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Green ammonia adoption in shipping: Opportunities and challenges across the fuel supply chain

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ABSTRACT

The IMO's 2023 revised targets increase pressure on shipping and trading organisations to urgently cut energy consumption and transition away from fossil fuels. Although there are several alternative fuel options for shipping, ammonia is a prominent contender. Green ammonia is produced from renewable hydrogen with no direct CO_2 emissions when combusted, making it an important option to interrogate. This research uses a mixed methods approach, including analysing shipping stakeholders' perspectives, to consider the full range of factors relating to its deployment and use. Challenges to its adoption include low fleet renewal as a result of uncertainties around being first movers, managing NO_x and N_2O emissions if used in a combustion engine and lack of economic incentives. Nevertheless, green ammonia's storage advantages over hydrogen, established experience of ammonia handling for the fertiliser industry and its direct emission free application in fuel cells, underpin interest in its development. The study emphasizes though that the on-ground realities of transitioning away from fossil fuels require significant developments across the entire fuel supply chain. This extends beyond considerations around ammonia's technological viability and encompass changes needed to onboard and portside infrastructure, incentives to accelerate retrofit and fleet renewal, and recognition of risks posed by first-movers in the sector. Furthermore, with short timeliness associated with Paris targets, and anticipated rising costs of new fuel infrastructure, there is an imperative to implement mitigation policy that focuses on urgently reducing reliance on liquid fuels, while alternative fuel deployment is established at scale.

1. Introduction

In 2022, global carbon dioxide emissions reached 40.7GtCO_2 [1]. Building on from the method used in Friedlingstein et al. [1] as of the start of 2024, 275 GtCO_2 remains to be emitted for a 50 % probability of limiting global warming to 1.5°C, although note that values provided in other carbon budget analyses might differ. Data from the 2021 submissions of nationally determined contributions (NDCs) demonstrate that the existing efforts to mitigate climate change will not suffice to keep emissions within the 1.5°C limit over the course of this century, a goal of the 2015 Paris Climate Agreement [2]. This risk of temperatures rising above 1.5°C, can only be mitigated if all sectors deeply and rapidly cut their emissions this decade and beyond. This means that sectors, such as aviation, shipping and industrial processes, that are considered to be 'difficult to decarbonise' must appraise all options available to them [3].

In 2018, the global greenhouse gas (GHG) emissions from shipping accounted for around 3 % of total emissions [4]. It is projected that under a business-as-usual scenario, international shipping emissions will increase by 90–130 % of 2008 levels by 2050 [4]. In 2023, the International Maritime Organisation (IMO) adopted a revised GHG strategy, a revision to the initial strategy adopted in 2018. The fresh objectives aim to curtail annual GHG from global shipping by "at least 70 %, striving for 80 %, by 2040, relative to 2008" [5]. This set of goals has

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greater ambition than the IMO's preceding target, which sought to achieve at least 50 % below 2008 levels by 2050 [6]. The strategy also sets outs a target for zero or near-zero GHG emissions technologies to make up minimally 5 % and up to 10 % of fuel/energy source by 2030. The IMO's carbon intensity reduction goals remain the same with the aim of at least 40 % below 2008 levels by 2030 through the International Convention for the Prevention of Pollution from Ships (MARPOL) [7]. To ensure compliance with these targets, the IMO has implemented the Energy Efficiency Design Index (EEDI), Energy Efficiency Existing Ship Index (EEXI), and the carbon intensity (CII) indicator and rating, which help the IMO to monitor energy and fuel efficiency standards [7]. The International Council on Clean Transportation's (ICCT) recent analysis suggests that despite greater ambition, if international shipping meets its revised strategy targets, it will still exceed 1.5°C budget in the next decade, but may well be able to align with the 2°C goal [8]. Similarly Bullock et al. [9] suggests that anything short of the strive targets (80 % by 2040) means that the shipping sector will be incompatible with even the sector's 1.5°C budget [9].

With greater ambition and the call for low and zero carbon fuel technologies, the sector faces mounting pressure to address its cumulative emissions [10]. To date, urgent mitigation measures have been hindered by the existing democratic decision-making process within the IMO and the complexities surrounding emissions apportionment methods [10–14]. The slow pace of policy decisions in the shipping sector also suggests that the global shipping fleet is unlikely to meet its mandated energy efficiency goals, such as the EEDI, by 2040 [15]. Moreover, the current rate of progress is anticipated to be "insufficient" in achieving the necessary emissions reductions within this decade to adhere to the 1.5°C limit outlined in the Paris Climate Agreement [8,15,16].

The maritime industry plays a crucial role in global trade and transportation, making it a significant contributor to GHG emissions. While it is recognised by many that the shipping sector will require a combination of measures to cut emissions, including energy efficiency, slow steaming, wind-propulsion with route optimization [17] demand management [18] and hybrid propulsion, here, the primary focus lies in examining the barriers surrounding the uptake of alternative fuels – specifically green ammonia. This paper aims to integrate insights from both grey and academic literature with empirical findings from workshops and interviews. Data is analysed using thematic analysis (TA) based on Braun and Clarke's guide [19] to assess the viability of green ammonia as a fuel option. It is important to clarify that this research does not advocate for or scrutinize the use of ammonia as a shipping fuel; rather, it explores practicalities around its use as a shipping fuel at scale, whilst interrogating the perceived and real barriers and opportunities surrounding its deployment.

2. Background

2.1. Alternative shipping fuels

The shipping sector has already embarked on its critical decade of transition [16,20], which is distinct from other hard-to-decarbonise industries like aviation, due to its access to a wide selection of mitigation options, including range of fuels, propulsion technologies, energy efficiency as well as operational measures [21]. Research has provided the shipping industry with insights into potential alternative fuels to fossil-based diesel and heavy fuel oil, including methanol, Liquified Natural Gas (LNG), Liquified Petroleum Gas (LPG), ethanol, ammonia, hydrogen and bio-derived fuels [22–30]. Notably, fuels such as LNG, biodiesel and methanol are already being used to a degree [22,31–33], but are yet to be sustainably scaled up to a penetration that has a meaningful impact on emission production. Moreover, each fuel presents its own set of challenges in terms of infrastructure, safety, combustion, levels of upstream and downstream emissions and other by-products, to the extent that some – notably LNG – can in practice have higher total GHG emissions than Heavy Fuel Oil (HFO) fuel when compared on a well-to-tank basis in part due to methane slip [34]. This is despite offering 20–30 % reductions in CO_2 when comparing tank-to-wake combustion [22]. Consequently, all potential opportunities and trade-offs must be carefully evaluated before adopting any of the specific fuels at scale.

Currently, economic factors make conventional fossil-derived fuels an obvious choice. Focusing solely on propulsion performance-based criteria, Table 1 illustrates that HFO, MDO, LNG and LPG all have a high volumetric energy density, making them cost-effective as ships carry relatively less fuel, with more room for payload, for the distance covered [36,39]. Likewise, LNG has gained popularity as an alternative fuel given a relatively high volumetric energy density and as noted previously, its lower CO_2 emissions on combustion than HFO, as well as an absence of SO_x and reduced PM emissions. It is also more cost-effective compared other alternatives and is readily available for some current engine configurations, unlike newer fuels such as hydrogen and ammonia [29,40–42]. It is therefore perhaps unsurprising that its use has grown in recent years. Notably, as of 2023, LNG-fuelled vessels accounted for 19 % of the global fleet orderbook [43], yet from a climate change mitigation perspective, such ships will only make sense if a reliable and sustainable supply of bio-derived methane is secured [44] and crucially if the issue of methane slip can be resolved [34]. It is therefore imperative to explore other fuel options that may more closely aligned with the scale and urgency of the challenge at hand.

2.2. Current alternative fuel landscape in shipping

Analysis based on the IMO 2008 emissions baseline suggests that the shipping sector has a 25-year window, starting from 2023, to align with the 1.5°C goal of the Paris Agreement [16]. Considering that 2050 is just one ship lifecycle away [16,45], it is crucial for fleet renewal efforts to be on track to meet the transition deadlines. Specifically, large ships and very large ships (> 5000 Gt), which account for 85 % of GHG emissions in the sector [46], will need to be replaced by ships with low-carbon propulsion technologies or be retrofitted.

The shipping sector is structured to ensure logistical efficiency, with ship operations streamlined to avoid the complexities associated with different engine configurations, safety protocols, storage requirements, and onboard operations for various fuels. Current bunker fuels i.e. HFO, Marine Gas Oil (MGO), Marine Diesel Oil (MDO), Low Sulphur Heavy Fuel Oil (LSHFO) and LNG are derivatives of two naturally occurring hydrocarbons - petroleum and natural gas, largely differentiated by their viscosities, carbon structure and boiling points [47]. Despite a multi-fuel transition being envisioned, vessels that are listed as using alternative fuels are relatively homogenous when fuel type and propulsion mechanism are concerned with most using LNG in diesel 2-stroke and diesel electric engines (Fig. 1).

In 2023, out of 104,673 vessels in service only 1.09 % were using alternative fuels (including LNG and LPG) [48]. Not all vessels that have a dual-fuel mechanism are listed as *alternative fuel use*, as some continue to use conventional bunker fuels – these instead would be classed as *alternative fuel ready* which made up 0.4 % of fleet in 2023 [48].

Fig. 2 summarises the fleet orderbook for alternative fuel use and alternative fuel ready vessels in 2023. Newer engines are most likely to be ammonia ready which illustrates an anticipated shift at some point. However, the current usage of ammonia as a shipping fuel is virtually non-existent. Considering the prevailing alternative fuel usage and the vessels ordered, it appears to be more likely that LNG and LPG will continue to dominate as the primary alternative fuel, despite having a carbon content more similar to that of HFO, MDO and MGO [49].

Table 2 shows the breakdown of alternative fuel planned usage in terms of gross tonnage for vessels to be built up until 2027. Given that the 75 % of the overall planned gross tonnage are for LNG vessels, this shows that there is a significant shortfall in planned fleet renewal efforts when considering emission reduction targets. While technological

Table 1
Properties of different shipping fuels in their liquid phase. Sources: DNV [30], ABS [35], Aronietis, et al# [36], Aziz, et al# [37],Cheliotis, et al# [38].

Properties		Fuel Type							
		Ammonia	Marine Diesel Oil (MDO)	Heavy Fuel Oil (HFO)	Liquified Natural Gas (LNG)	Liquified Petroleum Gas (LPG)		Methanol	Liquid Hydrogen
					Methane	*Propane*	*Butane*		
Storage	Temperature (°C)	−33	25	40	−162	−48		25	−253
	Pressure (kPa)	1800	100	-	500–1000	1800		100	100
	Relative [to Marine Gas Oil] tank fuel volume	2.45	1	0.96	1.86	1.66	1.4	2.45	4.51
Energy Density	Volumetric Energy Density (MJ/l)	12.9	38.4	38.3	21.6	23.2	27.4	15.7	4.5
	Gravimetric Energy Density (MJ/kg)	18.6	43	40.4	48	46.3	45.7	19.9	120
	Flame speed (m/s)	0.015	-	-	0.34	-		0.43	3.5

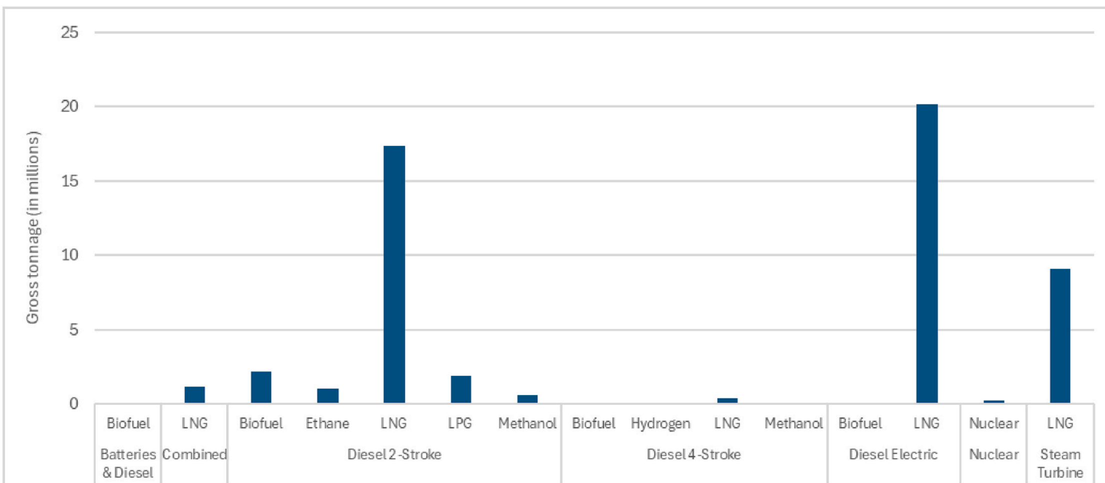

Fig. 1. Breakdown of alternative fuel use by types of propulsion mechanism against gross tonnage of vessels in 2022.[31] Source: Clarksons [43].

options are available, there is no discernible sign, especially among larger vessels, of widespread adoption of alternatives other than LNG. Critically, when considering future CO_2 emissions, the largest vessels are anticipated to continue to rely on conventional mechanisms, with some expected to remain in service well into the 2050 s. Although it has been highlighted that, in the context of decarbonisation, first-movers will be privy to benefits such as technology leadership, resource monopolization and brand recognition [50,51], it does not appear that this advantage is being capitalised upon, with just 0.07 %, of vessels in the global fleet's 2022 orderbook, scheduled for construction between 2022 and 2027, projected to be powered by low carbon alternative fuels excluding LNG and LPG [43].

Despite low uptake to date, there are some initiatives at a port scale to trial alternative fuels. At the Port of Singapore, the storage and bunkering capabilities of various fuels are being evaluated, with an aim to optimise turnover efficiency and determine the most favourable options in terms of emissions, cost and resource savings [27]. However, scalability and the necessary changes to the upstream supply chain will inevitably also need to be addressed. Nevertheless, some suggest that this exploratory phase that the sector is currently experiencing can ensure that it adopts the most appropriate fuel to cushion itself from volatile prices, fluctuating demand, and fuel availability that vary by region [52,53]. Moreover, as different regions will have varying access to and availability of alternative fuels, ships' ability to bunker in specific ports will be restricted [28,54].

Within this uncertain landscape, the potential of green ammonia as a viable fuel option is a candidate of interest with several studies having positioned it as a promising fuel for early adopters [22,38,55–57]. With its CO_2-free nature during combustion and arguably fewer obstacles than biofuels to securing a sustainable supply, green ammonia may have the potential to help the sector align more closely with the targets of the Paris Agreement. However, before it can be considered a safe, practical and low emission option, challenges relating to its production methods, safety protocols (such as onsite bunkering), non-CO_2 emissions, and risks associated with onboard fuel use must be interrogated and addressed.

2.3. Ammonia production processes

Conventional ammonia production involves the capital and energy-intensive Haber-Bosch process, which typically relies on fossil fuels for power. In this process, nitrogen (N_2) and hydrogen (H_2) are compressed together at pressures of 1×10^5-2×10^5 Pa and temperatures of 400°C to 500°C in a tall steel reactor [58]. An iron (Fe) catalyst facilitates the release of nitrogen atoms, which then react with hydrogen atoms to form ammonia [58]. Conventional ammonia production is responsible for approximately 1.8 % of global anthropogenic CO_2 emissions annually and consumes 1–2 % of global energy, with hydrogen production via steam methane reforming (SMR) using 80 % of that energy [59,60]. Each year, approximately 230 million tonnes of ammonia are produced using the Haber-Bosch process, with 70 % using natural gas as a feedstock and the remainder relying on coal, heavy fuel oil and naphtha [61,62]. Present-day production processes consume around 28 GJ of natural gas per million tonnes of ammonia, resulting in the emission of 1.6 tonnes CO_2 per tonne of ammonia [59,62]. Comparatively, emissions from coal, heavy fuel oil and naphtha range from 2.5 to 3.8 tonnes CO_2

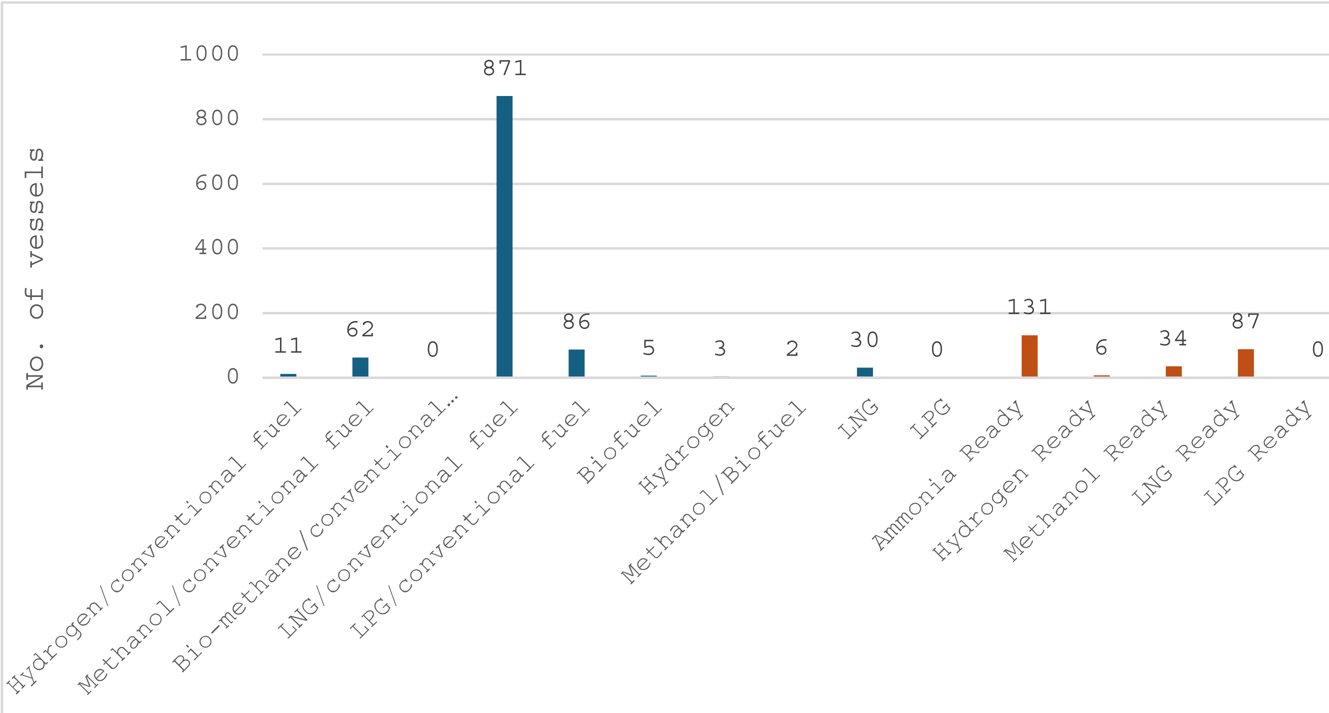

Fig. 2. The number of vessels of each alternative fuel in the orderbook as of 2023. Source: Clarksons [43], Tomos et al. [48].

Table 2
Alternative fuels vessels to be built by gross tonnage between 2022 and 2027. Source: Clarksons [43].

Alternative fuels	2022	2023	2024	2025	2026	2027	Total GT
Biofuel	2755		25,000				**27,755**
Biofuel/Methanol			12,000				**12,000**
Ethane/conventional fuel	97,139	112,876	18,965	279,465			**508,445**
Hydrogen	200	5500					**5700**
Hydrogen/conventional fuel	690		50,000	50,000	50,000	50,000	**200,690**
Hydrogen/LNG/conventional fuel		50,000	50,000		64,000	64,000	**228,000**
LNG/conventional fuel	2874,214	4333,914	8435,575	6678,465	1209,785	109,923	**23,641,876**
LPG/conventional fuel	477,803	2,530,145	675,388	173,051			**3856,387**
Methanol/conventional fuel	90,641	123,312	1250,482	822,905	518,504		**2805,844**
Nuclear						50,000	**50,000**
Nuclear/conventional fuel	30,000		30,000		30,000		**90,000**
Total GT	**3573,442**	**7155,747**	**10,547,410**	**8003,886**	**1872,289**	**273,923**	**31,426,697**

per tonne of ammonia [59,62]. Historically, ammonia has primarily been used in fertilizers, contributing significantly to the agricultural sector's ability to meet the demands of a growing population over the past century [63–66]. For ammonia to be considered a viable low-carbon fuel option, there is a need to transition away from conventional fossil-fuel based production methods.

Ammonia is considered "green," if the hydrogen used in its production is generated through the process of electrolyzing water and then combined with atmospheric nitrogen [68]. This synthesis takes place via an air separation unit and is carried out using the Haber-Bosch process, all of which should be powered exclusively by renewable energy sources [64,66]. Alternative methods of production for green ammonia are also being explored (see Table 3). Fig. 3 provides an overview of the alternative production routes for green ammonia. These endeavours are driven by an objective of fulfilling both existing and prospective demands, such as those stemming from the maritime sector. These processes are still at a nascent level as they are undergoing development across various scales and efficiency gradients, with further details provided in Table 3.

2.4. *Ammonia as a shipping fuel*

Numerous studies have underscored the technical and infrastructural advantages of green ammonia over other alternative fuels for shipping [26,38,56,57,78,79]. Adaptability, abundance and convenient storage and transportation capabilities of green ammonia have drawn attention from industry stakeholders as a promising future fuel. However, the realization of green ammonia as a shipping fuel, aside from issues of competing demands, not only for its use, but also for renewable energy required to produce it, necessitates the development of ammonia combustion engines, fuel cells, and/or a hybrid propulsion system that includes both efficient onboard storage and bunkering systems at ports, as well as ensuring safety throughout the lifecycle of the fuel [79–81].

There is also an active exploration of its role as a carrier for hydrogen. A comparative study conducted by McKinlay, et al. [82] identified hydrogen as a potential maritime fuel, primarily due to the energy-intensive synthesis process required for producing methanol or ammonia. However, hydrogen's low volumetric density and storage temperature pose significant obstacles to its use [83] requiring large and highly pressurised storage tanks. Conversely, ammonia which consists of

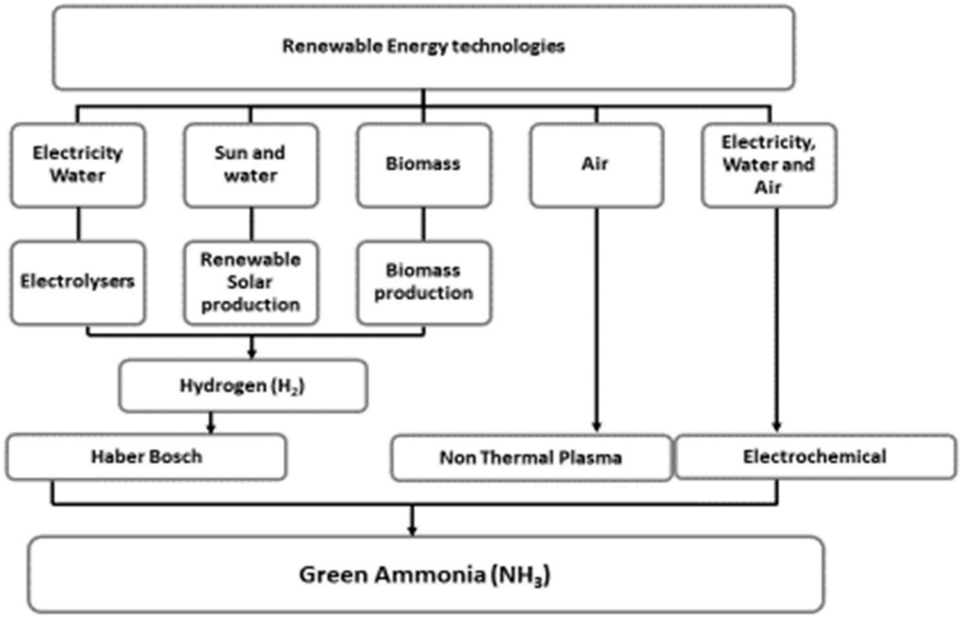

Fig. 3. Different production routes for green ammonia. Source: Laursen et al. [67].

Table 3
Description of different green ammonia production routes with their respective energy requirements and efficiencies.

Method	Process description	Energy Requirement (GJ/t of ammonia)	Efficiency (%)	References
Electrolysis	Renewable energy used to split water into hydrogen and oxygen using different electrolysers such as: (1) Solid Oxide Electrolyser Cell (SOEC), (2) Proton Exchange Membrane (PEM) electrolyser, (3) Alkaline Electrolyser.	SOEC – 24–27 PEM – 31–46 Other types of electrolysis technology – 20–60	54	Al-Aboosi et al. [26]; Laursen et al. [67], Rouwenhorst and Lefferts [69]
Renewable Solar Hydrogen	Solar power is also a prominent source of e-hydrogen known as photo-electrochemical (PEC) hydrogen. This is a water-splitting process that uses sunlight and semiconductor electrodes. The process uses photons to directly dissociate water molecules into hydrogen and oxygen.	200	9 (LHV)	Laursen et al. [67], Ozturk and Dincer [70], Sánchez et al. [71], Ahmed and Dincer [72]
Biomass hydrogen production	This uses thermal biomass gasification from woody biomass, supercritical water gasification from wet biomass (municipal solid/sewage waste) and dark fermentation which is the bioprocessing of microbial (bacteria), a part of the acidogenic step of an anaerobic digestion process (in the absence of oxygen) where a large spectrum of bacteria is decomposed and converted into hydrogen.	33	57	Laursen et al. [67], Detman et al. [73]
Non-thermal plasma process	The process is driven using plasmas that synthesise ammonia under low temperatures making it far less energy intensive than its conventional counterpart. This process operates at low temperatures of 50°C in atmospheric pressure.	50–150	12 – 37 (LHV)	Laursen et al. [67], Zhou et al. [74]
Electrochemical ammonia process	A voltage is applied to the electrode cell to release ions that pass through a separation membrane and an electrolyte to the electrode of opposite charge. The operational temperature range varies dependent on the electrochemical cells. There are three main operational ranges, low: <100°C, medium 100°C- 400°C and high 400°C – 750°C.	30–135	14–62 (LHV)	Laursen et al. [67], Garagounis et al. [75], Li et al. [76], Singh et al. [77]

over 18 % hydrogen by mass, does not need such high levels of pressurisation and is much simpler to transport and store [84]. As such, hydrogen's high flame speed and gravimetric density, crucial for optimal combustion, combined with the practicality of storing and transporting ammonia, position it as a viable hydrogen carrier [37].

Ammonia can be used as a fuel through various methods such as direct combustion, ammonia cracking (the conversion back to hydrogen), or ammonia blended with fuels like hydrogen, methane, or hydrocarbons to improve ammonia's flammability [65,85,86]. The low combustion rate of ammonia requires a catalyst, typically a fuel with a high flame speed like diesel or hydrogen, to ensure consistent and stable ignition [87]. While a limitation when combustion is concerned, its low flammability [38,55,66] is seen as an advantage in the context of the safety.

Other concerns associated with ammonia combustion include emissions of NO_x, a local air pollutant, the conversion of reactive nitrogen in air and water into N_2O, and ammonia leakage [88]. NO_x emissions can be higher from burning ammonia than conventional fossil fuels, and these lead to human respiratory irritation, tiredness and shortness of breath and wider ecological damage as a precursor to acid rain and deforestation. In the realm of diesel engines, NO_x emissions are commonly addressed through Selective Catalytic Reduction (SCR), a technology that effectively converts NO_x into N_2 at the tailpipe, and can achieve a 95 % reduction [66]. While SCR has abated NO_x concerns in industrial and road transport applications [56], it needs to be scalable for the maritime sector. Moreover, dual-fuel engine tests indicate that fuel blending (ammonia with gasoline) results in the same and/or increased level of NO_x production compared to single conventional fuels i.e., diesel and gasoline combustion [55].

N_2O is produced from ammonia combustion and is substantially more potent as a GHG compared to CO_2, with global warming potential (GWP) of 298 compared with a figure of 1 for CO_2 [89]. Production of N_2O will undermine ammonia's status as an appropriate alternative fuel that can minimise GHG emissions if it cannot be mitigated [48]. The specific rates of N_2O conversion from ammonia in marine applications lack comprehensive real-world data. Insights from a Life Cycle Assessment (LCA) conducted by Kanchiralla et al. [90] suggest that approximately 0.05–0.005 % of the nitrogen present in ammonia may convert into N_2O during combustion. If 0.4 % of the nitrogen in ammonia were to transform into N_2O, it could be sufficient to offset the GHG benefits associated with ammonia as an alternative fuel source [78]. Further research is therefore essential to quantify and understand the risks associated with ammonia combustion in ship engines [88].

Ammonia leakage or 'slip' onboard or when handling the fuel is hazardous to maritime workers as it is corrosive and cause severe burns to skin, eyes, and respiratory tract, including death if concentration levels are sufficiently high. It is also toxic to local marine environment if spilt [91]. As such, non-combustion options such as fuel cells are receiving attention. Fuel cells have the capability to power ships and provide energy for auxiliary activities whilst being emission free [92]. When considering ammonia as a fuel source, two types of fuel cells are commonly discussed: Solid Oxide Fuel Cell (SOFC) and Proton Exchange Membrane FC (PEMFC) [24,92–94]. The components used in SOFC make it durable enough to withstand the corrosive nature of ammonia, and its high operational temperatures contribute to its efficiency when using direct ammonia fuel [95]. However, the low power density of fuel cells limits its commercial deployment especially for larger vessels [38]. Additionally, in order to use ammonia in some fuel cell types, such as PEMFC, it must first be converted back into hydrogen [93,94]. Due to the higher cost and lower technology readiness level of SOFC compared to the commercial use and higher technological readiness of PEMFC, hydrogen is currently more likely to be used if fuel cell applications are being considered [96]. Consequently, research efforts have focused on the efficient use of hydrogen fuel cells [97–99]. Given the safety concerns regarding direct ammonia combustion, and potential for significant GHG emission reduction, fuel cells do offer an interesting avenue for further exploration [93,100–104] despite the trade-off between payload and performance currently presenting a barrier to development [105].

Within the context of the Paris Climate Agreement, it is essential that new fuels transitioned to are truly low carbon in the near as well as the longer term. This means transitioning away from using fossil fuels, not simply investing in 'alternative fuel ready' ships and avoiding fuel pathways that will be limited in terms of scaling. As such, this research looks to identify the key barriers and opportunities that can impact green ammonia's widespread adoption as a fuel with potential to deliver an appropriate emission reduction, and at scale, when compared with the currently dominant alternatives.

3. Methodology

Inspired by the iterative method proposed by Hoolohan et al. [106], the study continuously incorporates insights from participatory activities to enhance and refine project objectives. Fig. 4 provides a visual representation of the research methodology framework.

The focus on shipping here is part of a larger research project that specifically examines the feasibility of green ammonia as a fuel in both the aviation and shipping sectors. In the 'Stakeholder engagement' section, the inclusion of aviation stakeholders is discussed, emphasizing how their involvement influenced certain findings within this study.

3.1. Literature review

The literature review's aim is to gain an understanding of the current research landscape on the use of green ammonia in the shipping sector, and to identify gaps in the literature and determine the direction and focus of stakeholder engagement activities [107]. Literature is sourced using search phrases such as "green ammonia in shipping," "ammonia fuel," "ammonia production," "green ammonia fuel," "shipping transition," "ammonia in ICE," and "applications of ammonia." Articles that align with the study's title and abstract are examined, and references within those initial articles, as well as papers recommended in the "Recommended articles" section, contribute to the specificity of the literature review. Grey literature reports are also used to gain insights into the policy and industry landscape. The literature review intentionally seeks insights from diverse disciplines, spanning engineering to social science as the research question it aims to answer is interdisciplinary in its nature. Findings from the literature review are integrated into workshop and interview questions to ensure stakeholder engagement activities directly address and build upon the salient points identified in the literature. Additionally, data from the literature fed into part of the discussion to support findings from the primary data collection.

3.2. Stakeholder engagement

The primary data collection process is structured into two phases. The first involves a workshop with stakeholders from the shipping and ammonia supply chain. This workshop serves as a platform to gather initial perceptions and insights to address research questions around the on-ground realities of adopting green ammonia as a shipping fuel. The

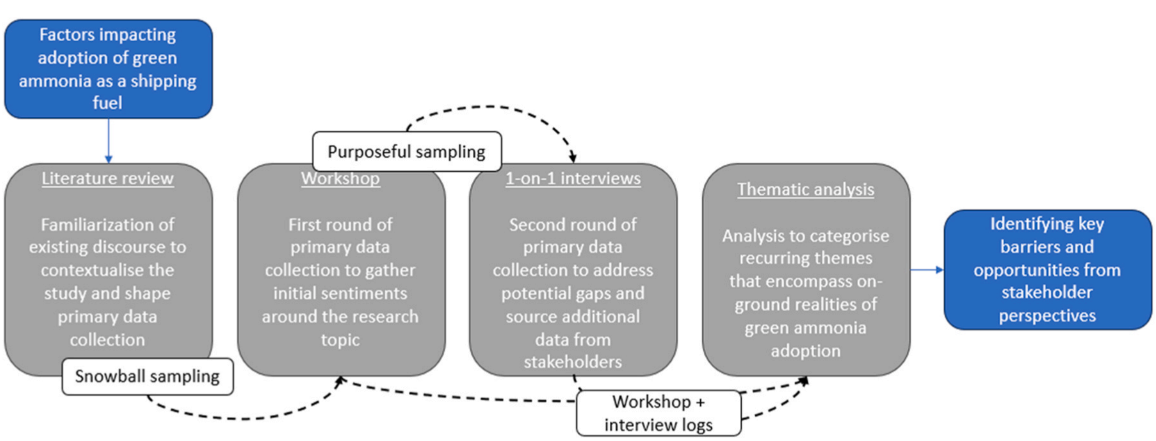

Fig. 4. Research methodology framework adapted from Hoolohan et al. [106].

second phase comprises of 1-to-1 semi-structured interviews with targeted stakeholders, for which questions were chosen based on the research gaps identified from the literature review and workshop.

In May 2022, a virtual workshop was conducted to gather expert perspectives from stakeholders within the shipping and ammonia fuel supply chain. To ensure a diverse range of participants, snowball sampling was employed to compile a list of experts [108] within the shipping supply chain and leveraging networks. The workshop was also promoted as an open event on Eventbrite to attract a wide range of stakeholders. While certain stakeholder groups are overrepresented due to their active involvement in the green ammonia or shipping sectors, breakout rooms were designed to create a balanced representation of perspectives. Participation followed the University's ethical compliance procedures.

The workshop has five sessions divided up into themes: economics, technology, operations, environment, and policy. Facilitators in each breakout room use the guide to ask and build on a set of pre-determined questions aligned with findings from the literature review. An example question from the session on technological factors is:

"What are the technological hindrances and opportunities in the applicability of green ammonia in shipping?

Probes:

a) *To what extent does on-board technology have to change to accommodate this fuel?*
b) *Does the current status of technological development enable this transition?*
c) *What are the current onboard safety concerns of using green ammonia (or green ammonia as a hydrogen carrier)?"*

To encourage natural discussions and ensure diverse perspectives, participants are placed in breakout rooms with individuals from different stakeholder groups. Due to dropouts among the registrants, there is a mix of aviation and shipping stakeholders in the last two sessions. Valuable feedback from aviation stakeholders influenced the findings related to the production, economics, and policy aspects of ammonia as both sectors share similar concerns around the upstream supply chain.

From July to November of 2022, in-depth, semi-structured interviews were conducted. These interviews delve deeper into the gaps and additional questions that emerged from the workshop and literature review. Purposeful sampling is employed to identify interview participants, ensuring a targeted approach that captures first hand perspectives and experiences [109]. The preliminary stakeholder list developed for the workshop served as the foundation for building the interview list. Participants whose experience aligned with the project objectives had follow-up interviews, allowing for a more in-depth exploration of their initial perspectives shared during the workshop.

The principles of in-depth semi-structured interviews are well-suited for this project, as they facilitate a conversational approach to understanding the stakeholder decision-making process [110,111]. This approach encourages both the interviewer and interviewee to approach the topic from various angles. The interview guide is tailored to each interviewee's expertise, formulated based on questions and gaps identified from the workshop transcript. For instance, an example question posed to a port manager was, *"What are the on-ground safety risks associated with green ammonia and/or hydrogen?"* while a question directed to a regulatory authority might be, *"What work is being undertaken to set up certification for novel fuels?"* The semi-structured nature of the interviews provide flexibility for both the interviewer and interviewee to explore sub-topics and deviate from the script when necessary [111].

Due to the international nature of the shipping sector and the need to engage with stakeholders from various locations, all interviews were conducted online. The study initially aimed to conduct 12 interviews based on the current sampling hypothesis, which suggests that saturation can be reached after 9–17 interviews [112]. With this objective in mind, initial communication targeted 43 stakeholders, assuming a response rate of 30–50 %. Ultimately, 15 interviews were conducted, encompassing both aviation and shipping stakeholders. In combination with the workshop, 27 stakeholders participated in the study, with 16 of them representing the shipping sector specifically. The participants spanned a wide range of roles, including operational equipment manufacturers (OEMs), policymakers, researchers, academics, investors, mariners, fuel producers, NGOs and port managers.

3.3. Limitations

The workshop was organized with the intention of attracting a wide range of stakeholders to gather diverse perspectives on the topic. Although 36 people registered for the event, only 12 were able to attend on the day. This limited the number and variety of responses that could be obtained, leading to a reconfiguration of the breakout rooms during the workshop. The recruitment process for 1-to-1 interviews was more systematic, resulting in different response rates from various stakeholder groups. Due to the project's time constraints, the interviews were conducted within a specific period, which, coupled with the period being impacted by COVID-19, made it challenging to reach certain stakeholder groups.

3.4. Data analysis

The responses collected from both the workshop and the interviews are transcribed using the Descript software. Thematic analysis is employed to understand perspectives, identify recurring themes, and organize the rich data [19,113–115]. The 6-phase theory-led thematic analysis is applied to the primary data. The approach used in this study is top-down as the coding process was influenced by the research question at hand i.e. to identify the barriers and opportunities. However, the analysis also aimed to identify data-driven recurring themes [116]. The responses are interpreted contextually, meaning that each stakeholder's response was analysed separately but also in relation with the wider conversation to explore the reasoning behind the responses [117]. Each transcription is reviewed, and categorised based on stakeholder type, sector, and the corresponding key finding. Key findings are divided by barriers and opportunities and further coded under recurring themes that resulted from the interviews and workshop.

4. Results and discussion

This section presents key findings and discussion based on thematic analysis. Drawing on semi-structured interviews and workshops, insights point to three recurring themes: 1) Uncertainty around being the first mover, 2) Infrastructure and safety, 3) Economics of shipping transition (see Table 4).

Responses suggest that there is agreement that shipping sector suffers from uncertainties around the future of its transition. These appear to have a domino effect on other barriers such a lack of investment due to unfamiliarity with technology and a divergent view on perceptions around safety. It was evident in the workshop and interviews that the potential risks associated with increased NO_x and N_2O emissions and shipping accidents serve as cautionary factors that may dissuade stakeholders within the sector from embracing ammonia over other alternative fuels. For these reasons, and despite the proven technical feasibility of using ammonia in combustion engines, the shipping industry remains divided as evidenced here and in literature [48,88,118]. However, there were participants in the workshop and interviews who expressed optimism, specifically highlighting the extensive knowledge around safety already in place due to the global shipping of ammonia and its prominent use in the agricultural sector. Economic factors range from incentives, derisking technology, and cost comparison between alternative and conventional fuels. Stakeholders pointed out that the underlying reason for this is the lack of demand signals which are

Table 4
Key barriers and opportunities for the adoption of green ammonia as shipping fuel and illustrative quotes.

Theme	Barriers	Opportunities	Selected quotes
Uncertainty around being the first mover	Shipping will likely try to latch on to existing decarbonisation strategies around ammonia (as a subset of a hydrogen economy) as it is unlikely to drive this. Rate of fleet renewal is slow and discouraging for engine manufacturers to produce engines that can only combust ‘green’ fuels – engines should be compatible with fuels in the market now. Shipping stakeholders may not want to invest in technology or scenarios that are unproven/too far in the timeline. Industry is waiting because cost of initiation is high - there is anxiety about being the first mover.	Ammonia is the most competitive deep sea shipping fuel, and it also has opportunities as a hydrogen carrier.	“It is just a question of knowing if this investment is what’s going to corner the market and it’s this prisoner’s dilemma sort of thing that nobody necessarily wants to go first.” “I doubt very much whether the shipping industry or the maritime industry on its own is going to become the global leader that drives a hydrogen economy. That’s a big ask for an industry like this.” “[…] fleet renewal is not high enough to motivate or to achieve [Paris Agreement] goals.” “We estimate that the [ammonia] market will be about 220 billion in 2050. Shipping is definitely, one of the big takers of ammonia going forward.” “…for a good part of the first half of my interaction with shipping, there was a denial that shipping needed to do anything, partly because it was a special case because it facilitated global supply chains.” “Everybody knew that something was going to happen sometime, but the shipowners would say, well, we are not going to shed loads of money for technology we don’t know anything about and nobody’s sure what’s going to be the wrong. So, there’s very much a sense of understanding the issues and playing that waiting game.” “The people have to see the investment opportunity in the timescale where they can where they can make the money. And I think we need to bear in mind that shipping doesn’t often do things just for itself.” “I think with hydrogen, I can kind of see ammonia as a subset of that. But shipping isn’t going to pay for the development of its own fuel. It’s never really done that before.”
Safety and Infrastructure	There is a difference between carrying a fuel as cargo versus using it as a fuel. There are additional safety implications if ammonia is being combusted. As ammonia is poisonous and toxic certain players within the shipping sector are unsure about current regulation around its suitability as a fuel, compared to other marine fuels on the market such as methanol. Reliable bunkering infrastructure is vital as it could dictate whether ammonia-fuelled ships can operate. Onboard infrastructure will drastically change especially in terms of tank size when compared with diesel. Efficient Selective Catalytic Reduction (SCR) needed onboard to ensure reduction of N_2O and NO_x emissions. Training and skills required in both handling ammonia as a cargo versus as a fuel.	Ammonia fuelled ships are commercially and technically possible as engine design is sufficiently modular to operate a ship under current conditions. Regulation around safety can be addressed as ammonia is produced and used in large quantities already.	“I’m sure things like the safety issues with ammonia and its storage problems can be solved. It is produced and used in large quantities […] so you must be able to solve these problems.” “There’s this idea that because it’s traded as fertilizer that we know how to handle it, but there’s a huge difference between something being in the engines of ships that are moving around and something being in a double-hull tank.” “One thing is clear to me is that bunkering could be a very sensitive issue because you got to store the ammonia in the port, and you’ve got to have a very reliable system of bunkering that works for all different sorts of ships coming in.” “It just seems to me like combustion is just not a way forward. If you combust in air, you’re always going to have nitrous oxide no matter how clever your combustion process. We need to liberate the energy from the energy carrier. And we can do that through fuel cells.” “…some of the big [industry] players are saying there are regulation issues with ammonia, that aren’t where for example, methanol and until these regulation issues are sorted out because it is highly poisonous and toxic, the industry might very well be reluctant to invest in it heavily.” “There are still a lot of safety issues that we need to kind of figure out. And there are some, of course, other issues but there’s an existing value chain.”
Economics of shipping transitions	While conceptually engine design does not have to change much; if combusting NH_3 produces N_2O and NO_x it makes an unmarketable product. Investors will be cautious of “floating assets” as opposed to land-based infrastructure. A bunker levy or tax should be put in place on conventional marine fuels as there is not enough of an incentive to move away from it.	Initial investment needed to derisk technology and regulatory uncertainties to prove that ammonia can function in a marine setting. Corporations can potentially dictate fuel transition through investment decisions. Current costing approaches of conventional fuels do not include externalities to calculate the “true	“You need some investment to get over some of the technological and regulatory problems and learn about some of these technologies in a marine environment where it isn’t directly translatable from small scale on trucks or something like that, or even land-based scale.” “But there’s a whole load of stuff that goes on into that the true upstream costs and not just sort of

(*continued on next page*)

Table 4 (*continued*)

Theme	Barriers	Opportunities	Selected quotes
	Scaling up green ammonia is currently an issue as cost of setting up wider infrastructure is expensive. Fuel flexibility in an engine is important at a time when geopolitics can trigger shortages of fuel in different geographical contexts.	cost". If included, then alternative fuels can be considered relatively more attractive options.	industrial costs, but the environmental costs of that […] If we put all those in, I think the green options will not appear like the kind of unpleasant, expensive pill that we all have to take for the greater good. It makes a lot more sense to be doing it this way economically as well." "So as soon as you start having to run a dual [engine] system, presumably it means you need insulation, special systems, and valves and what have you. That adds significantly to the cost and complication in the system compared to a conventional fossil fuel ship." "[…] setting up a large-scale green ammonia industry is a big issue because it's going to cost a lot of money and there is no there's no market incentive at the moment." "You need an expectation in the industry that we're going to move away from fossil fuels at some point in the not necessarily the short term, but definitely the medium to long term. And that's because all this [transition] is really expensive compared to conventional power systems. So, you've got to have a phase of getting more demonstrators into them showing that the technology works, and safety issues and the regulatory issues are dealt with so the cost can start to come down." "There's a lot of interest, but when it comes to actually putting the money down… I'm not certain."

necessary to lessen existing investment risks around fuels and offshore infrastructure. The sub-sections below delve deeper into the identified themes.

4.1. Uncertainty around being the first mover

Despite technological options available and viable for the shipping sector, there are no clear trends in terms of a significant number of first movers, especially amongst larger vessel segments, that are exploring a combination of alternative fuels and/or unconventional propulsion technologies (see Fig. 1.) The modular design of the ship engine has enabled OEMs to convert older configurations to make vessels alternative fuel 'ready', however this does not guarantee its use. An OEM stakeholder explained,

> "The engines being produced, let's say the last ten years, are retrofittable. Meaning providing that there's a business case, then they are sufficiently modular in the design and construction so that you can convert them into an ammonia fuelled engine".

Another hurdle to alternative fuel adoption has to do with lack of investments,

> "We are sensing that traditional finance sources are still more comfortable with land-based infrastructure as opposed to say a ship which is a floating asset. There are various risks involved as your asset is always moving, as well as complexity in ownership of shipping structures", insinuating that these factors make it difficult to attract necessary investment.

Further difficulties including unproven technology applications in shipping like fuel cells and scrubbers are a gamble for investors, which makes it difficult to become first movers as the "*cost of initiation is high*" as one stakeholder framed it.

Stakeholder views coupled with quantitative data (Fig. 2) strongly suggests that not only does planned fleet renewal fall significantly short of the requirements necessary to achieve the goals outlined in the Paris Agreement, but uncertainty around being first movers is negatively impacting on meeting decarbonisation targets.

4.2. Infrastructure and safety

Stakeholder inputs underscore the critical need to adapt and expand existing infrastructure, which is presently designed for a conventionally fuelled shipping sector. Sub-themes around safety and infrastructure encompass bunkering, storage, handling, and the by-products of ammonia combustion.

While ports remain open to exploring different options, a representative of an OEM highlighted the current homogeneity of the shipping sector,

> "So, when people talk about a multi-fuel future, it is in contrast to the picture you have today where overall there is one fuel. Yes, there are a few ships fuelled by methanol, LNG, and LPG but it is a single-fuel world right now."

Another stakeholder from the maritime industry shared findings from a hydrogen and ammonia conference they attended stating that,

> "There were actually a few people who really know what they are talking about who said that we [attendees] believe that maybe there is going to be a mix at the beginning, but they believe that there will be one fuel for all ships in the future".

Additionally, for demand to materialize, setting up the appropriate infrastructure at ports is crucial [45]. Safety regulations concerning fuels like ammonia and hydrogen during refuelling, bunkering and accommodating port energy usage for storage of cryogenic fuels, can all significantly impact their adoption as stated by stakeholders (see Table 4).

Although combustion of ammonia, while reducing CO_2 emissions when compared with MDO, is likely to contribute to other non-CO_2 emissions from shipping [78], the issue more evident in the minds of stakeholders relates to safety, given the absence of regulations around handling ammonia onboard as a fuel,

> "…some of the big players are saying there are regulation issues with ammonia, that there aren't with for example, methanol, and until these regulation issues are sorted out because it is highly poisonous

and toxic, the industry might very well be reluctant to invest in it heavily."

Finally, in most combustion scenarios, even if safety concerns are addressed, it will be difficult to completely mitigate N_2O emissions. In light of this, fuel cell development and its viability for use the shipping sector could be important to justify a transition to ammonia. Yet fuel cell technology suitable for large ships faces low readiness levels, limited investment and the need to address the trade-off between payload and performance [105].

The existing infrastructure will remain a significant challenge as it is deeply rooted in traditional fuel sources. The shipping sector's historical reliance on one, well understood and well regulated dominant fuel, derived from petroleum and natural gas, underscores the mismatch between the uniformity of maritime infrastructure versus changes needed in the case of any multi-fuel future, and particularly in the case of a fuel with the safety concerns ammonia has.

4.3. The economics of shipping transition

Conversations around economic factors in this study highlight the current economic risks around transitioning to low and zero-carbon technologies. Primarily flagging the impetus for flexi-fuel and dual-fuel engines to run on fossil fuels without needing to use low-carbon, zero-carbon fuels i.e., alternative fuel *ready*.

From an engineering standpoint, flexi-fuel/dual-fuel engines make business sense as the shipping sector is expected to transition. As shown by previous findings in Section 4b, slow portside infrastructural change coupled with uncertainties around future alternative fuels has created an optimal market for dual-fuel engines. The presence of dual-fuel engines for ships is an economic decision for OEMs. Arguably larger OEMs – even the few who dominate the ship engine manufacturing market, are not ready to risk developing single-fuel engines when there are geographic constraints on specific fuel availability. In this economic landscape, a single (alternative) fuel engine is an unmarketable product:

> "We have to be able to be flexible enough to use a fuel that is available at the right cost, the right emission levels and the right efficiency in a changing world. When the gas prices went through the roof, suddenly many gas users started to use diesel as a fuel. So, flexibility is the important thing", explained an engine manufacturer. Likewise, a second OEM stakeholder stated:

> "If you want to burn methanol, then you buy the dual-fuel methanol engine, which can run conventional fuels or green methanol. Similarly, you'll be able to run an ammonia engine with conventional fuels and ammonia. I don't think that [single-fuel engines] is economically feasible in with how things look now".

At the time of the study, ongoing external factors (separate from normal market forces) such as COVID-19 and the Russian invasion of Ukraine inevitably influenced responses. Manufacturers' internal projections suggests that ship owners are unwilling to buy from them if they *only* sold single-fuel engines, as the market is unlikely to shift in that direction. Manufacturers who participated in this study believe that ships will always have multi-fuel options, risking the continued use of conventional fuels. The oligopolistic nature of ship engine manufacturing market means that the top 10 OEMs such as MAN engines, Wartsila, Rolls-Royce plc, Hyundai Heavy Industries Co. amongst others are majority shareholders of the global market, forcing the rest of the shipping sector to be reliant on this top-down structure. To a certain extent, while they rely on demand signals and policy direction, they have an influence in dictating the pace of transition, because competition is relatively low.

Further analysis suggests that the transition of the shipping supply chain can challenge current lived-in business models. For example – development of fuel cells and their application might be viable in theory, however in practice the ship engine manufacturing sector cannot risk changing their selling structure solely based on the low- to zero-emission nature of the technology.

> "While technically you can operate and run a ship on a combination of fuel cells, batteries and ICE, lived-in infrastructure is very hard to uproot "

The sector in general, and more specifically stakeholders such as manufacturers, will always be reactive to fuel price, unless there are mechanisms that have greater influence, such as a very high carbon price or a strict regulation on carbon intensity. Innovation and implementation of new technologies can perhaps only be initiated when conventional fuel prices reach a point where alternative fuels become the more economically feasible at scale. The latter is only likely possible after the development of a wider alternative fuel network and supporting infrastructure, supported by a meaningful price placed on carbon or similarly strong regulatory approach.

Stakeholders are finding it difficult to move away from convenience of the current economic structure and navigate the complex interdependencies within the fuel supply chain, which is a major barrier to rapid and radical change needed for the shipping sector to align with Paris Agreement goals.

5. Conclusion

This paper explores the potential of green ammonia as an alternative fuel option for shipping. Green ammonia is considered to show promise based on the shipping industry's experience of storing and transporting ammonia for the global fertiliser industry and recent moves to incorporate dual-fuel engines into the fleet. However, the findings draw attention to a wide range of factors that challenge both its viability and its adoption as a truly 'green' option, at least within Paris-compliant timeframes.

To effectively align with the Paris Agreement's goal of limiting global warming to 1.5°C by 2050, the international shipping sector must overcome challenges around being first movers in order to transition into using alternative low-carbon fuels. While the current 'exploratory phase' that the sector is in may offer benefits such as stimulating technological innovation, it can create obstacles as the sector faces increasingly shorter timelines to meet the 1.5°C target, with little deployment of relevant supply-side infrastructure. As the transition timeframe diminishes, the costs of compliance are anticipated to escalate, which will be further compounded by the numerous technological and operational barriers associated with adopting new fuels.

There continues to be uncertainty surrounding the release of the potent GHG N_2O from ammonia combustion if used widely in real world conditions, leading to questions around its green credentials. However, it is ammonia's significant toxicity that leads stakeholders to highlight the importance of implementing new safety regulations to properly protect mariners and the marine environment. With an absence of clear policy drivers, coupled with competing demand for green ammonia and hydrogen from other sectors, stakeholders also perceive a range of economic risks impeding its adoption. This in turn feeds into the slow build-up of supply chain infrastructure required to mitigate midstream and downstream factors, particularly port storage, handling, and transportation, as well as a reticence to invest in specifically designed alternative fuelled ships. Although some are being built or retrofitted with dual-fuel engines to be 'alternative fuel ready', there is no sign currently of a shift to the use of lower-carbon alternatives at any meaningful scale, and at worst this could serve to delay the transition, increasing rather than mitigating the sector's climate contribution. With time of the essence, effective policymaking that can overcome the barriers highlighted must therefore consider all elements in the supply chain simultaneously.

Finally, it is important to note that many of the barriers highlighted for green ammonia adoption in shipping are also likely to be faced when adopting other alternative fuels. Particularly if those fuels are more energy and/or resource intensive to produce and in turn more costly to produce, store and transport. This is not to mention if they are also sought after by other sectors – something that the shipping industry has not previously had to consider. These findings therefore point towards a need for the industry to focus other emission mitigation measures in parallel, that can reduce the sector's overall reliance on liquid fuel. Options including slow steaming, wind-propulsion with route optimisation and the plethora of ship efficiency improvements already available, can all curb fuel use, and help to reduce financial risk. And importantly, unlike the fuel options available today, they have a greater chance of realizing near-term emission cuts aligned with the IMO's 2030 and 2040 'strive' targets.

Declaration of generative AI in scientific writing

During the preparation of this work the author(s) used Writewise in order to help with grammar and sentence structures and conduct a plagiarism check. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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CRediT authorship contribution statement

Abhilasha Fullonton: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Amanda R. Lea-Langton:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition. **Fatima Madugu:** Writing – original draft, Visualization, Data curation. **Alice Larkin:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Funding acquisition.

Declaration of Competing Interest

There was no conflict of Interest.

Data Availability

Data will be made available on request.

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