VANGUARD RENEWABLES

HOW THE IMO'S NET-ZERO FRAMEWORK CAN POWER AMERICAN INDUSTRY

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Vanguard Renewables is a leading US environmental services company and producer of biomethane from organic waste. Headquartered in Weston, Massachusetts, the company builds, owns, and operates on-farm anaerobic digesters that convert food, beverage, and agricultural waste into pipeline-ready renewable natural gas. Vanguard Renewables is rapidly scaling its national footprint, with operational sites across the Northeast and new facilities under construction in the Midwest and South. By diverting organic waste streams from landfills, the company is reducing greenhouse gas emissions at scale while supporting critical domestic energy infrastructure and regenerative agriculture for America's farms. Vanguard Renewables is a portfolio company of Global Infrastructure Partners (GIP), part of BlackRock.

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Executive Summary

The International Maritime Organization (IMO) is set to formally adopt its approved Net-Zero Framework in October 2025. The regulations establish annual greenhouse-gas intensity limits for large vessels and add a market-based measure that prices emissions above those limits. **By providing a unified prescription that could replace the emerging patchwork of regional regulations, the IMO framework could unleash a torrent of investment in the $2.2 trillion global maritime industry.**

The United States is well positioned to capture the benefits. It already produces 30%–35% of global renewable natural gas (RNG)—methane captured from manure, food waste, and landfills that is upgraded to pipeline-quality gas. RNG is the feedstock for bio-liquid natural gas (bio-LNG), which can achieve very low—at times negative—lifecycle carbon intensity when methane abatement is counted. With ~3 million miles of natural-gas pipelines and existing liquefaction facilities, the US can move and store bio-LNG using infrastructure in place today.

However, meeting maritime needs still requires **$120 billion–$220 billion in investment across US sectors** involved in production and delivery infrastructure. The modeled payoff is substantial: **$78 billion–$134 billion in added GDP each year through 2050 ($2 trillion–$3 trillion cumulatively),** as well as **$105 billion–$185 billion in total new revenues for agriculture and 390,000–680,000 jobs** across several sectors. Recent US LNG expansion—from 0.6 Bcf/d in 2016 to 11.9 Bcf/d in 2024—shows how quickly the US can scale when market signals are stable.

The final shape of the IMO rule will also determine LNG's role in the future shipping fuel mix. With appropriate credit for methane abatement, bio-LNG can complement LNG and improve fleet carbon intensity. Without it, LNG's lifecycle emissions face tightening thresholds and rising compliance costs under the market-based measure, weakening the investment case.

Two IMO implementation choices play an important role in shaping outcomes:

- **Recognizing methane abatement in lifecycle scoring.** Crediting avoided methane enables 10%–20% bio-LNG blends that lower a ship's carbon intensity while keeping LNG viable.

- **Enabling a secure, auditable book-and-claim system.** A tracking system that prevents double counting—and interoperates with other registries—would connect inland RNG production to coastal bunkering without requiring physical co-movement of fuel.

The IMO Net-Zero Framework offers a chance to align regional regulations into a consistent global system that incorporates the US's voice and opens the door for the country's leadership in clean fuels, logistics, and maritime export capacity.

Introduction

Market certainty catalyzes investment. When regulatory frameworks are unclear or inconsistent, capital sits on the sidelines. But when clear rules establish stable, long-term market conditions, industries respond decisively by mobilizing investment, accelerating innovation, and driving economic growth. The International Maritime Organization's recently approved net-zero regulations provide this type of certainty for the $2.2 trillion global maritime shipping industry. This presents an opportunity for the United States to stimulate a cumulative $120 billion–$220 billion in investment and $2 trillion–$3 trillion in GDP growth, while creating 390,000–680,000 jobs by 2050.

The IMO's Net-Zero Framework—accepted in April 2025 and up for formal adoption in October 2025—would create the clearest global standard yet for shipping fuel emissions. It combines a greenhouse-gas intensity target with a market-based pricing mechanism[i] and could replace the emerging patchwork of regional regulations[ii] [iii] with a single playbook that unlocks maritime investment.

Much of that investment would flow toward building out the clean fuel supply chain. Advanced fuels, both bio- and hydrogen-based, meet less than 1% of the maritime fuel demand today.[iv] To align with IMO targets, that share would need to grow to about 50%, or 6 exajoules (EJ) by 2050.[v]

One nation particularly well-positioned to capitalize on this massive transformation is the United States. The US already produces 30%–35% of global renewable natural gas (RNG),[vi] which is methane captured from manure, food waste, and landfills that is turned into pipeline-quality gas. RNG is the core component of bio-liquid natural gas (bio-LNG)—a ship fuel that can achieve a negative carbon-intensity (CI) score when methane abatement is counted. The US's 3 million miles of natural gas pipelines[vii] and robust liquefaction systems provide infrastructure that bio-LNG can use immediately—an advantage few countries can match.

The IMO's Net-Zero Framework at a glance

The draft IMO Net-Zero Framework outlines two major components of a new global regulatory regime:

1. A greenhouse gas fuel-intensity standard that sets annual carbon intensity limits for ships above 5,000 gross tonnes.

2. A market-based measure requiring purchase of "remedial units" for emissions above the allowable limit, effectively creating a carbon pricing mechanism.

Both pillars rely on a well-to-wake lifecycle accounting approach, which assesses total emissions from fuel production to onboard combustion.[1] This approach reflects the real environmental impact of fuels and aligns with national policies emerging in the EU and Southeast Asia.

While the overall structure has been agreed upon, details remain unresolved—including the treatment of low-carbon fuels, the value of methane abatement, and the mechanisms for certifying emissions reductions. These elements will determine whether innovative, US-made solutions like bio-LNG are fully credited under the system.

[1] International Maritime Organization. "IMO Approves Net-Zero Regulations for Global Shipping." Press briefing, April 11, 2025. https://www.imo.org/en/mediacentre/pressbriefings/pages/imo-approves-netzero-regulations.aspx.

Still, while the US has a solid starting foundation, meeting maritime fuel targets would require $120 billion–$220 billion of investment in production capacity and delivery infrastructure for US bio-LNG and other advanced fuels.[viii] The payoff is substantial. By driving new activity across agriculture, manufacturing, energy, and port systems, the US could boost its GDP by $78 billion–$134 billion annually, for a cumulative total of $2 trillion–$3 trillion by 2050.[ix] This would create 390,000–680,000 jobs, particularly in rural and industrial communities.[x]

The outcome of the IMO's regulatory process will determine whether this opportunity materializes—as well as the future of LNG in the shipping fuel mix. Depending on the design of the final rules, the framework could accelerate US LNG investments by enabling credit for bio-LNG as a carbon-intensity-reducing offset. This would position bio-LNG not as a competitor to traditional LNG, but as a complement that extends the life of LNG infrastructure while meeting climate goals. Without this recognition, however, many forecasts suggest LNG may fall out of the long-term maritime fuel mix altogether because its higher CI makes meeting tightening standards difficult.[xi]

Why US LNG and bio-LNG could see an expanded role in the global fuel mix

While the future fuel mix for maritime shipping remains uncertain, experts broadly agree that total shipping fuel demand will amount to 12–13 EJ annually through 2050.[xii] Decarbonizing maritime shipping would require scaling advanced cleaner fuels to meet 50% (6 EJ) of that volume, up from less than 1% today.[xiii] Biofuels such as bio-LNG, bio-oils, and biomethanol, could account for more than half of that total (Exhibit 1).[xiv] In such a case, bio-LNG alone could see demand of up to 100 million tonnes per annum (MTPA), or 1.6 EJ, by 2050. That is equivalent to 4–5X of total global production of RNG, bio-LNG's feedstock, today.[xv]

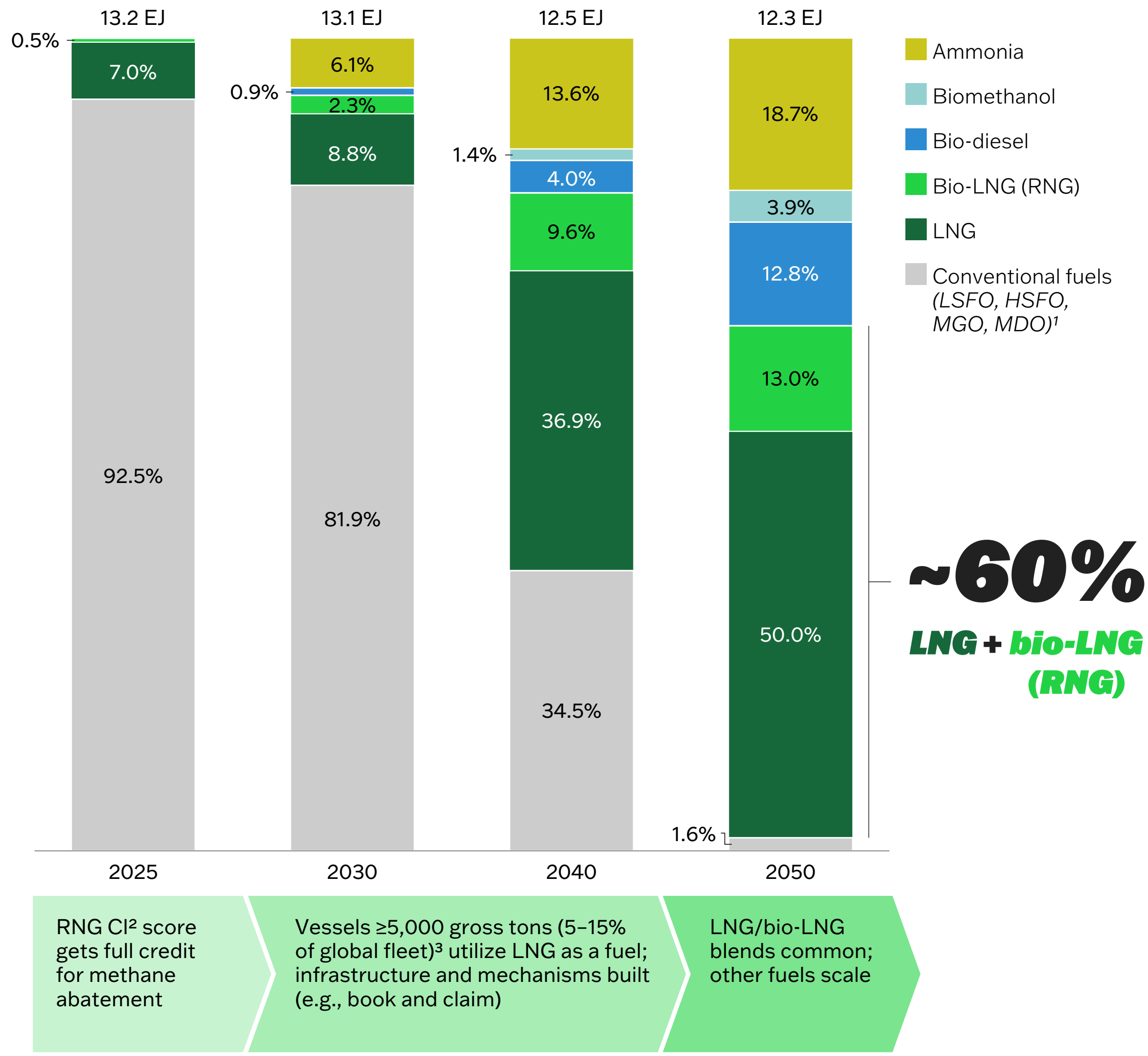
Bio-LNG offers several clear advantages to fleet owners relative to other bio- and hydrogen-based fuels, especially over the next decade (Exhibit 2). Bio-LNG is the most technologically mature, with energy density and performance similar to LNG.[xvi] When using the right agricultural feedstock, bio-LNG has a negative CI score, meaning it removes more greenhouse gas emissions from the atmosphere than it emits.[xvii] Accounting for existing EU Emissions Trading System and FuelEUR Maritime regulations and upcoming IMO penalties for emissions, bio-LNG could be 2%–10% more cost competitive than conventional fuels (e.g., low-sulfur fuel oil [LSFO], high-sulfur fuel oil [HSFO], or marine diesel oil [MDO]) and 30% more cost competitive than other alternative fuel options (e.g., biodiesel, ammonia, biomethanol).[xviii] Finally, bio-LNG's drop-in compatibility with existing LNG infrastructure allows fleet owners to forgo major vessel retrofits, enabling faster and less capital-intensive adoption.

Just as importantly for the US, bio-LNG can complement—rather than replace—conventional LNG. Today, approximately 4%–6% of the world's shipping fleet runs on LNG,[xix] with about 25% of this fuel volume supplied by the US.[xx] Should the IMO's final rules credit bio-LNG with a negative CI-score for methane abatement, blending even 20%–30% bio-LNG with conventional LNG will enable LNG use to continue while enhancing its environmental profile.[xxi] Without credit for methane abatement, however, the entire LNG ecosystem could face regulatory headwinds because the fuel's upstream emissions profile would fall short of future CI thresholds.

Exhibit 1

Bio-LNG and LNG could comprise 60% of the global maritime shipping fuel mix—if bio-LNG receives credit for methane abatement.

Maritime shipping fuel mix



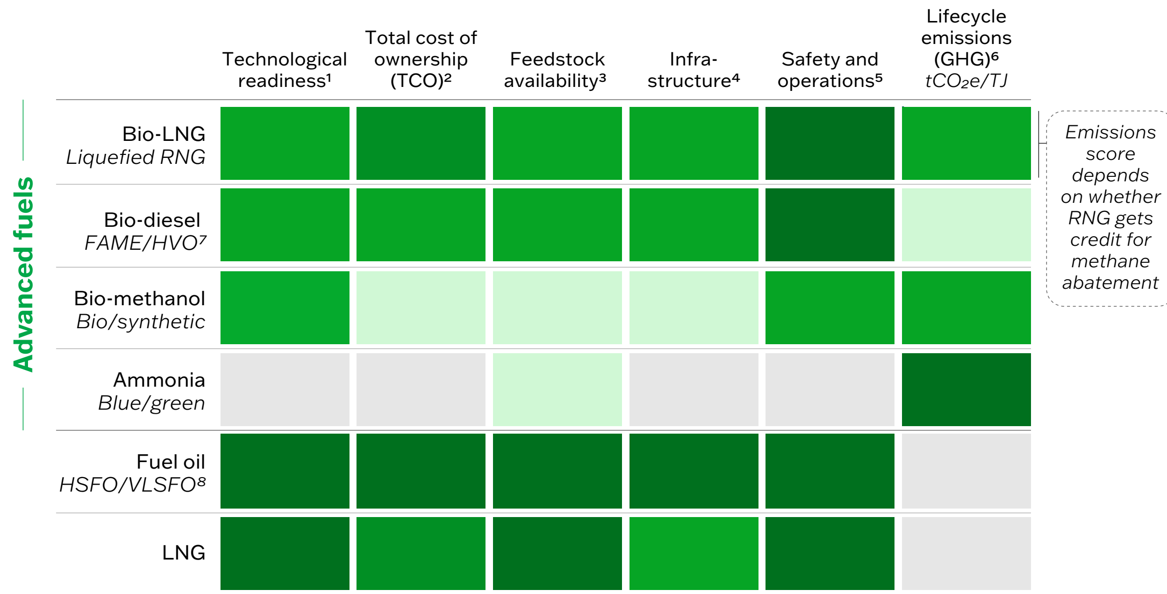
[1]Low sulfur fuel oil, high sulfur fuel oil, marine gas oil, marine diesel oil. [2]Carbon intensity (CI) score (gCO_2e/MJ). [3]Uses emission generation concentration (~85% of emissions driven by ships ≥5,000 GT, ~47% of global fleet) to estimate the percent of ships in the global fleet that would need to use LNG. Uses potential fuel weighting to estimate range of fleet conversion need.
Sources: Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, Lloyd's Register, SEA LNG

Exhibit 2

Bio-LNG offers advantages to fleet owners relative to other fuels.

Favorability of fuels for fleet owners

Unfavorable — Favorable



[1]TRL score (1–9) using Lloyd's Register Zero Carbon Fuel Monitor, averaging key ship components (e.g., fuel handling/storage). [2]All scores normalized against HSFO. Includes both operating and capital costs. [3]Scores normalized, with most favorable = abundant global feedstock, while unfavorable = scarce feedstock. [4]Based on bunkering and production. [5]Based on existence of long-standing standards and risk assessment. [6]Based on carbon intensity (CI) score ranges in multiple frameworks (Proposed IMO MEPC guidelines, FuelEU Maritime Regulation, and Argonne National Laboratory GREET Model. [7]Fatty acid methyl ester/hydrotreated vegetable oil. [8]High-sulfur fuel oil/very low sulfur fuel oil.
Sources: Lloyd's Register Zero Carbon Fuel Monitor, International Maritime Organization FuelEU Maritime Regulation + EU Renewable Energy Directive (RED), Argonne National Laboratory (US DOE Office of Energy Efficiency & Renewable Energy)

Seizing the opportunity requires strategic US investment

Stimulating the fuel growth needed to meet current IMO targets would require a significant expansion of current US production and delivery infrastructure, particularly to strengthen the "last mile," which includes bunkering, terminals, and barging capacity. The buildout, however, would benefit both LNG and bio-LNG producers as well as several sectors of the US economy (Exhibit 3).

- Advanced fuel production facilities, storage tanks, and pipelines—representing $95 billion–$175 billion in investment for new projects—would mobilize construction crews, engineers, and heavy equipment operators across the country.[xxxiii]

- Ports and maritime would receive $24 billion–$45 billion in investment to expand bunkering, terminal, and barging capacity, positioning the US as a critical fueling hub for global shipping.[xxxiv]

- The agricultural sector would see $105 billion–$185 billion in revenue from demand for feedstock and land, creating income for farmers and rural communities.[xxxv]

These investments would create 390,000–680,000 jobs[xxii] by 2050 across the sectors supporting the buildout, including 230,000–405,000 in manufacturing for developing fuel production facilities and 35,000–60,000 in maritime.[xxiii]

Exhibit 3

Meeting the fuel demand driven by IMO's net-zero target could require $120 billion–$220 billion in investment across US industries.

Industry	**Required infrastructure investment through 2050,** USD billions	**Investment examples**
Fuel production	35–70	• **ORAs,[1] anaerobic digestors** to produce bio-methane • **Haber-Bosch plants** to produce ammonia • **Biofuels manufacturing** (biomethanol/ bio-diesel)
Ports and terminals	20–40	• **LNG export terminals** (liquefaction trains, storage) • **Storage, terminals, and smaller scale liquefaction** co-located with ports and bunkering stations
Ship building	4–5	• **Bunker barges** to re-fuel ships (likely to be built domestically due to Jones Act requirements)
Power generation	35–70	• Additional **wind/solar generation** for production of e-hydrogen (feedstock for e-ammonia) • **Battery storage** and **grid capacity**
Hydrogen production	25–35	• **Electrolyzers to manufacture e-hydrogen** feedstock for ammonia production
Agriculture	*Required investment could increase utilization of existing agriculture and rail infrastructure, potentially providing a cumulative economic impact of **$105B–$185B** and **$30B–$55B** in the agriculture and railroad industries, respectively.*	
Rail		
Total	**120–220**	• **Driven by ranged assumptions in volume and cost inputs** (e.g., capital costs per facility or unit of throughput, fuel volume demanded, capacity factor of power generation)

[1]Organic resources for anaerobic digestion.
Sources: See Technical Appendix and end note vii

Altogether, the pickup in activity across the US economy could generate $78 billion–$134 billion in annual US GDP growth, amounting to $2 trillion–$3 trillion cumulatively by 2050 (Exhibit 4).[xxiv] Servicing European demand alone could generate $6 billion–$12 billion in additional export revenue and help meet Europe's commitment to purchase approximately $750 billion of US energy.[xxv] EU investment commitments for the US maritime shipping sector have already begun. In March 2025, France-based CMA CGM—the world's third-largest container shipping line—announced $20 billion to help fund the build out of US maritime infrastructure.[xxvi] An early example of the funds being put to work: CMA GGM's minority investment into Vanguard Renewables to ensure access to US-produced bio-LNG.[xxvii]

Exhibit 4

Meeting the demand for biofuels could boost US GDP by a cumulative $2 trillion–$3 trillion and create 390,000–680,000 jobs by 2050.

Industry	**Cumulative GDP impact by 2050,** USD billions	**Avg annualized GDP impact,** $ billions/year	**GDP uplift, %**[1]	**Workforce impact,** thousands
Fuel production	1,000–1,765	53	2.7	230–405
Ports and terminals	200–315	12	0.4	35–60
Ship building	10–20	1	2.1	2–3
Power generation	305–520	7	3.9	55–95
Hydrogen production	300–480	16	2.8	60–100
Agriculture	105–185	6	0.4	–
Rail	30–55	2	1.7	10–20
Total	1,950–3,340	106	0.4	**Total** 390–680

[1]Calculated as average annualized GDP impact divided by 2024 GDP in each sector.
Sources: See Technical Appendix and end note ix

The US effort would also position the country as one of the largest advanced fuel producers globally and a leading maritime fuel exporter—while benefiting the global maritime industry. US investments would enable the country to provide an additional 20–26 MTPA (1.2–1.7 EJ) of advanced fuels annually through 2050 to help close the projected global supply gap.[xxviii]

The US is ready to lead on bio-LNG

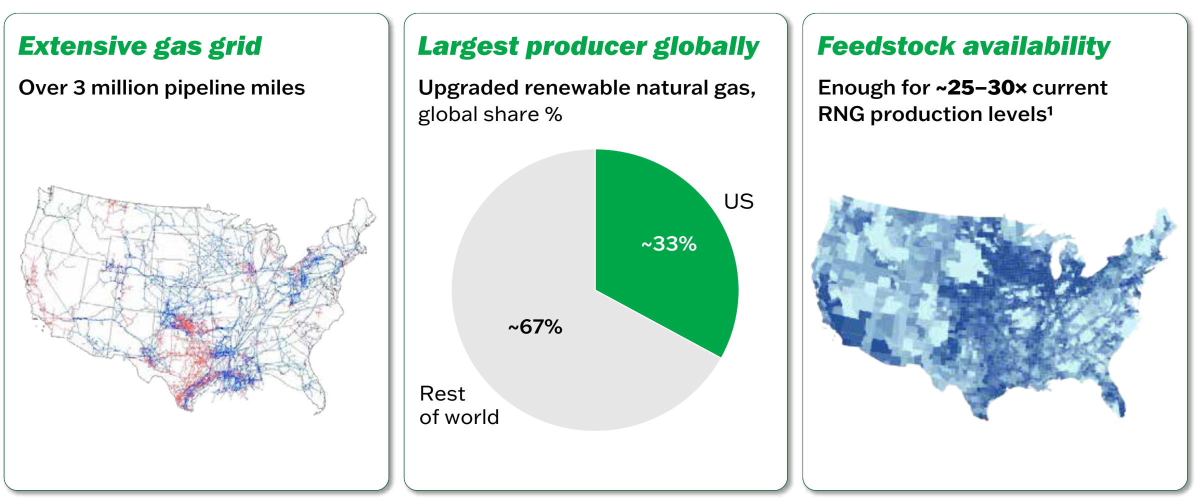
The US is well positioned to capture this opportunity, thanks to its leading nationwide grid and liquefaction facilities and a large-scale agricultural base capable of supplying ample feedstock for bio-LNG (Exhibit 5).

The country's production of RNG—the core component of bio-LNG—is currently 2–3 MTPA or 0.1–0.2 of EJ potential, amounting to 30%–35% of global production.[xxix] The US also has an extensive LNG distribution network that bio-LNG can leverage. US gas distribution and storage infrastructure—about 3 million miles of gas pipelines[xxx] and an extensive network of compressor stations and liquefaction systems—provide an advantage others cannot easily replicate.

In fact, the US's transformation in LNG offers a clear precedent that the scale of this industrial mobilization and the benefits it could yield are well within reach: In under a decade, the country grew from a marginal LNG exporter at 0.6 billion cubic feet per day (Bcf/d) in 2016[xxxi] to the world's top supplier at 11.9 Bcfd in 2024.[xxxii] By applying a similar playbook to bio-LNG, the US could secure new markets, extend its influence in global shipping, reduce foreign dependence, and solidify its energy leadership for decades to come.

Exhibit 5

The US has favorable conditions to become a world leader in bio-LNG production.



¹National total available for anerobic digestion process.
Sources: ICF Renewable Natural Gas Supply Assessment (2025), America Gas Foundation, Biomethane Industrial Partnership (BIP) Europe, S&P Global Platts, CEDIGAZ, IEA , US EIA, Poten & Partners, American Gas Foundation

The opportunity hinges on final IMO rules

The IMO's Net-Zero Framework could set the rules of the maritime shipping fuel game for decades to come. Small differences in definitions, scoring methods, and market mechanisms will determine which producers provide the fuel supply and capture the benefits. The following two areas are of particular importance for the US:

Crediting the methane abatement value of bio-LNG. US RNG producers are well positioned to deliver fuel with negative or near-zero lifecycle emissions when measured well-to-wake, in part due to large-scale methane abatement from dairy farm methane-emitting manure and food waste facilities. If this value is not fully recognized, US producers lose one of their most significant competitive differentiators: low-CI-score fuel that is able to decarbonize a tank of LNG. A well-to-wake accounting boundary, acceptance of project-specific CI values, and recognition of lifecycle assessment methods such as GREET (greenhouse gases, regulated emissions and energy use in technologies)—all verified to international standards—would increase the uptake of bio-LNG. If the negative CI value of bio-LNG is not recognized, US LNG would likely see a diminished role as a maritime fuel provider.

Establishing a secure, auditable book-and-claim system. Most advanced biofuel production facilities, including for RNG, are located inland near agriculture or waste sources, while bunkering occurs far away at coastal ports. Without book-and-claim, the need to physically move every molecule to a maritime user would decrease uptake of bio-LNG. An effective book-and-claim system allows certified fuel attributes to be transferred independently of the physical location of the molecule, while ensuring traceability and integrity of decarbonization. This would prevent double-counting and would enable coordination with other registries.

The IMO Net-Zero Framework offers a chance to align a patchwork of regional regulations into a consistent global system that incorporates the US's voice and opens the door for the country's leadership in clean fuels, logistics, and maritime export capacity. By fulfilling domestic and global demand for multiple fuel types, the US can boost its GDP, create hundreds of thousands of jobs, and build the infrastructure that powers the next era of maritime commerce.

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Technical Appendix

Primary data sources	
Not exhaustive of all industry reports, analyses, data sources, or information used. For a full list, please reference the end notes.	
Source	**How we used it**
Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping	The Mærsk Mc-Kinney Møller Center is an independent, industry-backed research institute focused on maritime decarbonization. Its *Fuel Option Scenarios* paper provides scenarios for the global maritime fuel mix to 2050, including adoption pathways for ammonia, methanol, biofuels, and LNG. This was used to validate demand trajectories, provide cross-checks on cost competitiveness, and ensure that infrastructure build-out assumptions were consistent with plausible adoption scenarios.
Lloyd's Register Maritime Decarbonisation Hub	Lloyd's Register is a global classification society and technical consultancy with a dedicated Maritime Decarbonisation Hub. Its report *The Future of Maritime Fuels* outlines potential adoption pathways and relative competitiveness of alternative fuels in shipping. This was used to validate demand trajectories, provide cross-checks on cost competitiveness and ensure that infrastructure build-out assumptions were consistent with plausible adoption scenarios.
SEA-LNG	SEA-LNG is an industry coalition promoting the use of LNG and bio-LNG as transitional marine fuels. Its *View from the Bridge* report combines industry data and outlooks on LNG bunkering capacity, infrastructure readiness, and emissions performance. This was used to benchmark the required scale of LNG and bio-LNG infrastructure investments, particularly at ports and bunkering terminals, and to ensure consistency with industry expectations of LNG's role in the fuel mix.
US Bureau of Economic Analysis (BEA)	The BEA is the US federal statistical agency responsible for producing official macroeconomic accounts. Its input–output tables and multipliers provide detailed information on inter-industry relationships, output, value added, and employment per unit of spending. The BEA final-demand multipliers were used to estimate both the economic output impacts (direct and indirect GDP contributions) and the employment impacts (jobs per $1 million of investment) of infrastructure spending across fuels and asset classes.

Guidehouse, Economic Analysis of Renewable Natural Gas	Guidehouse is a global consultancy producing technical and economic studies for the energy sector. Its *RNG Report* for the RNG Coalition provides a detailed cost analysis of renewable natural gas production in the US. Information in this report was used to benchmark facility sizing and unit capital costs for biomethane and bio-LNG production.
California Water Environment Association (CWEA)	CWEA is a professional body for water and wastewater operators. Its publications document biosolids and waste-to-energy infrastructure in California. CWEA case data was used to supplement cost assumptions for RNG and waste-to-energy facilities.
National Renewable Energy Laboratory (NREL)	NREL is the US Department of Energy's lead national lab for renewables. Its state-of-technology and biodiesel handling reports provide rigorous techno-economic assessments. The techno-economic assessments were used to define biofuel conversion yields and biodiesel storage/handling requirements and associated capital investment costs.
A roadmap to the Ammonia Economy (MacFarlane et.al)	Published in *Joule,* this peer-reviewed study presents a comprehensive techno-economic assessment of ammonia as an energy carrier. This was used to form and validate ammonia production cost assumptions.
IRENA & Methanol Institute, Innovation Outlook: Renewable Methanol	IRENA is an intergovernmental clean energy agency, and the Methanol Institute is the industry trade body. Their joint study provides global technology and cost outlooks for renewable methanol. Information from the joint study was used to derive unit production and storage costs for biomethanol facilities.
US Department of Agriculture (USDA) Economic Research Service (ERS) and Agricultural Marketing Service (AMS)	USDA ERS provides forecasts on US crop markets, and AMS publishes commodity price reports. These sources were used to assess feedstock availability and by-product impacts relevant to biodiesel and biomethane investments.
Det Norske Veritas (DNV)	DNV is a global risk management and classification society with deep expertise in maritime decarbonization. Its assessments of US port LNG bunkering were used to size incremental terminal and port investments.
OpenTug	OpenTug is a US maritime industry platform covering tug and barge markets. Its analysis of barge construction costs was used to estimate bunkering barge investment needs across multiple fuel types.

Investment, jobs, and GDP growth analysis: Scope and definitions	
Period	The period analyzed was 2026–2050, expressed in 2025 US dollars, real.
Fuels in scope	Liquified natural gas (LNG), renewable natural gas (RNG), bio-LNG, biomethanol, biodiesel, and ammonia (from renewable sources)
Infrastructure boundary	Includes the following: • Production facilities such as anaerobic digesters to produce renewable natural gas, Haber-Bosch plants to produce ammonia, and plants for biofuels manufacturing • Ports and terminals, such as LNG export terminals (liquefaction trains, storage), as well as storage, terminals, and smaller-scale liquification co-located with ports and bunkering stations • Ship-building of bunker barges to refuel ships. Assumes these bunker barges are built domestically to comply with Jones Act requirements. • Power generation required to create renewable ammonia. This requires additional wind and solar generation, as well as battery storage and grid capacity. • Hydrogen production, such as electrolyzers to manufacture e-hydrogen feedstock for ammonia production.

How we used data sources in the analysis	
Data use	**Description**
Future demand and fuel mix	Global fuel adoption scenarios from Mærsk Mc-Kinney Møller Center, Lloyd's Register, and SEA-LNG.
Unit capital costs (production facilities, power generation, hydrogen production)	Published techno-economic studies, government reports, industry disclosures, and technical brochures covering production facilities, storage, and port assets. Please refer to main data sources above, as well as the complete list in endnotes.
Ports and bunkering assets	Trade publications and case studies of bunkering operations in US ports.
Economic and employment multipliers	US Bureau of Economic Analysis input–output accounts.
State-level allocation of economic impact	BEA GDP by industry, used to distribute economic and jobs impacts geographically.

Methodology for estimating infrastructure investment and economic impact	
The approach used to estimate infrastructure investment followed a structured, bottom-up analysis from projected fuel demand to total investment required. The approach combined techno-economic assessments from industry and trade groups and was complemented with actual cost data from executed projects where publicly available.	
Step	**Description**
Step 1. Define future fuel mix demand	The estimation of infrastructure investment begins by defining future demand for alternative marine fuels, using published maritime fuel-mix scenarios to project how much LNG, bio-LNG, biomethanol, biodiesel, and ammonia (from renewable sources) may be consumed globally by 2050. The US contribution is estimated based on its current share of global bunkering capacity, reflecting the country's position as both a large-scale fuel producer and one of the world's most important maritime hubs. Meeting this share requires the build-out of new infrastructure at a scale far beyond what exists today.
Step 2. Convert demand to energy units	Future demand volumes are expressed in million tons per annum (MTPA) and converted into energy units to ensure consistency across fuels. These demand levels are then aligned with milestones for 2030, 2040, and 2050, ensuring that the modeled infrastructure build-out is consistent with the adoption curves in global scenarios.
Step 3. Determine production and capacity requirements	The projected demand is then converted into required production capacity. This step estimates how much production infrastructure must be installed by 2050 to deliver the required output. For instance, an ammonia demand pathway is translated into the number of Haber-Bosch plants, while bio-LNG demand is converted into the number of anaerobic digestion and upgrading plants.
Step 4. Map to infrastructure modules	Each fuel's supply chain is then broken down into the infrastructure modules necessary to deliver it. On the production side, this includes digestion and upgrading plants for bio-LNG, or chemical conversion facilities for ammonia and methanol. At the ports, module include liquefaction units, storage tanks, loading systems, and bunkering barges. Importantly, while all fuels require storage and handling capacity, the specifications are unique to each fuel—for example, cryogenic tanks for bio-LNG are fundamentally different from liquid storage for biodiesel. Thus, capital costs were based on the unique storage and handling requirements of each fuel. Special attention was taken to avoid double-counting across fuels.
Step 5. Apply unit capital costs	Unit capital costs are applied to each module based on published techno-economic studies, industry reports, and project disclosures. These unit costs reflect full facility expenditures, including engineering, equipment and construction costs (e.g., equipment costs plus energy, procurement, and storage [EPC] services and indirects). Where US-specific adjustments are available, such as regional labor or materials indices, they are incorporated to ensure cost realism.

Step 6. Scale capital costs and aggregate across fuels	The costs are scaled to the required capacity and aggregated across modules to produce total investment estimates for each fuel. The results are reported as ranges, directly reflecting the low- and high-end estimates from published sources. Finally, investments are aggregated across fuels to arrive at the estimate of total US infrastructure investment required between 2026 and 2050.
Step 7. Estimate economic impact	In addition to one-time capital investment, the analysis also captures the ongoing economic impacts associated with new fuel supply chains. These impacts arise from the revenues generated in supplying feedstocks (for example, payments to the agricultural sector for organic waste and residue inputs), and from service revenues for transportation (e.g., rail-line services for biodiesel and biomethanol) and ports and terminals (for example, liquefaction, storage, and bunkering fees). These recurring revenue streams are estimated by applying per-ton feedstock costs and handling charges to projected 2030, 2040, and 2050 volumes. Once quantified, both the infrastructure investment (CAPEX) and the ongoing revenue flows are mapped to relevant industry categories in the US BEA input–output accounts. For each sector, final-demand multipliers are used to estimate the direct and indirect GDP contributions and the employment impacts measured as jobs per million dollars of spending. In this way, the analysis translates the scale of investment and revenue into sustained job creation and economic growth across agriculture, ports, construction and supporting industries.

Methodology for estimating infrastructure investment: Bio-LNG (renewable natural gas) example

Step	Description
Step 1. Define future fuel mix demand	Maritime scenarios suggest that by 2050, the US could supply around 3.2–4.8 MTPA of bio-LNG into the global shipping market. This need defines the infrastructure pathway of new build-out of production and downstream infrastructure.
Step 2. Convert demand to energy units	To keep fuels comparable, we convert mass to energy. The 3.2–4.8 MTPA of bio-LNG corresponds (via standard energy content assumptions) to roughly 0.2 EJ of delivered energy by 2050. For upstream planning, this is further linked to feedstock needs: the 2050 target implies on the order of 5.3–8.0 MTPA of raw biogas feedstock that must be captured, upgraded, and liquefied.
Step 3. Determine production and capacity requirements	We then translate the 2050 energy target into installed production capacity needs. Using industry reports, we benchmarked typical facility output at ~300,000 MMBtu per year. Meeting the 2050 demand therefore implies ~460–690 new agricultural-waste biomethane facilities nationally. This provides a concrete build-out plan that aligns with scenario milestones in 2030, 2040, and 2050 (i.e., capacity is phased in line with the scenario trajectory, not assumed as a late “step change”).

Step 4. Map to infrastructure modules	Capacity is translated into tangible assets: Production — anaerobic digestion plus gas cleanup/upgrading at each facility. Midstream — local collection networks, compression, and intermediate storage. Ports/terminals (incl. liquefaction) — incremental liquefaction capacity sized to bio-LNG throughput, cryogenic tanks, and loading arms/skids. Bunkering — a bunkering-barge fleet matched to port throughput.
Step 5. Apply unit capital costs	Module-level unit CAPEX comes from published sources and project disclosures. For production plants, the composite per-facility cost ranges from $41 million–$61 million (synthesizing Global News/Alberta Major Projects/Anaergia diligence with Guidehouse). Port and bunkering modules use US LNG precedents (e.g., Cheniere/Freeport disclosures, GEM methodology) and OpenTug for new-build barge benchmarks. While we report total installed costs, underlying figures reflect standard CAPEX composition (e.g., equipment + EPC + owner's costs/contingency and other indirects).
Step 6. Scale capital costs and aggregate across fuels	Each module's unit CAPEX is scaled by required capacity (number of plants, liquefaction train size, tank volumes, barge count) and summed for biomethane. This yields a cumulative bio-LNG investment requirement of roughly $23 billion–$51 billion by 2050. The range directly reflects low/high bounds in the sources and design choices. Finally, we combine the biomethane total with analogous estimates for LNG, biomethanol, biodiesel, and ammonia to produce the total US infrastructure investment (in constant 2025 USD), phased in line with the 2030/2040/2050 scenario points.
Step 7. Estimate economic impact	Beyond CAPEX, the biomethane production capacity build-out generates recurring revenues. Supplying 5.3–8.0 MTPA of raw biogas feedstock produces substantial payments to the agricultural sector, representing new demand for crop residues, manure, and other organic waste streams. Similarly, the throughput of bio-LNG at US ports creates revenue for liquefaction services, storage, and bunkering operations. These revenue streams are estimated per ton of fuel handled, then mapped to agriculture and port service industries. Using BEA input–output multipliers, both the CAPEX investment and the ongoing revenues are translated into direct and indirect GDP contributions and employment impacts (jobs per $1 million). This framework captures not only the one-time boost from infrastructure construction but also the long-term economic benefits of operating the new supply chain, with measurable gains for US farming communities, port regions, and supporting industries.