

When is a stepping stone a dead-end? Insights into ‘stepping stone’ pathways from the maritime shipping transition

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Abstract

Sustainability transitions are urgent, but it is not always clear which pathways can lead to sustainable outcomes. Some apparent clean solutions are ‘dead-ends’ – pathways that show initial promise but that cannot deliver sufficient sustainability outcomes. Others are offered by advocates as ‘stepping stones’ or ‘bridges’, which are acknowledged not to be long-term solutions but which facilitate a subsequent transition to a long-term sustainable outcome.

We develop and apply an analytic framework for thinking about stepping stone pathways. We explore four types of complementary resources that are created by stepping stone pathways and that facilitate the subsequent emergence of a sustainable system. These are: material and financial resources; technological knowledge and capabilities; institutions; and expectations and narratives.

We apply our framework to the context of maritime shipping. Decision-makers in the global maritime shipping industry are currently grappling with pathway choices. While LNG and methanol ships offer initial promise, techno-economic analysis suggests that they are unlikely to deliver sufficiently deep carbon savings. We assess the extent to which LNG and methanol investments provide a stepping stone to a long-term ammonia fuel pathway. We find that neither offer direct stepping stones. LNG has the potential to provide a stepping stone pathway, but only if more-stringent policies drive the uptake of truly ‘ammonia ready’ LNG infrastructure.

Keywords: stepping stone pathways; dead end pathways; sustainability transitions; maritime shipping; multi-system interaction

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1 Introduction

Energy and transport systems must undergo radical transformation to prevent the worst consequences of climate change. However, there remains considerable uncertainty about the pathways by which socio-technical systems can achieve that transformation. Some apparent clean solutions are ‘dead-ends’ (Rosenbloom et al. 2025). Others are offered by advocates as ‘stepping stones’ or ‘bridges’, which are acknowledged not to be long-term solutions but which are nevertheless promoted as contributing to a feasible path to sustainability.

Recent scholarship has sought to identify “dead-end pathways” (Rosenbloom et al. 2025). In this article, we focus on “stepping stone” pathways. We define stepping stones as options that in the long term are themselves unsustainable, but which can provide a route to long-term deep decarbonisation while reducing emissions in the near term.

There are many papers suggesting that near-term technologies are “stepping stones” or “bridges” to more sustainable long-term outcomes. Examples include hydrogen in gas networks (Quarton & Samsatli, 2020), CCS-enabled coal (Haeseldonckx & D’Haeseleer, 2010), combined heat and power (Kim et al., 2019) and natural gas (Gillissen et al., 2019; Levi, 2013; McGlade et al., 2018). None of this previous work provides a clear conceptualisation of stepping stones or develops a framework that assesses the ways in which near-term investments can enable or prevent other long-term pathways.

The aim of the paper is to develop and apply an analytic framework for thinking about stepping stone pathways. In developing our analysis, we focus on a specific case: the global maritime shipping sector. Shipping is a growing share of global emissions, and investors, ship owners and policymakers confront a range of possible pathways, notably LNG, methanol and ammonia. Our research question is: *Are LNG and methanol stepping stones to ammonia in the global maritime shipping sector?*

2 Background: dead-end pathway risks in the maritime shipping transition

In their analysis of dead-end pathways, Rosenbloom et al. (2025) highlight three dimensions against which prospective pathways can be evaluated: their breadth (scalability), depth (whether they reduce emissions enough); and timeliness (whether they can deliver emissions reductions in a relevant timescale). Pathways that fail to meet these criteria can be judged to have high risk of becoming ‘dead-ends’.

Multiple pathways for decarbonisation in maritime shipping have been suggested. Incremental efficiency solutions—such as wind assist, slow steaming and hull lubrication—are insufficient to achieve the radical emissions reductions required to avoid the worst of climate change (Bouman et al., 2017; Rehmatulla et al., 2017). Both nuclear power and onboard carbon capture have been proposed for shipping, but both are currently deeply uncertain. In this paper we focus on scalable zero or near-zero emission fuels, for which evidence is currently stronger (Smith et al. 2023; Balcombe et al., 2019; Lindstad et al., 2021) and which are the focus of industry investment trends (Leitão et al. 2024). While techno-economic analysis is clear that ammonia is the most attractive long-term option (Schreuder et al., 2025; Velandia Perico et al.

2023; Lloyd's Register and Umas 2020), there are also advocates of LNG and methanol, both of which have been presented as stepping stones. In this section, we summarise the evidence on the dead-end risks associated with each pathway.

2.1 Liquefied Natural Gas (LNG) and Methanol

LNG and methanol are broadly similar – both are potentially lower-emission fuels that are currently derived from fossil sources. Fossil methanol has slightly higher well-to-wake emissions than conventional fuel oil, whereas fossil LNG can have lower emissions and thus offer near-term reductions (Englert et al. 2021). In both cases, advocates suggest that fossil feedstocks could be replaced with bio-LNG/bio-methanol, and eventually e-fuels (i.e. synthesised using captured CO₂ and hydrogen produced via electrolysis using renewable electricity) (Balcombe et al 2019; Lindstad et al., 2020)).

However, both LNG and Methanol face considerable dead-end risks, driven by structural constraints: limited sustainable bioenergy and the mitigation limits of fossil-based fuels. Sustainable biomass resources are constrained by multiple factors such as land, biodiversity and cross-sectoral demand, resulting in scalability limits (Creutzig et al., 2015). For e-methanol/e-methane, deep decarbonisation requires large volumes of low-cost renewable electricity for hydrogen and a sustained supply of low-carbon CO₂ (e.g., biogenic CO₂ or direct air capture). This adds additional material, energy and cost burdens (Brynnolf et al., 2018; Keith et al., 2018).

Alternatively, LNG/methanol could be used alongside carbon capture. However, shipboard capture studies highlight substantial energy/space penalties and high costs relative to switching to genuinely zero-carbon fuels (Luo & Wang, 2017; Feenstra et al., 2019). These constraints are compounded for LNG by methane slip (Bengtsson et al., 2011), which can erode lifecycle climate benefits (Kuittinen et al., 2024).

2.2 Ammonia

Green ammonia production relies on air-derived nitrogen and renewable hydrogen which does not depend on biomass availability or CO₂ sourcing (Machaj et al., 2022; Al-Aboosi & El-Halwagi, 2021). Importantly, like the other two major candidates (LNG and methanol) retrofits of existing ships to ammonia are possible. This means an ammonia transition does not require investments in an entire new fleet.

There are significant barriers to the adoption of ammonia in the near term. One major barrier relates to the toxicity of ammonia, and there is considerable need for learning about how ammonia can be managed safely (Cames et al. 2021; Kyung-Tae et al., 2023). There is a related lack of regulatory clarity, which inhibits investment since ammonia-related risks and potential liabilities cannot be priced effectively. However, provided these safety risks can be overcome, current evidence around scalability and techno-economic viability suggest that ammonia has the lowest dead-end risks of the major decarbonisation options.

Table 1. Comparative characteristics of selected transitional marine fuels (ammonia, LNG and methanol)

Criterion	Ammonia (NH ₃)	Liquefied Natural Gas (LNG)	Methanol (CH ₃ OH)
Energy density / storage volume requirement	Low volumetric energy density ; requires larger tanks than conventional oil fuels (e.g., WinGD reports ~ 2.8× relative volume per unit energy vs marine gas oil under the stated conditions).	Higher gravimetric energy density than liquid alcohols/ammonia, but lower volumetric energy density than oil fuels ; LNG properties vary by composition (WinGD examples show ~ 21.0–23.0 GJ/m³ liquid LNG in tank conditions).	Low volumetric energy density ; requires larger tanks than conventional oil fuels (WinGD reports ~ 2.5× relative volume per unit energy vs marine gas oil; MCA guidance also notes roughly ~ 2× tank capacity vs diesel in practice).
Hazard profile	High toxicity is the dominant safety concern; also corrosive. Additional safety systems (e.g., cofferdams, inerting, monitoring) are typically required.	Cryogenic and flammable gas ; key risks include low-temperature handling, gas leakage/fire/explosion hazards, and hazardous-zone management.	Toxic, low-flashpoint and corrosive ; requires enhanced safety systems (including cofferdams and inerting) and careful handling.
Storage temperature / pressure	Can be stored as a liquid at approximately –33°C at atmospheric pressure , or in pressurised tanks.	Stored at cryogenic temperatures (~–163°C) .	Liquid at ambient temperature and pressure (no cryogenic storage required).
Carbon emissions implications (TTW vs WTW)	No carbon in the molecule (i.e., no direct CO ₂ from fuel carbon at combustion), but overall GHG performance depends on production pathway and engine-side control of pollutants (including potential N₂O formation/slip).	May reduce CO ₂ emissions relative to oil fuels in some applications, but actual GHG benefit is highly system- and engine-dependent ; methane slip and boil-off/operational factors can materially reduce or negate benefits.	Strongly pathway-dependent : renewable/low-carbon methanol can reduce lifecycle emissions, but fossil-derived methanol (especially grey/brown methanol) may deliver poor WTW performance and can even exceed fossil diesel on a WTW basis.
Technical maturity (shipping use)	Emerging / early-commercial . Regulatory pathways exist (interim guidance + risk-based approval), but standards and operational practice are still developing.	Most mature of the three in maritime applications; established engine options and mature regulatory/classification frameworks exist.	Commercially deployed and scaling , but regulatory treatment still relies on interim IMO guidance in many cases pending fuller code integration.
Needs pilot fuel? (current two-stroke dual-fuel engines)	Yes (typically) in current dual-fuel diesel-cycle concepts; e.g., WinGD documentation indicates pilot fuel use and reports ~ 5% at 100% load (engine concept-dependent).	Engine-dependent, but generally yes for mainstream two-stroke dual-fuel designs (e.g., WinGD X-DF uses a small diesel pilot; ABS summarises approximate pilot fractions for major engine concepts).	Yes (typically) for current dual-fuel two-stroke concepts; MAN reports pilot oil use for ME-LGIM and notes pilot oil can be up to 5% of MCR fuel consumption in diesel-oil mode.

Source: Compiled by the author from MCA (2025a, 2025b), WinGD (2024; n.d.), ABS (2020), and MAN Energy Solutions (n.d.).

2.3 Stepping stones?

Given doubts about the long-term roles for LNG and methanol, and challenges to near-term investments in ammonia, the industry has increasingly emphasised that investments into fossil-based LNG and methanol are interim steps to either zero emissions LNG/methanol, or to ammonia. For the latter, advocates have highlighted the idea of “ammonia ready” ships as a bridging mechanism. Theoretically, this allows vessels fueled by LNG or Methanol to be retrofitted.

The question of this paper is: Do the current investments in LNG and Methanol help close these specific gaps (toxicity regulations and safety protocols, ammonia-ready infrastructure), or do they merely stabilize a fossil-based socio-technical system thus further postponing ammonia?

3 Theoretical background and conceptual framework

3.1 Characterising stepping stones

In developing the idea of stepping stones, we build directly on Rosenbloom et al.’s work on ‘dead-end pathways’ (Meadowcroft & Rosenbloom, 2023; Rosenbloom et al., 2025). We follow them both in conceptualising pathways as complex “*sequences of change across multiple social and technological dimensions*”, and in focusing on the ‘anchor technologies’ that lie at the heart of pathways. They describe dead-ends as pathways that “show initial promise” but that ultimately cannot deliver the deep environmental improvements required for ‘net zero compatible’ (or sustainable) pathways, because of weaknesses in ‘depth’, ‘breadth’ and ‘timeliness’.

Stepping stones are socio-technical systems that, like dead ends, “show initial promise” but that cannot be the anchor technology of a sustainable pathway because they fall short on the ‘depth’ or ‘breadth’ of emissions reduction potential. What distinguishes a stepping stone from a dead end is that stepping stones build capacity—such as adaptable infrastructure or transferrable skills—that facilitate a later shift to a sustainable long-term solution. In contrast, a dead end acts as a trap. While it may offer short-term emission reductions, it deepens reliance on fossil-based architectures and creates stranded assets—investments that lose their economic value prematurely because they cannot be repurposed for the final decarbonised regime. (Rosenbloom et al., 2025).

A key issue in discussions of stepping stones is sequencing and maturity. Stepping stones are available now, in comparison to longer-term, more sustainable options that are not yet able to scale up sufficiently quickly, because of technological immaturity, regulatory uncertainty, or other factors. While they lack ‘depth’ and ‘breadth’, stepping stones benefit from ‘timeliness’:

they enable progress in the near-term, while preserving the pathway to a follower anchor technology and ultimately a sustainable socio-technical system.

The development, diffusion and social embedding of a new anchor technology creates path-dependencies, potentially delaying the transition to a more sustainable system. At the same time, establishment of a stepping stone technology creates system resources that are then available for the follower option, enabling the subsequent transition to the sustainable outcomes. Judging whether an emerging option is a dead end or a stepping stone requires thinking through whether the forces of lock-in are likely to be more or less powerful than the creation of those resources that enable a sustainable transition.

In order to structure our analysis of stepping stones, we draw on the Technological Innovation Systems (TIS) framework (Bergek et al., 2008; Hekkert et al., 2007), and the related literature on complementarities between emerging technological systems (Markard & Hoffmann, 2016; Sandén & Hillman, 2011). By focusing on key innovation system processes such as knowledge development, resource mobilisation and legitimation, the TIS approach provides the core conceptual tools for examining competitive (e.g., capital diversion and lock-in) and complementary (e.g., shared regulatory learning) interactions among different systems. An emerging TIS, like that for ammonia, does not develop in a vacuum but interacts not only with existing regime but also with other emerging TISs such as methanol and LNG.

Most existing studies on inter-system interaction (Andersen & Geels, 2023; Andersen & Markard, 2024; Markard & Hoffmann, 2016) have focused on the way that emerging innovation systems make use of, or compete for, complementary assets associated with other (often mature) technological systems. Here, we explore likely complementarities or competitive dynamics between different emerging pathways that fulfil the same core function but that are built around different core technological systems, in order to assess the extent to which one emerging *stepping stone TIS* (LNG, methanol) creates resources that facilitate the emergence of a subsequent *sustainable follower TIS* (ammonia). This is similar to the intent behind Lin and Sovacool's (2020) discussion of 'inter-niche competition'.

3.2 Dimensions of complementarity/competition

We draw previous work on multi-system interactions (Andersen & Geels, 2023; Markard & Hoffmann, 2016; Sandén & Hillman, 2011) to highlight four core dimensions through which one system influences the potential emergence of another: material and financial resources, technological knowledge and capabilities, institutional alignment, and through expectations and narratives.

First, following Sanden and Hillman, we highlight the importance of the *material* dimension of TIS development. While others (e.g. (Binz & Truffer, 2017; Hekkert et al., 2007)) have emphasised financial resources and resource mobilisation, Sanden and Hillman's framework highlights the importance of such resources as embodied in long-lived physical assets and infrastructure, not only in the form of mobile financial resources. An emerging technological innovation system is a "stepping stone TIS" when its development creates physical assets and infrastructures established that can be directly used by, or easily repurposed for, a subsequent sustainable option (a "sustainable follower TIS"). Assets that cannot be re-used are at best unhelpful for the follower system, and may actively inhibit it (if they use up limited resources

such as physical space, such as in ports, or limited available capital on the balance sheets of relevant actors).

Second, we focus on technological knowledge and capabilities (a feature common to frameworks that explore technological system interactions; (Andersen & Markard, 2024)). We conceptualise technological knowledge in a similar manner to Binz et al. (2016) Technological knowledge includes both codified and tacit knowledge, and encompasses not only ‘know-how’, but also the ‘know-who’ that underpins the functioning of networks. A stepping stone TIS adds to the stock of knowledge and capabilities that facilitate the emergence of a sustainable follower TIS, for example by solving technical challenges shared by both anchor technologies.

Third, we explore institutional dimensions (also common to the various frameworks on technological system interactions; (Andersen & Markard, 2024)). The behaviour of actors within an emerging system is shaped by the existing institutional context, made up of both ‘hard’ formal rules (regulations, standards, etc.), and ‘soft’ rules (norms, cognitive rules). Actors also work to influence and change such rules (Geels, 2005)—they work to achieve alignment of the technological system with the institutional environment, a process often described as legitimation (Binz et al., 2016). This involves both adapting the technology to fit existing rules (a mode known as ‘fit and conform’, following (Smith & Raven, 2012)), while also seeking to reshape the regime of rules itself (‘stretch and transform’).

The legitimation efforts made by a stepping stone TIS create a new institutional environment in which the sustainable follower TIS will operate. In this dimension, we examine whether new rules that enable the development of the stepping stone TIS inhibit or enable the follower TIS.

Finally, we focus on expectations and narratives. Expectations—and the narratives actors deploy that reflect, shape and amplify them—play a key role in the development of technological innovation systems (Hekkert et al., 2007). Here we explore the extent to which developments in a stepping stone TIS generate (or not) foster positive expectations for the sustainable follower TIS.

The empirical analysis of this study is structured around these four core dimensions, shown in Table 2, which are derived from the TIS and multi-system interaction literatures (Andersen & Markard, 2024; Hekkert et al., 2007). These categories represent the key domains where system interactions manifest. This structure allows for a systematic assessment of the generated spillovers and complementarities that emerge from each category.

Within each category, we explore both complementarities, and spillovers. Complementarities are system resources that are created by the stepping stone TIS and that directly apply to the follower TIS. This framing positions complementarities and spillovers as the ‘connective tissue’ that bridges TIS functional dynamics with broader system interdependencies. The framework also allows to analyse the dual nature of these spillovers, assessing whether they function as positive spillover (complementary) which accelerate the development of the green ammonia TIS by creating enabling conditions through shared technological knowledge, creation of cross-compatible infrastructure or conducive regulatory environment or negative spillovers (competitive) which delay or inhibit green ammonia TIS by diverting investment, creating stranded assets or reinforcing resistant actor coalitions (Markow et al., 2023).

Table 2. Categories of complementary and competitive interaction

Core Category	Key Analytical Aspects	Key Guiding Questions
Material and financial resources	<ul style="list-style-type: none"> • Physical infrastructure compatibility and repurposability (e.g., bunkering, terminals, propulsion systems). • Mobilisation of financial capital for infrastructure. 	<ul style="list-style-type: none"> • Can investments in transitional fuel infrastructure (e.g., LNG terminals) be leveraged for ammonia? • What are the cost implications and lock-in risks of repurposing assets?
Technological Knowledge & Capabilities	<ul style="list-style-type: none"> • Research and Development (R&D) activities. • Transfer of technical expertise, skills, and capabilities (e.g., retrofitting, cryogenic handling). 	<ul style="list-style-type: none"> • Are there direct technological spillovers (e.g., shared technologies, dual-fuel engine R&D) that make transitioning from transitional fuels to ammonia easier? • Does the development of the transitional fuel generate capabilities that are applicable to ammonia?
Regulatory Systems & institutions	<ul style="list-style-type: none"> • Policy mechanisms (e.g., subsidies, tax incentives). • Risk mitigation policies for financial uncertainty. • Standardization and certification processes for safety and emissions. 	<ul style="list-style-type: none"> • Do regulatory changes for transitional fuels (e.g., safety certification norms) create procedural precedents for ammonia adoption? • How do policy mechanisms for LNG/methanol influence likely financial flows to ammonia?
Expectations & Narratives	<ul style="list-style-type: none"> • Perceptions of viability and scalability. • "Momentum effects" and actor expectations shaped by current investments. 	<ul style="list-style-type: none"> • Do investments in transitional fuels influence stakeholders' perceptions of ammonia's potential (e.g., by increasing attention or, conversely, framing it as "too distant")?

3.3 Interactions across the value chain

We have followed Rosenbloom et al. (2025) in describing stepping stones as being built around ‘anchor technologies’ – in our case, the fuel and associated systems on board ships. But clearly, each anchor technology and fuel is part of a wider ‘bundle of value chains’ (Sanden & Hillman 2011), and technological systems are structurally or functionally coupled to others (Andersen and Geels 2023). In our case, developments in shipping fuel technologies have implications for ports and upstream into energy systems.

In assessing whether a technological option is a stepping stone or not, it is important to think through the impacts across value chains. This includes ‘vertically’ (does development of potential stepping stone TIS A induce the development of upstream supply chains that also support sustainable follower TIS B?) and horizontally (does development of TIS A induce developments in structurally and functionally coupled systems that support the development of TIS B?).

Therefore, while our primary focus remains on ships and ports, our analysis captures how spillovers are mediated through these coupled systems. This approach acknowledges that a technological choice made at the vessel level—such as an engine retrofit—does not just affect the fleet; it sends demand signals that reinforce specific upstream energy architectures, creating a feedback loop between the ship and the supply chain. While we focus on the interactions within the core TIS—in our case related to the fuel systems for ships—we also examine whether and how there may be complementarities or competitive dynamics across the value chain.

4 Methodology

We employ a qualitative, single-case study design, selecting the global maritime shipping sector to investigate the broader phenomenon of stepping stone pathways in sustainability transitions. Shipping is a valuable case for studying stepping stones: there are several clear candidate pathways, with the possibility of ‘stepping stone’ dynamics highlighted by stakeholders.

We combine four data sources: i) semi-structured interviews (n=25) with professionals and stakeholders in the shipping industry; ii) technical and policy documents; iii) technical and economic data on ships from a commercial database (Clarkson’s World Fleet Register); and iv) patent data from Orbis IP. The triangulation of the data from these different sources bolsters the credibility and robustness of findings (Carter, 2014).

Semi-structured interviews were conducted online from March to October 2025, and are referenced throughout the text using the codes V1, V2, ..., Vn. Interviewees were selected based on theoretical sampling logic, to capture diversity of relevant perspectives. Participants include representatives from shipping companies and operators, engine and technology providers, ports, fuel suppliers, industry associations, universities and NGOs. Interview questions were structured around a core set of themes derived from our analytical framework, addressing the components of potential cross-pathway interactions.

Documentary analysis complemented the interview findings by providing contextual validation and additional insights. Documents included journal articles, industry and consultant reports, policy papers presented to the IMO, industry news articles, etc. Documentary sources were combined with interview data through triangulation, in which the main themes emerging from interviews were systematically compared and cross-checked against documentary evidence.

We adopted a hybrid coding strategy for interview and documentary data, with a deductive coding framework based directly on the analytical framework, coupled with inductive or "open coding" to capture new or unexpected themes that emerged from the data.

In addition to the qualitative analysis, quantitative analysis was conducted to calculate the techno-economics of retrofit. This included data collected from documentary sources and elicited from interviewees. In addition, an econometric analysis of the newbuild prices of a sample of 7,355 ships from Clarksons world fleet register was conducted to assess the newbuild premium paid for dual-fuel capability. Further details are provided in attached supplementary material.

Finally, to support the analysis of complementarities and spillovers related to technological knowledge and capabilities, we analysed patents using the Orbis IP database. Patent citations are widely used to study knowledge spillovers, including in studies of complementarities in emerging innovation systems (Mirzadeh Phirouzabadi et al., 2020). We collected patent families focused on shipping that refer to methanol and LNG, and explored the extent to which these patents are cited by patents related to ammonia use as a shipping fuel. We then retrieved patents that cite the methanol and LNG patents, and analysed both the relative citation frequency by ammonia related patents, and the technical nature of the citing patents. Further details are in the attached supplementary material.

5 Empirical Findings

5.1 Methanol

5.1.1 Material and financial resources: physical assets, infrastructures and balance sheets

Methanol investments do not appear to create financial or material assets that support a transition to ammonia, according to technical documents and interviews (V11; V12, V16, V21). Methanol infrastructure—including tanks, containment systems, and bunkering lines—has minimal physical overlap with ammonia requirements.

This lack of adaptability is also largely true upstream in the energy supply. While in the long term, advocates of methanol suggest that it will eventually be produced via electrolytic hydrogen, little investment in such infrastructure is expected in the near or medium term under a methanol pathway. Investments in methanol are unlikely to catalyse the development of significant green/blue hydrogen resources that would then be available for ammonia.

Because investing in methanol hardware does not create “steel in the ground” for ammonia, the validity of methanol as a transitional step in terms of material and financial resources rests on the economic feasibility of future conversion. Interviewees confirm that modern dual-fuel

engines can be designed to be relatively fuel-agnostic, making engine retrofits across different fuels technically viable, with one interviewee describing the engine modifications as "some tweaks," such as adapting the fuel injection systems, using different materials, and adjusting dimensions [V11].

Despite this engine-level adaptability, the rest of the system—such as storage and supply—remains difficult and expensive to adapt. Consequently, the cost of retrofitting a ship from methanol dual-fuel (DF) to ammonia DF is believed to be similar to the cost of retrofitting from conventional to ammonia DF. The subsequent retrofit cost comes on top of a significant upfront premium for new-build methanol ships compared to traditional ships. For example, our techno-economic analysis shows that newbuild methanol ships carry a premium of around 20% for a 14,000 TEU containership, compared to a conventional ship; **Error! Reference source not found.**)

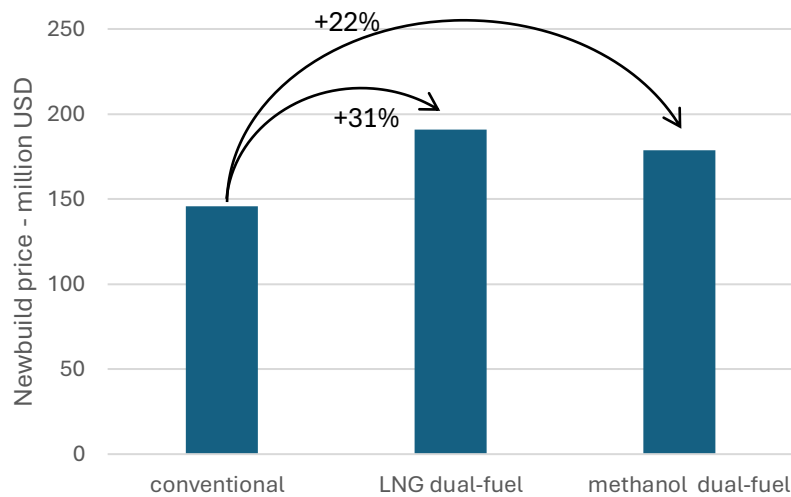


Figure 1: Estimated newbuild cost of a 14,000 TEU container contracted in 2025. Deadweight = 150,000 dwt, MCR = 55,000 kW. Estimated using model (4) in the supplementary materials

However, the cost of retrofitting conventional or methanol dual-fuel ships to ammonia is uncertain, and depends on ship-specific characteristics which are difficult to generalise (Maersk Mc-Kinney Møller Center for Zero Carbon Shipping, 2023, 2024). The literature suggests a wide range of retrofitting costs for ships of similar sizes (**Error! Reference source not found.**). For example, estimates for retrofitting a Very Large Crude Carrier (VLCC) to ammonia range widely, from USD 17 million to 48 million, depending on the study, the engine size and tank configuration (Maersk Mc-Kinney Møller Center for Zero Carbon Shipping, 2024; DNV, 2024).

Overall, investing today in a methanol dual-fuel ship with the explicit intention of retrofitting it later on makes little economic sense: taking the example of a 14,000 TEU containership, the shipowner would need to pay a premium of more than \$30 million at newbuild (**Error! Reference source not found.**), followed by a retrofitting cost of somewhere between \$20 and \$40 million when retrofitting to ammonia (**Error! Reference source not found.**), compared to a ship worth, if conventional, around \$150 million (**Error! Reference source not found.**).

Both fuels present toxicity challenges, and interviewees differed in their view on whether experience with methanol would create relevant capabilities for handling ammonia in this regard. While some argued this was an important similarity (V21), others viewed the nature of the hazards as too different to generate useful learning: *“both have toxicity problems but the toxicity is very different...[and] when you have a leak, how does the leak behave? That is also significantly different.”* (V18)

Interviewees did identify some ways in which experience with methanol could inform ammonia. For example, because both fuels are more difficult to ignite than conventional fuels or LNG, there is some shared technical learning regarding combustion assistance: *“the ...advantage of having worked with methanol before moving on to ammonia is understanding how to switch [to] a marine fuel ... which is quite resistant and needs help igniting, so it needs a spark or some other kind of assistance.”* (V16).

While participants identified few directly overlapping capabilities, some interviewees suggested that firms may acquire relevant “dynamic capabilities” (Teece et al., 1997)—i.e. they may become better at managing the processes associated with handling a new fuel (V9, V18). In this view, any new fuel has some stepping stone characteristics, since it is novelty itself that forces firms to develop organizational capabilities for managing change and risk, and in developing R&D capabilities for new fuels. For example, while training needs “would just be different” (V12), the organisational capability to deliver training around the fuel could be transferrable: *“what you can translate [from methanol to ammonia] is...how do you develop training, how do you develop a risk assessment?”* (V18)

Patent data also provides insight into the potential technological spillovers from methanol to ammonia. Of the patents citing methanol ship patents, around 17% mention ammonia. Of these, the most prominent technology topics relate to engines and fuel supply (IPC code B63H21), fuel tanks (IPC code B63B25) and exhaust after-treatment (e.g. IPC codes B63J4/00; F01N). These topics confirm engine technology as a key area of spillovers, as suggested by interviewees. There are, unsurprisingly, very few apparent spillovers relating to management of cryogenic liquids—again confirming the key issues raised by interviewees.

In conclusion, while the methanol pathway fails to provide a strong technical stepping stone to ammonia due to divergent chemical and physical properties, it may serve as an organisational catalyst. By forcing the maritime sector to transition away from deeply entrenched practices, early experiences with methanol cultivate the dynamic capabilities, safety cultures, and risk-assessment frameworks necessary for managing any novel, hazardous fuel. Consequently, at least some of the knowledge spillovers associated with methanol are procedural and cultural rather than strictly technological, building the industry's adaptive capacity for the ultimate transition to zero-carbon solutions.

5.1.3 Institutional

In the institutional domain, participants and documentary sources suggest that the regulations being developed around methanol are not directly relevant to the use of ammonia (V7). Specifically, the environmental hazard profiles of the two fuels necessitate divergent regulatory logic. Methanol *“doesn't pave the way for things that need very strict regulation”* like ammonia (V24).

Consequently, the institutional capacity built to govern methanol does not meaningfully reduce the administrative or regulatory friction for the highly rigorous safety protocols required for future ammonia adoption.

5.1.4 Expectations and narratives

Methanol is repeatedly framed through both a pragmatic near-term narrative (emphasising its timeliness), and a strategic long-term narrative (as “future-proof”/part of the 2050 solution). These narratives shape whether methanol functions as a complementary stepping stone (by normalising alternative fuels and building confidence), or as a competing pathway (by legitimising long-lived commitments that defer ammonia).

The evidence reveals a tension. On the one hand, it appears that methanol investments help to normalise the concept of alternative fuel transitions, raising positive expectations for other alternative fuels. The broader narrative frame of ‘alternative fuels’ accommodates, and is supported by, a variety of fuel-specific pathways. This “normalisation” dynamic is reinforced in the documentary analysis: across actor groups (classification societies, coalitions, news/media, and industry associations), methanol is consistently narrated as the most practical today alternative fuel, and is frequently presented alongside ammonia as part of an emerging multi-fuel decarbonisation portfolio. In this framing, methanol’s rapid scaling acts as a visibility and legitimacy device that keeps ammonia present in the imagined future fuel mix—even if ammonia is positioned as “next” rather than “now”.

On the other hand, dominant industry narratives in documentary sources often frame methanol not as a stepping stone, but as a final destination: “*it can be made from biomethanol and e-methanol. So it’s a fuel that can last to 2050 and beyond.*” (V10) This framing suggests that development in methanol undermines expectations for a future ammonia pathway (V20). Synthesising across interviews and documents, methanol’s narrative spillovers are therefore best characterised as “double-edged”.

5.2 LNG

5.2.1 Material and financial resources: physical assets, infrastructures and balance sheets

LNG is sometimes marketed by incumbents as a hardware bridge. Because LNG and ammonia are both gases requiring cryogenic storage, the argument is that investing in LNG today builds the physical assets for ammonia tomorrow (V10;V14;V25). This view is championed by technology providers like Wärtsilä, who argue that their LNG engine platforms act as a ‘future-proof’ investment, stating that “*the modular design of the engines... allows for a conversion to future carbon free fuels*”, thereby linking LNG capital expenditure to a future regime based on ammonia (Wärtsilä, 2023).

However, there is a gap between the bridge narrative and current implementation of LNG assets. While the potential for technical overlap exists, many current LNG investments are not being

designed and built in a way that makes this overlap easy to achieve, even when they are described as ‘ammonia ready’.

Our techno-economic analysis of retrofitting costs casts doubt on the physical bridge narrative for LNG ships. LNG dual-fuel ships come with a large premium on today’s newbuild markets (**Error! Reference source not found.**). This premium can be justified by fuel savings if LNG as a marine fuel is cheaper than conventional fuels, if it helps the ship meet (relatively weak) emissions compliance requirements, or/and if the LNG dual-fuel capability leads to significant savings at retrofitting, the latter being critical for LNG to play a bridge role. Our analysis reveals that the economic viability of the LNG-to-Ammonia bridge is strongly influenced by the level of initial retrofit “readiness”, a term found to be highly ambiguous in practice (V8).

Several sources of evidence provide insight into likely costs associated with retrofit. Hapag-Lloyd’s retrofit of the *Sajir* to LNG cost around \$35 million¹. While the *Sajir* project was a retrofit from Fuel Oil to LNG, and reflects a "First-of-a-Kind" premium, it illustrates that retrofitting cryogenic storage into an existing hull is a major capital project. A future switch from LNG to Ammonia may face similar barriers unless LNG assets are designed to facilitate future retrofit. In addition to these capital costs, there is also the "Off-Hire" penalty, i.e. the costs associated with the operational pause required for retrofit. The analysis assumes a retrofit requires time off-hire in a shipyard (usually several months), representing a substantial loss of revenue and cargo opportunity cost.

The literature shows the cost of retrofitting an LNG dual-fuel ship to ammonia is uncertain, with estimates varying substantially between ship types (**Error! Reference source not found.**). The literature (Maersk Mc-Kinney Møller Center, 2022 and 2024, Lagouvardou et al, 2023) and interviewees (V4;V5;V6;V7; V15) suggest that retrofitting from LNG to ammonia can be cheaper than retrofitting from conventional to ammonia, particularly if this retrofit has been anticipated in early design choices. The level of expected cost savings associated with ‘readiness’ varies widely in the literature (from 3% to 50% reduction in retrofitting cost compared to a retrofit from conventional, **Error! Reference source not found.**). For a 14,000 TEU containership, the route of LNG dual fuel to ammonia dual fuel implies an initial additional investment of \$40 million at newbuild (an increase of 30% relative to a conventional ship), followed by a retrofitting investment of \$15 to 30 million if it was built ammonia-ready (e.g. piping, cabling and ventilation in place) (**Error! Reference source not found.**).

Interviewees provided insight into what ‘ammonia ready’ means in practice. While adapting the engine itself is relatively straightforward, the wider vessel architecture presents challenges. This is due to the greater density, toxicity and corrosiveness of ammonia, requiring heavier tanks and distinct containment materials (V12; V21; V25). LNG and ammonia both share a need for heavy insulated cryogenic tanks, which require a stronger deck than is found in a conventional ship. While tanks built for LNG will have the cryogenic systems necessary for ammonia, they may not be able to handle the additional weight associated with ammonia (V25). Designing ammonia-ready tanks and stronger decks is possible, but adds upfront cost.

Similarly, both LNG and ammonia ships require a fuel preparation room, in which the cryogenic fuel is brought to the right temperature, pressure etc. prior to combustion. LNG ships will already have a fuel preparation room, so in principle again LNG assets may be easier to retrofit

¹ <https://shipandbunker.com/news/world/738570-hapag-loyd-lng-bunkering-retrofit-for-boxship-to-cost-35-million>

[V4]. However, the needs for fuel preparation differ, and ammonia may require larger fuel preparation facilities. Boil-off is also an issue with cryogenic fuels, and there is a need for vent pipes. But because of the toxicity of ammonia, a vent pipe designed for LNG is unlikely to be appropriate unless it has been specifically designed for ammonia [V4]. As with tanks, while it is possible to design fuel preparation facilities and vent pipes that work for both LNG and ammonia, this flexibility comes at a cost.

Critically, interview data (V6, V7) also reveals that very few “ammonia-ready” ships actually meet the high readiness standard required to achieve the savings associated with readiness. Formal readiness ‘notations’ are variable and often amount to little more than a drawing on paper (V4). Interviewees described LNG investments as creating a sunk cost dynamic where owners, having paid a premium for LNG, will be reluctant to switch to ammonia as long as LNG remains regulatory compliant [V7].

In the absence of true ammonia readiness, there is a real risk that LNG investments create a negative spillover in the form of capital crowding out. The mobilisation of financial resources into LNG infrastructure risks contributing to socio-technical lock-in, rather than creating a stepping stone. By absorbing the green premium capital available in the market, incumbent LNG investment flows (V20, V23, V24) can crowd out the resources needed to commercialize ammonia. The findings confirm that while LNG is marketed as a stepping stone, in practice current investments risk actively delaying ammonia through asset lock-in.

A similar divide regarding transitional viability exists when examining onshore bunkering infrastructure. Again, it appears that there are potential commonalities, but that this depends on early design choices. Documents and interviews agree that LNG terminals and bunkering networks can, on paper, be adapted for ammonia with additional CAPEX of 11–20%. Some stakeholders express optimism about this overlap [V14; V22], while others were more sceptical [V15]. The story for upstream fuel supply is similar to that of methanol: near-term LNG investments are not creating the upstream green or blue hydrogen production infrastructure that will underpin ammonia.

5.2.2 Technological knowledge and capabilities

On a technical and operational level, interviewees suggested that LNG does create knowledge and capabilities that are relevant to ammonia. Both LNG and ammonia are stored well below zero, and stakeholders argued that while the systems differ, the capabilities developed for LNG would facilitate the subsequent adoption of ammonia [V25]. This relates to fuel handling protocols and cryogenic systems.

However, interviewees also expressed some ambivalence about the potential for skills and training associated with LNG to be transferrable to handling ammonia, in particular because of toxicity [V21]. While LNG training provides experience with cryogenics, interviewees stressed that ammonia introduces additional, fuel-specific safety and training requirements because of its toxicity, so LNG experience should not be assumed to translate directly into preparedness for ammonia (V21). The safety culture required for LNG (focused on flammability) is distinct from the hyper-vigilance required for the extreme toxicity of ammonia.

As with methanol, it is plausible that diffusion of LNG as a shipping fuel—beyond its established niche in LNG tankers—could help actors across the shipping system to develop ‘dynamic

capabilities', i.e. the capabilities required to adjust to a new fuel. This could help to facilitate subsequent adoption of ammonia.

Data from patents makes clear that there are likely technology spillovers between the LNG and ammonia. There are both numerous patents related to shipping that mention both ammonia and LNG, and around 11 % of forward citations of LNG patents related to shipping mention ammonia. The areas of technology reflect some of the discussions about potential physical asset complementarities. Prominent technology fields in ammonia patents linked to LNG (either through co-mentions or through citation) include inventions related to: gas storage technologies and gas cargo tanks (IPC code groups F17C and B63B25/16); engines and propulsion systems (IPC code group B63H); technologies relating to boil-off and liquefaction (e.g. IPC codes under F25J); and some structural features of hulls, bulkheads etc. (IPC codes under B63B73).

This pattern suggests that the development of LNG technologies does indeed create knowledge that is useful for ammonia, including in areas that are not advanced by R&D and experience in methanol ships. The patterns echo some of the discussions by stakeholders, reflecting the challenges associated with tanks, storage, fuel handling, and the structural reinforcements required for the additional weight.

In conclusion, there are clear technological spillovers and complementarities between LNG and ammonia, shown through both expert knowledge and patent data. However, stakeholders emphasised that there are limits to such knowledge transfer. The extreme toxicity of ammonia is something new, for which LNG-related experience is of limited value.

5.2.3 Institutional

Some positive spillover potential was identified in the regulatory domain. The development of the IGF Code² for LNG has created a procedural template for alternative fuels (V7). Interviewees noted that while ammonia safety parameters are unique (driven by toxicity rather than flammability) and cannot be "copied and pasted," the institutional capacity built through licensing LNG bunkering provides a valuable "sandbox" that can accelerate regulatory approval for ammonia (V18; V20). This procedural learning reduces the administrative friction for ammonia, even if the specific safety regulations themselves must be developed anew.

5.2.4 Expectations and narratives

Interviews and document analysis reveal contested views on whether and how LNG investments reshape expectations about ammonia. Across actor groups, LNG is narrated simultaneously as i) a "bridge" that proves alternative fuels are manageable and creates confidence, and ii) a "slow-transition" option that entrenches incumbents and delays the sector's willingness to confront ammonia's distinct risk and governance requirements.

To some extent, there is 'symbiosis' across *all* alternative fuel options, in the sense that they all support the narrative that decarbonisation and transformative change is possible (a point also made by (Havinga et al., 2024)). Multiple interviewees invoked this idea, describing developments with new fuels as being mutually reinforcing: experience with LNG "means [companies] can be more open to considering other fuels." [V17]; also V15].

² The IGF code is the International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels

However, the “LNG as bridge” story is continuously countered by dominant competing narrative in which LNG is framed as a pathway with strong economic and infrastructural inertia that makes later switching harder – a short term “sugar fix” that does long term damage [V20]. Interviewees highlighted that once fuel-specific infrastructures and asset bases are established, they generate expectations of continuity and create resistance to disruptive change. [V18].

Much like in the case of methanol, the narratives around LNG are double-edged, with interviewees perceiving LNG as simultaneously supporting a ‘transitions are possible’ narrative that benefits ammonia, while also undermining ammonia specifically by entrenching LNG-specific expectations.

5.3 Summary across pathways

We summarise our findings for each pathway in Table 3 below. Overall, the evidence suggests that both pathways create some resources for a future transition to ammonia. LNG offers the potential—through ‘real’ ammonia readiness—to provide a clear hardware-based stepping stone, but achieving this in practice would require a global regulatory regime that was credible over the long term. Without this hardware bridge, investments in LNG and methanol provide only limited resources for an ammonia transition, while competing for available financial resources.

Table 3. Summary of findings for each pathway

Categories	LNG	Methanol
Material & financial resources	There is potential for LNG ships to be retrofitted, but only if designed as fully ammonia-ready. There are limited potential overlaps in bunkering infrastructure, but little to no overlaps in upstream fuel supply.	Methanol investments do not create material or financial resources that are available for subsequent ammonia developments.
Technological knowledge & capabilities	There are direct knowledge spillovers related to engines, cryogenic fuel handling and storage. There is also some evidence for limited transfer of skills and capabilities. Some potential for development of transferrable dynamic capabilities in managing a new fuel.	Some knowledge spillovers associated with engines (e.g. ignition assistance), but with narrower scope than for LNG. Some potential for development of transferrable dynamic capabilities in managing a new fuel.
Regulatory systems & institutions	Regulatory processes developed for LNG are expected to facilitate development of standards for ammonia	Little evidence of direct complementarities or spillovers
Expectations and narratives	Ambivalent for both pathways: LNG or methanol investments are seen as both bolstering the view that radical transformative change	

	is possible, but each also offers a long-term narrative that competes with ammonia.
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6 Discussion and conclusions

This paper makes two key contributions. First, we make a contribution to the wider literature on dead-ends, stepping stones and analysis of transition pathways, by developing a conceptual framework for identifying and assessing stepping stone pathways. This builds on existing literature on ‘dead end pathways’, to provide a set of conceptual tools for identifying whether and how near-term investments in an apparently dead-end pathway may still provide a viable route to a sustainable future. Our framework provides a flexible structure for evaluating the extent to which near-term technological options may be considered ‘stepping stones’ to a more sustainable system.

Our framework focused on the resources created by stepping stone technologies. In future research, it would be valuable to expand this to incorporate analysis of the political economy of stepping stones, exploring the extent to which the resources (including capabilities and networks) created by stepping stones influence advocacy coalitions, or re-shape the political environment facing the follower TIS.

Second, we provide new evidence directly relevant to stakeholders involved in the global maritime shipping industry – addressing our empirical research question (*Are LNG and methanol stepping stones to ammonia in the global maritime shipping sector?*). Our work highlights that near term investments in methanol and LNG do not provide a direct stepping stone to a clean ammonia future. A key finding is that LNG ships will only act as a stepping stone where they are truly ‘ammonia ready’ – designed to cost-effectively retrofit. But with current technologies the economics of this remain difficult. It is possible that technological innovation could bring down the costs of retrofit to ammonia, but unless this happens, significant LNG investment risks making it more difficult—rather than less—to achieve deep decarbonisation in shipping.

However, while stakeholders believe that neither LNG nor methanol ships can cost-effectively retrofit to ammonia, investments in both fuels do contribute to both technological and regulatory learning and processes that may help to clear the path for a switch to ammonia. Given the lack of direct physical complementarities, however, the spillovers generated by investments in LNG or methanol may be outweighed by the further entrenchment of fossil fuel infrastructure.

For policymakers, this research suggests a number of conclusions. First, it highlights the importance of seeking to build long-term credibility around emission reduction goals, so that investors value the optionality created by ‘ammonia ready’ assets, and bring forward deeper emission reduction options like ammonia. In the absence of such credibility, investments in less-sustainable LNG and methanol assets are unlikely to facilitate ammonia in the long term.

Second, policymakers must do more to accelerate the development of ammonia, to address ammonia's 'timeliness' problem and to offset the risks of ending up in an expensive LNG or methanol dead end. Technology R&D, demonstration trials, and regulatory standards need dedicated support. Ammonia deployment needs to start this decade, even if only within niches from which it can subsequently grow.

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9 Supplementary material

9.1 Interviewees

Code	Organisation type
V1	Technology provider
V2	Commodity trading company
V3	Commodity trading company
V4	Shipping company
V5	Shipping company
V6	Shipping company
V7	Shipping company
V8	Commodity trading company
V9	University
V10	Industry association
V11	University
V12	Technology provider

V13	Port operator
V14	Shipping and logistics company
V15	Technology provider
V16	University
V17	Consultant
V18	Energy company
V19	NGO
V20	NGO
V21	Technology provider
V22	Consultant
V23	University
V24	NGO
V25	Technology provider

9.2 Sample Interview Questions

A. Technical & Technological Dimensions

1. What technologies are shared between LNG, methanol, and ammonia systems?
2. What are the main technical challenges in adapting existing systems for ammonia use?
3. Which skills, capabilities, or infrastructure from LNG and methanol systems could be transferable to ammonia?
4. How have “ammonia-ready” developments and retrofitting experiences contributed to technological preparedness?

B. Regulatory & Policy Dimensions

5. In what ways might current LNG or methanol regulations support ammonia adoption?
6. Which institutional structures (e.g., safety committees, standards bodies) are most relevant for ammonia?
7. What are the key regulatory or institutional obstacles to ammonia uptake, and how might they be addressed?
8. Which policy mechanisms (e.g., mandates, incentives) could accelerate the transition toward ammonia fuels?

C. Financial Dimensions

9. Does investment experience in LNG and methanol reduce investor risk perceptions related to ammonia?

10. What financial instruments and programs (e.g., green financing, PPPs) are applicable across different fuels?
11. What lessons from prior investments in LNG or methanol could help de-risk ammonia adoption?
12. How do financial institutions adjust investment criteria when evaluating emerging fuels such as ammonia?

D. Operational & Safety Dimensions

13. Which elements of existing bunkering, storage, and supply chains from LNG or methanol could be leveraged for ammonia?
14. How do training and safety requirements differ for ammonia compared to other fuels?
15. To what extent can safety protocols from LNG and methanol operations be adapted for ammonia handling?
16. Are there examples of retrofitting or operational transitions that illustrate the feasibility of ammonia adoption?

E. Narrative, Knowledge, and Advocacy Dimensions

17. How have industry perceptions of LNG and methanol evolved, and how do these experiences influence ammonia's prospects?
18. Which stakeholders (e.g., industry groups, NGOs, policymakers) are currently advocating for or against ammonia as a marine fuel?
19. What lessons or best practices from LNG/methanol adoption could accelerate ammonia uptake?
20. How are cross-fuel learnings shared through knowledge networks, collaborations, or policy dialogues?

F. Retrofitting Pathways and Technical Feasibility (Second Round Focus)

21. What are the key technical steps involved in converting ships from conventional fuels (LSHFO/MGO) or LNG to ammonia?
22. How does the complexity of retrofitting vary across different starting fuels (e.g., LSHFO → ammonia vs. LNG → ammonia)?
23. What are the relative costs of retrofits, and which technical factors (e.g., fuel systems, storage, safety, engines) most strongly affect cost?
24. Do "ammonia-ready" classifications meaningfully reduce future conversion costs?
25. How feasible is conversion from LNG dual-fuel systems to ammonia operation in practice?

9.3 Literature review of the retrofit cost

We collected available estimates of retrofitting costs from the following literature: QUOTE. When interviews provided estimated retrofitting cost for a specific ship, we also included it. (DNV, 2024; Lagouvardou et al., 2023; Maersk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022, 2024). Each study tends to report the estimates in different units, so we harmonized the results by calculating the total cost of retrofitting in absolute terms. For (Maersk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022, 2024), it meant making an assumption on the newbuild value of the 3 ships studies, as results were given in percentage of fuel oil newbuild value (16 235kW for the 115 000 dwt oil tanker, 30 573kW for the 300 900 dwt oil tanker, 56 066 for the 15 000 TEU container, based on the average engine size for ships of the same segment and similar size reported in Clarksons WFR). The engine size (maximum continuous rating) corresponds to the one referenced in the study when it was included; or the average of similar ships in Clarksons WFR failing that.

DNV. (2024). *COMPREHENSIVE IMPACT ASSESSMENT OF THE BASKET OF CANDIDATE MID-TERM GHG REDUCTION MEASURES – Draft Final Report* (Number 462).

Lagouvardou, S., Lagemann, B., Psaraftis, H. N., Lindstad, E., & Erikstad, S. O. (2023). Marginal abatement cost of alternative marine fuels and the role of market-based measures. *Nature Energy*, 8(11), 1209–1220. <https://doi.org/10.1038/s41560-023-01334-4>

Maersk Mc-Kinney Møller Center for Zero Carbon Shipping. (2022). *Preparing Container Vessels for Conversion to Green Fuels*. <https://cms.zerocarbonshipping.com/media/uploads/documents/Fuel-Options->

Maersk Mc-Kinney Møller Center for Zero Carbon Shipping. (2024). *Preparing Tanker Vessels for Conversion to Green Fuels*.

9.4 Cost analysis for LNG and methanol

To estimate the newbuild premium paid for LNG and methanol dual-fuel ships, we conduct a regression analysis of newbuild prices reported in Clarksons World Fleet Register. The original sample is composed of 7,272 observations, whose distribution is plotted on Figure 3. Conventional ships unsurprisingly represent the vast majority of the sample, but LNG dual-fuel ships and to a lesser extent methanol dual-fuel ships are also well represented. Only a few ammonia dual fuel ships are covered. The breakdown between ship types is in line with the overall fleet composition, with containerships, bulk carriers and tankers representing the large majority of the sample. It is worth noting that although offshore vessels are well represented in the sample, in practice this segment covers a wide range of ship types and specifications and is therefore much less homogenous. Finally, South Korea, China and Japan as building countries together represent the bulk of the observations, which is in line with the composition of the wider fleet.

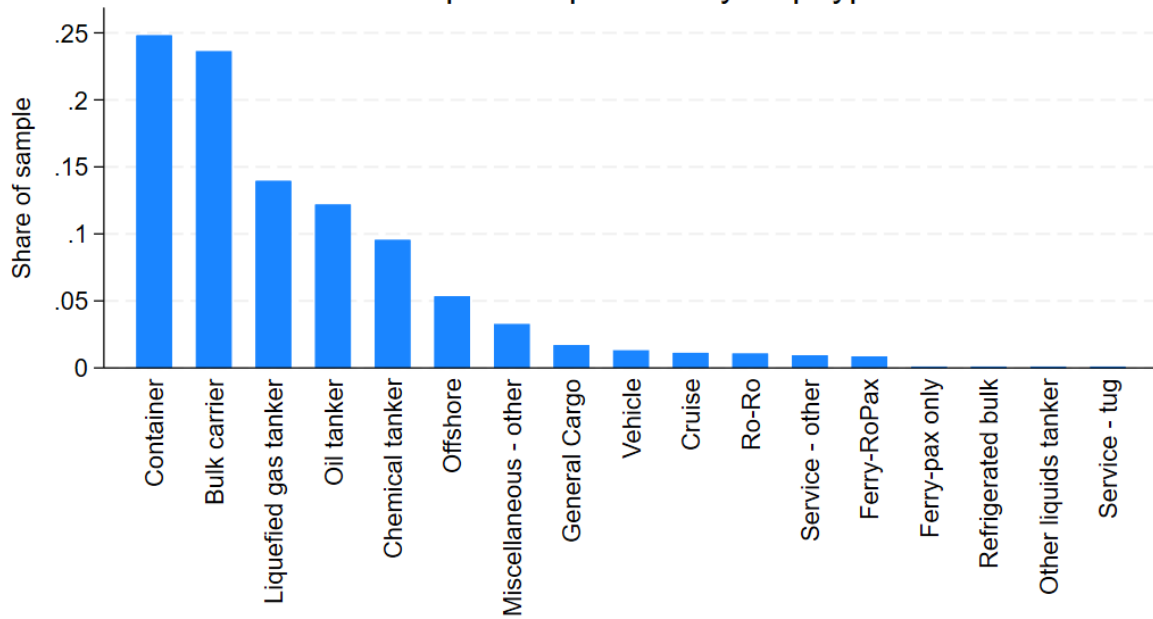
To estimate the newbuild premium that dual-fuel ships attract compared to conventional ships, we conduct an OLS regression of the newbuild prices by:

- An interaction term between engine size and fuel type. Engine size is measured by the maximum continuous rating, in kW; fuel type includes LNG dual-fuel, methanol dual-

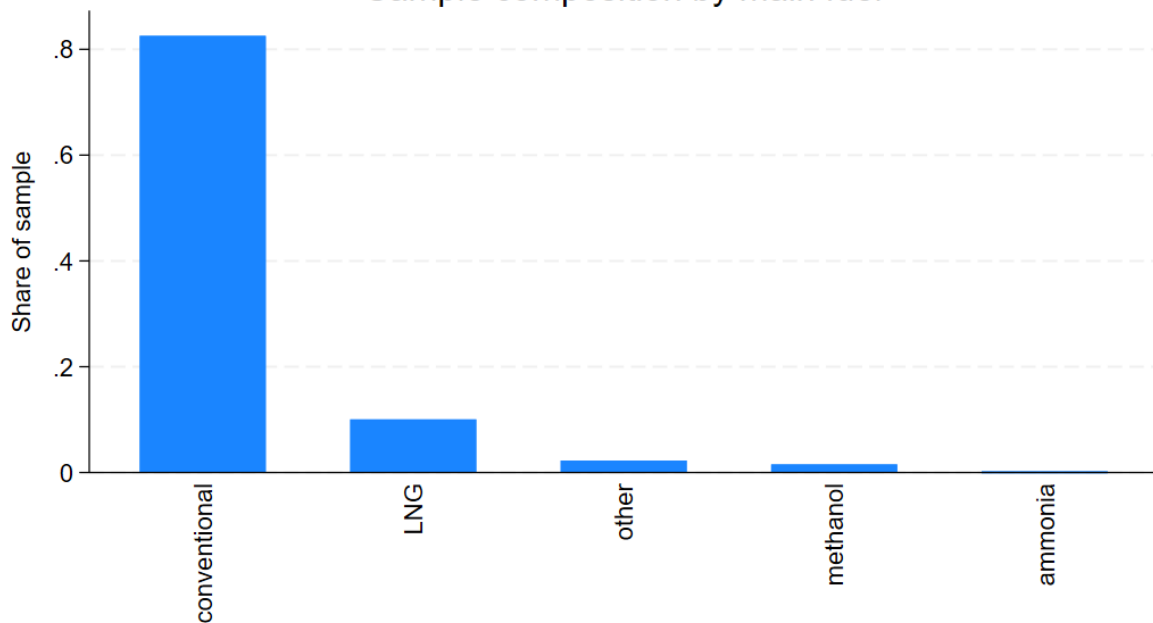
fuel and conventional; the sample for ammonia dual-fuel ship was not sufficiently large to provide meaningful results and they were therefore excluded.

- An interaction term between the ship size (measured in deadweight) and ship type. The sample was restricted to the largest ship types, as the other types did not have enough data points (e.g. refrigerated bulk), and/or were too internally heterogeneous to lead to meaningful results (e.g. offshore, cruise).
- Fixed effects on the builder country, contract dates, build dates and ship types are also included in the various model specifications, to control for the unobserved impact of the market.

Sample composition by ship type



Sample composition by main fuel



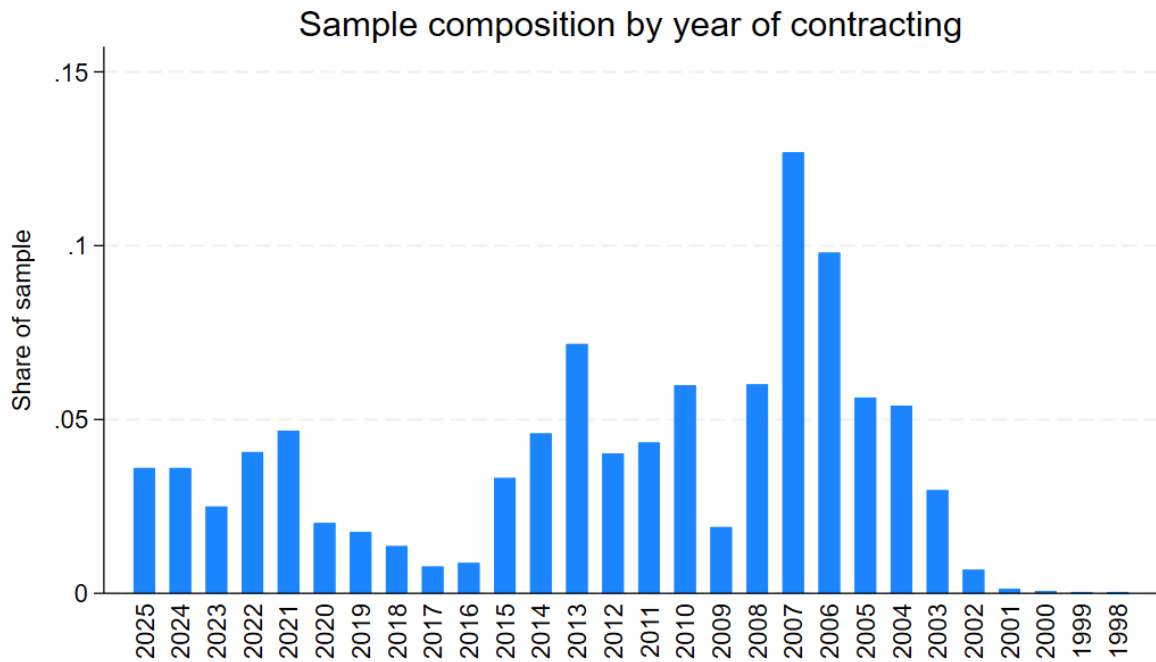
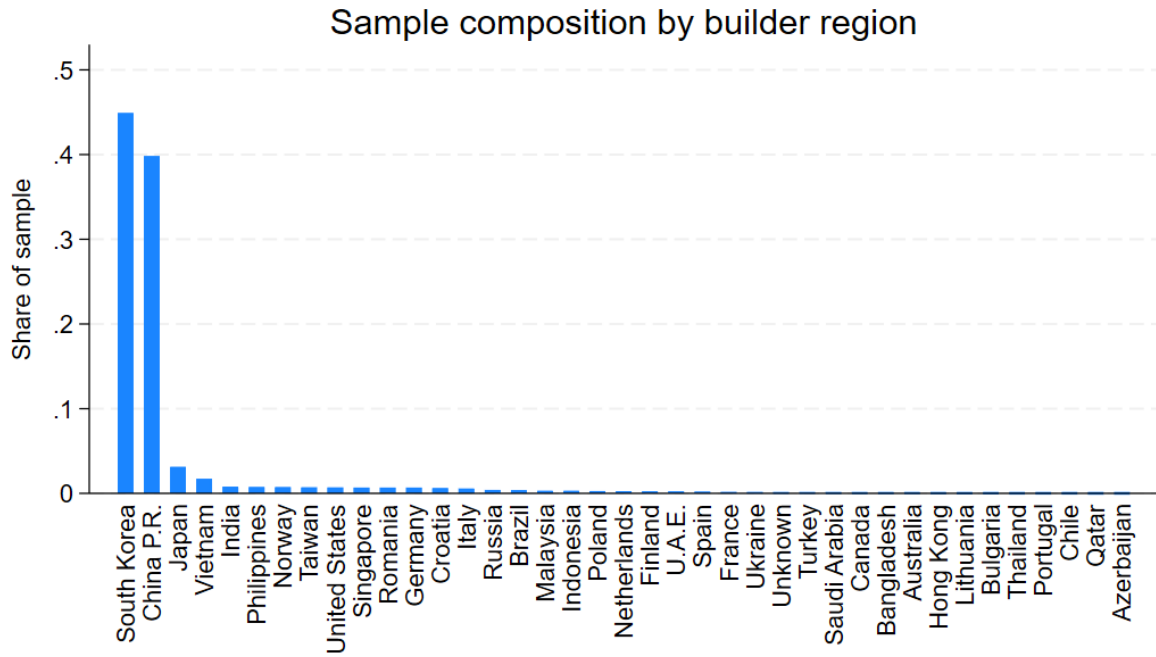


Figure 3: Distribution of the regression dataset

Table 4: Summary statistics

	mean	sd	min	max	count
Price (million USD)	96.96165	166.7034	2.52	4000	7653
Deadweight (000s DWT)	83.19244	77.3979	.033	499.125	7633
Main engine MCR (000s kW)	22.66255	18.9363	.736	105.6	7474
Build year	2014.783	6.569552	2005	2030	7653

Contract year 2011.836 6.588645 1998 2025 7653

The detailed results are provided in Table 5. In model (1), we include all shipping segments and no builder and contract year fixed effects. Model (2) restricts the analysis to segments which are relatively homogenous and well covered by the dataset, as estimations in the other segments might be largely biased by unobserved characteristics. Model (3) introduces fixed effects on contract year to account for the heat of the market and on builder country, to account for the fact that some building countries attract a premium. Finally, model (4) introduces a fixed effects on the interaction term between contract year and IMO type, to account more precisely for the heat of the newbuild market.

Model (4) performs best at explaining the variation in newbuild prices, with R2 = 95%. LNG and methanol dual-fuel price consistently and significantly attract a newbuild premium compared to conventional ships across model specifications. The scale of the effect largely decreases once the sample is restricted to homogeneous segments, and then is fairly consistent across model specifications. The interaction coefficients between the engine size and the fuel types are however statistically significant, suggesting that dual-fuel ship do attract a significant premium which is correlated to the size of the engine.

Table 5: Results of the regression analysis of newbuild prices

	(1) Price (million USD)	(2) Price (million USD)	(3) Price (million USD)	(4) Price (million USD)
LNG # Main engine MCR (000s kW)	3.44*** (0.00)	1.83*** (0.00)	1.77*** (0.00)	1.82*** (0.00)
ammonia # Main engine MCR (000s kW)	3.72** (0.00)			
conventional # Main engine MCR (000s kW)	2.34*** (0.00)	0.77*** (0.00)	0.89*** (0.00)	1.01*** (0.00)
methanol # Main engine MCR (000s kW)	3.43*** (0.00)	1.64*** (0.00)	1.57*** (0.00)	1.60*** (0.00)
other # Main engine MCR (000s kW)	2.58*** (0.00)			
Bulk carrier # Deadweight (000s DWT)	0.08*** (0.00)	0.19*** (0.00)	0.18*** (0.00)	0.18*** (0.00)
Chemical tanker #	0.15	0.38***	0.37***	0.34***

Deadweight (000s DWT)	(0.10)	(0.00)	(0.00)	(0.00)
Container # Deadweight (000s DWT)	-0.06*	0.44***	0.41***	0.38***
	(0.03)	(0.00)	(0.00)	(0.00)
Cruise # Deadweight (000s DWT)	42.11***			
	(0.00)			
Ferry-RoPax # Deadweight (000s DWT)	1.00			
	(0.59)			
Ferry-pax only # Deadweight (000s DWT)	0.00			
	(.)			
General Cargo # Deadweight (000s DWT)	0.89*	1.31***	1.40***	1.46***
	(0.02)	(0.00)	(0.00)	(0.00)
Liquefied gas tanker # Deadweight (000s DWT)	1.19***	1.72***	1.64***	1.65***
	(0.00)	(0.00)	(0.00)	(0.00)
Miscellaneous - other # Deadweight (000s DWT)	-0.04			
	(0.86)			
Offshore # Deadweight (000s DWT)	6.82***			
	(0.00)			
Oil tanker # Deadweight (000s DWT)	0.08***	0.21***	0.18***	0.17***
	(0.00)	(0.00)	(0.00)	(0.00)
Other liquids tanker # Deadweight (000s DWT)	-0.84			
	(0.74)			
Ro-Ro # Deadweight (000s DWT)	0.69*			

	(0.02)			
Service - other # Deadweight (000s DWT)	6.67*** (0.00)			
Service - tug # Deadweight (000s DWT)	0.00 (.)			
Vehicle # Deadweight (000s DWT)	0.84 (0.27)	1.17** (0.00)	0.68* (0.02)	0.91** (0.00)
Bulk carrier	0.00 (.)	0.00 (.)	0.00 (.)	0.00 (.)
Chemical tanker	5.11 (0.20)	-0.04 (0.98)	0.39 (0.79)	15.34 (0.35)
Container	-12.72*** (0.00)	-1.90 (0.09)	-4.25*** (0.00)	30.70* (0.02)
Cruise	59.98*** (0.00)			
Ferry-RoPax	54.49*** (0.00)			
Ferry-pax only	-6.69 (0.87)			
General Cargo	-5.27 (0.39)	-12.93*** (0.00)	-14.96*** (0.00)	2.79 (0.86)
Liquefied gas tanker	-6.89* (0.04)	-15.33*** (0.00)	-11.29*** (0.00)	31.00* (0.03)
Miscellaneous - other	8.87 (0.06)			
Offshore	29.89*** (0.00)			
Oil tanker	10.45*** (0.00)	9.86*** (0.00)	10.57*** (0.00)	45.03*** (0.00)
Other liquids tanker	28.94 (0.72)			
Ro-Ro	7.12 (0.42)			

Service - other	-3.11 (0.73)			
Service - tug	-3.12 (0.94)			
Vehicle	12.80 (0.44)	20.40** (0.01)	29.59*** (0.00)	77.85*** (0.00)
Constant	5.30*** (0.00)	15.32*** (0.00)	5.67 (0.72)	-1.99 (0.91)
Builder country FE	No	No	Yes	Yes
Contract year FE	No	No	Yes	No
Contract year * IMO type FE	No	No	Yes	Yes
Observations	7272	6303	6303	6303
R^2	0.875	0.905	0.948	0.954
<i>AIC</i>	74352.92	55027.38	51404.74	50778.79
<i>BIC</i>	74594.13	55142.11	51877.16	52034.06

a. FE: fixed effects

b. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

9.5 Analysis of patents

We used the Orbis IP database to identify patents related to the handling and use of methanol, ammonia and LNG in the context of maritime shipping. Given information from our interviewees about the relevance of experience in transporting and handling these fuels (rather than only their use as a fuel aboard ship), we used a broad search strategy that would include, for example, inventions related to the transport of ammonia.

To retrieve relevant patents, we searched for terms related to the fuel of interest (LNG, “liquefied natural gas”, methanol, methyl alcohol etc.) in the abstract, title, claims and description of patents. We based the analysis on patent families, rather than individual patent publications, to avoid double-counting of multi-family patents. In order to focus on patents related to shipping, we restricted the search for LNG and methanol patents using classification codes from the International Patent Classification (IPC) system – specifically patents tagged with B63, which encompasses “Ships or other waterborne vessels; related equipment”. In order to reduce false positives, we then manually reviewed the return lists of patents, and as a result excluded patent codes associated with methanol and ammonia in contexts unrelated to their handling, storage or use as a fuel. These were largely related to petrochemical processing, and were: B01J, C07C, C10G, C01B. This resulted in two lists: an LNG-related patent list, and a methanol-related patent list.

We then examined these lists to identify the extent to which there was overlap between LNG and methanol patents and those related to ammonia. We also then retrieved the forward citations of the two lists. We searched these citing patents to identify those related to ammonia, and then examine the most prominent areas of technology.