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ZERO AND LOW-CARBON AMMONIA SHIPPING FUEL

Introduction. Around 90% of traded goods depend on the maritime transport sector as its main transportation mode and the OECD estimates maritime trade may increase three-fold volume-wise by 2050 [1]. In 2019, maritime trade volumes reached 11.08 billion tons according to UNCTAD, and while the COVID-19 pandemic that began in 2020 resulted in a volume decrease of 4.1%, recovery in 2021 should result in a 4.8% expansion in trade volumes, according to their latest report on maritime transport [2].

While maritime transport remains the most energy and cost efficient mode for movement of large volumes of goods all over the world (a breakdown of the types of goods transported in 2019 is presented in Fig. 1), the sheer size of this sector means that its associated emissions are still significant.

The International Maritime Organization (IMO) estimates that maritime transport GHG emissions totaled 1,076 Mt $CO_{2,eq}$, or 2.89% of anthropogenic GHG emissions in 2018, with accompanying energy consumption of 9.1 EJ [3]. Current IMO "business as usual" (BAU) forecasts, taking into consideration future shipping demand, fleet composition and fuel mix indicates that 2050 CO_2 emissions could be 90–130% of baseline 2008 values (equivalent to 100–150% of 2018 values). These values agree with IEA BAU scenario estimates, which place 2050 CO_2 emissions by the maritime transport sector at 135% of 2018 values [4].

While the aviation sector, another "hard-to-decarbonize" transport sector, has recently announced its goal to achieve industry-wide net-zero carbon emissions by 2050 [5], the maritime sector has yet

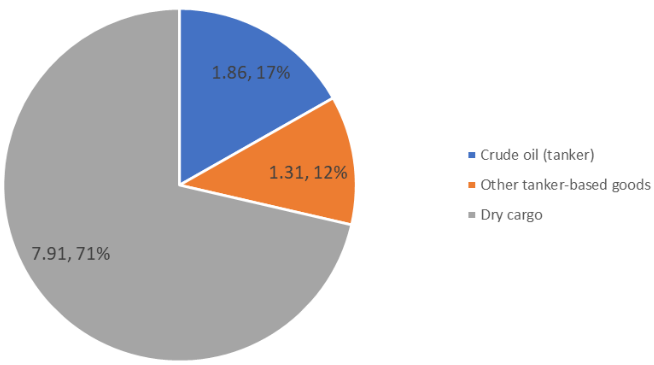

Fig. 1. Type of goods transported via maritime shipping in 2019 (billion tons) [2]

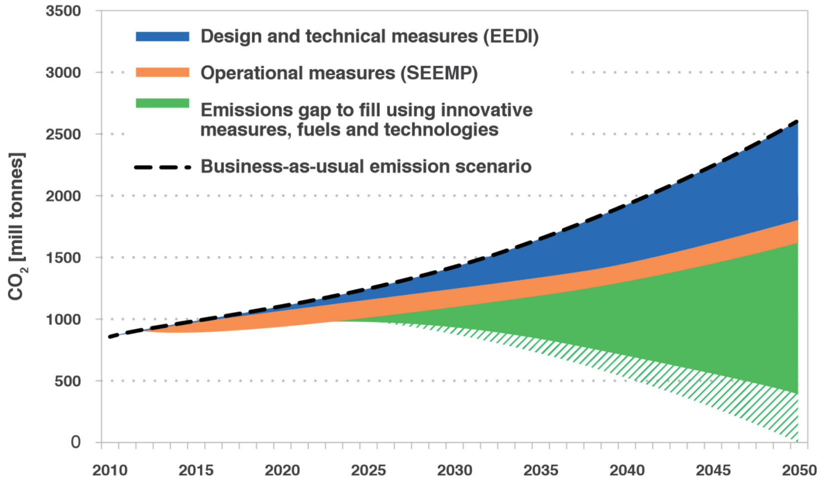

Fig. 2. Overall GHG reduction pathway to achieve IMO's ambitious goals. Note: EEDI: Energy Efficiency Design Index; SEEMP: Ship Energy Efficiency Management Plan. Current emissions reduction targets are shown in green, while dashed green represent a potential path towards net-zero emissions by 2050 [7]

to make such pledge. Although the maritime shipping industries in individual countries (e.g., Nordic countries, such as Denmark and Norway) have announced their carbon neutrality goals for 2050 [6], current IMO GHG emissions reduction targets still expect positive emissions from the sector in the medium term (i.e., 40% CO_2 reduction by 2030 and 70% CO_2 reduction by 2050, and up to 50% reduction of total GHG emissions by 2050, from a 2008 baseline), as illustrated in Fig. 2.

Accelerating the decarbonization of the maritime transport sector will require swift action from policymakers, industrial stakeholders, and technology developers, if goals in line with limiting the increase in global average temperature by the end of this century to 1.5 °C relative to pre-industrial levels are to be met. Furthermore, if the IMO decides on the adoption of net-zero emissions targets by 2050, as seen in recent sectoral and national pledges [8], a portfolio of solutions is likely to be necessary in order to effectively decarbonize the maritime transport sector.

Among these solutions, adoption of decarbonized fuels (with associated development of fuel production, supply infrastructure and compatible propulsion systems) is the key to reducing direct emissions (Table 1). Currently, multiple decarbonized fuels, such as biofuels, electricity (i.e., e-fuels and battery/fuel cell systems), low-carbon hydrogen (and its derivatives, such as ammonia and methanol), are still under consideration and remain promising options. Among these, hydrogen, and ammonia in particular, has emerged as promising candidates to serve as shipping fuels of the future. We therefore assess decarbonized ammonia as a shipping fuel in greater detail in the following sections.

Technology

The use of ammonia as an energy vector is proposed for use cases where energy density (i.e., amount of useful energy per unit mass and/or unit volume) is paramount, and where direct electrification presents a challenge due to the inherent handicaps of current battery technologies. Despite recent advances in battery technology for electrical energy storage, chemical energy storage remains orders of magnitude higher from an energy density perspective and thus represents a more viable option for heavy duty and long-distance transport needs. Among potential chemical fuels, both carbon-containing and carbon-free molecules are considered for use as renewable fuels with the final classification depending on how they are produced.

According to the IEA Net Zero Emissions Scenario (NZE2050), by 2050 around one-third of hydrogen demand may stem from the production of hydrogen-based fuels such as ammonia, synthetic kerosene and synthetic methane. This transport-specific demand represents an increase from the current value of approximately 20 kt H_2/yr to more than 100 Mt H2/yr by 2050 [10]. The expansion of use cases for ammonia beyond existing applications in the chemicals sector (primarily for fertilizers) is most notable in maritime transport (in particular long-distance shipping), where up to 45% of global shipping fuel demand could be met by ammonia in the NZE2050 scenario.

Table 1

Overview of potential emissions reduction and key aspects of alternative shipping fuels [9]

Fuel candidate	Maximum GHG reduction potential (%)	Current fuel cost ($/GJ)	Carbon cost-effectiveness ($/$t_{CO2}$)	Compatibility with existing propulsion systems
LNG	10%	7.1	340.1	Requires gas-fed or dual-fuel engine and associated cryogenic storage
Bio-LNG	169%[a]	113	49.5	
Methanol	92%	28.7	305.3	Not drop-in, compatible with ICE with retrofits
Ammonia	79%[b] / 100%[c]	31.9	400.5	Compatible with ICE (spark ignition coupled with hydrogen, or dual-fuel with pilot diesel)
Hydrogen	95%[b] / 100%[c]	89.2	1,028.7	Compatible with ICE (spark ignition or dual-fuel with pilot diesel), requires compressed or cryogenic storage
FAME	84%	17.0	174.0	Drop-in (blended < 20% FAME into fossil HVO)
Bio-HVO	91%	17.2	163.3	Drop-in (blended or neat)

Note: [a] – negative emissions are possible assuming use of bioenergy with carbon capture and storage (BECCS) during production; [b] – assuming biological pathway is used; [c] – assuming chemical synthesis pathway with renewable or carbon-neutral electricity; LNG – liquified natural gas; FAME – fatty acid methyl esters; HVO – heavy fuel oil; ICE – internal combustion engine.

Ammonia is favored for shipping applications as its energy density of 23 MJ/kg is comparable to that of fossil fuels, such as LNG (55 MJ/kg) and bunker fuel (i.e., heavy fuel oil, at 30–40 MJ/kg). Even though hydrogen itself has a much higher energy density per unit mass (142 MJ/kg), hydrogen's volumetric energy density at ambient conditions is only 13 MJ/m^3, which is just a fraction heavy fuel oil's volumetric energy density of 41,500 MJ/m^3 [11]. Liquefaction of hydrogen to achieve a volumetric energy density of 10,039 MJ/m^3 requires cooling hydrogen to a temperature of –253°C and this comes at a significant energy cost. Ammonia, on the other hand, can be liquefied by cooling it at atmospheric pressure to –33°C. The resulting liquid has a volumetric energy density of 15,600 MJ/m^3 making ammonia more suitable than hydrogen for applications that require high volumetric energy density, such as shipping fuel [12]. Table 2 summarizes the main attributes of low-carbon shipping fuel alternatives currently explored for adoption by the maritime transport sector.

Industrial production of ammonia is an established process dating back to the early 20th Century. The most widely adopted and technologically mature production pathway is the Haber-Bosch process, in which pure nitrogen gas (N_2) is combined with hydrogen gas (H_2) in a reactor in the presence of a catalyst under high temperature and pressure conditions. This is an exothermic (i.e., energy producing), thermodynamically favorable reaction, represented by the following net equation:

$$\mathrm{N_2} + 3\mathrm{H_2} = 2\mathrm{NH_3} \qquad \Delta G = -\frac{33kJ}{mol}. \tag{1}$$

In reality, the main reactions involved in ammonia production, combustion and fuel cell use are summarized below [18]:

Table 2

Comparison of main low-carbon fuel alternatives for use in maritime shipping

Parameter	Alternative and lower-carbon maritime shipping fuels					
	Hydrogen	Ammonia	Methanol	Biomethane	LNG or Bio-LNG	Biodiesel
Carbon content (wt.%)	0	0	37.5	74.8	≈75 (90–99% CH4)	86.9 (C_8–C_{20} range molecules)
Density at 15°C (kg/m^3)	0.08 (1 bar) 39.69 (700 bar) 72.41 (liquid)	0.72 (1 bar)	794.6	422.5[a]	431 to 464[a]	833 to 881
Boiling point at 101.3 kPa (°C)	–253	–33	64.5	–161.5	–160	163 to 399
Net heating value (MJ/kg)	142	23	20	50	55	42.5
Volumetric energy density (MJ/m^3)	13 (ambient*) 5,600 (700 bar) 10,000 (liquified, –253°C)	15,600 (liquefied, –33°C)	16,000 (ambient*)	37.8 (ambient*) 32,000 (800 bar)	20,000–22,000 (–160°C)	36,000 (ambient*)
Propulsion technology	ICE (single-fuel) Fuel cell (PEM, HT-PEM, alkaline, phosphoric acid, molten carbonate, solid oxide)	ICE (single- or dual-fuel engines) Fuel cell (alkaline, alkaline membrane, hydrazine borane, ammonia borane and ammonia-fed solid oxide) Hydrogen fuel cell b (onboard conversion to hydrogen)	ICE (single- or dual-fuel engines) Fuel cell (direct methanol, phosphoric acid, molten carbonate, solid oxide) Hydrogen fuel cell b (onboard methanol reforming to hydrogen)	ICE (single or dual-fuel engines)	ICE (single or dual-fuel engines)	ICE (single fuel, conventional engine drop-in fuel)
TRL[c]	7 (ICE) 5 (FC)	6 (ICE) 5 (FC)	5–6 (ICE) 8–9 (FC)	10+ (ICE)	10+ (ICE)	10+ (ICE)

Note: * – ambient conditions at standard ambient temperature and pressure equal to 25°C and 1 bar; [a] – using methane boiling point; PEM: proton exchange membrane; HT-PEM – high-temperature PEM; FC – fuel cell; ICE – internal combustion engine; [b] – in case of onboard conversion to hydrogen, hydrogen fuel cell technologies are applicable; [c] – TRL values based on the extended scale by IEA for evaluation of Clean Development Technologies [13]. Adapted from [9–11, 14–17].

Traditional Haber-Bosch ammonia synthesis:

$$6H_2O + 4N_2 + 3CH_4 = 8NH_3 + 3CO_2 \quad (2)$$

Renewable ammonia synthesis:

$$6H_2O + 2N_2 = 4NH_3 + 3O_2 \quad (3)$$

Ammonia combustion (use in internal combustion engines, ICE):

$$4NH_3 + 3O_2 = 6H_2O + 2N_2 \quad (4)$$

Ammonia splitting (use in fuel cells):

$$2NH_3 = 3H_2 + N_2 \tag{5}$$

The focus on ammonia as shipping fuel stems from its lack of CO_2 emissions when combusted as a fuel in propulsion engines. However, it is important to emphasize the need to account for whole value chain emissions in the production of ammonia, as otherwise associated CO_2 emissions are merely moved upstream towards the point of fuel production.

The nitrogen gas for ammonia is usually sourced from the atmosphere using an air separation unit (ASU), the hydrogen reactant has traditionally been produced using conventional fossil sources. Around 95% of ammonia production worldwide is reliant on fossil fuels with 72% of global ammonia production originating from hydrogen produced from natural gas via steam methane reforming (SMR) and 22% of global ammonia production originating from hydrogen produced from coal gasification (where China is the major producer via this pathway) [19]. The hydrogen produced from natural gas reforming is often referred to as grey hydrogen whereas the hydrogen produced from coal is referred to as brown or black depending on the source of coal.

Lower-carbon, and even zero-carbon, ammonia production may be achieved by adoption of low-carbon and renewable energy sources to supply energy for air separation, heating, filtration and purification and the use of blue hydrogen (i.e., grey, brown or black hydrogen coupled with CCUS), green hydrogen (i.e., water electrolysis using renewable power), turquoise hydrogen (i.e., methane splitting via pyrolysis) or pink hydrogen (i.e., water electrolysis using nuclear power). Low-carbon hydrogen, which in the context of this work includes zero-carbon hydrogen, can also be produced via the organic fraction of municipal solid waste (OF-MSW), from wastewater treatment plants (WWTP), or via bioelectrochemical systems, such as microbial electrochemical cells (MEC). Currently, however, such bio-based ammonia synthesis pathways are not primary contributors to industrial ammonia industrial production.

Thus, the main alternatives for industrial ammonia production tend to be separated by the "color" of hydrogen used in the Haber-Bosch synthesis: green hydrogen, from renewable energy sources, leads to the so-called "green ammonia", while blue hydrogen from fossil sources coupled with carbon capture, utilization and storage (CCUS) technologies leads likewise to "blue ammonia". These two varieties of low-carbon ammonia production are illustrated in Fig. 2 and 3, respectively. While blue hydrogen production may utilize CCUS technologies, such as enhanced oil recovery (EOR) and/or synthetic hydrocarbon production (e.g., methanol synthesis) for the generation of other value-added products (Fig. 3), the blue ammonia generated from this hydrogen feedstock would not be truly carbon neutral. If

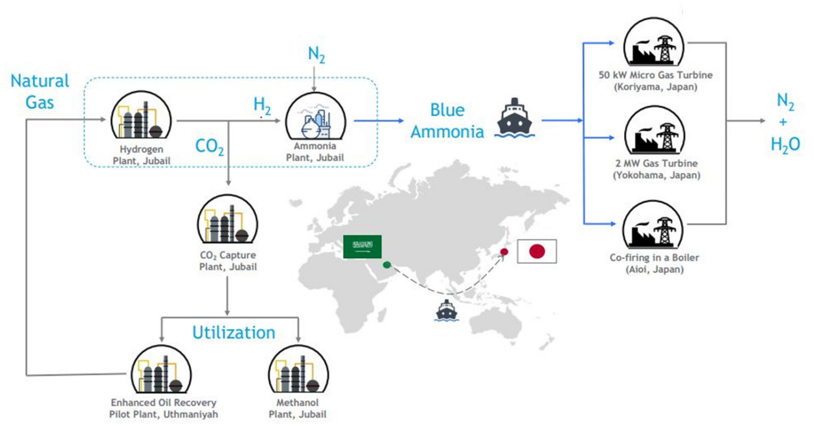

Fig. 3. Conceptual Flow Diagram of Blue Ammonia Supply Chain Demonstration [20]

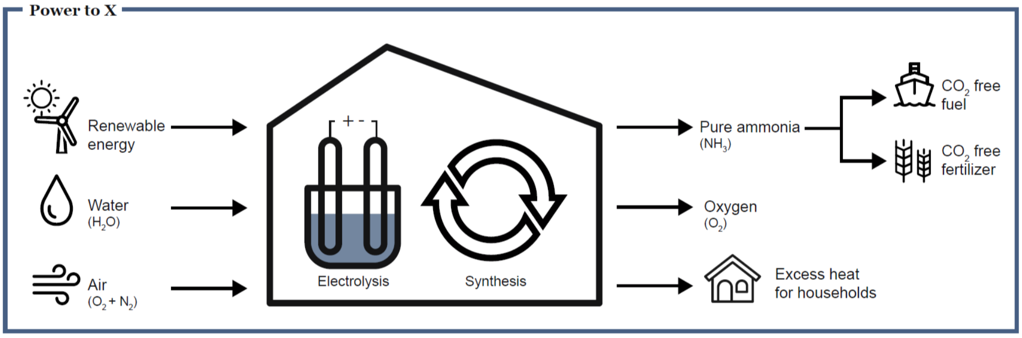

Fig. 4. Green ammonia production as an example of “power-to-X” application [21]

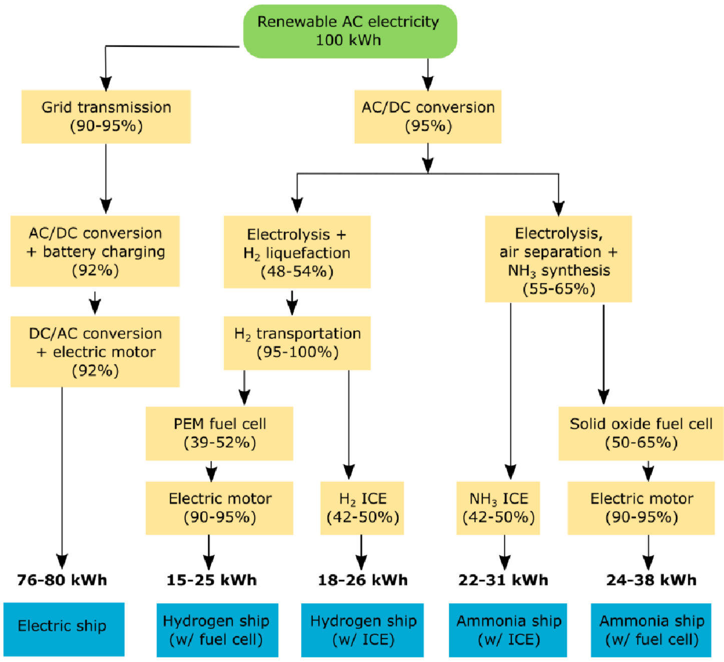

Fig. 5. Energy efficiency of potential maritime fuels created from renewable electricity source [6]

zero-carbon ammonia is the desired product, production via green hydrogen is necessary (in line with the “power-to-X” concept, Fig. 4).

Both hydrogen and ammonia already have existing infrastructure in place for transmission, storage and distribution, as the former is currently used primarily in oil refining and petrochemical industries while the latter is one of the main products (at around 175 Mt/yr) of the chemical industry sector, particularly for use in fertilizer production [22]. While wider adoption of either energy vector for fuel applications would require further investments in dedicated infrastructure, the potential to convert or repurpose existing liquefied petroleum gas (LPG) propulsion technology and infrastructure for ammonia-based systems tilts the balance in favor of the latter option [23]. In addition, engines capable of combustion of ammonia blended with conventional hydrocarbon fuels (i.e., dual-fuel use engines) provide a transition pathway option where gradual replacement of conventional maritime fuels is possible [24, 25].

Low-cost technologies for the production of green hydrogen remain the major obstacle for its widespread adoption, while blue hydrogen faces challenges in the economic feasibility of CCUS, particularly CO_2 storage. Further, the use of ammonia derived from low-carbon hydrogen as a shipping fuel must take into consideration trade-offs between decarbonization alternatives, as demonstrated in Fig. 5. While direct electrification of propulsion systems via renewable electricity coupled with energy storage could provide up to 80% energy conversion efficiency, the energy density of current battery technologies is not sufficient for large, long-haul ships, as cargo capacity would need to be reduced to allow for the substantial battery weight and volume requirements. In comparison to lithium-ion batteries, which have gravimetric energy densities of approximately 1 MJ/kg and volumetric energy densities approximately 2800 MJ/m^3, low or zero-carbon ammonia has a gravimetric density of approximately 23 MJ/kg and a volumetric energy density, in the liquid state, of approximately 15,600 MJ/m^3. Hence, ammonia would have a much smaller storage requirement and be a more suitable decarbonization option for heavy fuel oil. Regarding the trade-offs between liquid hydrogen and liquid ammonia for use as shipping fuel, liquid ammonia has about a 55% higher volumetric energy density than hydrogen and can be liquefied at atmospheric pressure by cooling to –33°C whereas hydrogen requires cooling at atmospheric pressure to –253°C to achieve the liquid state. Hence, ammonia is altogether a more cost-effective fuel option.

Economic potential

The production costs of green ammonia remain a barrier for its wider adoption [26], as current estimates put its price at 480 $/t$_{NH3}$ (around 1,080 $/toe), based on a levelized cost of hydrogen of 3.0 $/kg [27]. By 2030, the levelized cost of ammonia could fall to 350 $/tNH3 (around 790 $/toe), and as low as 310 $/tNH3 (under 700 $/toe) in certain geographical locations, such as Oceania [28]. Although bunker fuel commodity prices exceeded 600 $/toe in late September 2021 [29] with the recovery of oil prices above 80 $/bbl [30], fuel costs per ton and mile of cargo shipped are still higher for green ammonia relative to heavy fuel oil due to the fact that ammonia weighs twice as much and requires three time more space to contain the same amount of energy as heavy fuel oil. On a cost per unit energy content, the levelized cost of green ammonia would have to fall by more than 65% and approach 60–70 $/MWh to match the cost range of maritime fossil fuels, which as seen in Fig. 6 is not likely in the near term.

Standards and Regulations

Industry standard setting bodies, such as the American Bureau of Shipping (ABS), have published in 2021 guidance documents for the design and construction of ammonia-powered vessels [32]. Other relevant documentation published in 2021 includes certification and notation class rule sets, e.g., by

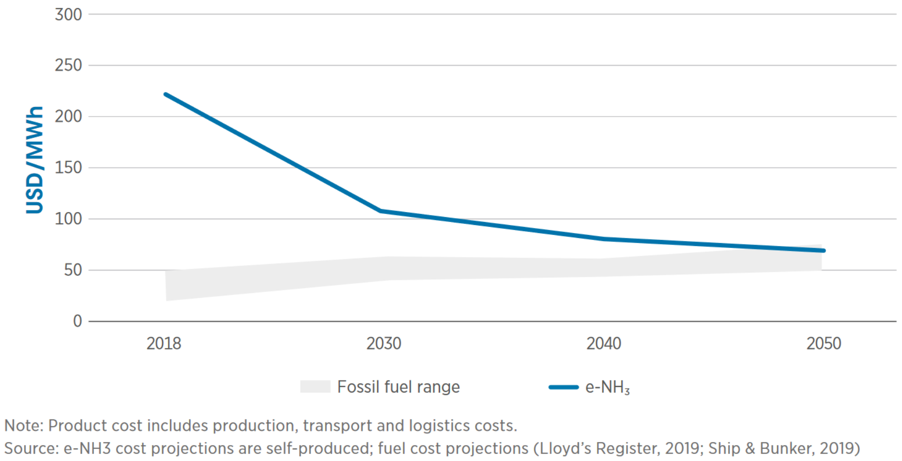

Fig. 6. Production cost comparison and forecast projection between green ammonia (e-NH$_3$) and maritime fossil fuels [31]

Bureau Veritas (“NR671 ammonia-fueled ships - tentative rules”) [33], RINA (“Ammonia as fuel” and class notation “Ammonia Ready”) [34], DNV (new notation covering ammonia as fuel, “Gas fueled ammonia”) [35], and Korean Register ("Guidelines for Ships Using Ammonia as Fuels") [36].

These guidance documents are in line with safety standards such as the “International Code of Safety for Ships Using Gases or Other Low Flashpoint Fuels” (also known as the IGF Code) by the International Maritime Organization (IMO). It is also in line with other IMO efforts to promote sustainable development, such as the 1973 “International Convention for the Prevention of Pollution from Ships” (“MARPOL Convention”) and the sectoral GHG emissions reduction targets.

Path Forward

In evaluating the potential for zero and low-carbo ammonia for shipping fuel, a number of notable advantages and opportunities are evident:

- **Established production of carbon neutral or low-carbon ammonia with broad benefits**: The production of fossil fuel-derived ammonia in the chemicals sector was responsible for around 406 Mt CO_2/yr in CO_2 emissions in 2018, larger than that of methanol production (at 211 Mt CO_2/yr) and of other high-value chemicals production (at 258 Mt CO_2/yr) [22]. The wide adoption of ammonia as a shipping fuel will require extensive deployment of renewable and low-carbon hydrogen production, or the environmental benefits from the adoption of ammonia by the maritime transport sector will not be realized. Nonetheless, such benefits extend beyond decarbonization as the replacement of heavy fuel oil with ammonia is broadly beneficial to the marine environment (Table 3) [37, 38].
- **Infrastructure and propulsion technology retrofits**: The relative ease of retrofitting existing shipping-associated infrastructure for ammonia is a further opportunity, particularly when compared with the requirements for hydrogen infrastructure. This is due to scale (i.e., ammonia shipping infrastructure is more widely developed than that of hydrogen bulk shipping, in particular liquid hydrogen), technical (e.g., infrastructure for maritime shipping use of liquified petroleum gas, LPG, is similar to that needed for ammonia and may more readily be converted) and regulatory (i.e., although ammonia is considered a toxic chemical, safety regulatory frameworks are already in place for its use in the maritime transport sector, while equivalent regulations for hydrogen use are still being developed) [23, 39].
- **Safety, performance and regulatory aspects**: Regarding challenges for use of ammonia as a shipping fuel, use in engines and for power production in general requires attention. Ammonia use in compression ignition engines is hindered by higher compression ratio requirements for ignition than current fuel oil. Overcoming this constraint is possible via use of ammonia with spark ignition engines or use of a pilot fuel with a lower ignition point. While the former is less desirable from a technological perspective due to inherent reliability issues with ammonia flammability characteristics, the latter is technologically achievable via in situ ammonia cracking for hydrogen production (which has a much wider ignition range and thus fits the role of a pilot fuel) [40]. Emerging technologies for use of ammonia to generate power include solid oxide fuel cells (SOFC) and direct combustion in gas/steam turbines, but energy efficiency yields (both work and thermal efficiency) are yet to match those of current combustion engines [41].

In order to realize these benefits and opportunities, however, concerted actions are needed, particularly:

- **Continued investments in R&D**: Stakeholders in the shipping industry must commit to an ongoing effort to support R&D efforts on the development of renewable and low-carbon ammonia production systems. This effort is directly aligned with the development of the hydrogen economy, as whether electricity-based ammonia or fossil-based ammonia coupled with CCS are pursued, both pathways share multiple technologies with hydrogen production as an energy vector. In addition, further developments for ammonia-based fuel use can have direct implications in the development of use cases in stationary applications, such as grid-balancing and power systems. Thus, research efforts typically needed to bring low- and mid-TRL technologies to market should be targeted, and include topics in the scaling up of

Table 3

Percentage reduction of broader environmental impacts when using ammonia or hydrogen fuel, in impact per ton.km relative to conventional Heavy Fuel Oil [37]

Vessel type	Fuel	Energy sourse for fuel production	Marine sediment ecotoxicity	Marine aquatic ecotoxicity	Acidification	Abiotic depletion	Ozone layer depletion	Abiotic depletion
Freight ship	NH_3	Biomass	68%	69%	55%	63%	90%	63%
		Geothermal/municipal waste	73%	77%	83%	64%	90%	64%
		Hydropower	72%	75%	82%	60%	89%	60%
		Wind	67%	69%	82%	56%	87%	56%
	H_2	Biomass	80%	80%	75%	83%	94%	83%
		Geothermal/municipal waste	80%	86%	96%	85%	94%	85%
		Hydropower	82%	84%	95%	81%	93%	81%
		Wind	78%	80%	94%	76%	93%	76%
Tanker	NH_3	Biomass	74%	74%	77%	53%	85%	53%
		Geothermal/municipal waste	77%	77%	90%	54%	85%	54%
		Hydropower	76%	76%	90%	55%	83%	55%
		Wind	74%	74%	89%	49%	81%	49%
	H_2	Biomass	77%	78%	86%	70%	88%	70%
		Geothermal/municipal waste	79%	80%	96%	71%	88%	71%
		Hydropower	78%	79%	96%	68%	90%	68%
		Wind	75%	77%	96%	61%	90%	61%

technology pathways, design and implementation of transmission, distribution, and storage systems, as well as business models and policy and regulatory drivers to enable ammonia adoption in reasonable timeframes. Furthermore, potential synergistic opportunities with other end-use sectors, such as agriculture, terrestrial transport and chemicals industry must also be investigated, as industrial clusters can provide de-risking opportunities for new investments in ammonia projects [18].

- **Capital requirements for fleet replacements and technology investments**: In order to achieve wider adoption of ammonia use as a shipping fuel, current seagoing vessels will need to undergo retrofits or be replaced by ships powered by propulsion systems capable of dual-fuel use (i.e., blending of fuels for simultaneous combustion) or adapted ammonia use. Recent scenarios investigated by DNV put the total investment in the 250–800 billion dollars range, with peak investment as high as 60 billion $/yr, between now and 2050 [17]. Furthermore, upstream investments would be necessary to ensure up to 8 TW of renewable energy production capacity, or 750 Mt CO_2/yr of CCS, for the production of sufficient green and blue ammonia, respectively, by the year 2050. In total, up to 2.4 trillion dollars might be needed to achieve net zero goals by 2050 for complete decarbonization of the maritime sector, with 0.6 trillion dollars for ship efficiency interventions (e.g., drag reduction, exhaust treatment and power systems not including engine retrofits), 0.1 trillion dollars for operational efficiency interventions (in particular via digitalization and big data analytics), and 1.7 trillion invested in alternative shipping fuels (mainly hydrogen and ammonia production, storage and transmission infrastructure; bunkering, onboard storage and engines and propulsion systems) [42]. Without increased efforts to develop and implement mechanisms to enable access to capital markets and infrastructure investment opportunities, the transition to ammonia as a decarbonized shipping fuel may not be possible given the large sums required.
- **Policy support and consumer expectations**: Clear and harmonized policy frameworks are necessary to support efforts by shipping companies to pursue emissions reductions via technology investments and

adoption of low- and zero-carbon fuels. In particular, the establishment of appropriate carbon pricing mechanisms that avoid leakage across borders is paramount, as economic incentives for decision-makers are often an important nudge factor to overcome organizational inertia and unwillingness to innovate [43]. In addition, international companies whose movement of goods depend heavily on the international maritime shipping industry may also push their logistics providers to accelerate the adoption of net zero or low-carbon initiatives. Global companies such as Amazon, Ikea, Unilever and six others have voluntarily pledged in October 2021 to only use cargo vessels powered by zero-carbon fuel by 2040 [44]. This type of “corporate activism” is a reflection of a larger trend of Environmental, Social, and Governance (ESG) considerations informing business practices and investments, as companies re-align their fiduciary obligations with wider (and previously ignored or underrepresented) impacts of externalities [45].

Should these actions be taken toward enabling low and zero-carbon ammonia shipping fuel and the noted opportunities and benefits realized, a major advance will have been made for one of the notoriously “hard-to-decarbonize” sectors. Already a substantial number of announcements about low and zero-carbon ammonia shipping fuel have been made by industrial stakeholders in 2021, ranging from feasibility studies to pilot and demonstration scale initiatives. While not all these projects target ammonia for use as a shipping fuel, they provide the essential scale-up of low-carbon ammonia production that is required to reduce costs for shipping fuel applications. Notable projects from shipbuilding companies are pursuing the use of ammonia-fueled propulsion systems in Japan (e.g., Mitsubishi Heavy Industries [46], Nihon Shipyard [47] and Nippon Yusen Kaisha [48]) and Korea (e.g., Hyundai Heavy Industries [49] and Samsung Heavy Industries [50]), developed in partnership with major industrial stakeholders in European countries (e.g., A.P. Møller – Mærsk, Wärtsilä, MAN Energy Solutions, ECONNECT Energy) and also in the chemicals sector (e.g., Yara International [51]).

Concluding remarks

The inherent advantages of low-carbon and carbon-free fuels for the decarbonization of the maritime transport sector will only be achieved if low-carbon production pathways are used and full value-chain emissions are considered. Both hydrogen and ammonia seem poised for adoption as low-carbon fuels as production costs are driven down by technology innovations, wider industrial adoption and captive market demand and policy mechanisms that support harmonized pricing of CO_2 emissions are adopted. In the maritime transport sector, ammonia appears to have an advantage over other low-carbon fuel options, as ammonia has good gravimetric and volumetric energy density and is largely compatible with existing shipping infrastructure.

While industrial efforts around the development of ammonia as a shipping fuel have surged in 2021, continued support for the development of ammonia production systems (both blue and green) and technology pathways is required. Alignment of the sector with other industrial activities where ammonia is relevant, as well as applications where it is used as a primary feedstock, may enable faster development of infrastructure while also serving to de-risk project investments. Finally, while regulatory efforts for use of ammonia use as a shipping fuel are moving ahead, the maritime transport industry through its international representation and trade bodies, must ensure that its sectoral goals towards climate change mitigation move in tandem with ambitious climate change mitigation global targets towards at the global level.

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