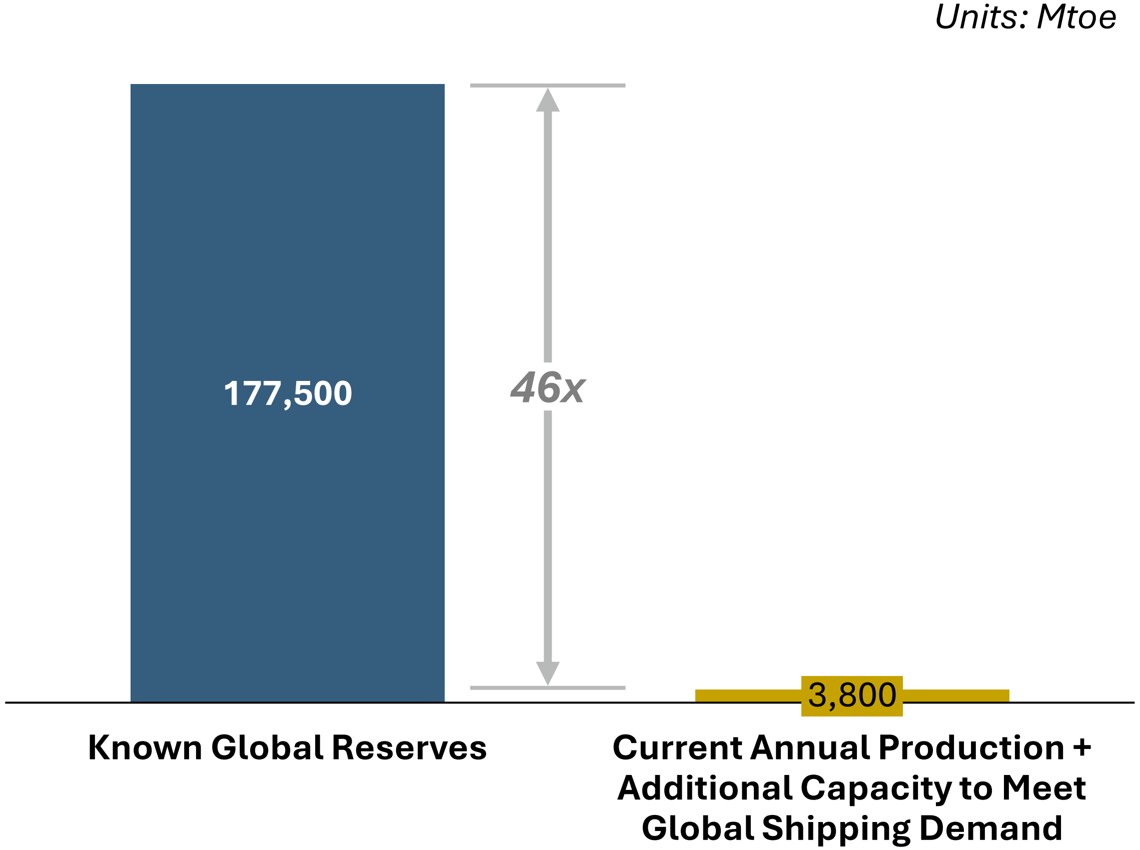


(i) Note: Interim guidelines have been agreed upon for use of ammonia as a fuel as of September 2024 at the IMC Sub-Committee on Carriage of Cargoes and Containers

Sources: PortEconomics.org, LNG powered vessels…; Energy.gov, PNNL, Ammonia as a Maritime Fuel; IMO, Amendments to the IGF Code… For Alternative Fuels and Related Technologies; (Figure 8) Offshore Energy.biz, 185 global ports can bunker LNG, Port of Rotterdam to fuel ships with methanol…; 2023 DNV Maritime Forecast 2050, Fortescue.com, Successful propulsion and maneuverability…; 2023 DNV Maritime Forecast 2050 (Figure 9)

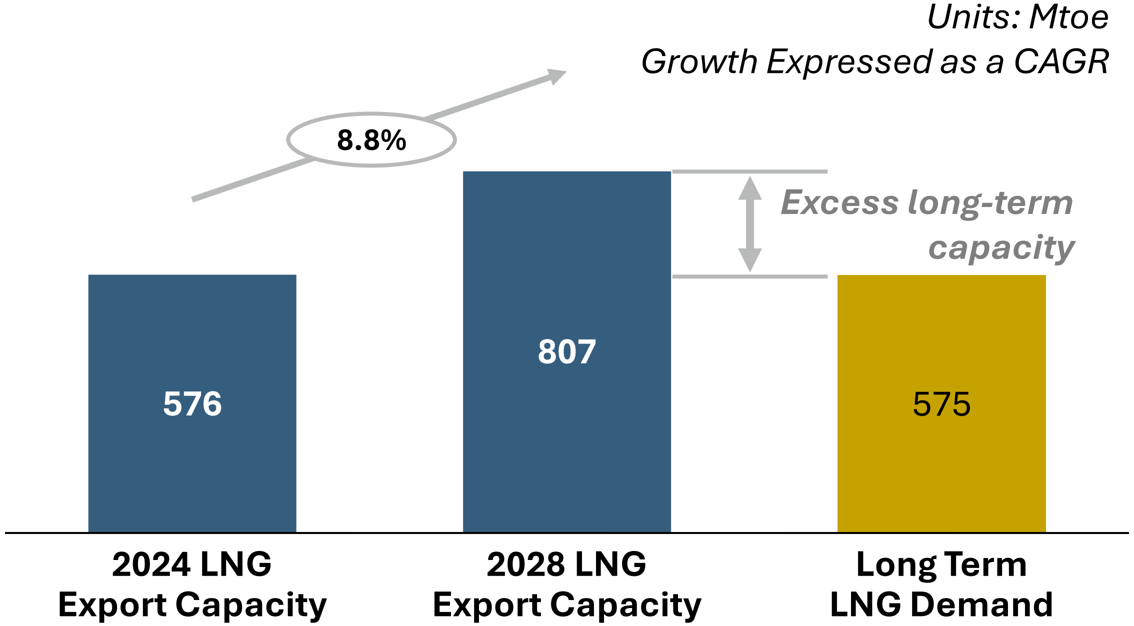
Shipping has a near-term opportunity to immediately reduce GHG emissions at-scale by leveraging existing fossil fuel natural gas supplies and growing LNG export capacity

Figure 10: An Abundant Global Natural Gas Supply (2023)



- *Only considering known reserves, the global fleet could be powered by natural gas for over **46 years***

Figure 11: A Growing Global LNG Export Capacity Surplus



- *High LNG prices in the early-2020s have incentivized a wave of new liquefaction projects to come online by 2028*
- *Meanwhile, LNG demand is projected to fall across Europe, Japan, and South Korea as these regions seek to reduce grid reliance on fossil fuels and energy imports*
- *Excess capacity in these key LNG import markets could be used to support offtake by the maritime shipping industry*

Sources: Statista.com, Global Natural Gas Production and Reserves (2023) (Figure 10); IEEFA, Global LNG Outlook 2024-2028 (Figure 11)

Though requiring much near-term development, renewable fuels of non-biological origin offer a long-term, fully-scalable, and complete emissions reduction solution for maritime shipping

Despite fast-paced near-term growth projections, clean fuel production lacks the scale for fleetwide adoption

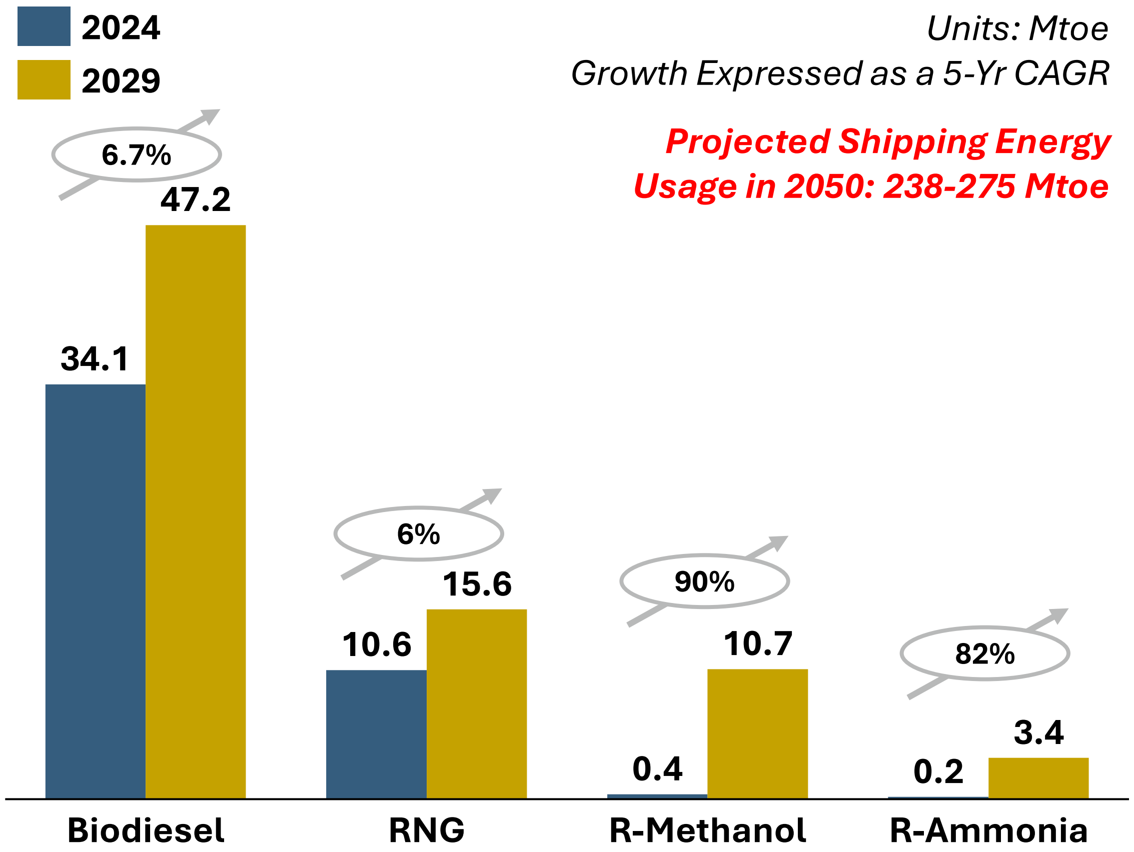


Figure 12: Near-term Projected Renewable Fuel Supply(i)

Feedstock constraints and competing demand will limit the procurement of renewable, biogenic fuels

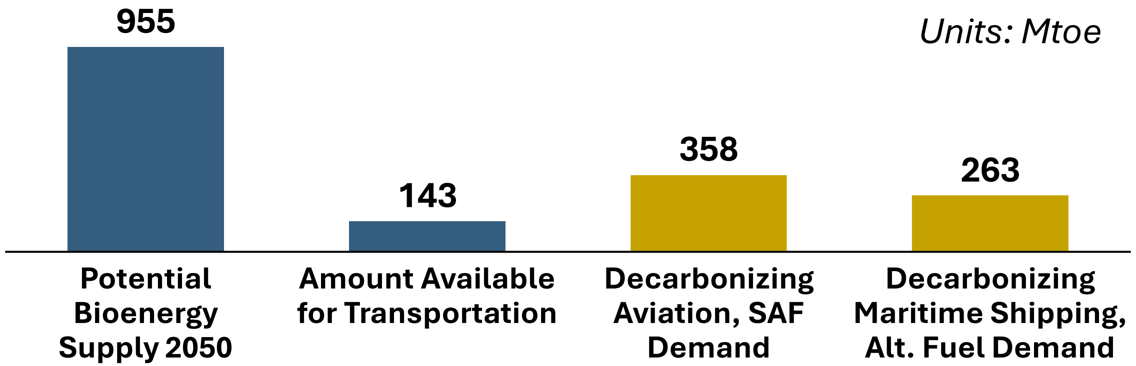


Figure 13: 2050 Biogenic Fuel Limitations(ii)

- *IRENA estimates only 15% of bioenergy supply will be secured by the transportation sector in their 1.5 C by 2050 scenario*
- *Under ideal circumstances, BCG estimates biogas-pathway fuels could only decarbonize up to 15-30% of global shipping*

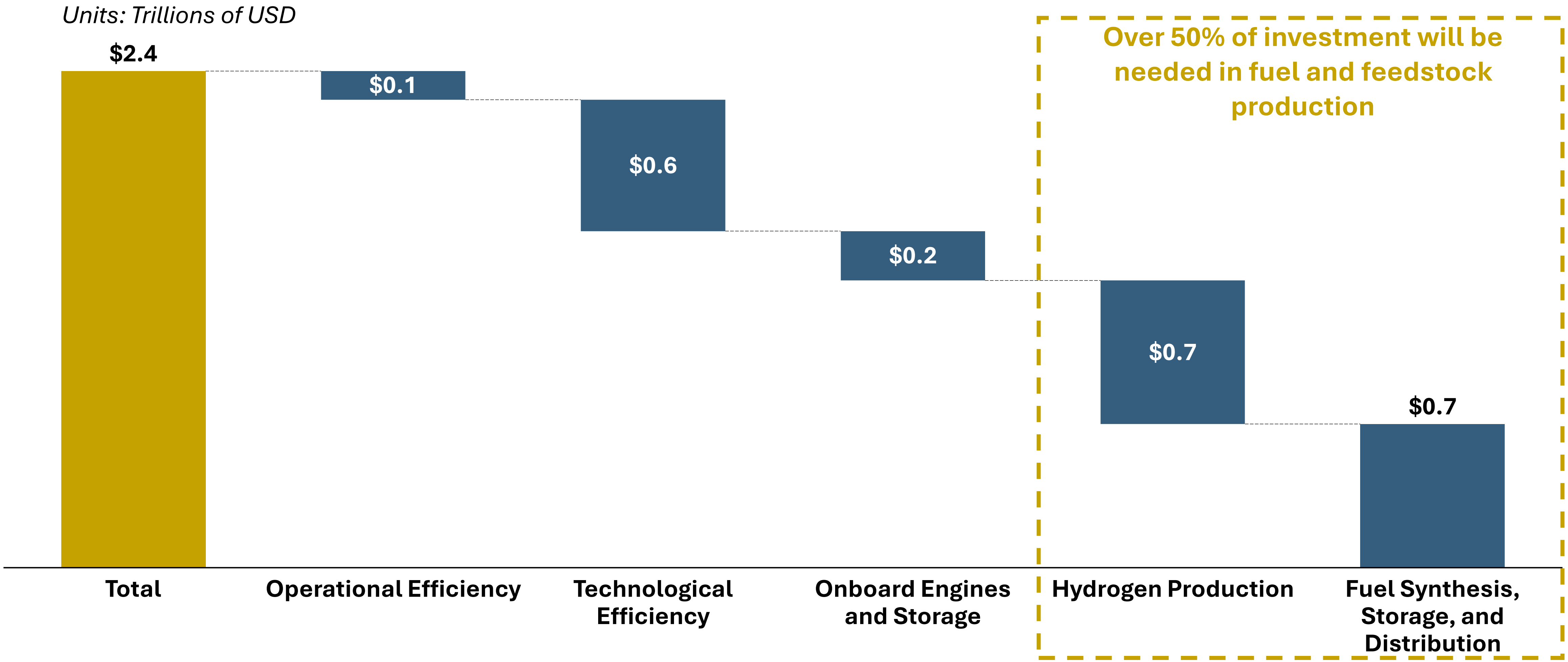
However, renewable fuels of non-biological origin (RFNBO) will not have similar feedstock limitations

- Using CO_2 or N_2 captured from the air and H_2 split from water or methane using carbon-neutral processes, unconstrained quantities of clean LNG, methanol, and ammonia are possible

i) Note: "R" indicates "Renewable," or variants of fuel that are sourced from biogenic or synthetic sources.
ii) Note: Bioenergy potential is widely debated with the most optimistic supply estimates as high as 5732 Mtoe. IRENA estimates a supply of 3654 Mtoe.
Sources: Research and Markets.com (Through BusinessWire), Global Biodiesel Market Analysis, Global Biomethane Market Analysis; Methanol Institute, Renewable Methanol; Irena.org, Innovation Outlook- Renewable Ammonia, Bioenergy in the Energy Transition; BCG.com, Biogas can help global shipping go green; IEA.org, Aviation…

Maritime shipping's transition to RFNBOs will depend on development in hydrogen production as well as fuel synthesis, storage, and distribution

Figure 14: Investment Needed to Achieve Net-Zero by 2050 in Maritime Shipping



Sources: BCG – Global Shipping's Net-Zero Transformation Challenge

Differences in processes used to create hydrogen feedstock, synthesize fuel, and sequester carbon drive the varying amounts of resources needed to transition to RFNBOs at scale

Based on Fleet Energy Demand of 238-275 Mtoe	Blue Ammonia[(i)]	Turquoise Ammonia[(i)]	e-Ammonia	e-Methanol	e-LNG
Hydrogen Production	Steam-Methane Reforming	Methane Pyrolysis	Water Electrolysis		
Hydrogen Required	105-115 MTPA			100-110 MTPA	105-115 MTPA
Carbon Capture	Requires usage or sequestering of carbon byproduct post-hydrogen production		Not Required	Requires capture of carbon as a feedstock to the fuel itself	
Carbon Capture Required	570-620 MTPA	310-340 MTPA (Solid Carbon Black)	None Required	725-790 MTPA	580-630 MTPA
Electricity Needed[(ii)]	60-70 TWh	300-360 TWh	4900-5700 TWh	5000-5800 TWh	5300-6100 TWh

Numbers in Perspective:

Annual Production of one 2.2 GW Nuclear Power Plant: **~17 TWh**

Amount of Carbon Dioxide Captured Globally in 2023: **49 MTPA**

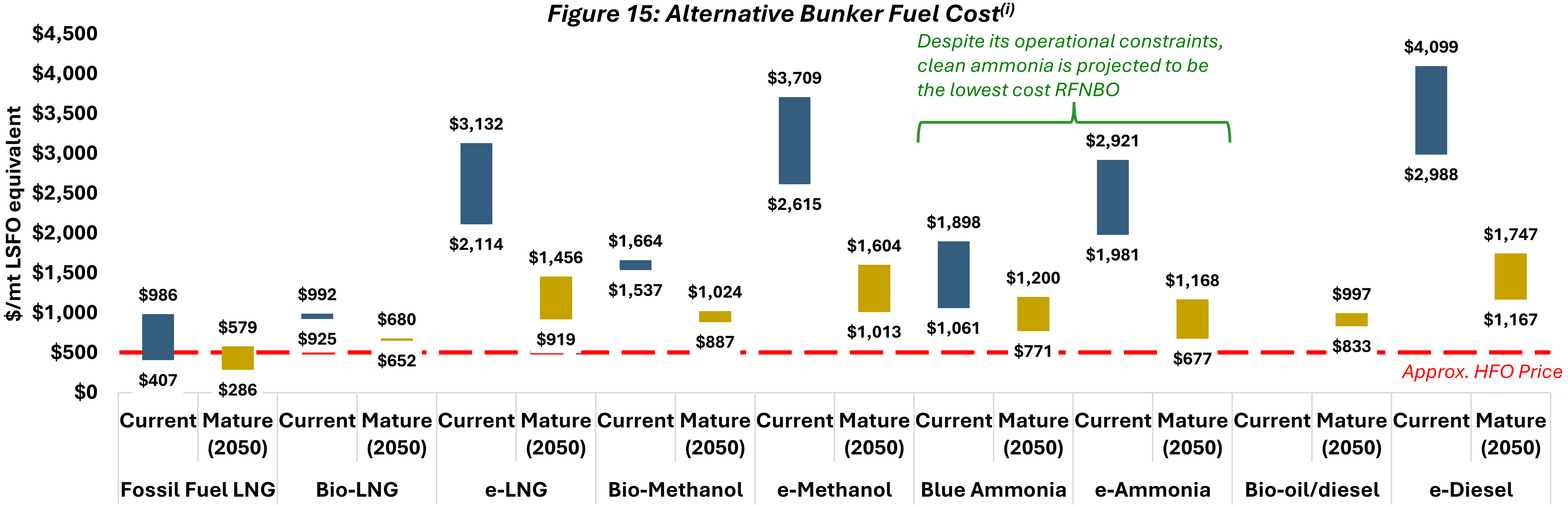
World's Largest Carbon Capture Project Capacity: **14.6 MTPA**
Alberta Carbon Trunk Line

CO_2

Blue and turquoise hydrogen-based ammonia variants will face fewer obstacles in reaching the production scale required to transition the global fleet away from fossil fuels

i) Note: Blue and Turquoise Methanol and LNG pathways are possible, but require additional carbon capture (with its associated cost) compared to ammonia counterparts
ii) Note: Does not include additional energy requirements for fuel synthesis or desalinization in a water scarce situation for fuels requiring electrolysis. Assumes 0.45MWh required per ton of CO_2 captured in e-fuels; 0.6 MWh/ton H_2 for SMR with carbon capture; 3.13 MWh/ton H_2 for Methane Pyrolysis; and 50 MWh/ton H_2 for Electrolysis
Sources: Energy.gov; ACS.org; Statista.com; Sustainable Production and Consumption (Vol 26); Internal Calculations

Even at mature cost profiles, green freight premiums will present a significant barrier to voluntary low-carbon alternative shipping fuel adoption



- ***Substantial green premiums will result from a combination of higher fuel costs and initial capital expenditures***
  - *A hypothetical 50% fuel premium would result in 10-30% higher OPEX for shipping companies(ii)*
  - *LNG and dual-fuel methanol/fuel oil or ammonia/fuel oil ships cost 10-20% and 10-15% more, respectively, than traditional ships*
  - *10-15% freight premiums will be needed to decarbonize shipping in 2050, with premiums as high as 30-40% in the near term*
- ***However, there is currently low appetite to pay for a large green-premium in the market***
  - *Recent surveys indicate 80% of shipping customers would pay for a small green premium, about 4%*
  - *Only a few shipping customers indicated they were willing to pay for premiums exceeding 10%*

i) Note: Turquoise H_2 is comparable in cost to Blue H_2 not including the resale of carbon byproduct. Assume Turquoise Ammonia is Comparable to Blue Ammonia Price.
ii) Note: Uses Maersk cost profile as an example (bunkers are ~20% of OPEX). Fuel premiums would have a larger effect on less fuel-efficient carriers (bunkers ~60% of OPEX)
Sources: Maersk Mc-Kinney Moller Center for Zero Carbon Shipping (Figure 15); UNCTAD Review of Maritime Transport 2023; Maersk Annual Financial Reports 2019-2023; BCG.com, The Real Cost of Decarbonizing Shipping (2024), BulletinofAtomicScientists.org; Chemical Engineering Online

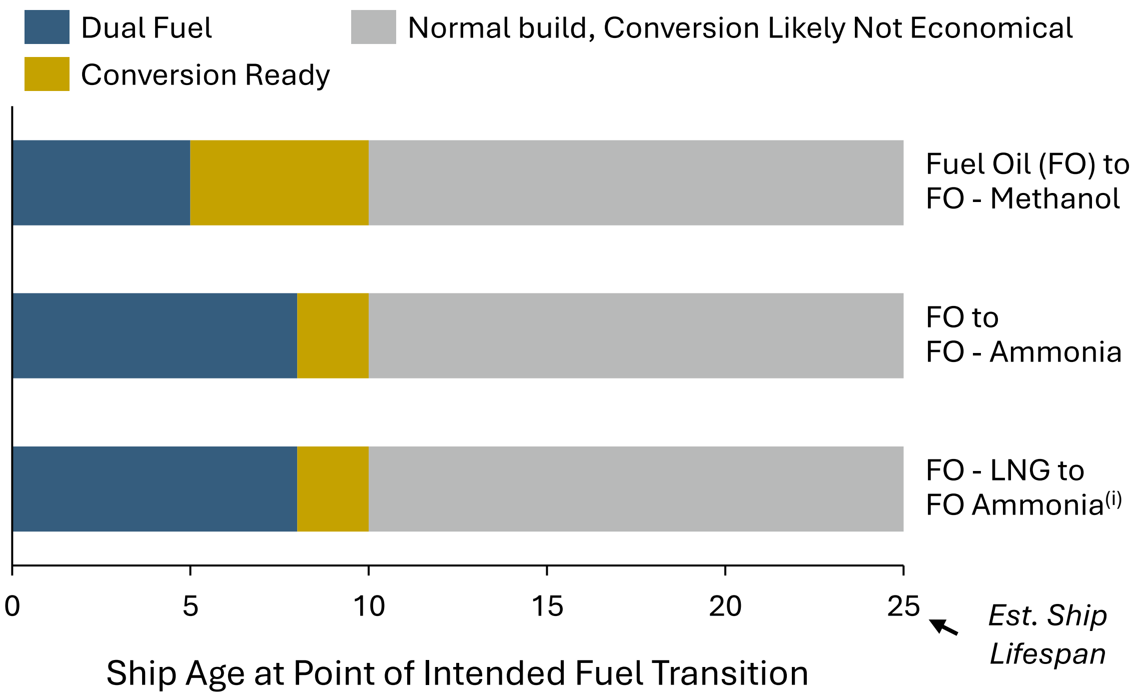
Building and converting to dual-fuel powered ships can mitigate uncertainty for owners in the early stages of the maritime fuel transition

Optionality in dual-fuel solutions and ship conversions provide owners a way to mitigate risk

- Shipowners can either continue normal operations and defer transitioning to different fuels as various pathways mature **or,**
- Switch fuel pathways should their chosen one become more supply constrained or too expensive
- ***Example:*** *Difficulties with clean energy procurement make e-fuel production too costly or limited - blue and turquoise ammonia fuels become more attractive as a result; a shipowner chooses to convert his fleet from LNG to ammonia*

Risk Type	Discussion
Regulatory:	Emissions reduction requirements set by governing bodies are still rapidly evolving
Technology:	Pathways are still developing; the choice remains unclear as to which will be the least costly in terms of fuel and ship design
Scaling:	How fuel feedstock inputs, production and supporting infrastructure will be able to grow to meet global demand is uncertain

Figure 16: Recommended Ship Newbuild Configuration



- *Conversions can require significant CAPEX (upwards of 33% of a newbuild) due to necessary:*
  - *Spatial and structural changes from fuel density differences*
  - *Hardware and systems for containment and, in some cases, cryogenic conditions*

(i) Note: Dual Fuel in this instance means it would have been more economical to have built a FO-Ammonia Ship in the first place rather

Sources: UNCTAD Review of Maritime Transport 2023; Maersk Mc-Kinney Moller Center for Zero Carbon Shipping, Preparing Container Vessels for Conversion to Green Fuels (2022); GCMD-BCG, Voyaging toward a Greener Future (2023)

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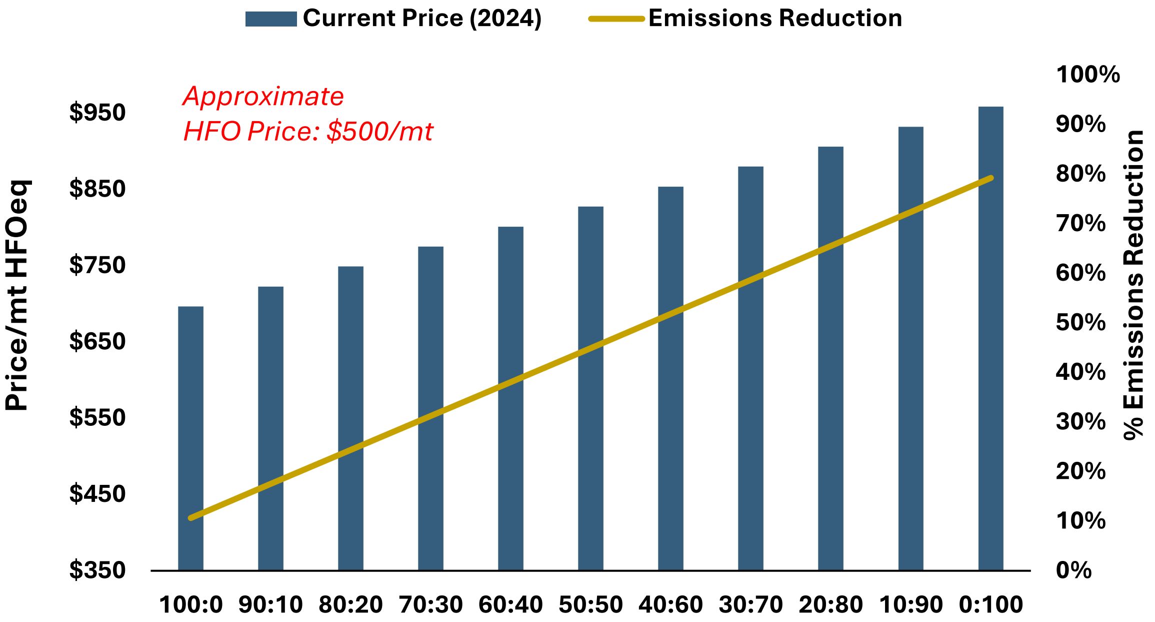
Early in the maritime fuel transition when price and supply of low-carbon fuels may be constraining, blends and offsets can provide ship owners with greater cost-emissions optionality

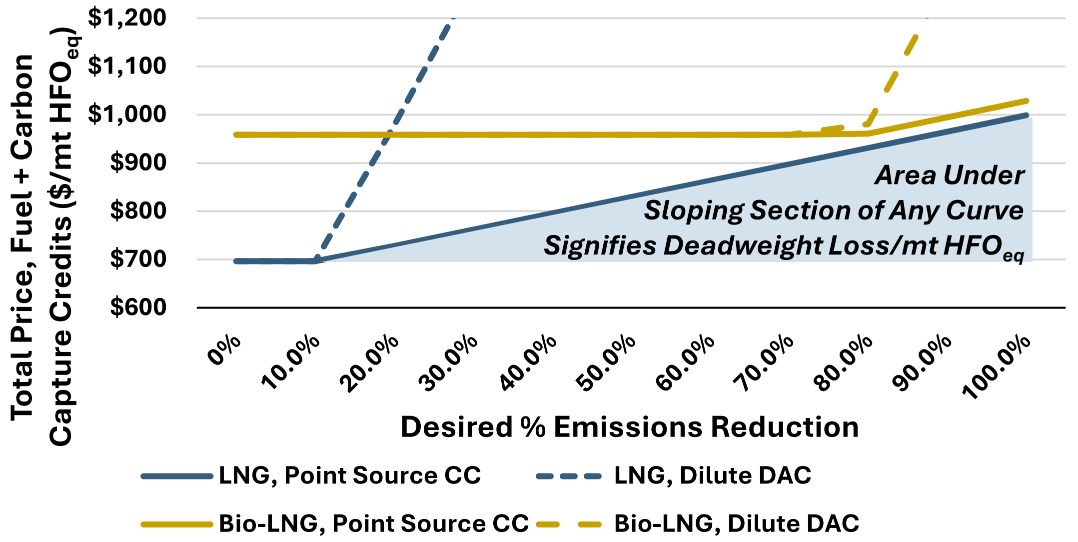
Figure 17: Blending Effects on Cost-Emissions Profile and Fuel Demand (Example - LNG:Bio-LNG Mix)



Bio-LNG Needed (Mtoe)	0	29	59	88	117	146	176	205	234	263	293

- *While fuel blending can physically be done, a book and claim system would likely be the easiest way to help shipowners create the right fuel cost/emissions profile(i)*

Figure 18: Effect of Carbon Capture (CC) Offsets on Fuel Cost-Emission Profile(ii)

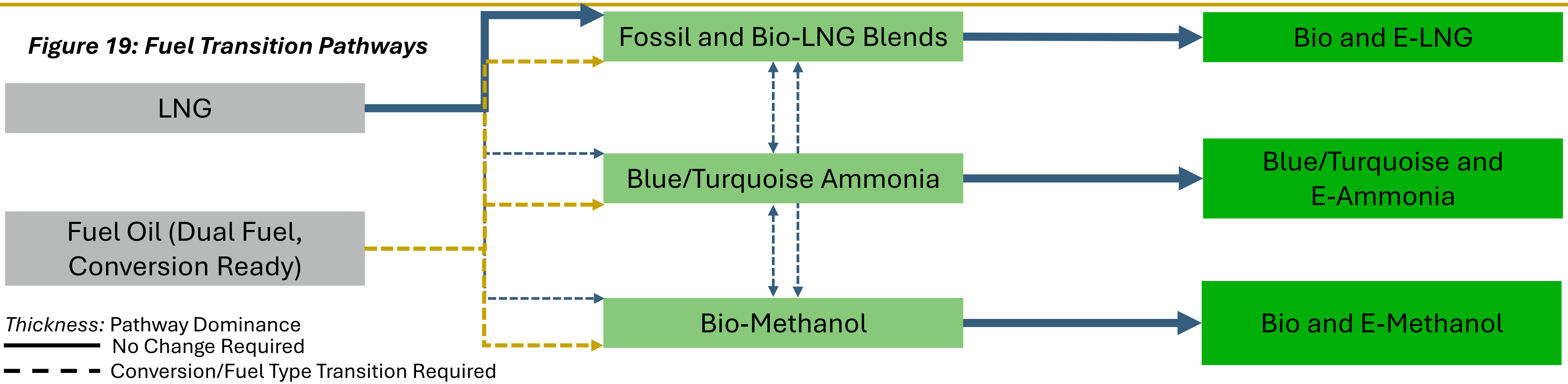


- ***While carbon offsets can be used to meet emissions goals should alternative fuels be in short supply, they are generally not preferred for a few reasons:***
  - *Fuel off-takers desire as much control over their supply chains and costs as possible*
  - *Deadweight loss for fuel off-takers*
  - *Stigma around not actually reducing emissions and "greenwashing"*
  - *Unable to be claimed as scope 3 emissions reductions*

i) Note: See Appendix
ii) Note: Modelled using current average prices of $90/mt CO_2 point source carbon capture (CC) and $800/mt CO_2 dilute direct air capture (DAC). Average mature nth-of-a-king DAC prices are roughly similar to current point source CC prices at $85/mt CO_2.
Sources: Ship and Bunker Rotterdam LNG Prices 2023-2024; BCG, Carbon Capture Paradigm (2023), Biogas can help shipping go green (2024); Wood Mackenzie, What is shaping CCUS carbon capture costs?; 2023 DNV Maritime Forecast 2050; Catalyst Podcast Interviews, CO_2 Utilization (5/2/24), Understanding SAF Buyers (5/16/24)

In summary, the required shift to alternative fuels will likely need to be spearheaded by cheap and readily available LNG before graduating to lower-carbon intensity substitutes

Figure 19: Fuel Transition Pathways



As alternative fuel production develops:

- Fossil fuel-based LNG can provide
  - Cheap, available fuel supply for immediate ship conversions
  - Up to 23% potential reduction in GHG emissions
- Fuel-oil-powered ships with dual-fuel capabilities or that are classified "conversion-ready" can be ordered

With greater biofuel and blue/turquoise ammonia capacity available:

- Virtually or physically blend Bio-LNG and LNG in proportions that meet cost and emission goals
  - 70-80% reduction in emissions
- Transition dual-fuel and alternative fuel capable ships off fossil fuels
- Convert existing ships where possible

With significant bio and e-fuel capacity available:

- Physically blend or purchase biofuels and e-fuels in proportions that meet cost and emissions goals
  - ~100% reduction in emissions as value chain decarbonizes
- Order ships optimized for a single fuel
- Continue existing ship conversions

High Carbon Intensity, Until 2035[(i)] — **Mid-term: 2035-2045** — **Low Carbon Intensity, 2045-On**

(i) Note: Reference points on fuel transition timeline are based around meeting emissions reduction requirements set by FuelEU Maritime

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Eliminating maritime GHG emissions requires uptake in energy efficient solutions and shifting to alternative fuels supported by key pillars of partnerships, policy, and infrastructure deployment[i]

Bringing the global shipping fleet to net-zero will require a phased and flexible transition involving energy efficient solutions and alternative bunker fuels such as low-carbon LNG, methanol, and ammonia variants

- Energy-efficient design and operational solutions can help facilitate the transition to alternative maritime fuels
- While multiple alternative fuel options are available, no single solution exists to easily transition maritime shipping off fossil fuels, creating uncertainty and a need for optionality and flexibility
- LNG offers an immediate, partial decarbonization solution today as other less carbon intense fuel pathways develop
- Without rapid development, alternative low-carbon maritime fuels could be supply constrained in the near-term
- Transitioning to low-carbon fuels will result in a green premium that will need to be addressed through regulations or incentives
- Dual-fuel and conversion ready ships, fuel mixes, and carbon capture offsets can provide flexible cost and emissions solutions during the early stages of the transition to cleaner fuels

Key Supporting Factors Necessary to Catalyze the Development and Adoption of Alternative Maritime Fuels:

Strategic Partnerships

- Long term offtake agreements and shipping contracts, joint ventures, and technology sharing alliances are ways to share and reduce risk associated with alternative fuel adoption
- Examples of these partnerships exist across all fuel pathways

Policy and Regulation

- Through emissions restrictions and incentives, regulators can promote clean fuel adoption with minimal effect on the global economy
- Green Shipping Corridor Agreements can help reduce uncertainty around supporting infrastructure

Deploying Fluid and Power Transmission

- Greater amounts of fluid and power transmission will be necessary regardless of the fuel pathway chosen
- Several solutions exist to overcome challenges and opposition to deployment including reusing existing rights of way and optimal project siting

i) Note: Another potential solution is to reduce the overall amount of global shipping (i.e. nearshoring). This solution was not a part of this project's analysis as it has other, more complex supply chain and political implications which would need to be considered.

To catalyze the transition to any alternative shipping fuel, many risks underpinning high cost of capital must be addressed[i]

Figure 20: Key Risks Associated with Alternative Fuel Production

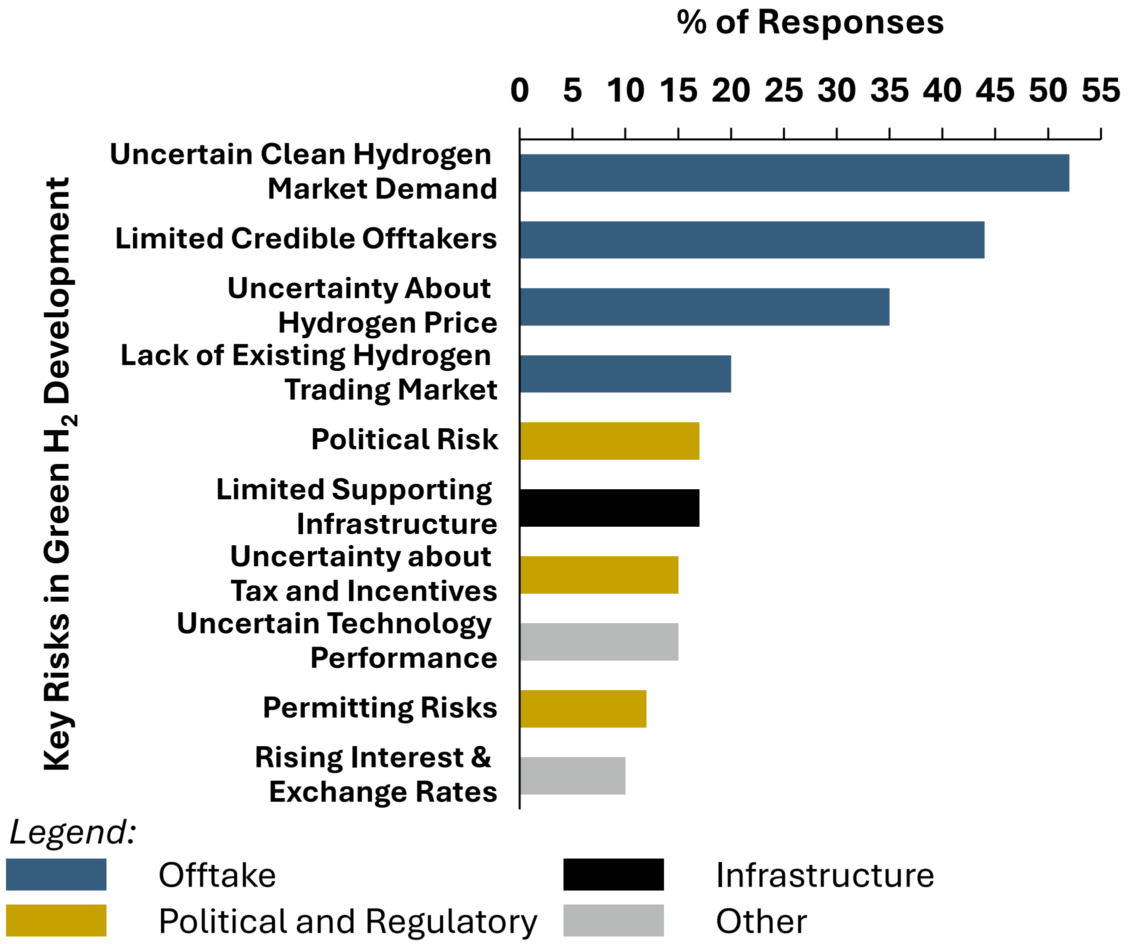
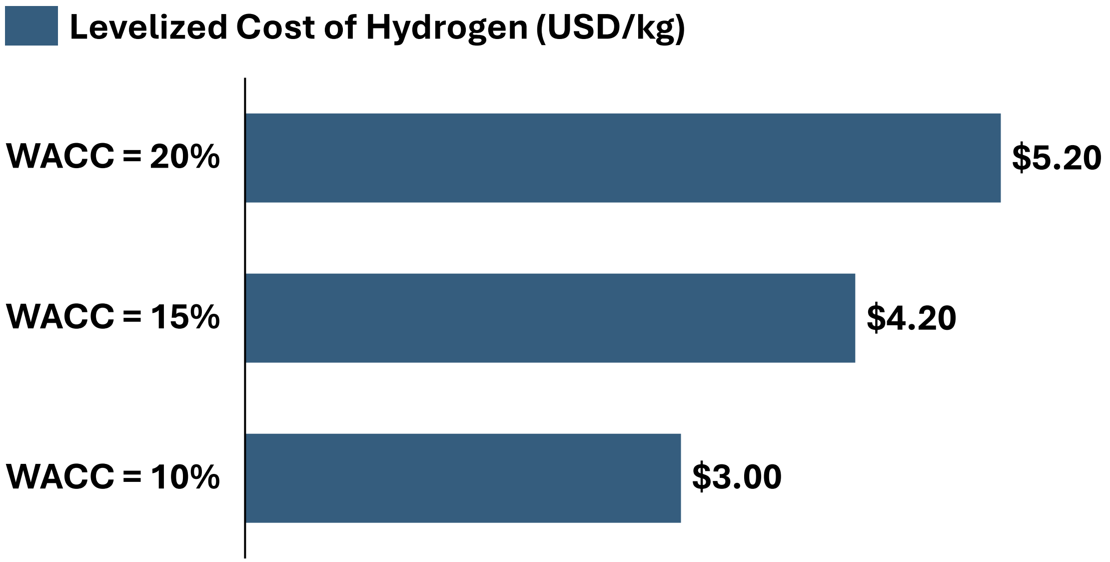


Figure 21: High Cost of Capital and Fuel Costs



- *Select clean hydrogen companies cost of capital (WACC used) ranged from 6.4-24%*
- *For capital intensive green hydrogen projects (and RFNBO projects), product cost is heavily dependent on cost of capital*
- ***Along with continued innovation, driving risk and cost of capital down can have a material impact on clean fuel production and adoption***

i) Note: Green Hydrogen is used as a conservative proxy for RFNBO projects which would ultimately supply maritime shipping. RFNBO risk could be higher due to compounding project-on-project risk (clean hydrogen production and carbon capture/sequestration)

Sources: OECD, Financing Cost Impacts on Cost Competitiveness of Green Hydrogen in Emerging and Developing Economies

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Strategic partnerships can facilitate investment in alternative fuels by reducing project risk and overall exposure for individual stakeholders

	Long-term Contract & Offtake Agreements	Joint Ventures & Development	Technology Sharing Alliances
Description & Structure	Two main forms: • Long-term contracts between shipping customers and shipowners seeking to reduce their Scope 3 emissions • Long-term offtake agreements (20+ years) between shipowners and fuel producers	• Multiple equity stakes in a venture or project • Fee distributions for the stakeholder controlling and operating the venture or project	• Shares low-carbon technology across industries and sector
Key Benefits	• Long-term contracts provides shipowners the certainty they can pass additional costs for low-carbon attributes onto consumers and subsequently make investments in low-carbon fuels and ship designs • Long term offtake reduces project risk and associated financing cost for alternative fuel projects by defining project's revenue generating potential	• Reduced financial exposure for risky, capital intense projects • Appropriately allocate risk and work to stakeholders with the appropriate expertise • Resource sharing can reduce upfront equity requirements at the project level and even reduce overall risk • Higher growth potential for the RFNBO start-up and faster time to achieve efficiency gains and economies of scale • More optionality than M&A in the long-run	• Similar to a joint venture in that investment cost and risk is shared – specifically with R&D • More agile option than Joint Ventures – easier to enter and leave
Key Challenges	• Finding the "first-movers" willing to pay for green shipping, alternative shipping fuels, and alternative shipping fuel compatible ships without facilitating or compulsory regulatory requirements	• Need for JV formation expertise • Project governance and control more difficult • Tensions over value each member brings, and the associated distributions received	• Loss of potential competitive advantage through technology transfer • Lower level of commitment by those involved

Sources: OECD, Financing Cost Impacts on Cost Competitiveness of Green Hydrogen in Emerging and Developing Economies; KPMG, Success in Joint Ventures; BCG, the Innovation Power of Alliances

Several alternative fuel producers are already taking advantage of strategic collaborations and partnerships across industries and value chains

Examples	Blue Ammonia	Turquoise Hydrogen	e-Ammonia	e-Methanol	e-LNG
Key Player(s)	ExxonMobil, ADNOC, Mitsubishi Heavy Industries, Ltd., Air Liquide	Monolith, NextEra Energy, SK chemicals, Goodyear	Topsoe, Skovgaard Energy, Vestas	Maersk, C2X	TES, TotalEnergies
Project(s) and Capacity	• ExxonMobil; Baytown, TX • FID expected in 2025[i] • 1 bscf/day Blue Hydrogen • 1 MTPA Blue Ammonia	• Monolith; Olive Creek, Nebraska Expansion • Est. Completion in 2026 • 0.275 MTPA[ii]	• Topsoe, Skovgaard, Vestas; Ramme, Denmark Demo: • Completed 2024 • 5 KTPA	• Multiple C2X projects across Spain, Egypt, US, India, and Australia • 3-5 MTPA by 2030	• TES/TotalEnergies; US Project: • FID expected 2024 • 0.1-0.2 MTPA
Facilitating Partnerships and Investments	• (2024) ADNOC acquires a 35% equity stake in Baytown project • (2024) H_2 feedstock and distribution access with Air Liquide partnership • (2022) Mitsubishi Heavy Industries carbon capture technology alliance[iii]	• (2021) Goodyear Tire and Rubber collaboration; Matures into a Goodyear becoming a carbon black customer in 2023 • (2021) strategic investment by Nextera Energy, a potential future supplier of clean electricity and customer	• (2024) Commercial demo combining Topsoe's skill in Power-to-X with renewables development expertise from Vestas & Skovgaard	• (2024) Shipping giant Maersk and its parent company launch C2X, a green methanol start-up • (2023) Maersk signs green shipping deals with Amazon and Inditex	• (2023) studies begin; TotalEnergies would take a 50% stake and operate the plant; energy procured through long-term PPAs; resulting gas can be liquified
Other Key Strategic Moves	• 2023 acquisition of Denbury, giving Exxon the most CO_2 pipeline capacity in the US (1300 mi)	• Mitsubishi Heavy Industries is another notable strategic investor[iii] • Joint venture with SK Inc. to expand outside the US with production in South Korea	• Licensing Ammonia Technology to CF Industries, which is evaluating and e-Ammonia plant with collaboration from Mitsui & Co[iii]	• (2022-2023) Maersk forms numerous offtake agreements, guaranteeing 0.73 MTPA by 2025 - enough for its first 12 methanol ships	• (2024) Strategic supply chain partnership with "K" Lines [iii] and Itochu

i) Note: FID: Final Investment Decision; if decision goes through, anticipated plant startup date is expected in 2029
ii) Note: Enough feedstock to produce 1.1 MTPA of turquoise ammonia
iii) Note: Mitsubishi Heavy Industries, Mitsui & Co., and "K" Lines all have either prominent shipbuilding or shipping business units
Sources: Press Release from ExxonMobil.com, Monolith.com, Topsoe.com, Maersk.com, TES.com, Financial Times, and Renewables Now

Eliminating maritime GHG emissions requires uptake in energy efficient solutions and shifting to alternative fuels supported by key pillars of partnerships, policy, and infrastructure deployment(i)

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Non-market solutions play a critical role in alleviating the challenges associated with alternative fuel adoption

Challenge	Discussion	Non-Market Solutions

High Green Premiums for Alternative Fuels	• Without regulation, shipowners would be more averse to adopting more expensive clean fuels, knowing competitors could undercut their rates or the more expensive fuels would erode operating margins
	• Without widespread offtake, financing alternative fuel production projects becomes difficult
	• With fewer projects reaching commercial operation, economies of scale and efficiency gains are slowly or never achieved; fuel prices remain high
		• ***Demand Side: Create and enforce limits on shipping emissions***
		• Supply Side: Lower Fuel Prices Through Production and Investment Tax Credits
		  • US Tax Code Section 45V for Clean Hydrogen
		  • US Tax Code Section 45Q for Carbon Capture and Sequestration

Limited Supporting Infrastructure for Alternative Fuels	• Facilitating the construction of fluid/gas transmission and port bunkering infrastructure can significantly reduce the frictions associated in the development of alternative fuel markets	• **Green Shipping Corridor Agreements between nations with budgetary support for clean bunkering infrastructure** • Streamlined permitting for transmission and pipeline construction and reuse
Restrictions on Alternative Fuel Usage	• Ammonia, a promising alternative shipping fuel, has restrictions around commercial use as a shipping fuel	• Amending maritime regulations permitting the safe use of ammonia fuels

Solutions analyzed further in this report

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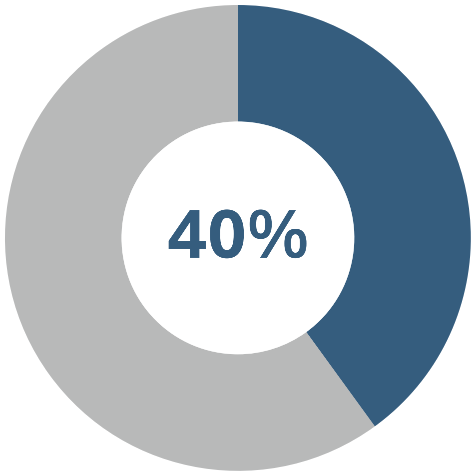
US and China alignment with current IMO guidelines or EU regulations could have a substantial impact on influencing alternative maritime fuel adoption globally

Governing Body	Key Actions and Commentary
IMO INTERNATIONAL MARITIME ORGANIZATION	• Has set various regulatory guidelines for emissions reduction including Energy Efficiency Existing Ship Index and Design Index (EEXI, EEDI) and Carbon Intensity Indicator (CII) • **However, the IMO has no enforcement capability**
	• Maritime sector included in the EU's cap-and-trade emissions trading systems (ETS) starting in 2024 • FuelEU Martime Law (taking effect in 2026) creates additional regulation to promote alternative fuel adoption • **Requires self-reporting, includes provisions to audit emissions reports** • **Includes fines for non-compliance**
	• The U.S. has several bills as aggressive in nature as IMO and EU standards that have been introduced (Clean Shipping Act of 2023, International Maritime Pollution Accountability Act of 2023) • **No current regulations on shipping GHG emission limits**
	• While China's national ETS commence operations in 2021, it only covers power production • **There are no planned expansions of the ETS to include the maritime sector**



Amount of containerized trade between Asia, Europe, and the United States in 2021

Sources: Clyde & Co, IMO, DNV, Congress.gov, UNCTAD

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Compulsory compliance with emissions regulations would negligibly affect the global economy

Figure 23: Maritime Logistics Cost Impact on GDP and Trade

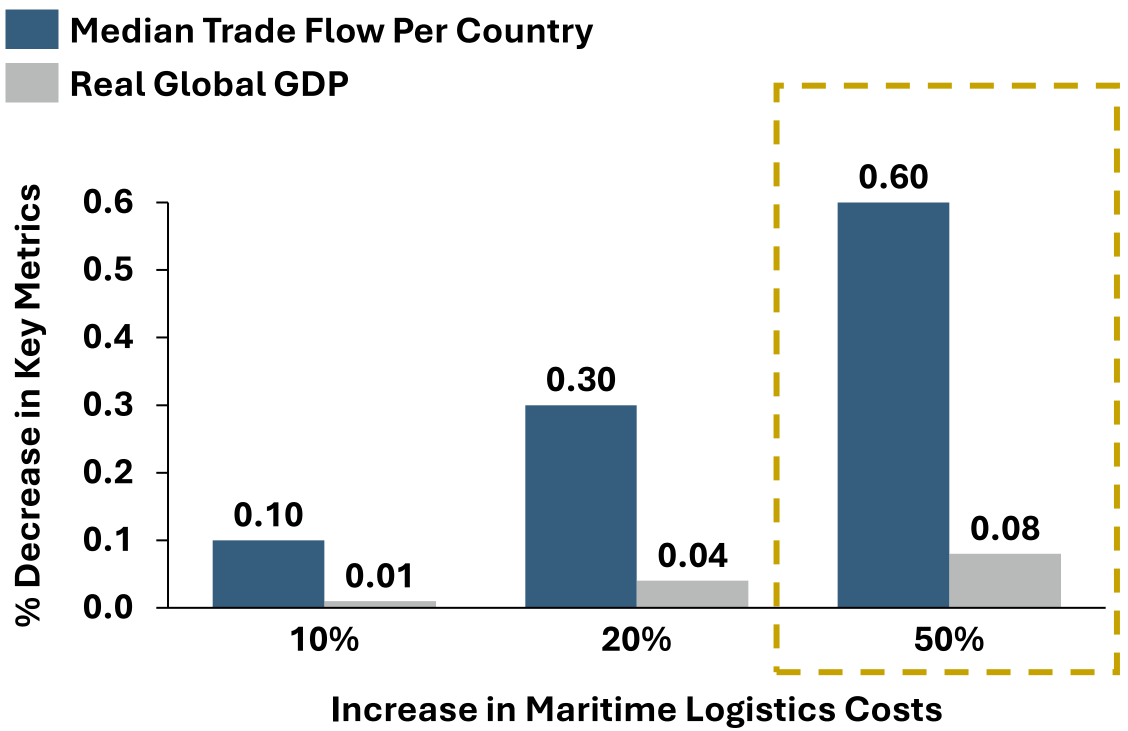
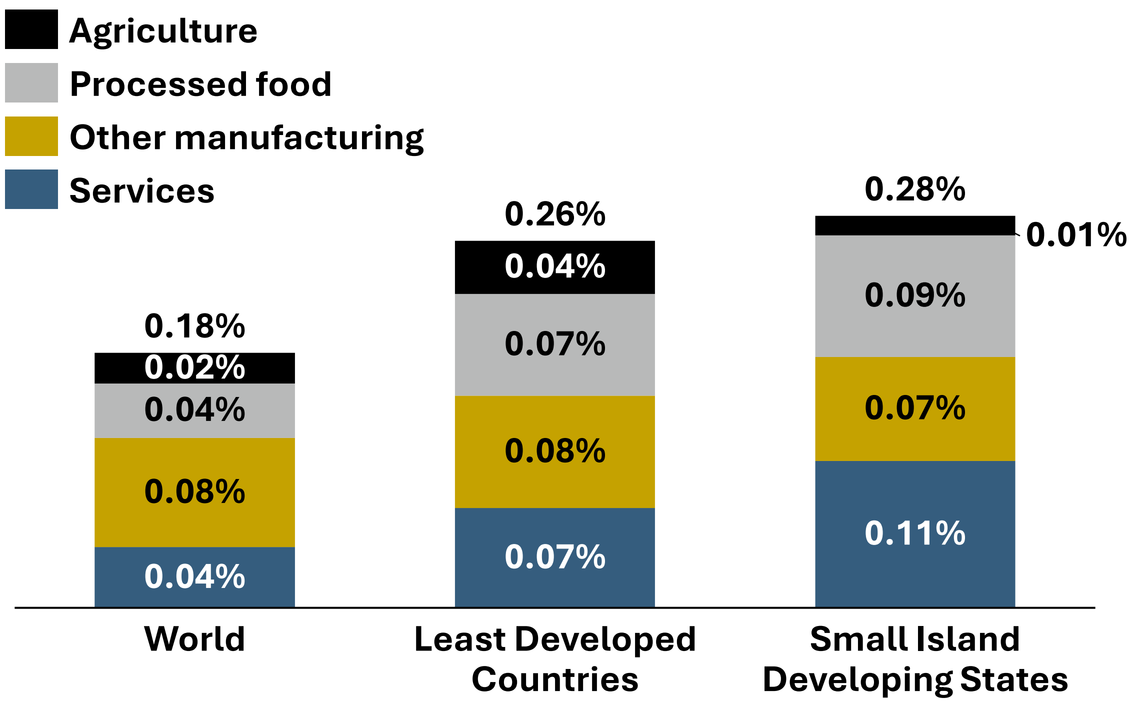


Figure 22: Illustrative Impact on Consumer Good Prices Assuming a 50% Shipping Green Premium(i)



- *With a projected real global GDP of $108 Trillion in 2024, a hypothetical increase in maritime logistics costs of 50% reduce GDP only by about $86 Billion*

- *Supply chain disruptions in 2023-2024 due to conflict in the Red Sea and a severe drought affecting operations in the Panama Canal have affected consumer good prices **over 4x** than decarbonizing green shipping would*

i) Note: Linearly scaled down from price impact seen from ~150% freight rate increases experienced over the course of October 2023-June 2024 in the Shanghai Freight Index. BCG estimates a 30-40% green shipping premium in the near term and a 10-15% green premium in the long run to decarbonize maritime shipping
Sources: UNCTAD Review of Maritime Transport 2023, High Freight Rates Strain…

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Green Shipping Corridors, promoted through policy, can be a key catalyst for the maritime fuel transition

Green Shipping Corridors (GSCs) connect clean fuel supplying ports

Figure 24: Illustrative GSC Example

- **At COP 26, 22 countries agreed to create at least six GSCs by the mid-2020s in the Clydebank Declaration**
    - Establishing a GSC includes cross-value-chain collaboration, demand for low-carbon shipping, a viable fuel pathway, and supporting policy and regulation

GSCs can help promote widespread adoption of alternative fuels

- **GSCs increase certainty:**
    - Known fuel supply might sway shipowners to adopt alternative fuel compatible ship designs
    - Demand signals will help alternative fuel projects get financed and production to scale
- **GSCs allow policymakers to better focus incentives and regulation**
- **Creating GSCs around the largest ports can yield disproportionate results to resources committed**
    - ~50% of containership trade goes through the 25 largest ports
    - GSCs can have positive spillover effects to neighboring ports

Case in point: 2023 LA-Shanghai GSC Agreement

- **Current Design**
    - Scope: gate to gate of each port
    - Partners include large shipowners Maersk, CMA CGM, and Cosco
    - Voluntary collaboration to provide input to a long-term roll-out plan
- **Current Carrier Goals**
    - Develop and improve operational efficiency for all participants
    - Begin deploying reduced carbon emissions ships by 2025
    - Use the world's first Zero-Carbon Emission ship by 2030
- **Significant implementation still needed (i.e. deploying infrastructure)**
- **Only two GSCs have plans for initial implementation worldwide**

Sources: UNCTAD Maritime Transport Indicators; World Shipping Council, Top 50 Container Ports; The World Economic Forum, The Next Wave; BBC news, Green Shipping Corridors Gaining Momentum; Port of Los Angeles – Port of Shanghai Green Shipping Corridor Partnership Implementation Plan Outline

Eliminating maritime GHG emissions requires uptake in energy efficient solutions and shifting to alternative fuels supported by key pillars of partnerships, policy, and infrastructure deployment[i]

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i) Note: Another potential solution is to reduce the overall amount of global shipping (i.e. nearshoring). This solution was not a part of this project's analysis as it has other, more complex supply chain and political implications which would need to be considered.

Building greater amounts of power and fluid transmission infrastructure necessary to scale the deployment of RFNBOs requires overcoming several obstacles

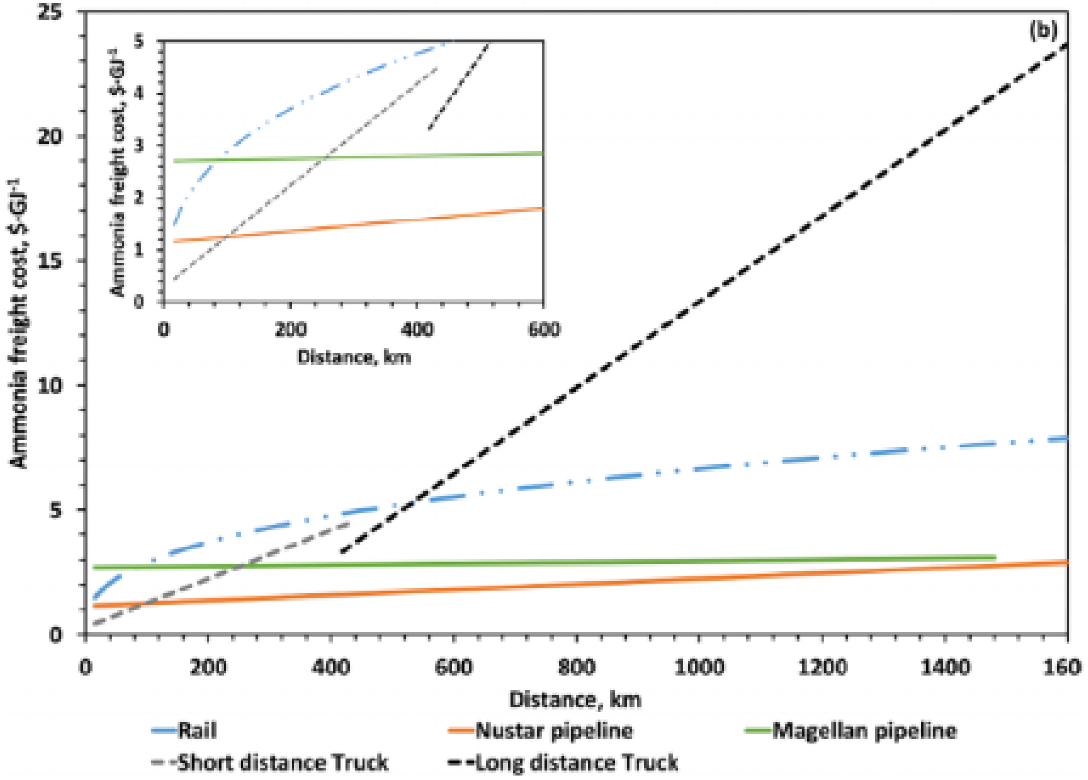
Transmission lines and pipelines will be necessary to deploy RFNBOs at low cost

- **RFNBOs require long-distance transport as feedstock inputs, demand, and byproduct offtake are in dissimilar locations**
  - **Inputs:** natural gas, water, carbon, low-cost wind/solar generation, large amounts of buildable land
  - **Demand:** ships and trading hubs located at major ports, normally in developed, densely-populated areas
  - **Byproduct offtake:** geologic storage, carbon customers
- In general, pipelines are the most economical means of transporting large amounts of fluids long distances over land
  - For example, it costs 3-10x more to ship carbon dioxide by truck or rail than by pipeline

Horizontal infrastructure development faces many external challenges

- Right of way issues and landowner buy-in
- Political opposition
- Environmental compliance
- Lengthy permitting processes

Figure 25: Cost of Ammonia Transport by Pipeline, Rail, and Truck in the US, ($/GJ)



i) Note: This analysis assumes that feedstock hydrogen production occurs on or near the same site as fuel production; eliminating the need for significant amounts of hydrogen transport.

Sources: EEIA.org, A Roadmap to At-Scale Deployment...; American Chemical Society, Progress and Prospective of Nitrogen... (Figure 24); Frontiers in Energy Research, Transport Cost for Carbon Removal...; International Journal of Hydrogen Energy (Vol 47, Issue 48), Large-scale long-distance land-based hydrogen...

Improperly handling challenges to projects can result in project delays or failures

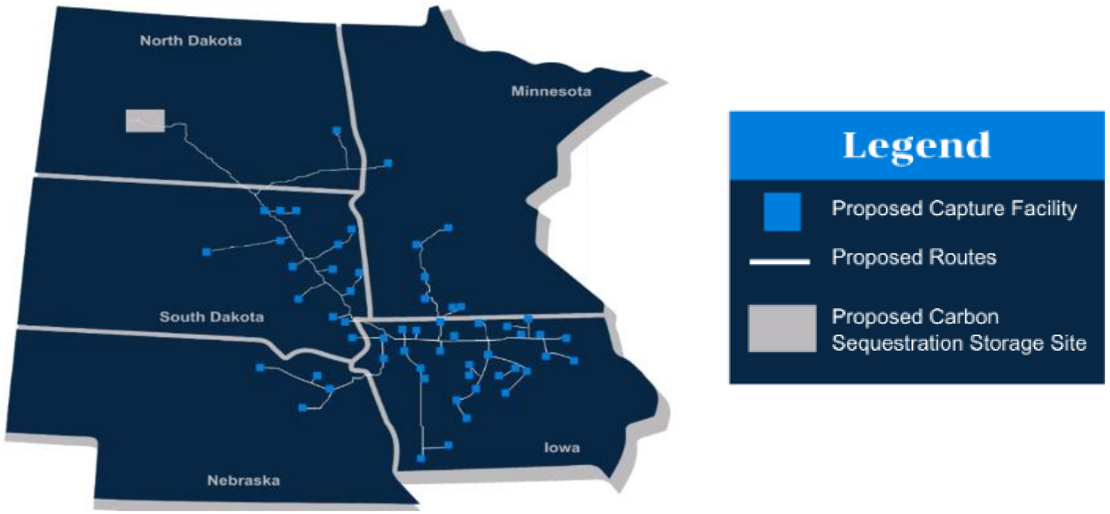
Carbon Sequestration Pipeline Case in Point: Midwest Carbon Express Slowed

- 2000 mi, $4.5B pipeline by Summit Carbon Solutions, moving up to 12 MTPA CO2 from Midwestern ethanol plants to N. Dakota for geologic storage
- Will cut carbon intensity in half and unlock 45Q carbon sequestration tax credits for 15% of the US ethanol industry
- Pipeline expected to become operational two years late due to
  - Landowner concerns around safety and crop damage
  - North Dakota building permits initially rejected due to lack of local support and siting compliance

Transmission Line Case in Point: Northern Pass Abandoned

- 182 mi, $1.6B transmission project by Eversource to bring 1.1 GW of clean Quebec hydropower New Hampshire
- New England consumers would $600 MM in annual energy costs
- Abandoned in 2019, nine-years after planning began due to:
  - Local opposition over concerns of environmental damage
  - Denied state permit application on the basis the project would disrupt orderly regional development

Figure 26: Summit Carbon Solutions Project Footprint



Opposition from farmers, tribes, and environmentalists is growing as Summit is now seeking permits to allow the company to use eminent domain to forcibly obtain easements from landowners who have previously held out from selling land rights

i) Note: This analysis assumes that feedstock hydrogen production occurs on or near the same site as fuel production; eliminating the need for significant amounts of hydrogen transport.
Sources: Reuters.com, US Carbon capture pipeline setbacks reflect..., Focus: Giant pipeline in U.S. Midwest...; Summit Carbon Solutions; Nhpr.org, After abandoning Northern Pass...; IndepthBH.org, One Final Light is Turned off...; Grist.org

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Several potential solutions exist which can aid in deploying power and fluid transmission at a greater pace

Repurposing Pipelines or Rights of Way

- **Repurposing existing gas pipelines:**
  - Easily done for e-methane
  - Promising concept for ammonia, methanol, hydrogen, and CO_2 but could face technical limitations such as:
    - Different corrosion mechanisms with pipeline steel
    - Higher pressure ratings and required pipe size
- **Co-locating pipelines:** depleted oil and gas reserve volumes can be suitable CO_2 sequestration sites
- **Sharing rights of way:** leverage existing railways, highways, transmission lines or pipelines
  - May require zoning policy and regulation changes

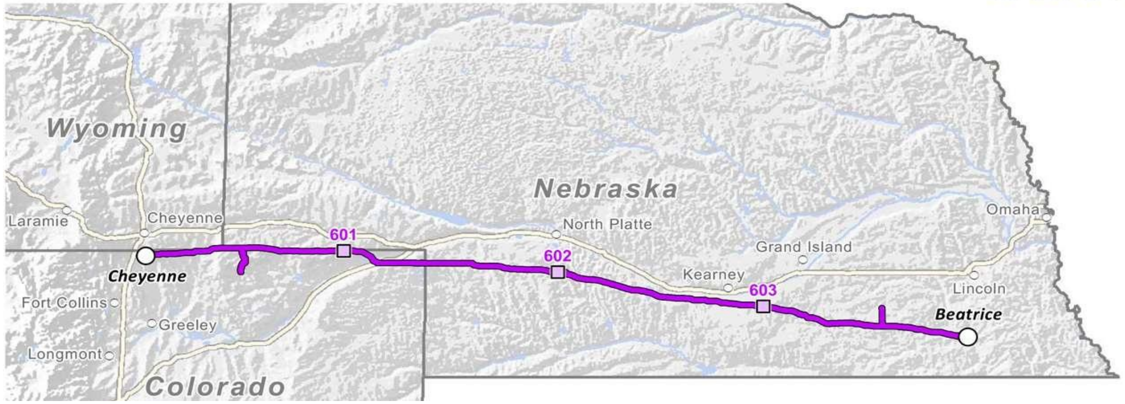
Proper Community Engagement

- Properly engaging with local landowners, tribes, and governments could prevent public opposition and project delays – as was seen in the Summit Carbon Pipeline
- Community stakeholders want to feel like their concerns are heard (particularly around safety), their rights are protected, and that they have a say in the decision-making process

Turquoise Hydrogen Adoption(i)

Trailblazer Pipeline Company

TALLGRASS ENERGY



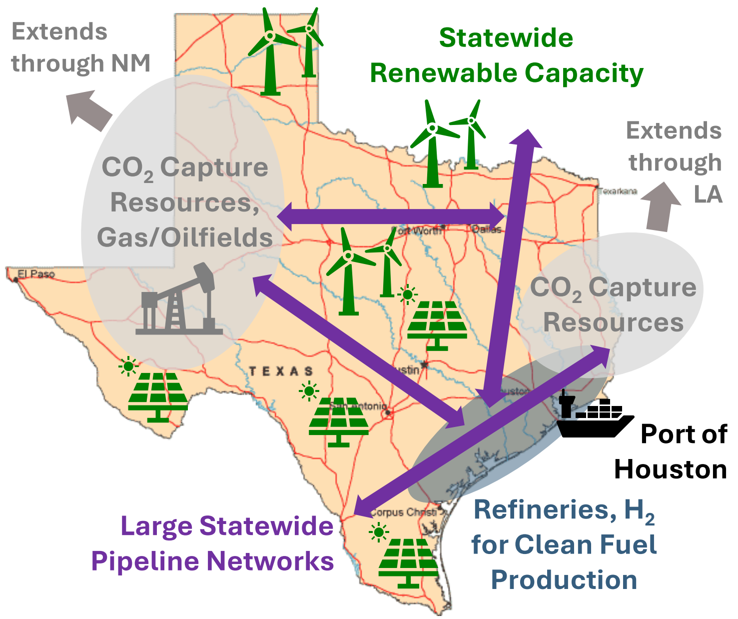
Case in Point: Trailblazer CO_2 Sequestration Pipeline

- Will service industries in Nebraska, Colorado, and Wyoming with a 10 MTPA service capacity
- Will connect emitters to geologic sequestration in SE Wyoming
- Unique attributes:
  - **Natural gas to CO_2 pipeline conversion – permit granted by FERC in less than 18 months**
  - **First-of-a-Kind Community Benefits Agreement with the Bold Alliance(ii) and 11 statewide organizations – widespread public support for the conversion effort**

i) Note: Turquoise Hydrogen could help reduce infrastructure needs through lower power requirements and producing solid carbon black byproduct (see first section)
ii) Note: The Bold Alliance is a Nebraska Environmentalist Group well-known for its opposition of the Keystone XL Pipeline
Sources: OSTI.gov, Transport of Methanol by pipeline (Technical Report); Energy.gov, Compatibility of Natural Gas Pipeline Infrastructure Materials…; Tallgrass.com (CO2); Expert Interviews

Optimizing alternative fuel project siting will also be key in avoiding delays and higher costs associated with fluid and power transmission

Figure 27: Optimal Project Siting – Texas as an Example



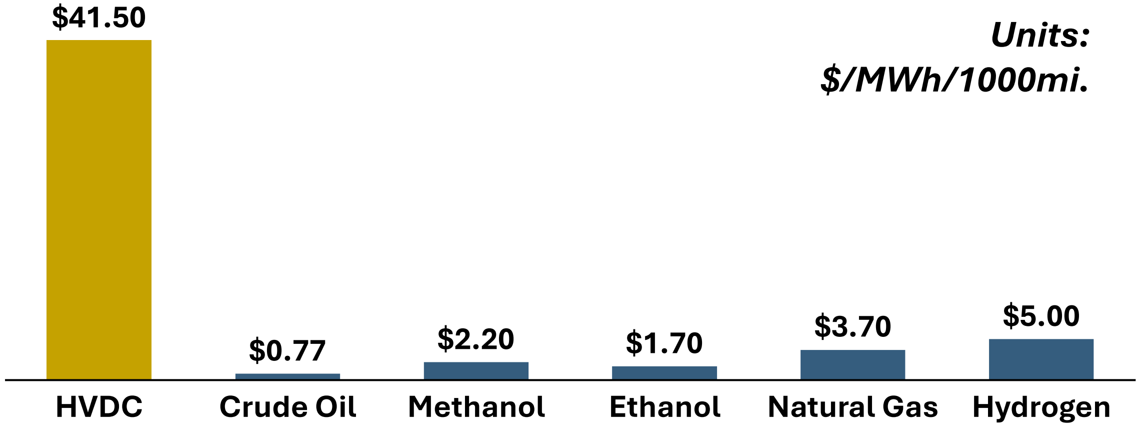
Other Favorable Areas:

- *Persian Gulf*
- *North Sea*
- *North Argentina*
- *Northwestern Australia*

Key Factors:

- ✓ *Strong renewable energy resource*
- ✓ *Existing pipeline and refinery infrastructure*
- ✓ *Nearby carbon storage capacity*
- ✓ *Access to a major commodities port*

Figure 28: Energy Transport Cost and Permitting Time



Transmission Type	Average Permitting Timeline
Electric	4.3 years
Pipeline	1.5 years

For e-fuel projects in attractive areas, it is more economical and faster to fully develop a site closer to renewable energy sources than the off-take location

i) Note: Partnerships and community engagement are considered in the next section

Sources: NREL.gov, Cost of long-distance energy transmission by different carriers; Niskanen Center, Contextualizing electric transmission…, Siting, leasing, and permitting…

In conclusion, a successful maritime emissions reduction strategy rests not only upon new fuel and energy efficient solutions, but facilitating partnerships, policy, and infrastructure

- Maritime shipping is a vital sector of the global economy that requires prompt action to meet climate-related goals
- Shipping's international nature and need for energy-dense fuels complicate efforts to reduce greenhouse gas emissions
- Successfully reducing maritime emissions will require significant uptake in energy efficient solutions and a shift to alternative fuels supported by key pillars of partnerships, policy, and infrastructure development
    - While reducing shipping consumption and energy efficiency solutions can have a material impact, shifting to alternative fuels will be necessary to completely eliminate greenhouse gas emissions
    - While there is no clear winner amongst alternative fuels to be adopted by the maritime community, LNG offers one of the best near-term options for shipowners to begin to reduce their emissions
    - Regardless of the fuel pathway chosen, partnerships, the right policy, and scaling up fluid and power transmission quickly can catalyze the development and adoption of alternative fuels by reducing and, or sharing risks associated with them

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- Jake Hite, ExxonMobil Hydrogen Business Development
- Doreen Wong, Office of Innovation and Commercialization – University of Hawaii
- Nick Alexander, Nordex-Acciona

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Questions?

Please reach out to me at sam.haber@emory.edu

Artistic Rendering of the Yara Eyde, a clean-ammonia powered vessel operated by a Joint Venture between Yara International and North Sea Container Line; the Yara Eyde is projected to go into operation by 2026.
Sources: Ammonia Energy Association

Appendix: Energy Efficiency Calculations

- % Reduction in Emissions and Fuel Costs Estimate Derived from DNV 2023 Maritime Forecast: ~35%
- % Reduction in Emissions and Fuel Costs Stated in UNCTAD 2023 Review of Maritime Transport: 30%
- Independently Derived Estimate using Data from Multiple Sources:
  - Adoption weighting: estimated likelihood of adoption fleetwide from GCMD | BCG 2023 Shipping Decarbonization Report
  - Capability weighting: assumes half of ships would be able to be fitting with wind assisted propulsion or onboard solar panels
  - Reduction in Emissions and Fuel Costs Estimate without wind and solar: ~30%
  - Reduction in Emissions and Fuel Costs Estimate with both wind and solar: ~40%

Top Energy Efficiency Reduction Factors	%Reduction in Fuel Consumption	Adoption Weighting	Capability Weighting	% Reduction	w/o Wind and Solar	% of Original Fuel Consumption	w/o Wind and Solar
Slow Steaming	50%	25%	100%	12.500%	12.500%	87.5%	87.5%
Weather Routing	7%	25%	100%	1.625%	1.625%	98.4%	98.4%
Prop Maintenance	5%	25%	100%	1.250%	1.250%	98.8%	98.8%
Hull Maintenance	12.50%	25%	100%	3.125%	3.125%	96.9%	96.9%
Autopilot Adjustment	1%	50%	100%	0.500%	0.500%	99.5%	99.5%
Adv Hull Coatings	10%	25%	100%	2.500%	2.500%	97.5%	97.5%
Prop Improvements	2.50%	50%	100%	1.250%	1.250%	98.8%	98.8%
Hydrodynamic Design	8%	75%	100%	6.000%	6.000%	94.0%	94.0%
Air Lubrication	5%	90%	100%	4.500%	4.500%	95.5%	95.5%
Solar Panels	10%	90%	50%	4.500%		95.5%	
Wind Power	25%	90%	50%	11.250%		88.8%	
Weighted Avg Total Reduction Factor						**60.0%**	**70.8%**

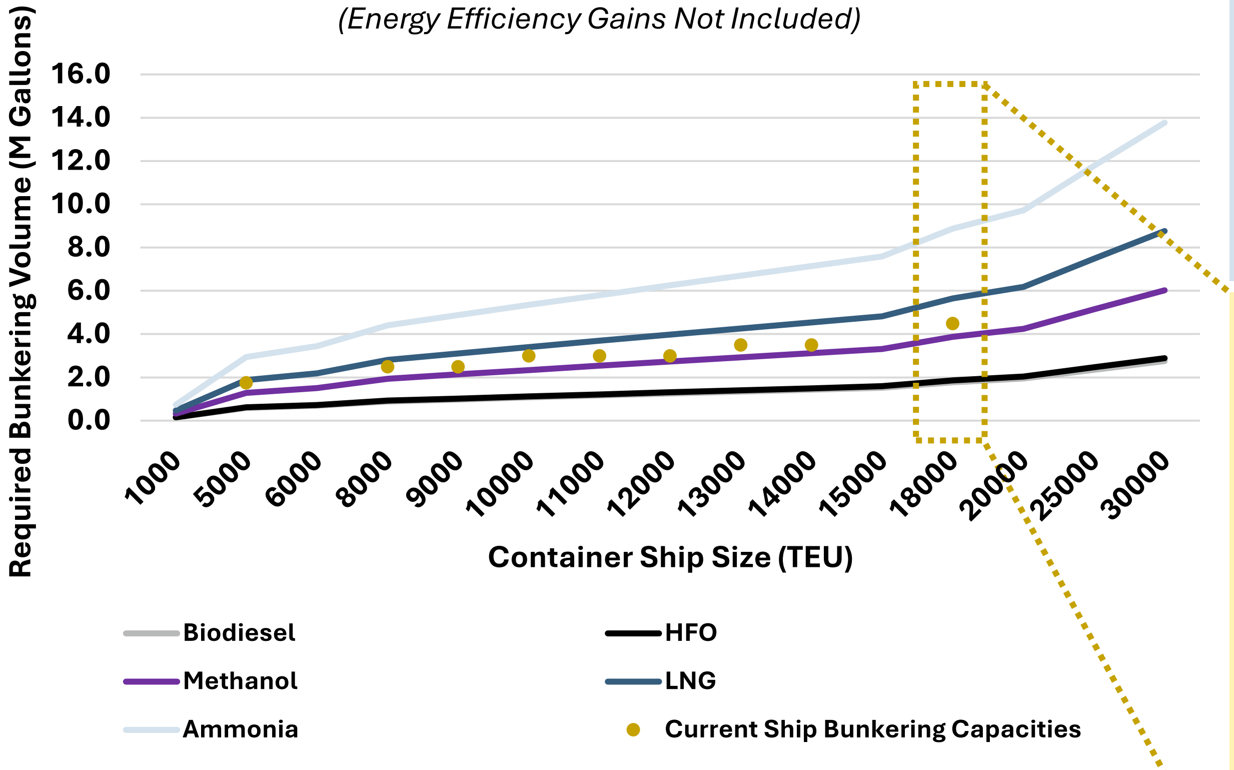
References: GCMD BCG Report 2023.pdf, Fuel Consumption by Containership Size and Speed | The Geography of Transport Systems (transportgeography.org), What is weather routing, who uses it, and how effective can it be? – DTN, How Propeller Polishing Impacts Fuel Efficiency? (nereussubsea.com), Autopilot adjustment and use: GreenVoyage2050 (imo.org), The Power Of Marine Coatings: Driving Efficiencies To Enable The Future Fuels Transition | Coatings World, 7 Technologies To Reduce Fuel Consumption Of Ships (marineinsight.com), Solar-Powered Shipping to Save 250 Million Tons of Fuel Per Year (thomasnet.com), DNV 2023 Maritime Forecast

Appendix: Enabling LNG and ammonia fuel pathways will require increasing shipboard bunkering capacity and, or fuel economy

Differences in volumetric energy density will need to be accounted for across all ship sizes

Figure A: Required Bunkering Volume by Ship Size and Fuel

(Energy Efficiency Gains Not Included)



Key Model Inputs:

30 day, one-way voyage Shanghai -> LA

19 knot speed of advance

No fuel reserve or excess bunkering space

$1500/TEU

- **Including containment structures, the least volumetrically-energy-dense fuel alternatives (LNG and Ammonia) could require additional fuel storage capacity**
- **With a 30% gain in energy efficiency, the required additional bunker capacity could be:**

Eliminated	**Reduced Under 50%**
For LNG Fuels	*For Ammonia Fuels*

- **To avoid lost revenue and upward pressure on emissions per volume of goods shipped(i), additional fuel capacity must be found outside space dedicated to storing cargo**
  - *Without the appropriate design changes, an 18,000-TEU LNG or ammonia-powered vessel from Shanghai to LA would have to forgo over 112 and 429 TEU of cargo space/trip, resulting in around $169k and $645k in lost revenue, respectively*
  - *With energy efficiency gains, only ammonia would cause the same vessel to forgo over 168 TEU of cargo space for fuel, equivalent to over $250k in lost revenue*
- **Vessels have been able to spatially adapt to using LNG, with the Jacques Saade setting a world record in 2020 for most containers loaded on a single vessel**

(i) Note: With fewer goods shipped per trip due to cargo space being forgone for bunker space, more shipping round-trips will need to be made on average – contributing negatively towards emissions

Sources: UNCTAD Review of Maritime Transport 2022; The Bunkerist.com, Fuel Stored and Transported by a Containership; Maersk.com, Logistics Explained, Sea Freight Guide; Emerald.com, Can Growth in Containership size be stopped?; Transportgeography.org, Fuel Consumption in Containership by size and speed, CMA-CGM

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Appenidx: Ammonia must overcome stronger operational and environmental safety headwinds than LNG and Methanol in becoming a maritime fuel at scale

	LNG	Methanol	Ammonia	Commentary
Safety Concerns while Fueling	SIMOPs have been successfully demonstrated for both LNG and Methanol		• Ammonia, despite having a strong safety record as a traded commodity, has yet to demonstrate it can be safely bunkered during SIMOPs	• Safety protocols may prevent ships from bunkering volatile fuels simultaneously with (SIMOPS) or in the same location as transferring cargo • The additional measures could reduce ship's operational tempo
Shipboard Safety Concerns	• Gaseous at normal temperatures and pressures • Long record of safe handling despite risk of explosion	• Safest alternative • Handles like gasoline • Only toxic if large amounts ingested	• Gaseous at normal temperatures and pressure • Highly toxic	• Greater onboard safety measures could lead to additional operating expenses in equipment and insurance
Environmental Safety Concerns	• Safest maritime fuel for the hydrosphere during a spill – methane boils off into atmosphere	• 195X less harmful to the environment than HFO and is biodegradable	• Ammonia is 1160X more lethal to wildlife than HFO to wildlife and can significantly alter local water pH	• Environmental damage translates directly to spill clean-up costs or indirectly through insurance costs

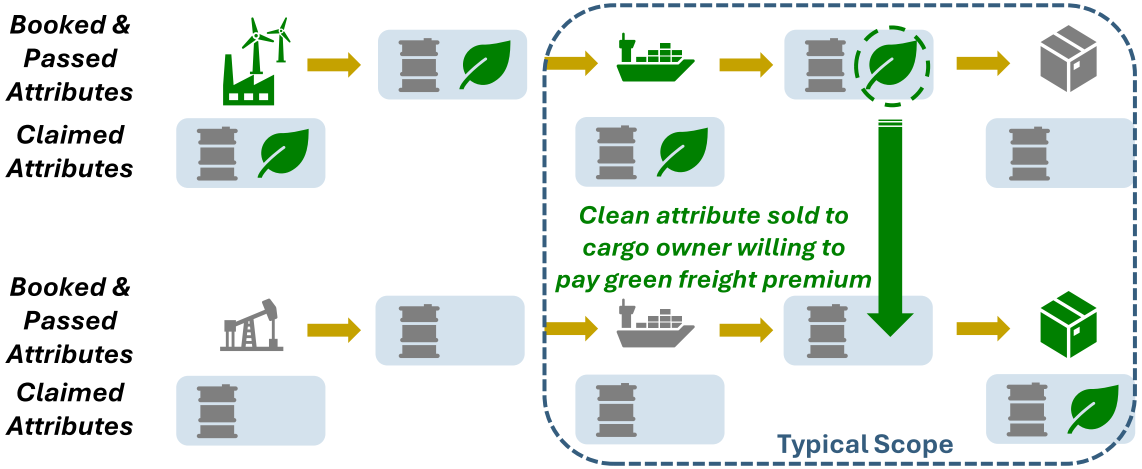
Sources: Methanol.org, Marine Methanol Future-Proof Shipping Fuel; Marinelink.com, Container Vessel Bunkered with Methanol During Cargo Operations; Safety4sea.com, SEA-LNG aids in USA's first ever SIMOPs LNG bunkering;

Appendix: Participating in book and claim systems can help facilitate exchanges in the nascent clean shipping fuel market and prepare shipowners for complying with emissions regulations

Book and claim removes barriers between alternative fuel supply and demand

- Book and claim decouples the low emissions attributes of a fuel from its physical nature allowing them to be sold separately
  - Clean fuel producers or shipowners(i) “book” and pass along/sell the low emissions benefits
  - Cargo owners purchase and “claim” low emissions benefits ***from outside their physical supply chain***
- Reduces transaction cost in clean fuel procurement
- Shipowners able to adopt clean fuels and keep customers who are not willing or able to pay for green freight premiums

Figure B: Simplified Book and Claim Example(ii)



Significant overlap exists in book and claim systems and reporting for regulatory authorities

	IMO Regulations	Fuel EU Maritime Regulations	MMMCZS Book and Claim
Emissions Intensity Unit	gCO_2/tnm	gCO_2/MJ	gCO_2/MJ
Emissions Considered	CO_2	CO_2, CH_4, N_2O	CO_2, CH_4, N_2O
Scope of Analysis	Well-to-Wake	Well-to-Wake	Well-to-Wake
Vessels Subject to	> 5000 gross tonnage	> 5000 gross tonnage	> 5000 gross tonnage
Ship Required to Monitor and Collect Primary Voyage Data	✓	✓	✓
Ship Required to Submit Data to Independent 3rd Party Verifier	✓	✓	✓

i) Note: For simplicity, shipowners refer to an organization that owns and operates an ocean-going vessel.
ii) Note: Scope and boundary limited to the maritime shipping value chain is in-line with the proposed Maersk Mc-kinney Moller Center for Zero Carbon Shipping Book and Claim Model. While the scope could be extended to fuel producers to allow trading upstream of shipowners and provide more flexibility, this would act more like an offset program and could limit real decarbonization of the maritime sector.
Sources: Maersk Mc-Kinney Moller Center for Zero Carbon Shipping Maritime Book and Claim System Overview and Design Decisions, Justifications;

Appendix: Source Links, Listed In Order of Reference (Page 1 of 3)

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Quick guide to ocean freight transit times | Maersk
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Successful propulsion and manoeuvrability trials by Fortescue's dual-fuelled ammonia-powered vessel in the Port of Singapore | Fortescue
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Fuel Cost Calculator | Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping
Real Cost of Shipping Decarbonization | BCG
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Khaled bin Mohamed bin Zayed Witnesses Signing Ceremony for ADNOC and ExxonMobil Partnering in World's Largest Low-Carbon Hydrogen Facility | ExxonMobil
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Maersk launches new green methanol company (renewablesnow.com)
TES H2 (tes-h2.com)
TES and "K" LINE Partner for Sustainable Maritime Shipping Solutions | TES H2 (tes-h2.com)
TES partners with 7 large international companies to create a global e-NG coalition | TES H2 (tes-h2.com)
United States: TotalEnergies and TES Join Forces to Develop a Large-Scale e-NG Production Unit | TES H2 (tes-h2.com)
World's first of its kind green ammonia plant inaugurated by Skovgaard Energy, Vestas and Topsoe (hydrocarbonprocessing.com)
World's first of its kind green ammonia plant inaugurated by Skovgaard Energy, Vestas, and Topsoe
Topsoe awarded contract to support FEED study for new low-carbon ammonia plant in Louisiana, US
EU Emissions Trading System for Maritime Transport Explained – Part 1 of 6 : Clyde & Co (ALL 6 PARTS)
2023 IMO Strategy on Reduction of GHG Emissions from Ships
Text - S.1920 - 118th Congress (2023-2024): International Maritime Pollution Accountability Act of 2023 | Congress.gov | Library of Congress
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Appendix: Source Links, Listed In Order of Reference (Page 3 of 3)

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Growth in containership sizes to be stopped? | Emerald Insight
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CMA CGM | The CMA CGM Jacques Saadé, the world's largest liquefied natural gas-powered containership, has set a new world record for the number of full containers loaded on a single vessel
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