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Advanced Power and Energy Program

Ocean Going Vessels
Emission Control Technology Assessment

February 4, 2026

Agenda

- Introduction to Ocean-Going Vessel (OGV) Technology Assessment
- Technology Evaluation: Engine and Emissions-Control Technology Assessment
- International Program Synergies Evaluation
- Maritime Fuels Availability Assessment
- Key Takeaways
- Next Steps

OGV Technology Assessment Update

- **Update a 2018 CARB Technology Assessment of OGV engine emissions characteristics and technologies and strategies to reduce emissions from OGVs**

- **Goal is to provide a current information base to inform consideration of In-Transit emissions regulation for OGVs**

- **Expand scope of original study to include:**
  - Assessment of the evolution of fuel supply and bunkering infrastructure for Low Carbon Marine Fuels (LCMFs)
  - Assessment of potential synergies of CARB objectives with other mandatory and voluntary emissions control programs internationally

OGV Technology Assessment Elements

Study Element	Task Description
Technology Evaluation	• Alternative Fuel Marine Engines • Efficiency Measures • Aftertreatment Systems
International Program Synergies Evaluation	• Comprehensive review of international efforts underway to reduce emissions from OGVs • Evaluation of opportunities to adopt or emulate programs and regulations in California
Maritime Fuels Availability Assessment	• Compile studies and forecasts on the maritime fuel mix • Evaluate the likely evolution of LCMF supply availability for OGVs

Technologies & Strategies Evaluated

- **Evaluated a wide range of promising technologies and strategies for emission reductions, including:**
  - Alternative Fuel Engines
    - Liquified Natural Gas (LNG)
    - Methanol
    - Ammonia
    - Hydrogen
    - Biofuels
    - Nuclear Power
    - Electricity (Batteries)
  - Carbon Capture, Utilization, and Storage (CCUS)
  - Efficiency Measures
  - After-treatment Systems

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Technology Evaluation: Engine and Emissions-Control Technology Assessment

Elements Analyzed for each Technology and Strategy

- **The technology evaluation section of the report included the following analysis for each evaluated technology and strategy:**
  - Technology description
  - System/network suitability and operational infrastructure needs
  - Potential emissions reductions
  - Technology readiness
  - Economics
  - Next steps to demonstration/deployment

- **Material shared in these slides has been condensed due to time constraints and the details will be contained in a forthcoming report**

Alternative Fuel Engines

Liquified Natural Gas (LNG)-Powered Vessels

- **Technology Description: Use LNG in internal combustion engines (ICE) for propulsions. Engines can be single- or dual-fuel systems and two-stroke (slow-speed) and four-stroke (medium-speed). Dual-fuel engines can operate on LNG or conventional marine fuels (e.g., HFO, MGO) with flexibility based on fuel availability and price. Diesel pilot fuel is required for ignition.**

- **Technological Readiness: Commercially mature and globally deployed, supported by an expanding bunkering network at major ports. Over 600 LNG-fueled ships and 700 LNG carriers currently in service and 800+ on order globally.[1] Proven dual-fuel 2-stroke and 4-stroke engines from engine manufacturers including WinGD, Everllence (MAN), and Wärtsilä**

- **Emission Reductions: Eliminates sulfur oxide (SO_x) and reduces particulate matter (PM) up to 90%. Reductions in oxides of nitrogen (NO_x) (~85–95%) under favorable engine/operation conditions but high-pressure engines typically require SCR/EGR to meet IMO Tier III regulations. Up to 25% lower CO_2 on a tank-to-wake basis due to higher hydrogen-to-carbon ratio; however, methane slip (unburned CH_4) must be controlled. Life cycle GHG reductions range from minor (fossil LNG) to significant (bio-LNG, synthetic-LNG).**

- **Benefits/Challenges: Most commercially mature alternative marine fuel benefiting from decades of experience in LNG carriers. Cryogenic fuel systems add complexity/cost and require additional space and insulation which could impact cargo capacity, but are well-established in commercial use today. Control of methane slip is essential for GHG benefits.**

1: Lloyd's Register, 2025

Methanol-Powered Vessels

- **Technology Description:** Simple alcohol that can be produced from a variety of feedstocks. Used in dual-fuel and single-fuel ICE including two-stroke diesel-cycle and four-stroke lean-burn Otto-cycle configurations. Dual-fuel engines are expected to dominate in the near- to mid-term. Requires pilot injection of diesel fuel for ignition. Can also be used in fuel cells that convert methanol chemically into electricity but maturity is low.

- **Technological Readiness:** High with commercially available dual-fuel engines including two-stroke (Everllence B&W ME-LGIM, WinGD X-DF-M) and four-stroke (Wärtsilä, Everllence, HD Hyundai Heavy Industries). Proven reliability at pilot and early-fleet scale. As of late 2024 34 ships running on methanol with another ~240 on order[1]. Full market maturity expected ~2030.

- **Emission Reductions:** Eliminates SO_x and reduces PM by 95%. Reductions in NO_x of 30% to 83% depending on combustion and after-treatment strategy. Among the lowest GHG combustion-based fuels with well-to-wake reductions of 25-40% (fossil natural gas feedstock) to 70-90% (renewable feedstock) to potentially net negative if bio-methane waste streams are used.

- **Benefits/Challenges:** Can use conventional tank designs similar to fuel-oil systems. Lower energy density means ships must carry 2–3 times larger fuel volumes for equivalent range. Toxic and flammable, necessitating specialized handling, ventilation, and detection systems. Significant expansions to both fuel availability and bunkering infrastructure will be needed.

1: DNV. 2025. Alternative Fuels Insights

Ammonia-Powered Vessels

- **Technology Description: Hydrogen-based fuel composed of nitrogen and hydrogen (NH_3) combusted in ICE. Ammonia engines are being developed in both two-stroke and four-stroke configurations for main propulsion and auxiliary applications. Current engines are dual-fuel and require diesel pilot fuel.**

- **Technological Readiness: Medium/High. Development of engines by J-ENG, Everllence, Wärtsilä, and WinGD is underway with commercial demonstrations beginning now. As of late 2024, 3 ships are running on ammonia with another ~26 on order[1].**

- **Emissions Reductions: Significant reductions in SO_x, CO, and PM emissions but aftertreatment needed to manage NO_x. Slip (unburned NH_3) must be minimized as both a pollutant and a precursor to secondary $PM_{2.5}$. Zero-carbon fuel eliminates CO_2 in exhaust. Formation of N_2O is a concern, but appears controllable. Well-to-wake GHG impacts include increases (fossil no CCUS) to reductions ranging from 0-60% (fossil with CCUS) to 60-90% (renewable).**

- **Benefits/Challenges: Highly toxic and corrosive requiring specialized materials, ventilation, and detection systems to mitigate health and environmental hazards. Benefits from an existing global network for fertilizer but significant expansions to both fuel availability and bunkering infrastructure will be needed.**

1: Lloyd's Register, 2025

Biofuel-powered Vessels

- **Technology Description:** Bio-based liquid fuels derived from renewable sources including renewable diesel (HVO) and biodiesel (FAME) that are combusted in compression ignition diesel engines. HVO is produced through hydrotreatment processes similar to petroleum refining. FAME is produced via transesterification of oils, animal fats, or waste cooking oils and contains O_2 in its molecular structure, resulting in slightly different combustion properties.

- **Technological Readiness:** Commercial. Renewable diesel is a true drop-in fuel and biodiesel is semi-drop in and may require minor engine modification. Wärtsilä and Everllence confirm compatibility across major 2-stroke and 4-stroke engine platforms.

- **Emissions Reductions:** Eliminate SO_x and reduce PM 38% to 90%. Impacts on NO_x are nuanced based on fuel type, engine type, load, etc. Generally, studies have shown similar/slightly lower NO_x for HVO. FAME blends may cause slight NO_x increases (≈3–7%) depending on blend and load conditions. Life-cycle GHG depend on feedstock, renewable diesel up to 65–80% reduction and biodiesel 50–70% reduction depending on blend level (e.g., B20–B100). HVO from waste oils and green hydrogen yields near-zero net GHG.

- **Benefits/Challenges:** Compatibility with existing engines, bunkering, etc. is a major benefit. Feedstock constraints and competition with other sectors may limit biofuels' role in shipping to a transitional contribution.

Nuclear-Powered Vessels

- **Technology Description:** Nuclear reactors are used to generate heat to produce steam, which in turn drives turbines for ship propulsion and onboard electrical power generation. Small Modular Reactors (SMRs) are advancing and could "unlock" nuclear marine applications due to lower capitol costs, quicker deployment, greater flexibility in siting, improved scalability and enhanced safety.

- **Technological Readiness:** Proven track record in military vessels but civilian applications limited. SMRs are progressing but commercial marine certification not achieved. Major stakeholders are running regulatory/feasibility studies for next-gen reactor ships[1], with first commercial pilots potentially in the 2030s.

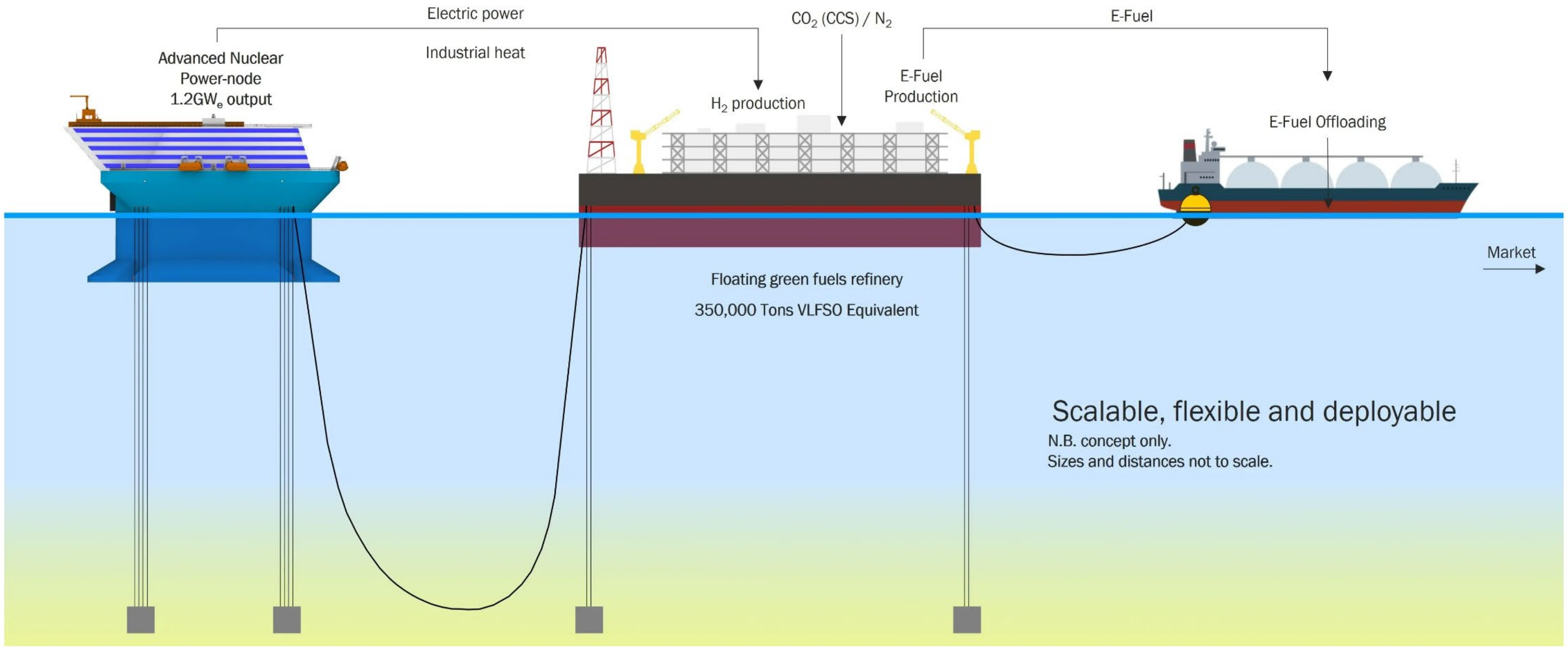
- **Emission Reductions:** No combustion eliminates all tank-to-wake pollutant emissions. Among the lowest GHG emissions of any marine option, with zero direct and very low life-cycle impacts compared to conventional and alternative fuels. Significant air quality and GHG benefits in all stages of vessel operation.

- **Benefits/Challenges:** Compact size, high energy density, and ability to operate potentially for years without refueling. High upfront capital costs though operating costs are low. Lack of existing regulatory frameworks (e.g., dedicated IMO nuclear vessel code) and negative public perception are challenges.

1: Lloyd's Register, 2024 "*LR and CORE POWER to conduct next-generation nuclear container ship regulatory study*"

Floating Nuclear Power Plants (FNPP)

- **SMRs installed on floating barges can provide zero-emission power or fuels to ships/ports and serve as a stepping stone to nuclear-propelled merchant ships**
  - The Russian *Akademik Lomonosov* is the world's first FNPP with two SMRs together capable of producing 70 megawatts of electricity and 50 gigacalories per hour of thermal energy



Source: CORE POWER

Hydrogen-Powered Vessels

- **Technology Description:** Hydrogen can be combusted directly in an ICE (H_2-ICE) or used in fuel cells (FC) that convert hydrogen electrochemically into electricity for propulsion or auxiliary power. FC systems have high efficiencies and produce negligible emissions. H_2-ICEs are modified reciprocating engines that can be spark-ignited, dual-fuel (hydrogen–diesel), and direct-injection systems.

- **Technological Readiness:** Medium/low. H_2-ICEs are in early demonstrations for smaller vessels. FC require advancements in power density, cost, and durability and studies indicate that fuel cells are most feasible for auxiliary or hybrid roles in the near to mid term for OGVs.

- **Emissions Reduction:** FC systems produce only water and achieve large reductions in pollutant and GHG emissions. H_2-ICEs deliver reductions in SO_x, PM, CO, and HC and eliminate CO_2, but NO_x remains the main technical challenge. GHG reductions from green and blue hydrogen range from 50–100% depending on production method.

- **Benefits/Challenges:** Low energy density creates storage volume constraints. Hydrogen bunkering networks are essentially non-existent and the wide-spread availability of green hydrogen, safe bunkering and storage infrastructure, and further progress in regulation and standardization are needed.

Electricity-Powered Vessels

- **Technology Description:** Batteries can be used both for fully electric vessels and hybrid propulsion systems. For OGVs, batteries are mostly being considered as hybrid systems for peak shaving, port-area zero-emission operation, and hotel loads in the near-term. Cold ironing involves shutting down a vessel's onboard diesel generators while at berth and supplying all required power from shore, eliminating in-port emissions and reducing noise and fuel consumption.

- **Technological Readiness:** Medium for hybrid/port-area/hotel applications (5-20 MW) and very low for propulsion (80+ MW). Cold ironing is commercially mature and deployed at major ports around the world.

- **Emissions Reduction:** Battery electric technologies have no direct emissions although life cycle GHG impacts will be determined by electricity pathways. Cold ironing significantly reduces pollutant and CO_2 emissions from diesel auxiliary engines.

- **Benefits/Challenges:** True zero emissions option but low energy density of batteries requires huge amounts for propulsion, e.g., even optimistic projections of marine battery energy density imply thousands to tens of thousands of tons of batteries would be needed with very high costs, significant cargo displacement, and ship redesign. Additionally massive infrastructure build-outs would be required to provide necessary charging.

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Carbon Capture, Utilization, and Storage (CCUS)

Carbon Capture, Utilization, and Storage (CCUS) Systems

- **Technology Description:** Systems designed to separate and capture CO_2 from marine engines or fuel exhaust streams, prevent its release into the atmosphere, and either store it safely or repurpose it into useful products.

- **Technological Readiness:** Proven in land-based applications but unproven in marine applications. Studies show that CCUS systems can potentially be applied safely on ships, but further development and marine optimization are necessary for widespread adoption.

- **Emissions Reductions:** CCUS can reduce direct CO_2 by 20–70%, depending on system efficiency and vessel type. Does not inherently eliminate other pollutants like NO_x, SO_x, or PM unless combined with other systems.

- **Benefits/Challenges:** CCUS systems could be a retrofit-friendly pathway to reduce GHG from existing OGVs, particularly when converting to alternative fuels is cost-prohibitive. While technically feasible and compatible with current engine systems, widespread adoption depends on overcoming challenges in energy efficiency, CO_2 storage logistics, and regulatory harmonization.

Efficiency Measures

Efficiency Measures

- **Technology Description:** **Encompass a suite of operational and technical strategies that reduce the overall energy demand of a voyage.**

- **Technology Readiness:** **Varies by measure from fully commercially mature to prototype.**

  - **Commercially mature, low-cost options offer immediate returns with short payback times include:**
    - Optimized routing
    - Engine de-rating, coatings
    - Shaft generators
    - Lighting upgrades

  - **Longer-term measures have higher capital costs and integration requirements but greater potential for emission reductions, particularly when paired with alternative fuels. These technologies include:**
    - Air lubrication
    - Wind assist
    - Waste heat recovery systems

Efficiency Measures (continued)

- **Emissions Reductions:** Emission reductions occur from reduced fuel consumption which has the benefit of reducing all pollutant and GHG species. Individual reductions range from ~1% to 20%. When applied together, the measures can collectively reduce total fuel use and emissions by 20-50% depending on vessel type, operational profile, and age. However, stacking many of the measures has diminishing returns, e.g., speed optimization + weather routing + propulsion optimization is not perfectly additive.

- **Benefits/Challenges:** Can be a near-term, low-risk, and cost-effective solution for emission reductions that is compatible with other alternative fuels, although some measures have a high upfront cost. Suitability for some measures is determined by vessel profiles and not all measures are suitable for all vessel types, e.g., trim optimization, air lubrication, and hull coatings depend on hull condition, fouling, and operating profiles.

After Treatment Systems

After-Treatment Systems

- **After-treatment systems are devices installed downstream of the engine exhaust to capture or chemically convert pollutants to less harmful compounds.**

Technology	Target Pollutants	Typical Reduction (%)
Selective Catalytic Reduction (SCR)	NO_x	NOx: 85-95%, Designed to meet Tier III standards
Exhaust Gas Recirculation (EGR)	NO_x and Methane (CH_4) Slip	NO_x: 10-80% CH_4: 30-50% in otto-cycle gas mode
Scrubbers	SO_x, PM, Some NO_x	SO_x: >90% PM: 20-50% NO_x: 0-10%
Diesel Particulate Filter*	PM	PM: >90%
Diesel Oxidation Catalyst *	CO, Hydrocarbons, PM	CO/HC: 50-90% PM: 20-40%
Wet Electrostatic Precipitators (WESP)*	PM	PM: 60-95% (scrubber + WESP)

*Emerging Technologies, not well established for OGVs

After-Treatment Systems

- **After-treatment systems are devices installed downstream of the engine exhaust to capture or chemically convert pollutants to less harmful compounds.**

Technology	OGV Commercial Maturity	OGV Outlook
Selective Catalytic Reduction (SCR)	Commercial, widely adopted for 2- and 4-stroke engines for both main and auxiliary applications. Can be used by single- and dual-fuel engines.	Currently favored Tier III NOx compliance technology for both main and auxiliary. Can be used with alternative fuels.
Exhaust Gas Recirculation (EGR)	Commercial, largely 2-stroke main engines. Largely used for main engines but can be used on auxiliary gensets. Can be used for single- and dual-fuel engines.	Tier III 2-stroke engines hampered by urea logistics, LNG engines (methane slip).
Scrubbers	Fully commercial and widely adopted for 4-stroke and newbuild 2-stroke engines. Focus on main engines but can be used by auxiliary engines. Moderate retrofit of 2-stroke engines. Wash water management can be a concern	Industry-standard for compliance with IMO sulfur regulations.
Diesel Particulate Filter	Commercial for 4-stroke auxiliary gensets using distillate fuels (low sulfur). Regeneration needed from time to time	Potentially suitable for some 4-stroke engines. Likely not suitable for 2-stroke.
Diesel Oxidation Catalyst	Commercial for 4-stroke auxiliary gensets using distillate fuels (low sulfur).	Potentially suitable for some 4-stroke engines. Likely not suitable for 2-stroke.
Wet Electrostatic Precipitators (WESP)	Marine WESP are emerging/early commercial. Several companies now market marine-specific WESPs.	Low-speed 2-stroke engines. 4-stroke auxiliary gensets.

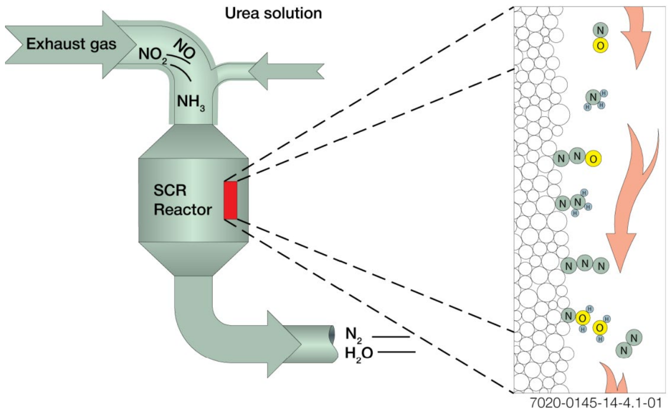
Emerging Technologies, not well established for OGVs

After-Treatment Systems

- **Currently Available for OGVs**
  - SCR: Used for meeting IMO Tier III NO_x emission standards for both current and alternative fuel engines
  - EGR: Commercial, largely used for 2-stroke engines. Can be used for single- and dual-fuel engines
  - Scrubbers: Fully commercial and widely adopted for 4-stroke and newbuild 2-stroke engines. Moderate retrofit of 2-stroke engines.

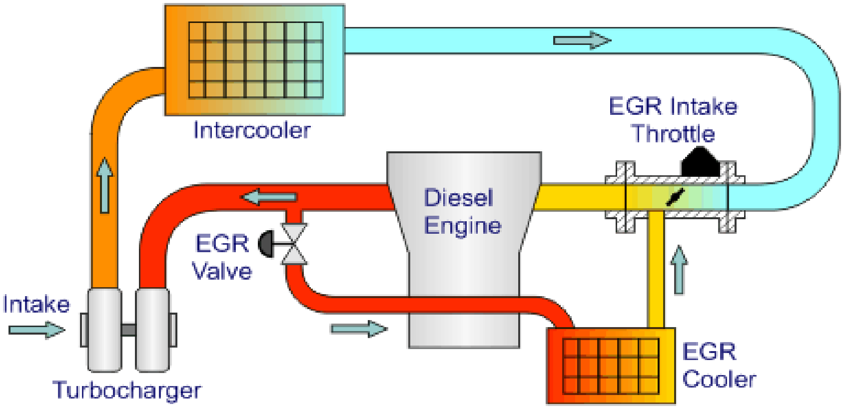
- **Other options are still emerging and could evolve to play a role in future**

Principles of SCR (NOx)



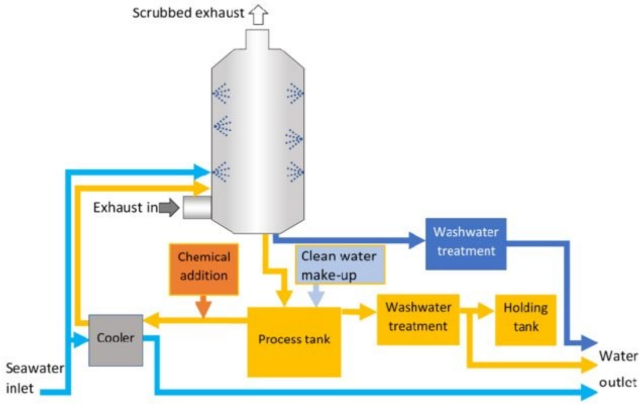
~~From~~ Source: Everllence, 2020

Principles of EGR (NOx & CH4)



Source: Dieselnet.com

Principles of Scrubber (PM, SOx)



Source: ICES Scientific Reports, 2020

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Technology Evaluation: Key Takeaways

UCI Takeaways

- **The transition to alternative fuels in shipping is already underway**
  - The shift toward low- and zero-emission marine technologies is progressing, with LNG, biofuels, and methanol already in service and ammonia engines expected commercially by ~2030.

- **There is no "silver bullet" and the sector is almost certain to include a range of alternative fuels and technologies in the future**
  - A portfolio approach that matches technology to vessel type, route, and regulatory context will yield the largest emission benefits, particularly in the near- to mid-term.

- **Dual-fuel engines will play an essential role in alternative fuel adoption in the near- to mid-term**
  - Dual-fuel setups allow vessels to adjust fuel ratios based on availability and emissions performance, ensuring flexibility during early infrastructure build-out

- **Demonstrations and policy alignment are necessary steps in the transition**
  - Commercial viability depends not on technological feasibility alone, but on coordinated regulatory frameworks, financial incentives, and infrastructure readiness, industry collaboration and crew engagement/training.

Potential Timeline of Technology Readiness

- **Time-scales of adoption will likely depend on a convergence of technological, economic, regulatory, infrastructure, and supply-chain factors**

Near-Term → Mid-Term → Long-Term

Near-Term: Efficiency measures, LNG, and exhaust treatment systems offer immediate pathways to reduce pollutant emissions. Biofuels can reduce GHG emissions. Shore-side power (cold ironing) can address local air quality concerns.

Mid-Term: Methanol and ammonia can significantly reduce pollutant and GHG emissions. Both will require NO_x control and ammonia will require ammonia slip control. Fuel cell and battery systems can provide reductions from auxiliary engines.

Long-Term: Fuel cell and battery electric systems in propulsion/hybrid roles, nuclear powered OGVs have the highest pollutant and GHG emissions reduction potential. CCUS systems can reduce direct GHG emissions.

Takeaways

- **Alternative fuels available now and in the near- to mid-term can provide large reductions in pollutant and GHG emissions and improve air quality near coastal populations**
  - LNG, methanol, ammonia, biofuels, and hydrogen eliminate SO_x and significantly reduce PM and other pollutant emissions, e.g., heavy metals, unburned hydrocarbons, etc.
  - **However, NO_x control is essential and will require after-treatment strategies for most alternative fuels that still rely upon combustion**
  - Other unwanted byproducts (e.g., methane and ammonia-slip) must be minimized

- **However, mature and cost-effective after-treatment systems will remain vital until near- or zero-emission options for propulsion and auxiliary engines are commercially ready**
  - Provide important near-term reductions from conventional fuels and will be required to achieve the full benefits of some alternative fuels including ammonia

- **Emerging technologies show long-term promise for a near- and zero-emission marine sector**
  - Nuclear propulsion, fuel cells, and battery electric technologies could ultimately achieve zero pollutant and GHG emissions but both face significant cost, safety, and regulatory hurdles
  - CCUS systems could be a retrofit-friendly pathway to reduce GHG from existing OGVs, particularly when converting to alternative fuels is cost-prohibitive, but require advancements in technological maturity for marine applications

Takeaways

- **Layering emission reduction approaches represents the optimal approach**
  - Use of operational and efficiency measures to reduce total fuel demands
  - Transitions to alternative fuels for cleaner combustion in the near- to mid-term
  - Co-deployment with after-treatment systems to control NO_x, PM, ammonia and methane slip, etc.
  - Transitions to near- and zero-emission technologies when feasible

- **The requirement of pilot fuels for dual-fuel engines may negate some of the pollutant emission benefits of alternative fuels**
  - Pilot fuel use near-shore could carry local air quality concerns, e.g., if engine ignition occurs at-berth or while transiting in and out of port
  - The use of low-carbon biofuels can prevent degradation in GHG benefits

International Program Synergies Evaluation

Overview

- **There are many programs ongoing internationally to address emissions from the maritime sector – more than 50 programs reviewed**
- **There are several layers:**
  - Multinational programs and regulations, particularly the International Maritime Organization
  - Country-level programs and regulations
  - State and local programs and regulations including port initiatives
  - Non-government programs such as Green Shipping Corridors and industry collaboratives (shipbuilders, shipping customers, equipment providers
- **Relative to OGVs, there is a major focus on carbon although there is also some focus on near-shore non-carbon emissions**
- **LCMFs are very-low sulfur and most have low propensity to create PM but all will require NOx mitigation to meet California standards if combusted near shore**
- **Emissions Control Areas (ECAs) offer the best opportunity to mandate international NOx standards (established under treaty)**

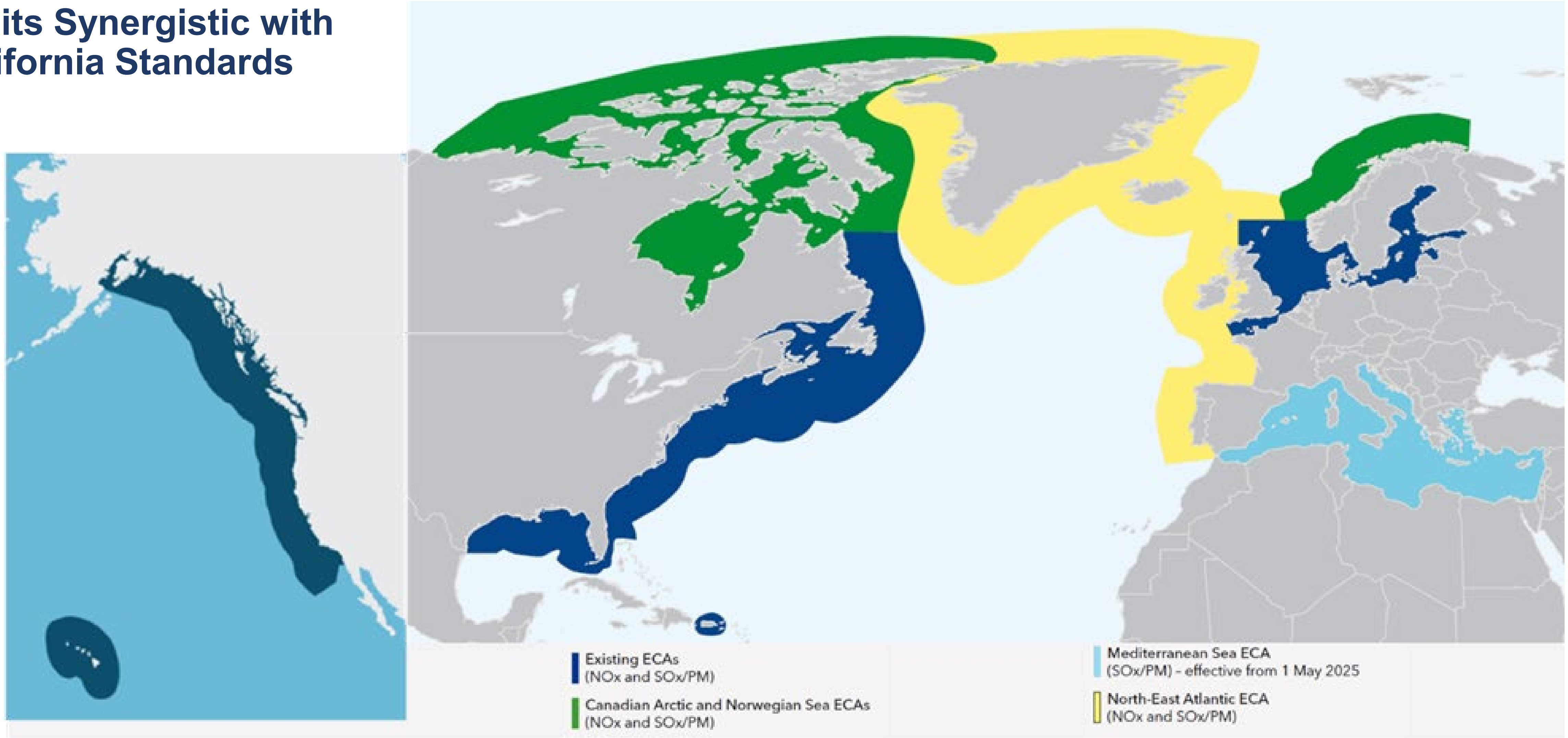
IMO is the Primary International Actor

- **Policy and regulation advanced via the Maritime Environmental Protection Committee (MEPC)**
- **The IMO has adopted several regulations that impact emissions:**
  - The Energy Efficiency Design Index (EEDI)
  - Energy Efficiency eXisting Ship Index (EEXI)
  - Carbon Intensity Indicator (CII)
  - Ship Energy Efficiency Management Plans (SEEMPs)
- **IMO / MEPC policies and regulations become binding when they are incorporated into MARPOL regulations**
- **MARPOL (short for Maritime Pollution) is an international treaty which establishes the legal authority for binding regulation of maritime emissions**
- **MARPOL regulates NOx and SOx through the establishment of ECAs of which there are currently 7 (next slide)**
- **Greenhouse Gas Regulation has been an area of increasing focus – the IMO GHG strategy was adopted in 2023 and is being implemented in steps**

All ECAs Limit Sulfur and PM

Ultra-low Fuel Sulfur Limits Synergistic with California Standards

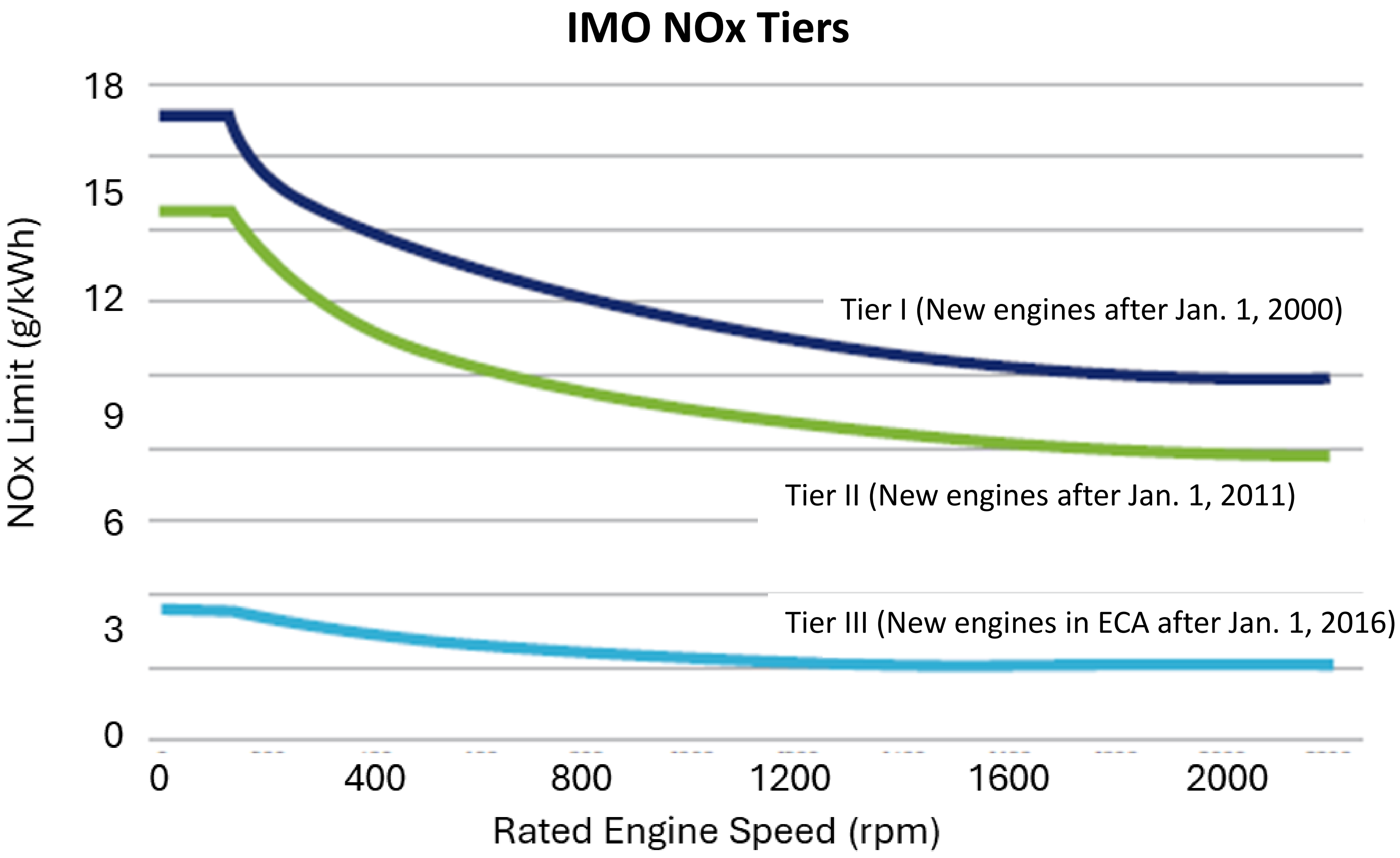
Current Emissions Control Areas



Source: DNV

NOx Regulation within ECAs

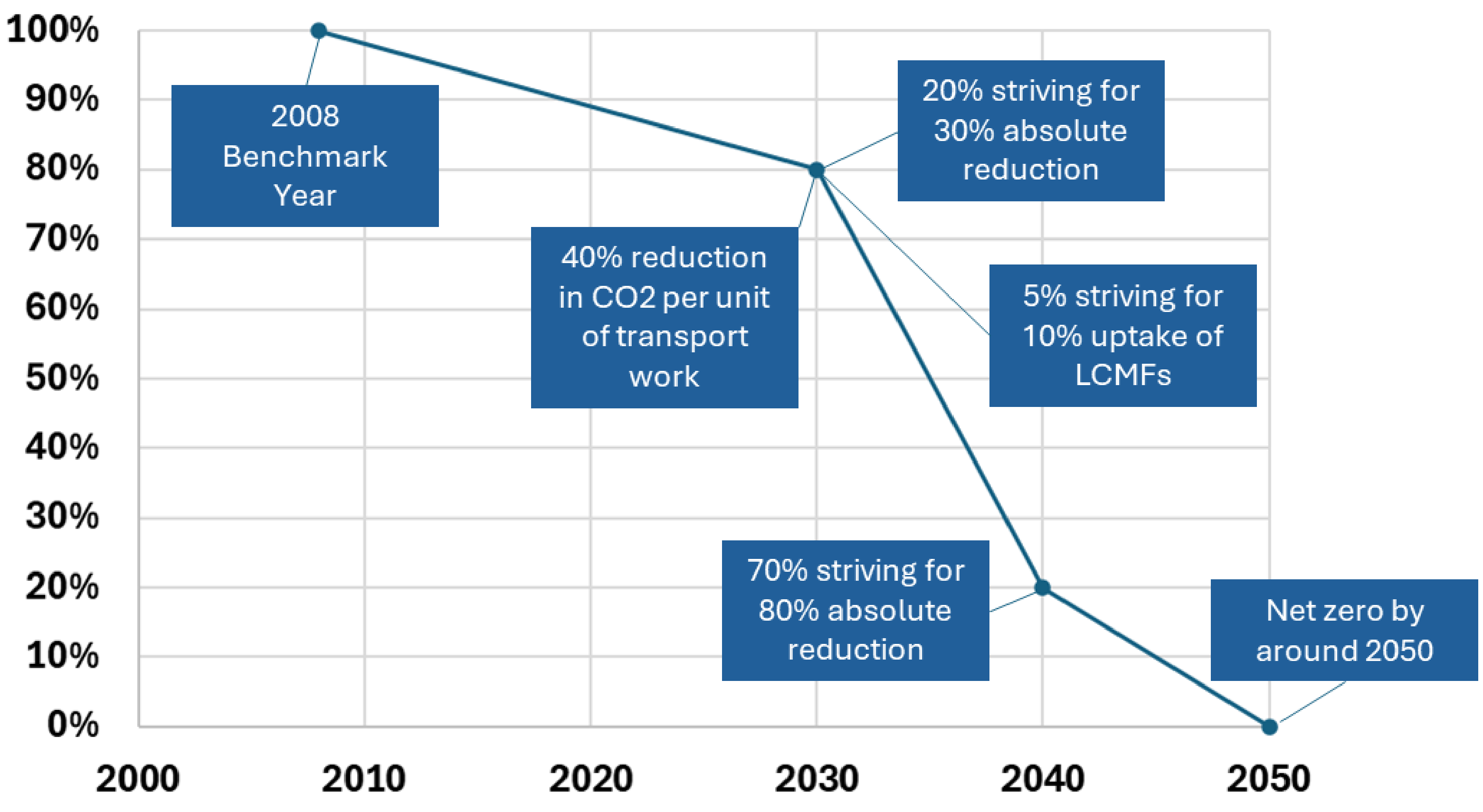
- **NOx regulated by Tier based on the age of the vessel**
- **An MEPC effort is in progress to strengthen NOx regulations**
- **Initiated by 8 countries working group targeting definitive proposal by 2027**
- **Issue – no East-Asian countries (primary U.S. trade routes) participating**



Source: IMO

IMO Net-zero Framework Adopted April 2025

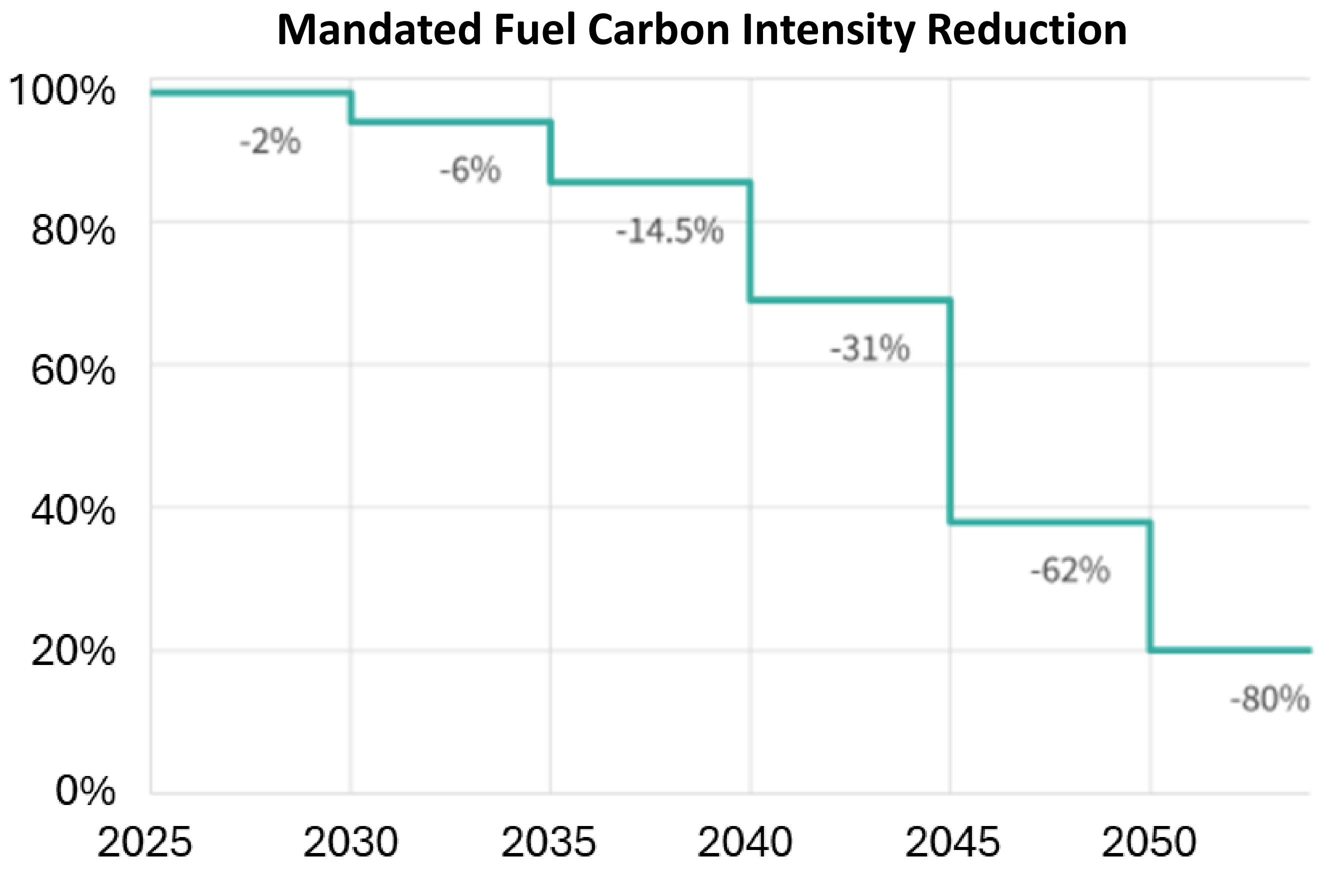
- **Combination of technical and economic measures, such as a fuel carbon intensity standard and a pricing/reward mechanism.**
- **New chapter planned for MARPOL Annex VI to make measures binding pushed back at October 2025 MEPC meeting**
- **Impact on plan for entry into force on March 1, 2027, with the first reporting under the new rules starting in 2028 TBD.**



Source: IMO

The European Union Maritime Fuel GHG Limits

- FuelEU Maritime regulation is a Carbon Intensity Standard
- EU Emissions Trading System (ETS) established to facilitate compliance



Source: Loyd's Register

Other Stakeholder Initiatives

- Major maritime engine manufacturers are developing engines to operate on LCMF's and several have already been certified
- 11 of 15 large ship builders have committed to transitioning to building only zero-GHG-emission ships by 2050
- Numerous ports have "clean ports" initiatives of various types but many are focused on at-berth emissions, land-side operations and harbor craft
- 62 Green Shipping-Corridors have been announced focused on OGVs but carbon-reduction is the focus
- Many of the largest global shipping customers have commitments to low or zero carbon shipping – 35 major retail brands have committed to purchasing only zero-carbon fueled shipping by 2040

Synergy Opportunities

- **California's challenges with meeting criteria emission standards are unique – no other jurisdiction is as focused on addressing non-GHG emissions to meet federal attainment levels and public health goals**
- **Virtually all of the LCMF's are ultra-low in their sulfur content and most have a lower tendency to form PM providing significant synergy with California efforts**
- **Meeting NOx standards, however, will require aftertreatment systems**
- **There are a number of areas where California can exert influence to support its goals:**
  - Support ongoing efforts to increased stringency in MARPOL Annex VI NOx emissions regulations
  - There are currently no East-Asian ECAs. Supporting the establishment of ECAs in East Asia would introduce NOx and SOx emissions control requirements on both ends of the majority of voyages to and from California
  - Green Shipping Corridors are generally very GHG-focused. California could consider funding pilot projects to ensure non-GHG emissions are included in green-corridor goals.

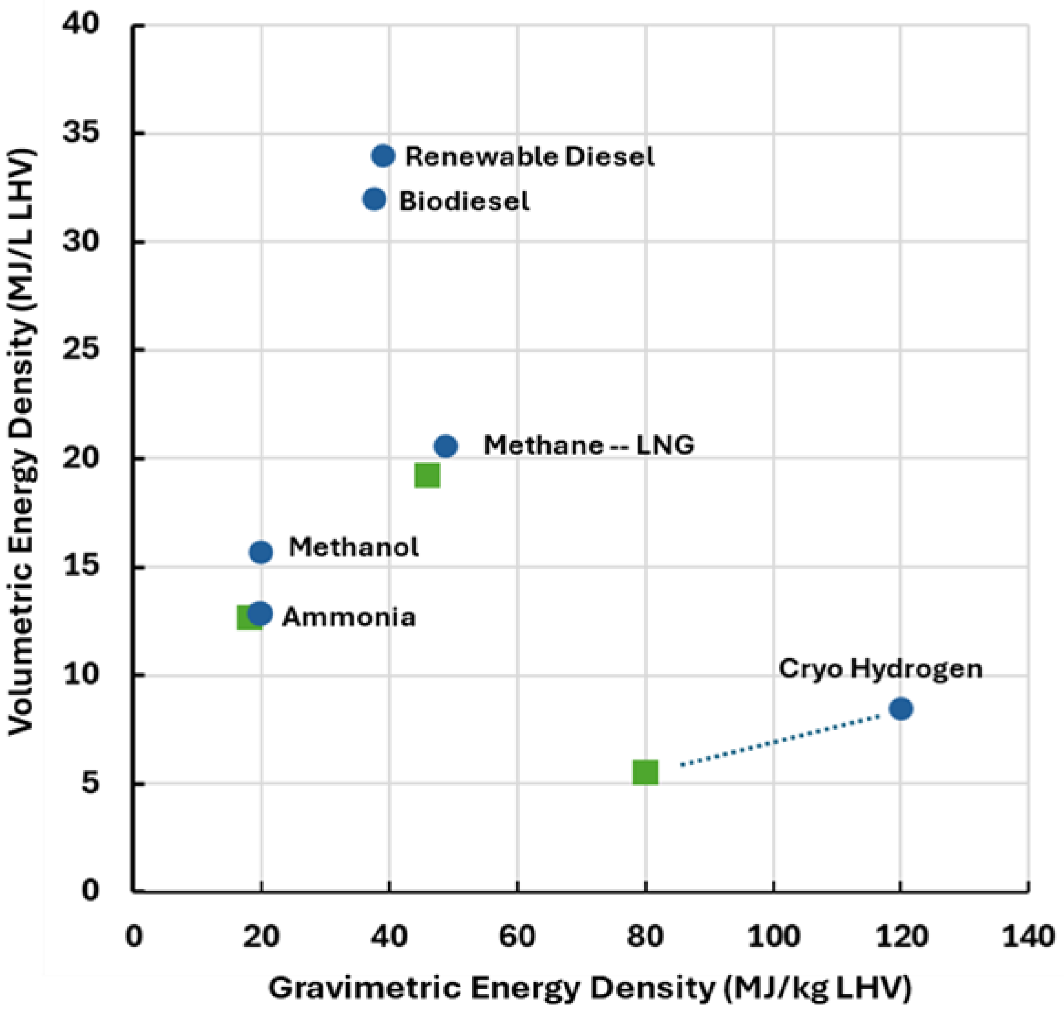
Maritime Fuels Availability Assessment

Fuels Assessed and Key Features

- LCMF Key Features:
  - Hydrogen (H_2) = must be stored as cryo-liquid; leak prone and highly flammable
  - Liquified Natural Gas (LNG) -- (Methane (CH_4)) = cryo-liquid, methane slip a potential issue
  - Ammonia (NH_3) = liquid under modest pressure; toxic and corrosive
  - Methanol (CH_3-OH) = liquid at room temperature
  - Biofuels, including biodiesel (FAME) ($CH_3(CH_2)_n$– $COOCH_3$) and renewable diesel ($CH_3(CH_2)_nCH_3$) (HVO) = can leverage existing infrastructure and require no or modest engine modifications

LCMF On-board Storage Characteristic

- Low volumetric energy density is a challenge for most LCMF's



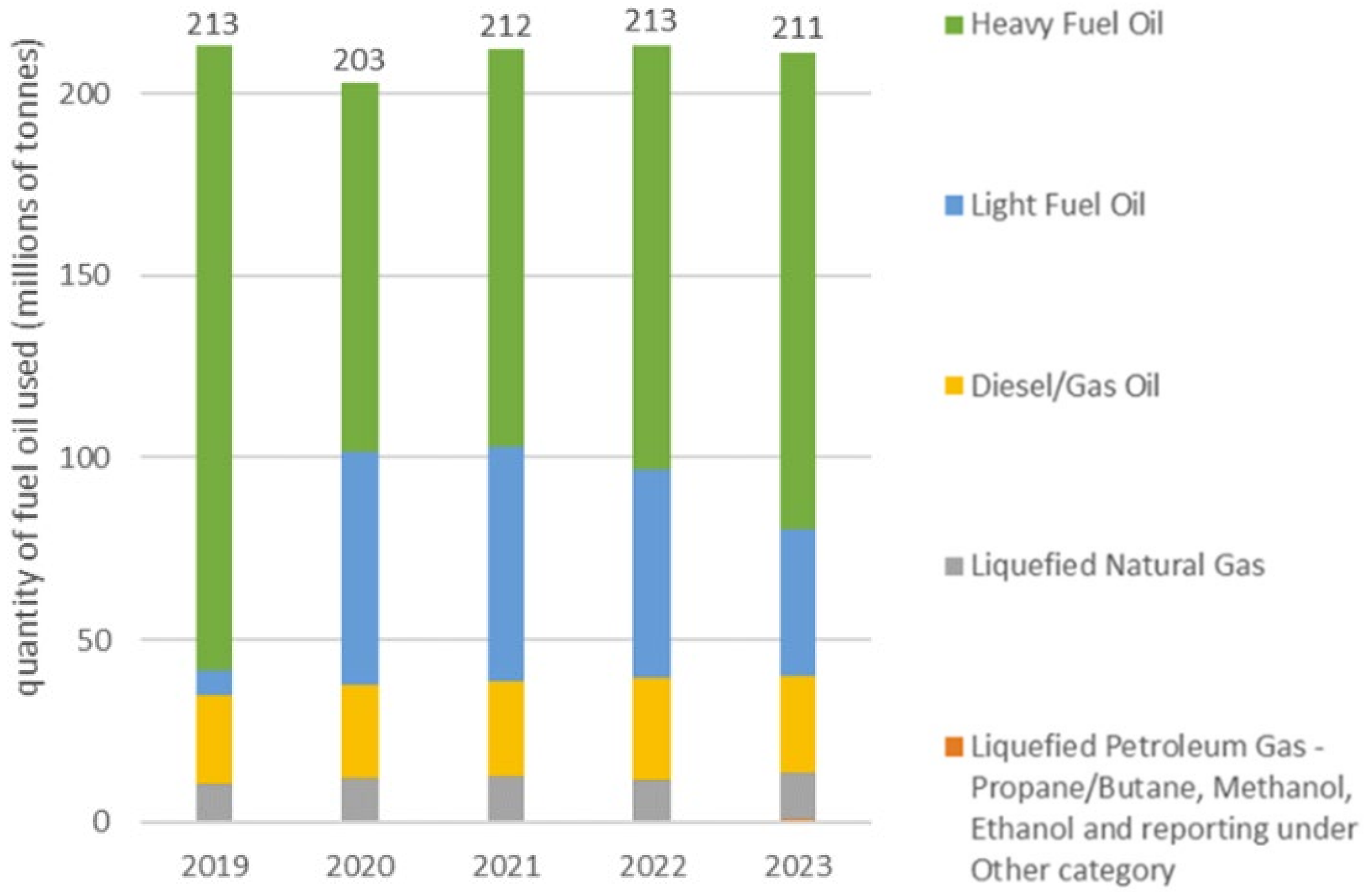
Green squares include liquefaction energy where required

Source: American Bureau of Shipping and UCI

Other than LNG LCMF Use Minimal through 2023

- LNG currently constitutes about 5% of marine fuel consumption in the international shipping sector (vessels over 5,000 GT) – other LCMFs are at the pilot stage

Large-Vessel Fuel Use by Fuel

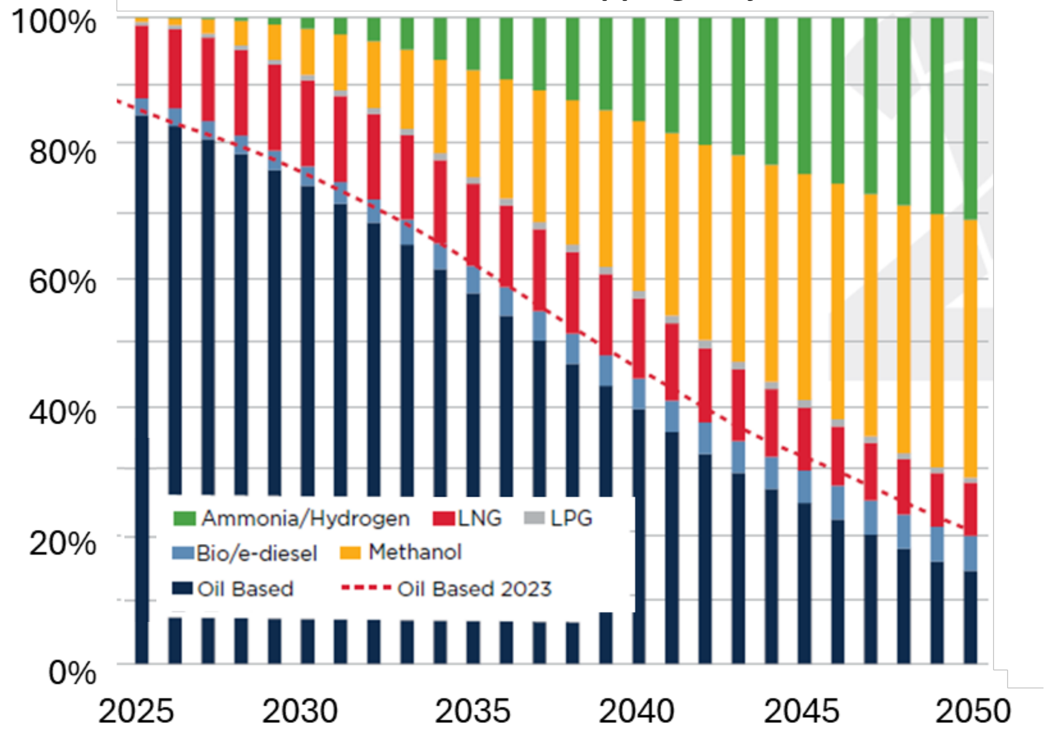


https://futurefuels.imo.org/home/latest-information/fuel-consumption-dcs/

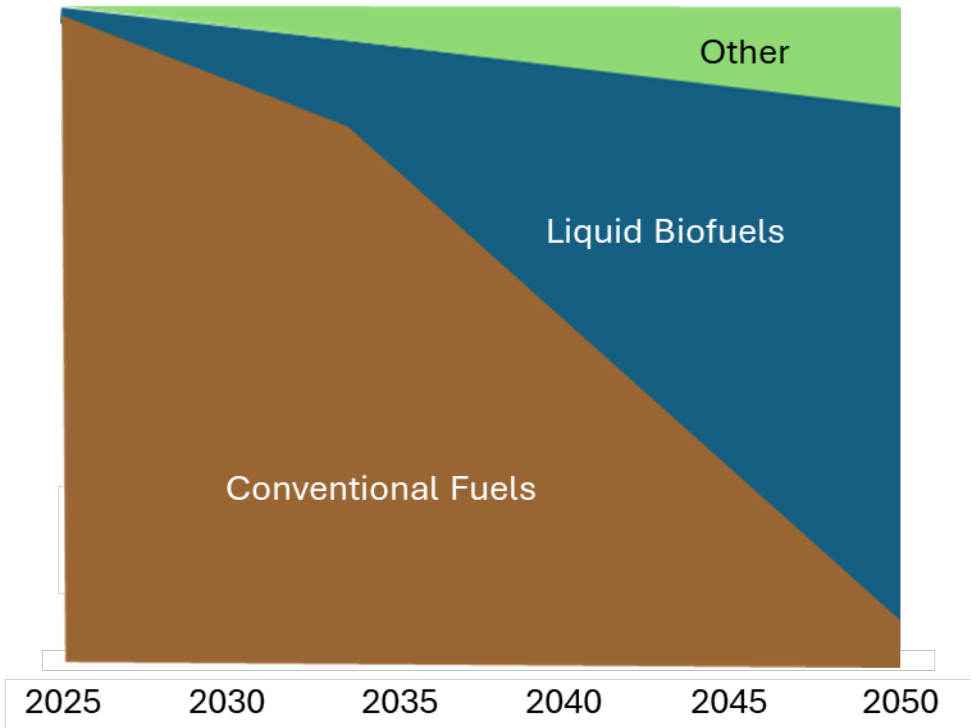
No Consensus on Long-term Fuel Mix

- Long-term projections are mixed -- many studies project that ammonia or methanol will be the dominant fuel beyond 2050 but many others favor liquid biofuels

American Bureau of Shipping Projection

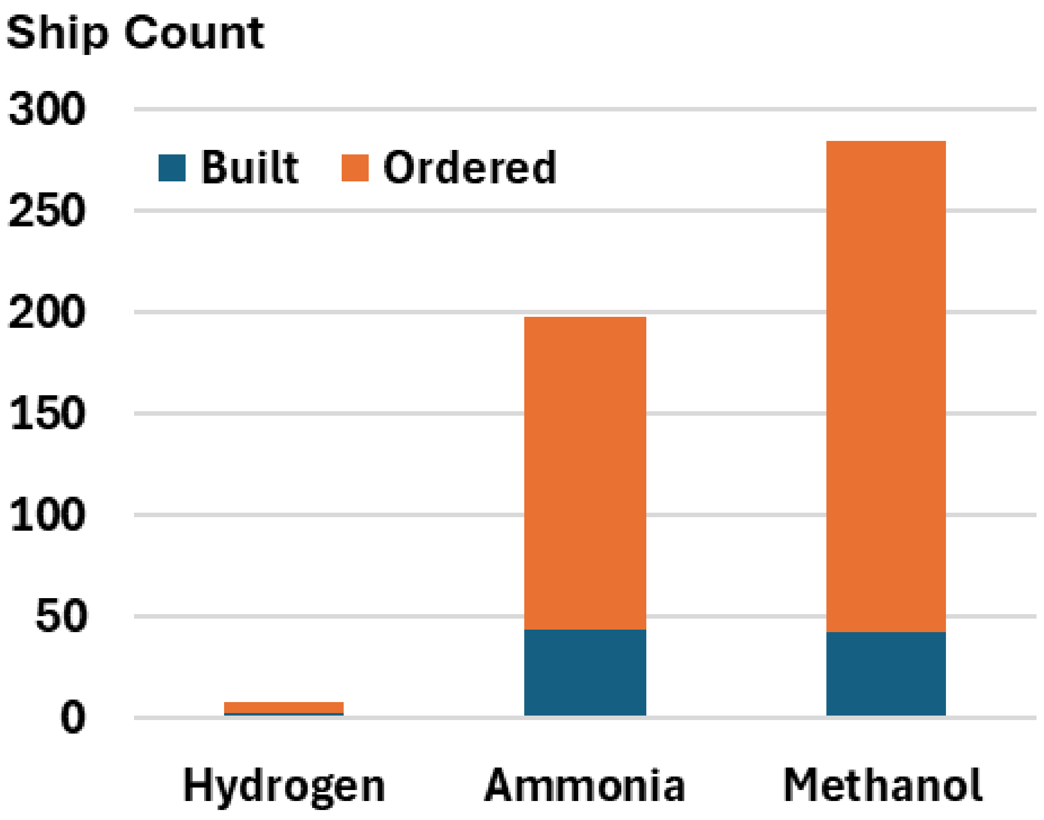


Lloyd's Register High Liquid Biofuels Scenario



Methanol and Ammonia Shipbuilding Activity

- Among the lighter fuels, methanol is seeing significantly more activity than ammonia

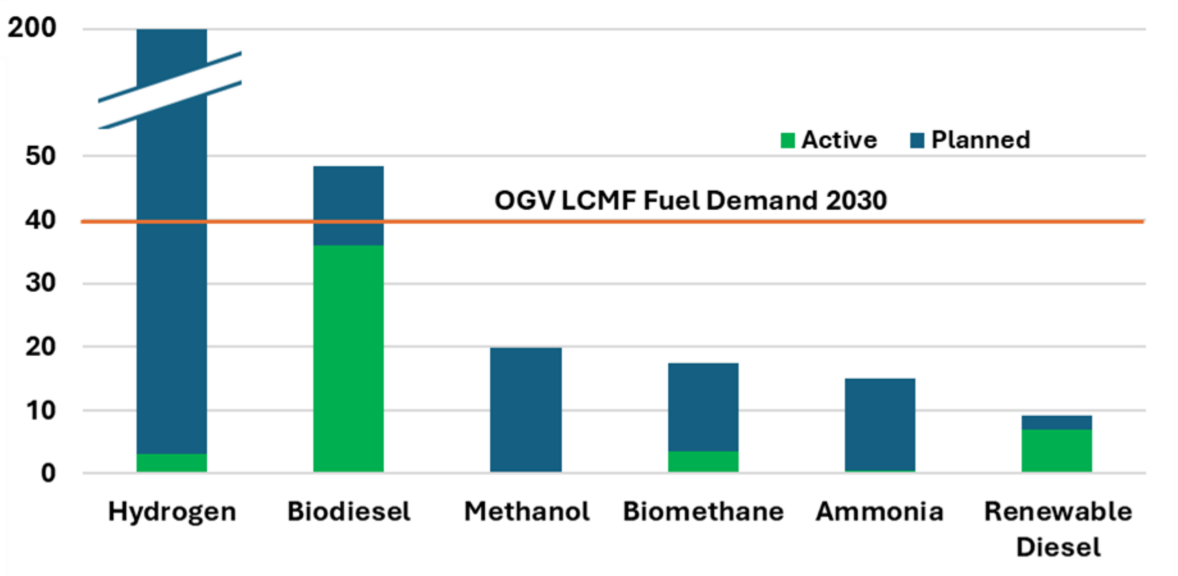


Source: Carr et al. 2024

Supply and Demand

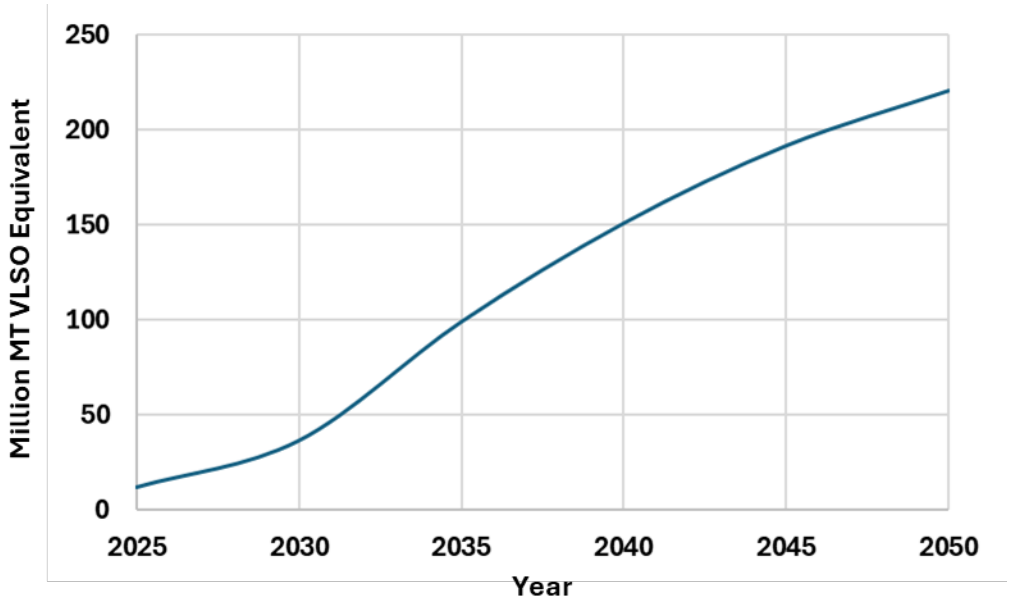
- In aggregate LCMFs active and planned capacity exceeds 2030 demand
- Regardless of which fuels are dominant in the maritime sector in 2050, a major production capacity and infrastructure build-out will be required

Active and Planned LCMF Capacity 2030 vs. Demand



Source: Multiple sources

Global LCMF Demand Projection Consistent with IMO Goals

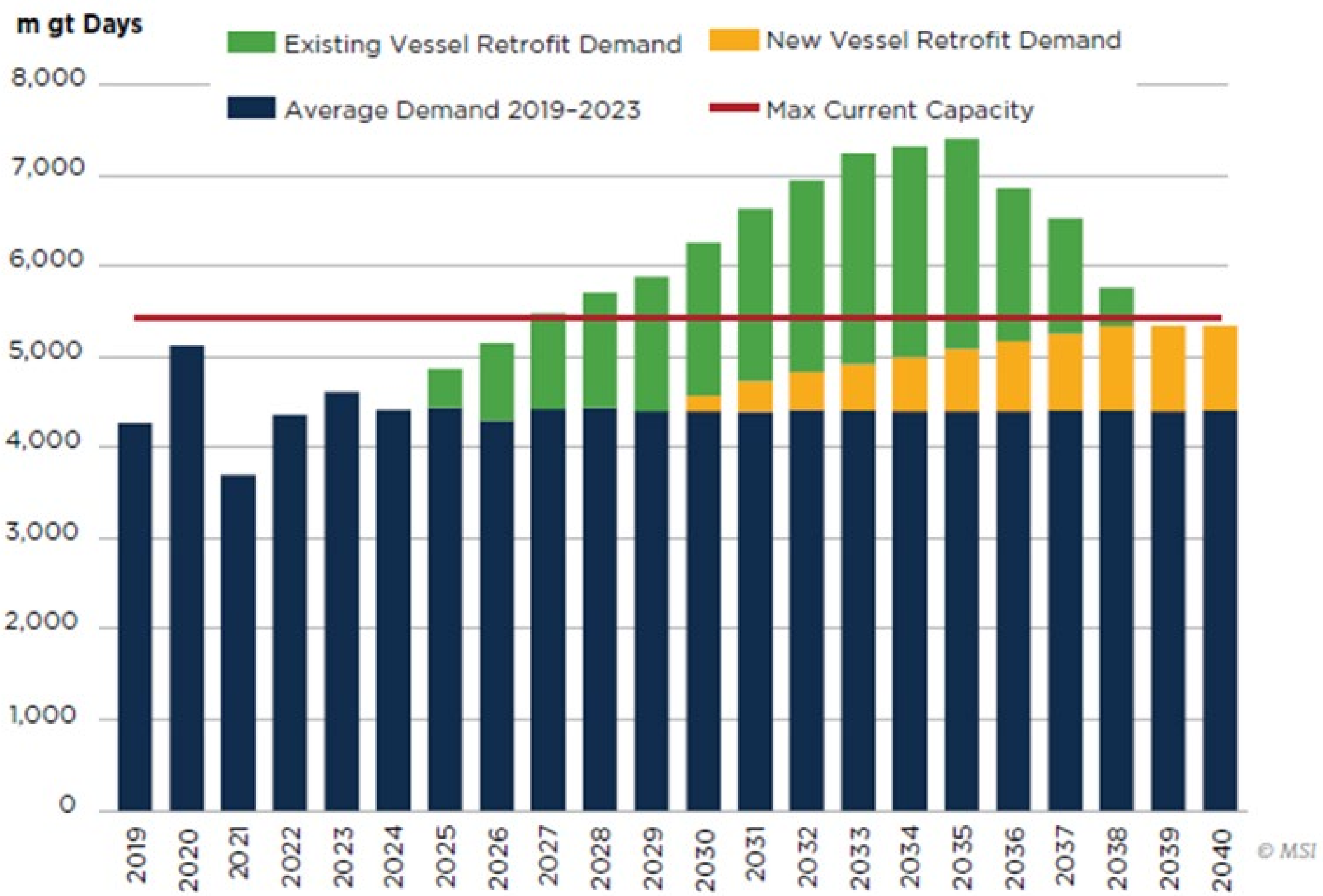


Source: UCI

Will Shipyard Capacity be a Bottleneck?

- One study concludes that shipbuilding capacity will be a constraint on expanded use of LCMFs in the 2030s

Shipyard Capacity and Projected Demand



Source: Carr et al. 2024

LCMF Distribution, Storage and Bunkering

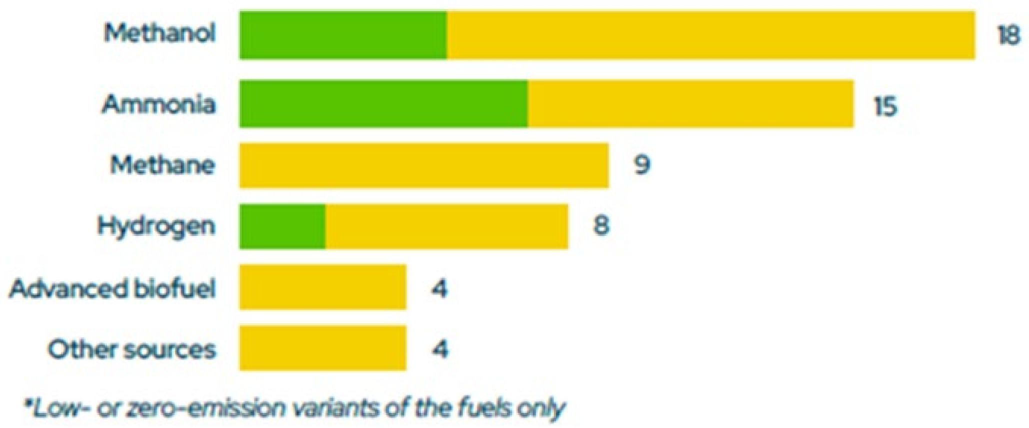
- Hydrogen and ammonia present the greatest bunkering challenges although all LCMF's are seeing significant planning and piloting via Green Corridor initiatives

LCMF Bunkering Requirements and Degree of Challenge

Fuel	Distribution and Storage	Bunkering
Fuel oils	Low - Can use existing distribution and storage facilities for distillate fuel	Low - Can use existing bunkering infrastructure for distillate fuel
Methane	Low - Can use existing (and still developing) distribution and storage facilities for LNG	Low - Can use existing (and still developing) bunkering infrastructure for LNG
Hydrogen	**High - Distribution and storage infrastructure very limited (associated with refining and chemicals manufacturing)** **Numerous international plans for H2 infrastructure build-out in the 2030s**	**High -- No existing bunkering infrastructure** **Local bunkering operations have been demonstrated**
Methanol	Low- Can build on existing distribution and storage facilities from global network of terminals, used for global methanol trading/transport	Medium - Partially developed bunkering infrastructure at 90 ports worldwide Demonstration of bunkering operations has been successful, ship-to-ship bunkering proven
Ammonia	Low - Can build on existing distribution and storage facilities from global network of terminals, used for global ammonia trading/transport	High -- No existing bunkering infrastructure Local bunkering operations have been demonstrated

Source: Adapted from DNV 2024

Planned Fuels for use on Green Shipping Corridors
Green = Only Fuel Yellow = One of Multiple Fuels



Source: Global Maritime Forum

Fuels Availability Conclusions

- The pipeline of active and planned LCMF production facilities is adequate to meet demand projections through 2030 assuming all projects come to fruition
- Beyond 2030, supply expansion must reach a pace that is feasible (comparable to rapid expansion of fuel supply seen in the past) but challenging
- New bunkering capacity for non-fuel oils will be more challenging than for fuel oils but initial action to establish protocols and expand capacity are underway
- Shipyard capacity may pose a constraint on LCMF demand growth based on current shipyard capacity and without accounting for displacement of "conventional" shipyard activity with LCMF retrofit activity
- While significant and coordinated international action is needed, LCMF supply can in principal meet demand growth needed to meet IMO decarbonization targets

Recommended Next Steps

- **Conduct further research focused on:**
  - Improving the understanding of capital, operating, and lifecycle cost trajectories as technologies mature and scale, including the effects of learning curves, standardization, supply-chain development, and the economic risks of early adoption such as stranded assets and technology lock-in.
  - Developing clearer guidance on when retrofits are technically and economically viable versus when newbuilds are preferred.
  - Improving the characterization of real-world emissions performance for alternative fuel engines under varying loads, routes, and duty cycles
  - Clarifying the long-term engine durability, emissions control performance, and system integration under sustained commercial OGV operation for alternative fuel engines including methanol and ammonia.
  - Technical advancements to support emerging technologies show long-term promise for a near- and zero-emission marine sector including batteries, hydrogen fuel cells, and nuclear powered-vessels
  - Assessing how emerging technologies align with existing port, fuel, and electrical infrastructure
  - Tracking the evolution of fuel supply and bunkering capacity
  - Tracking the evolution of green corridors and related initiatives as they mature
- **Develop and pursue an engagement strategy (e.g., with U.S. EPA) for influencing international NOx and SOx regulations via the IMO**

Contact Information

- **Provide feedback by via e-mail by February 20, 2026**

Jeff Reed – jgreed@uci.edu

Mike MacKinnon – mam@apep.uci.edu