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« Maritime Decarbonization : What progress has been made ? »

Maritime transport stands as a major emitter of greenhouse gases (GHGs). The shipping sector's annual GHG emissions expanded by 9.6% in 2018 compared to 2012. In 2018, the industry released 1,076 million tonnes of GHG emissions (expressed in carbon dioxide equivalent, CO_2e). This volume is roughly equivalent to the annual carbon footprint of Japan, accounting for 2.89% of total global anthropogenic CO_2 emissions.

Furthermore, maritime transport operates as one of the primary facilitators for the continuous utilization of fossil energies: the transport of fossil fuels represents approximately one-third of global seaborne shipping volumes (comprising 11% coal, 16% crude oil, and 5% natural gas). Additionally, it has enabled developed economies to structurally outsource manufacturing to developing nations, thereby shifting a substantial share of their carbon emissions to these countries. The International Maritime Organization (IMO) estimates that under baseline trade growth assumptions, shipping's CO_2 emissions could skyrocket by 50% by 2050 compared to 2008. What then are the operational incentives and levers of action to ensure that shipping converges toward absolute carbon neutrality?

A still overly hesitant stance from the IMO

The IMO is the specialized international organization tasked with engineering global regulations for the maritime sector. This mandate encompasses defining measures to reduce GHG emissions originating from international shipping. One of the primary legal instruments at the IMO's disposal is the International Convention for the Prevention of Pollution from Ships (MARPOL), adopted in 1973 and amended multiple times since. Its Annex VI deals specifically with the prevention of air pollution from ships. The "Initial IMO GHG Strategy on Reduction of GHG Emissions from Ships," adopted in 2018, outlines the foundational direction toward the deep decarbonization of international maritime transport. The baseline ambition targets reducing total annual GHG emissions by at least 50% by 2050 compared to 2008, coupled with a 40% reduction in the carbon intensity of the global fleet by 2030, also relative to 2008 baselines. This initial IMO strategy provides a structured regulatory roadmap divided into short-, medium-, and long-term measures.

Current global regulations focus heavily on optimizing the energy efficiency of vessels. Since 2015, all newly delivered vessels must comply with a mandatory minimum energy efficiency standard at the design phase, varying by vessel type and dimensions, known as the Energy Efficiency Design Index (EEDI). Simultaneously, the IMO introduced an administrative mechanism to optimize operational energy efficiency: the Ship Energy Efficiency Management Plan (SEEMP), deploying the Energy Efficiency Operational Indicator (EEOI) as a continuous monitoring tool.

These mandates apply to both greenfield newbuilds and existing vessels in service. The objective targets fuel-efficient ship operations through routing optimization, slow steaming, high-efficiency propeller retrofits, and waste heat recovery systems. However, their actual impact on net emission reductions remains relatively limited.

Since the adoption of the initial IMO strategy in 2018, subsequent mandates have been locked in, and reduction factors have become increasingly stringent. In 2021, IMO member States agreed upon two supplementary measures that entered into force: the Energy Efficiency Existing Ship Index (EEXI)—a technical framework governing the physical characteristics of the vessel—and the Carbon Intensity Indicator (CII)—an operational framework tracking the vessel's live exploitation.

The EEXI operates as a technical mandate targeting the energy efficiency of existing ships in service over 400 gross tonnage (GT). Concurrently, the CII consists of an operational carbon balance framework applied to vessels over 5,000 GT. Under this mechanism, ships are evaluated based on their live carbon intensity and graded on a structural rating scale from A to E, where A represents the top performance

and E the worst. If a vessel is graded D or E for three consecutive calendar years, its owners are legally mandated to submit an optimized action plan to elevate its rating to a baseline minimum of C. Conversely, administrations, port authorities, and alternative stakeholders can deploy positive commercial incentives for vessels achieving an A or B rating.

Nevertheless, the EEXI and CII mechanisms will highly likely prove insufficient to meet the levels of ambition outlined in the initial 2018 IMO strategy, and are unlikely to reduce total annual GHG emissions by 50% by 2050 compared to 2008.

A second wave of mid-to-long-term measures is currently under intense negotiation and will be discussed during the IMO's Marine Environment Protection Committee (MEPC 80) session in July 2023. This year will stand as a crucial milestone for defining stricter decarbonization targets than those locked in back in 2018, with both technical measures (such as a mandatory fuel greenhouse gas intensity standard) and market-based economic mechanisms under active evaluation. The regulatory workflow of the IMO is powerfully catalyzed by the initiatives of the European Union (EU), which, through its European Green Deal, aims to transform Europe into the world's first carbon-neutral continent by 2050.

The EU as the environmental trendsetter for global shipping

The European Green Deal locks in an intermediate 2030 target to slash greenhouse gas (GHG) emissions by 55% compared to 1990 levels, driven by the Fit for 55 legislative package (launched in July 2021). Multiple regulatory instruments form the core of these frameworks. Five specific Fit for 55 proposals exert a direct structural impact on maritime transport CO₂ emissions:

- The inclusion of maritime transport within the EU Emissions Trading System (EU ETS): GHG emissions from vessels over 5,000 GT (with ongoing institutional discussions to lower this threshold) calling at EU ports will be priced following a progressive phase-in schedule between 2025 and 2027, explicitly incorporating methane (CH₄) and nitrous oxide (N₂O) emissions as early as 2026. Non-compliant vessels face detention or absolute denial of entry into EU ports¹.
- The FuelEU Maritime Regulation: This framework introduces mandatory annual average limits for the GHG intensity of the energy utilized on board by ships over 5,000 GT. These reductions commence in 2025 with a 2% efficiency upgrade compared to a 2020 baseline reference. The standards tighten over time, requiring a 6% optimization in 2030 and culminating in an 80% reduction by 2050. This fuel standard applies to 100% of the energy utilized on voyages between EU ports, and 50% of the energy consumed on voyages connecting an EU port to a non-EU port. Furthermore, lawmakers have locked in a mandatory 2% usage target for renewable fuels of non-biological origin (RFNBOs) starting in 2034.
- Onshore Power Supply (OPS): Container ships and passenger vessels will be legally required to utilize onshore electricity at berth starting in 2030. This binding obligation will expand to encompass all European gateways by 2035, subject to specific technical exemptions.
- The Energy Taxation Directive (ETD) revision: This overhauled framework aims to terminate long-standing tax exemptions traditionally granted to conventional marine bunker fossil fuels, structurally incentivizing the adoption of alternative energies.
- The Renewable Energy Directive (RED III) revision: This framework establishes a brand-new binding EU-wide target of at least 42.5% of energy originating from renewable sources by 2030², coupled with a mandatory 14.5% GHG intensity reduction target within the transport sector—explicitly encompassing maritime shipping—by 2030. It now falls upon maritime stakeholders to identify and deploy the technical solutions required to achieve these targets.

Decarbonization as a geopolitical battleground

A defining hallmark of this era is the European Union's determination to "build energy sovereignty" by accelerating green energy deployment, epitomized by the European Commission's proposal for the Net-Zero Industry Act (NZIA).

The core target dictates that by 2030, 40% of the EU's requirements for clean technologies must be supplied by domestic European industrial capacities. This macro-project operates as a direct counter-

¹ At the beginning of 2018, emission allowances were traded at €8 per tonne of CO₂ (€tCO₂); by March 2022, the price skyrocketed to €80–€90 per tCO₂ and is projected to expand further driven by supply and demand dynamics.

² The EU recently integrated nuclear energy into its green energy taxonomy. However, nuclear power does not achieve consensus among the 27 Member States.

strategy facing Chinese and American competition, both of which have long deployed aggressive protectionist measures, massive State aid, and heavy corporate tax slashes for businesses operating on their soil. The Biden administration's Inflation Reduction Act (IRA) allocates a monumental \$370 billion investment into green technologies, renewable energies, transport grids, and energy efficiency. The underlying political message is firmly "Made in USA", regardless of whether such frameworks contravene World Trade Organization (WTO) regulations.

Conversely, the EU has repeatedly re-affirmed its institutional attachment to free-trade agreements and strict compliance with WTO principles. This creates an internal dilemma, as the widespread liberalization of public subsidies directly disrupts the level playing field of the European single market.

Its strategy does not rely on corporate tax slashes or sweeping State aid, but rather on elevating energy taxes, expanding the emissions trading market to targeted sectors (road transport, maritime shipping, aviation, and buildings), and deploying a Carbon Border Adjustment Mechanism (CBAM). Nonetheless, major funding frameworks exist within the Union, driven by REPowerEU and its €250 billion budget—originally engineered to mitigate dependency on Russian hydrocarbons—complemented by the €225 million (or billions) allocated under the Recovery and Resilience Facility deployed during the Covid-19 crisis.

The Net-Zero Industry Act (NZIA) will be further amended in the coming months by Member States and Eurodeputies. Among the green clean technologies targeted by the European text—and directly intersecting the maritime sector—are wind turbines, solar panels, renewable hydrogen, CO₂ storage networks, electrolyzers, fuel cells (FC), and biogas/biomethane. Conversely to the IMO, which enforces a strict principle of technological neutrality and relies on market forces to execute operational trade-offs, the EU has established a rigid classification of environmentally sustainable activities via its Taxonomy. Remarkably, gas and nuclear energy are included within these acceptable transitional options. Whatever the pathway, achieving absolute carbon neutrality by 2050 will prove exceptionally capital-intensive. A study published by Det Norske Veritas (DNV) projecting a carbon-neutral maritime economy by 2050 estimates that required capital expenditures for vessels will range, depending on the selected scenarios, between \$8 billion and \$28 billion annually. For shoreside infrastructure networks (production, storage, and distribution), this represents a monumental investment of \$28 billion to \$90 billion per year.

Alternative marine fuels: (still) an ocean of possibilities

There are several core operational domains where environmental efficiency gains can be achieved, namely logistics (slow steaming, routing optimization), hydrodynamics (hull shape optimization, air lubrication systems, advanced antifouling coatings), marine engine optimization (waste heat recovery systems), alternative fuel selection, and finally exhaust gas treatment via Onshore/Onboard Carbon Capture and Storage (OCCS / CCS). Among these five emission reduction levers capable of being activated simultaneously, the selection of the fuel alternative is the one yielding the most substantial environmental benefit.

Ocean carriers must transition to low-emission or carbon-neutral fuels. They can alternatively opt for "blue fuels", which consist of conventional petroleum-derived marine fuels coupled with onboard carbon capture technology. The long-term relevance of this option will depend fundamentally on carbon capture efficiency rates, alongside the existence of heavy permanent carbon storage infrastructures or commercial end-use markets for the captured CO₂.

The primary overarching question remains the global availability of renewable energy (decarbonized electricity, sustainable biomass) required to manufacture electro-fuels (e-MGO, e-LNG, e-NH₃, e-methanol) or advanced biofuels (bio-MGO, bio-LNG, bio-methanol). This baseline prerequisite assumes the progressive, upstream phase-out of fossil fuels within global power generation grids. Collectively, this matrix of coexisting possibilities generates an acute layer of complexity for corporate investment decision-making.

Alternative obstacles persist: heavy capital expenditures, a chronic lack of global availability, a deficit in international bunkering infrastructure, the extreme pricing of these fuels, and the requirement for substantial supplementary onboard storage space. Safety also remains a paramount concern, compounded at times by a lack of prescriptive rules and clear regulations, which complicates the practical implementation of the required technology on board.

The technical applicability and commercial viability of alternative fuels vary substantially depending on vessel segments. Notably, the majority of vessels currently deploying alternative fuels can identically navigate utilizing conventional petroleum-derived marine fuel oil.

According to a 2022 study published by DNV, evaluated in terms of gross tonnage (GT), 5.5% of vessels in active service and 33% of those on the global newbuilding order book were capable of operating with alternative fuels (including methane carriers). When evaluated strictly by vessel headcounts, this represents 1.1% of the active fleet and 21% of the fleet on order. LNG firmly commands the top of the podium: out of the 923 vessels operating on LNG, 630 are dedicated methane carriers (*méthaniers*) and 293 encompass alternative vessel types.

Liquefied Natural Gas (LNG), which remains a fossil marine fuel, is heavily favored by numerous ocean carriers, most notably across the roll-on/roll-off (Ro-Ro) and container ship segments. Short-sea shipping was the first segment to deploy LNG as a marine fuel. For short-sea passenger ferries, the contemporary trend leans toward full electrification, while alternative operators turn toward hydrogen and fuel cell (FC) technologies to extend their operational autonomy. LNG presents the distinct advantage of being available on a worldwide scale, conversely to the vast majority of alternative fuels. With a performance profile yielding a 20% to 25% reduction in CO_2 emissions and a near-total eradication of sulfur oxides (SO_x), nitrogen oxides (NO_x), and fine particulate matter (PM), the industrial sector is well-structured. The liquefaction of natural gas is achieved by chilling it to a cryogenic temperature of -162°C (at atmospheric pressure), though LNG storage consumes twice as much space as conventional heavy fuel oil (HFO).

However, during the engine combustion process, the phenomenon of "methane slip" (*fuite de méthane*) occurs: a fraction of the fuel escapes unburned into the atmosphere. Methane, the primary component of LNG, has a shorter atmospheric lifespan than CO_2 , but its structural impact as a greenhouse gas is 80 times more potent over a 20-year timeline, making it the second-largest direct contributor to global warming. Marine engine manufacturers are only beginning to rigorously quantify this phenomenon to determine its exact source and volumetric scale. To address this, *Hitachi Zosen Corporation*, *Mitsui O.S.K. Lines* (MOL), and *Yanmar Power Technology* (YPT) are actively collaborating on a joint research project aiming to reduce methane slip from LNG-fueled vessels by 70% by 2026.

Methanol (CH_3OH) is a toxic, corrosive chemical product widely utilized across industrial manufacturing. It is predominantly manufactured from natural gas or coal, but can alternatively be derived from renewable sources (hydrogen, recycled CO_2), biomass, agricultural waste, and timber). The deployment of methanol completely eliminates sulfur oxide (SO_x) emissions and curtails fine particulate matter (PM), whereas nitrogen oxide (NO_x) emissions remain fundamentally dependent on the specific engine technology deployed on board. It can be stored within standard, non-cryogenic fuel tanks as it remains liquid at ambient temperatures. Methanol is relatively easier to store and handle than alternative cryogenic marine fuels.

A non-negligible operational advantage lies in its compatibility with conventional marine engines, meaning shoreside and onboard infrastructure costs are significantly more modest. The energy density by mass of methanol is approximately two times lower than that of conventional heavy fuel oil (HFO), yet it remains more energy-dense than ammonia and hydrogen. Consequently, the requirement for onboard storage space will expand, necessitating frequent bunkering operations. It is already readily available across 141 ports worldwide, and truck-to-ship bunkering is technically viable. However, the risk of fire remains highly critical, characterized by a flashpoint sitting below 60°C , which mandates supplementary fire prevention and mitigation systems during handling and storage.

Historically, methanol was an operational choice dedicated exclusively to specialized methanol tankers trading the commodity, with 11 vessels in active service and 14 newbuild tankers on order. Yet, in 2022, a major market pivot occurred with 21 methanol-fueled container ships formally ordered.

First-generation or conventional biofuels³ represent a fuel source widely developed for land-based transport networks. They are technically compatible with modern marine diesel engines and can be safely utilized on board merchant vessels. However, they enter into direct competition with the global food supply chain, mechanically triggering an inflation of agricultural commodity pricing. Furthermore, the long-term viability of agro-fuels can be severely undermined if crops are managed unsustainably, precipitating soil depletion, water table pollution, and the destruction of natural ecosystems.

³ A biofuel is a liquid or gaseous fuel created from the processing of non-fossil organic materials derived from biomass, such as plant matter produced by agriculture (sugar beet, wheat, corn, rapeseed, sunflower, potato, etc.).

The International Energy Agency (IEA) estimates that biofuels could supply up to 27% of global transport energy by 2050. The ultimate positioning of biofuels within the future maritime energy matrix will be fundamentally conditioned by the development of second-generation biofuels. The latter do not interfere with food production, as they utilize cellulosic raw materials such as timber, agricultural residues, leaves, and plant stalks. While not yet deployed at a full industrial scale, solid medium-term application perspectives are mapping out, with large-scale commercial production projected across the 2020–2030 timeline.

Ammonia (NH_3) is generally manufactured by extracting hydrogen from fossil hydrocarbons and combining it with nitrogen captured from liquefied air. Under ambient conditions, it stands as a colorless gas with a characteristic sharp, pungent odor. It is currently manufactured from natural gas, but there is clear potential to integrate carbon capture technologies to contract its emission footprint (blue ammonia), or to manufacture it exclusively from renewable sources (green ammonia). The maritime supply chain should be engineered with relative ease, given that anhydrous ammonia already operates as a widely transported seaborne cargo.

Nevertheless, ammonia is a highly toxic molecule even at low concentrations, as well as highly corrosive. It represents a marine fuel that raises intense safety hurdles. Its engine combustion must be rigidly controlled to minimize emissions of nitrous oxide (N_2O)—a potent greenhouse gas possessing 273 times the global warming potential (GWP) of CO_2 . Furthermore, its volumetric energy density is low, hovering at approximately three times less than conventional fuel oils, which drastically restricts available cargo space on board for commercial freight. While pilot studies exist, the technological bottleneck (*verrou technologique*) remains too substantial today for widespread deployment.

Hydrogen (H_2) stands as a zero-carbon energy vector when manufactured utilizing renewable electricity, and is already being actively tested on board inland waterway crafts and harbor tugs. Hydrogen operates as both a highly explosive and extremely flammable molecule. Its exceptionally low volumetric density will compel vessels to store massive quantities on board. It must be stored utilizing ultra-low temperature cryogenic technologies (-253°C) or under extreme high-pressure conditions (exceeding 250 bar). Given this low energy density, hydrogen is structurally more suited for short-sea shipping and coastal trades than for long-haul transoceanic deep-sea vessels.

The EU aims to transform its territory into a global hub for green hydrogen. A brand-new public institution, the European Hydrogen Bank, backed by a €3 billion financial envelope, is slated for deployment, launching its first pilot auctions for renewable hydrogen production under the Innovation Fund framework in the autumn of 2023.

The French Agency for Ecological Transition (ADEME), within a 2020 technical brief entitled *"Rendement de la chaîne hydrogène, cas du Power to H_2 to Power"* (Efficiency of the Hydrogen Chain: the Case of Power-to- H_2 -to-Power), maps out the estimated efficiencies of diverse equipment components, including electrolyzers, compressors, and fuel cells (FC), to evaluate the global round-trip efficiency of the chain. This cascading sequence of energy transformations results in a severe degradation of the initial energetic potential, yielding a net electric-source-to-end-use efficiency of a mere 25% to 30%, even when deploying the highest-performing contemporary equipment assets. ADEME highlights that electrochemical storage via accumulators or lithium-ion batteries displays a significantly superior round-trip efficiency, hovering around 70% according to the agency's data.

E-methane consists of converting decarbonized electricity into hydrogen via water electrolysis, an architecture that notably allows for the storage of electricity when generation is surplus to grid demand. In February 2020, the Jupiter 1000 demonstrator facility injected hydrogen produced via "Power-to-Gas" from renewable electricity into the gas grid for the very first time, pioneering the electro-fuels (e-fuels) family.

A supplementary installation on the Jupiter 1000 site has recently been commissioned to manufacture a synthetic gas, or "e-methane," via methanation—a process that consists of blending green hydrogen and recycled CO_2 . This synthetic gas can be directly injected into existing gas grids, requiring zero construction of greenfield transport infrastructures, while dividing greenhouse gas (GHG) emissions released into the atmosphere by an average of two compared to conventional fossil natural gas, as highlighted by GRTgaz.

Nuclear propulsion represents the sole energy substitute that displays the exact same energy density profile as petroleum-derived fuels. Small Modular Reactors (SMRs) utilizing molten salt reactor technology are generating a strong resurgence of interest. However, greenfield reactor technologies must first be fully developed and operated ashore before any onboard deployment, to accumulate operational experience and thus expertly master risks and capital costs. For nuclear propulsion to be significantly adopted across mainstream merchant shipping, broad societal acceptability will be strictly mandatory.

The utilization of wind as a primary or auxiliary propulsion source (hybrid propulsion setups) for commercial vessels is returning in force. As an inexhaustible, safe, and free energy source coupled with advanced meteorological routing software, it presents numerous operational benefits. Wind shipping harnesses a primary energy source without relying on complex cascading energy conversion loops—such as the standard sequence: primary energy, conversion into electricity, transport grid, conversion into synthetic fuel, transport logistics, and final engine combustion—which are frequently heavily subsidized and where each intermediate processing step severely degrades the final energy efficiency and round-trip yield. Finally, within the panel of available decarbonization solutions, wind-assisted technologies can equip greenfield newbuilds as well as be installed via shoreside retrofits. Wind propulsion stands as one of the very few technologies potentially delivering double-digit fuel savings from day one, without entering into resource competition with alternative industrial sectors.

Ultimately, there is no silver bullet or miracle solution. Deeply decarbonizing the global maritime transport sector demands massive energy resources to manufacture clean fuels, coupled with heightened energy efficiency and optimized logistics. The acute uncertainty surrounding the future pricing and availability of alternative energy sources means that fuel flexibility and Fuel Ready solutions remain paramount corporate strategies to mitigate the catastrophic risk of investing in stranded assets. The climate crisis stands as a monumental energetic challenge, yet one that does not lack industrial initiatives.

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