Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping

GLOBAL MARITIME FORUM

Global Centre for MARITIME DECARBONISATION

The shipping industry's fuel choices on the path to net zero

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Industry leaders know they must adopt greener fuels in order to decarbonize. Is a multifuel future in store?

Shipping companies—encouraged by regulation, customer demand, investor pressure, and internal goals—are searching for ways to decarbonize their fleets. More than 95 percent of ships today are powered by internal-combustion engines (ICEs) that run on various petroleum products, such as heavy fuel oil (HFO), marine gas oil (MGO), and marine diesel oil (MDO).[1] Any comprehensive effort to reduce emissions will require finding greener fuel to propel vessels across the water.

Greener-fuel possibilities abound in the maritime world (see sidebar, "Future fuel choices"), and the industry is in a period of experimentation and exploration to understand the implications of adopting such fuels. Because adoption at scale will require entirely new value chains to cohere, ship owners and operators, ports, fuel providers, engine manufacturers, shipyards, and other players are looking to one another for clues about where the industry is gravitating. In the meantime, the lack of demand-side signals for greener shipping from policy makers, suppliers of goods, and consumers seeking greener products and services makes it difficult for the industry to move forward with confidence. Apprehensions about the use of greener fuels—involving the potential for health, safety, and environmental concerns; higher costs; lower energy density; new capability requirements for the crew; and limited availability at ports of call—exacerbate these demand-side challenges.

[1] Other terms like low-sulfur fuel oil and very-low-sulfur fuel oil are also used for these fuels. We use the term "fuel oil" throughout the article to represent all of these variants.

Future fuel choices

Several fuels are in focus for the shipping industry. There is almost certainly no one-size-fits-all answer. Many, if not all, of these options could achieve some level of adoption over the next 30 years:

Fuel category	Fuel 'family'	Fuel(s)
Ambient liquid fuels	*Fuel oil and diesel*[1]	**Heavy fuel oil (HFO), marine gas oil (MGO), marine diesel oil (MDO):** Fossil fuels that can only be decarbonized with the use of onboard carbon capture.
		Biodiesel: A "drop in" fuel that burns in existing internal-combustion engines (ICEs), biodiesel can provide up to 50 to 90 percent decarbonization compared with HFO, MGO, and MDO (depending on the feedstock and production process); faces biofeedstock constraints (given that these feed-stocks are also in demand for fuels in other sectors such as aviation); and has limited cost-reduction potential (because the production processes are mature). Second-generation biodiesels, which could boast stronger sustainability credentials than current biodiesels in the market, require further technological maturation (for example, hydrothermal liquefaction, pyrolysis).

[1] E-diesel is also a potential fuel in this family.

Future fuel choices (continued)

Fuel category	Fuel 'family'	Fuel(s)
Ambient liquid fuels (continued)	*Methanol*[2]	**Biomethanol:** Derived from biofeedstocks, biomethanol can be a carbon-neutral fuel (on a "well to wake" basis). There are marine engines today that can burn methanol. It is liquid at room temperature, so it can be handled and stored (helping to counteract the cargo capacity loss from its volumetric energy density, which is lower than that of fuel oil). However, it has a limited cost-reduction potential due to a mature production process.
		E-methanol: Derived from green hydrogen and captured CO_2, e-methanol is more expensive than biomethanol today but will likely become cheaper in the long run (as the costs of renewables and green hydrogen come down). It will always be more expensive than e-ammonia, as the latter is manufactured from nitrogen, which is abundantly available in the air. CO_2 is emitted during e-methanol's combustion, but if sourced from captured biogenic CO_2 or direct-air capture (DAC), e-methanol is generally considered carbon neutral on a well-to-wake basis.
Cryogenic liquefied fuels	*Methane*	**Liquefied natural gas (LNG):** LNG, a fossil fuel, reduces CO_2 emissions versus heavy-fuel oil by approximately 20 percent on a "tank to wake" basis. However, on a well-to-wake basis, the CO_2 emissions from the production and transportation of LNG—coupled with methane slip issues across the value chain—cause LNG to have, in some cases, a worse greenhouse-gas footprint than traditional fuel oil.[3]
		Biomethane/bio-LNG: Derived from biofeedstocks and leveraging existing LNG infrastructure (such as storage, bunkering, and ships), biomethane/bio-LNG can be used to displace fossil-based LNG but can also face methane slip issues. Cost-reduction potential is comparatively limited because production processes are mature.
		E-methane/e-LNG: Derived from green hydrogen and captured CO_2 and leveraging existing LNG infrastructure, e-methane has a similar cost structure to e-methanol (and is likewise more expensive than e-ammonia). CO_2 is emitted during combustion, but if sourced from biogenic CO_2 or DAC, e-methane is generally considered carbon neutral on a well-to-wake basis. It may face methane slip issues during the combustion process, especially in medium-speed four-stroke engines.
	Hydrogen[4]	**Green/blue hydrogen:** Given its disadvantaged volumetric energy density, pure hydrogen—probably in liquefied form—seems most likely to find a market only in short-sea segments such as tugs, ferries, offshore supply vessels, and potentially cruise ships. Hydrogen fuel cells are one possible use case, but they have yet to be stress-tested at scale in a marine environment.
Refrigerated fuels	*Ammonia*[5]	**E-ammonia:** Derived from green hydrogen and nitrogen pulled from the atmosphere, e-ammonia is a truly zero-carbon fuel and has the most attractive costs of any of the "e-fuels" (plus an attractive cost-reduction trajectory as the costs of renewables and green hydrogen come down). However, ammonia is toxic, so leaks and safety are a major concern, and an ammonia engine won't be commercially available until the mid-2020s. Ammonia needs to be stored in refrigerated tanks, which can reduce ships' cargo capacity. Combusting ammonia can create nitrous oxide (N_2O), a greenhouse gas more potent than CO_2, which can be addressed with the use of engine tuning and scrubbers.
		Blue ammonia: Produced via blue hydrogen (autothermal or steam-methane reforming with carbon capture and storage) and nitrogen pulled from the atmosphere, blue ammonia is considered a low-carbon fuel based on the effectiveness of the carbon capture and the fugitive methane emissions in upstream natural-gas production. Its economics are driven by its ability to capture economies of scale, the cost of natural gas, and the cost of carbon capture and storage. Onboard the vessel, it faces the same challenges as e-ammonia (for example, toxicity, engine availability, storage, and potential nitrous oxide emissions).
Other	*Nuclear*	**Nuclear:** The closest thing to zero-carbon shipping on the water today (used in navies and by ice-breaking vessels), nuclear still needs to overcome environmental, regulatory, economic, and societal acceptance issues to be adopted at scale in commercial shipping.

[2] Grey methanol is also a fuel in this family.
[3] Especially when measured on a CO_2-equivalent (CO_2e) basis over 20 years.
[4] Other versions of hydrogen also exist including pink (derived from nuclear power) and turquoise (derived from pyrolysis).
[5] Grey ammonia is also a fuel in this family.

To understand how industry leaders are thinking about future fuels, the Global Centre for Maritime Decarbonisation, the Global Maritime Forum, and the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping recently conducted a survey (with analytical support provided by McKinsey) of 29 shipping companies.[2] Collectively, these companies own and operate fleets—including container ships, tankers, dry bulkers, gas carriers, car carriers, cruise ships, tugs, and offshore vessels—comprising roughly 20 percent of the world's total capacity.[3] Respondents, professionals responsible for the decarbonization efforts of these organizations, were asked about their plans and projections to adopt cleaner fuels and efficiency-boosting technologies.

Many explorations of the green-fuel conundrum take an outside-in approach, using techno-economic modeling to point to future scenarios. This survey takes an inside-out approach by asking industry leaders to state their intentions and expectations.

The survey participants are primarily companies formally affiliated with three large maritime decarbonization entities.[4] These shipping companies tend to harbor more ambitious decarbonization goals than their industry peers, with about half targeting net-zero emissions by 2050.[5] They are, on average, larger than most shipping companies,[6] and their fleets are, on average, younger.[7] Notably, respondents' survey answers indicate that they are planning for decarbonization at a faster pace than the current targets established by the International Maritime Organization (IMO), which is the industry's global regulatory body. Given these facts, respondents' views—and eventual choices—about decarbonization are likely to exert significant influence over the industry.

The snapshot that emerges from respondents' answers portrays a world with many fuels in the mix through 2050. Many respondents expect their fleets to run on multiple types of fuel well into the future. This suggests that shipping's route to decarbonization could be complex—especially given the knotty interdependence between ship owners and operators, ports, engine manufacturers, and fuel providers. How the industry builds out and manages multiple fuel supply chains over the next decades will have a decisive effect on the speed at which it decarbonizes.

But companies that are currently plotting investment strategies might consider viewing this inchoate moment as an opportunity for bold decision making. Multiple fuel pathways continue to be viable, and advantages for first movers are there for the taking. It's worth noting that many companies are already piloting green-fuel alternatives, and an increasing number are beginning to make sizeable orders for vessels that can consume lower-carbon fuels.

The prospect of multifuel fleets

Presently, 46 percent of surveyed companies (12 respondents) say that they've already run pilot programs involving one or more low-carbon fuels (for instance, operating ship engines on biodiesel instead of traditional

[2] The survey was sent to 63 companies, of which 29 responded, and was in the field from October to November 2022.
[3] Measured by deadweight tonnage for cargo vessels and compensated gross tonnage for cruise ships.
[4] Some survey participants are shipping companies not formally affiliated with the three maritime decarbonization entities (Global Centre for Maritime Decarbonisation, the Global Maritime Forum, and the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping).
[5] Fifty-two percent (15 out of 29 respondents) have net-zero by 2050 (or earlier) targets, whereas previous work by the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping found that approximately 17 percent of the top 30 companies in the container, dry bulk, tanker, and roll-on/roll-off segments have set net-zero targets. See *Maritime decarbonization strategy*, Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, December 8, 2022.
[6] The average survey respondent owns 80 vessels and operates 200 vessels. The global maritime consultancy Clarkson estimates there are about 100,000 vessels, 26,000 owners, and 27,000 operators (many companies are both owners and operators) in the shipping industry as a whole, meaning the average owner or operator has about four vessels in its fleet.
[7] The average age of respondents' owned vessels is 6.4 years and operated vessels is 10.4 years, versus a global fleet average of 22.3 years.

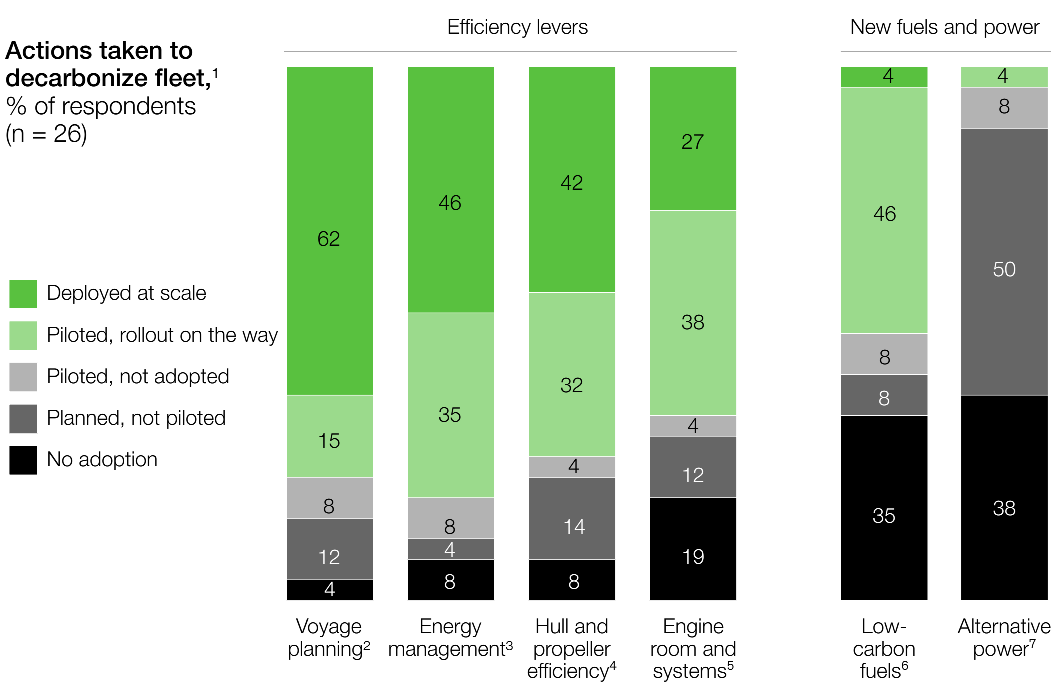
fuel oil) and have established plans for further implementation, whereas 35 percent (nine respondents) have taken no action with regard to greener fuels (Exhibit 1).[8]

It is no surprise, then, that one-third of respondents say that they "don't know" which types of fuel they expect their fleets to run on in 2030 and 2050 (Exhibit 2).[9] The remaining two-thirds of respondents express diverging expectations about what their 2030 and 2050 fuel usage will look like. They project that 66 percent of their fuel consumption in 2030 will be fuel oil, with biodiesel and liquefied natural gas (LNG) representing 10 percent each, and the remaining 14 percent distributed across other fuels.

Respondents' projections for their fleets' fuel consumption in 2050 are split evenly among a wide variety of options: green ammonia, biodiesel, and fuel oil lead the way with 16 to 17 percent of the fuel mix each, followed by blue ammonia, LNG, e-methanol, biomethanol, biomethane, and e-methane each representing a 6 to 10 percent share.

Exhibit 1

Shipping companies report widespread adoption of efficiency levers, but few have taken actions to adopt new fuels and alternative power systems.

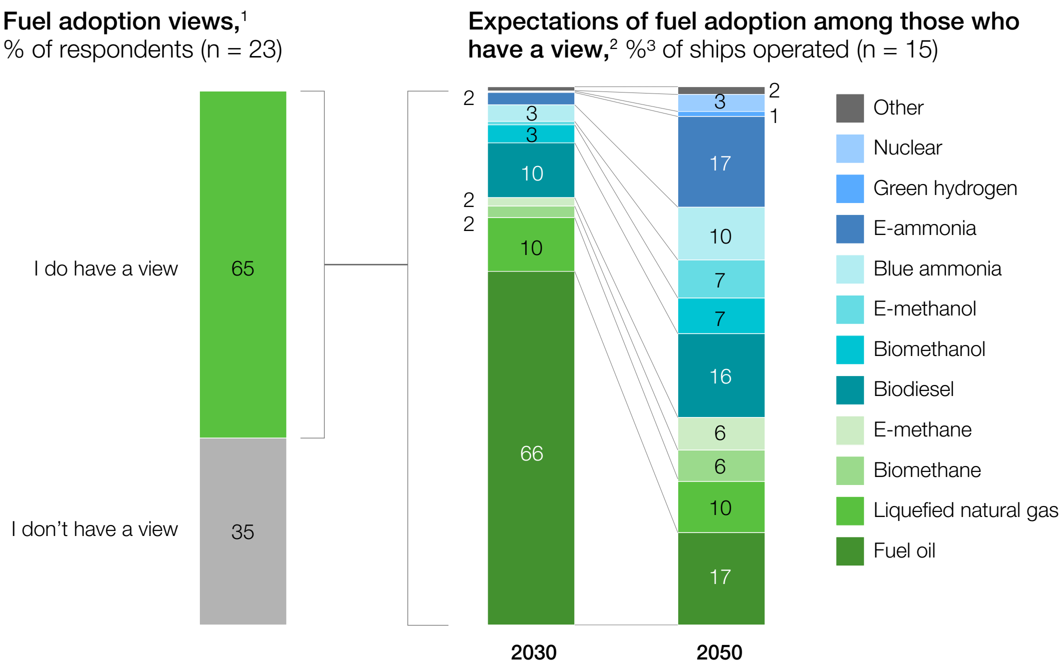


Note: figures may not sum to 100%, because of rounding.
[1]Question: What actions have you taken so far to decarbonize your fleet? [2]For example, weather routing and voyage optimization, trim and draft optimization. [3]For example, speed management and load optimization. [4]For example, air lubrication, hull coating, hull form optimization, propeller cleaning, propeller improvement devices. [5]For example, waste heat recovery, recovery of energy using a shaft generator, machinery improvements, engine derating. [6]For example, biodiesel, bio/e-methanol, e-ammonia, bio-LNG, e-methane. [7]For example, wind assistance, solar panels.
Source: Survey of shipping companies conducted October–November 2022

[8] Out of 27 respondents that answered the question.
[9] Eight out of 23 respondents answered the question.

Exhibit 2

Two-thirds of shipping company respondents have views on what their fuel usage will look like in 2030 and 2050, although expectations vary.



[1]Question: Do you have a view on what types of fuel your fleets will run on in 2030 and 2050?
[2]Question: What is your expectation of your fleet's adoption of the following fuels?
[3]Weighted by fleet size.
Source: Survey of shipping companies conducted October–November 2022

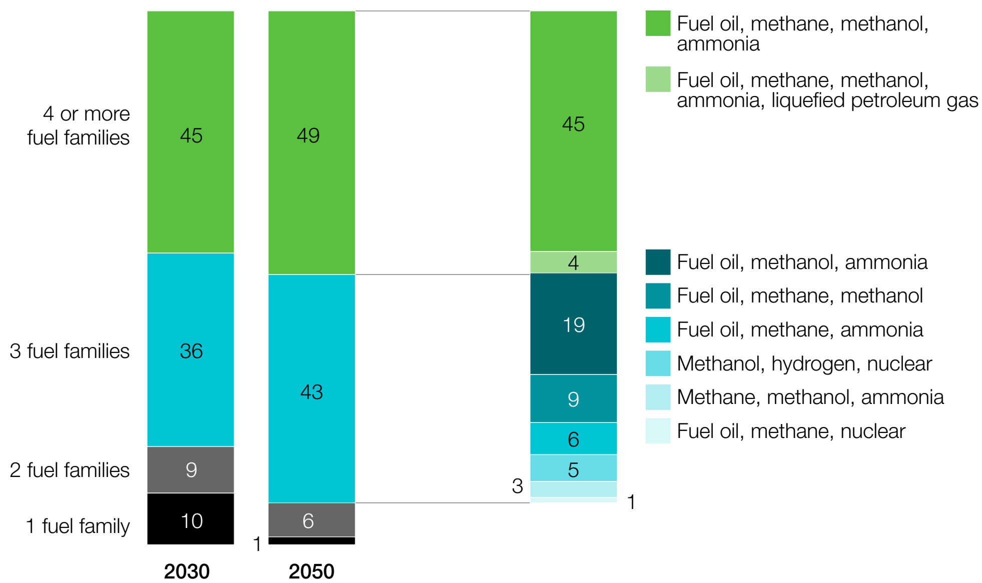
While predicting a company's fuel consumption more than 25 years into the future is fraught with challenge, it is noteworthy that the mix is not the result of each respondent choosing a single "destination" fuel; rather, it is a case of intentional diversification, with each respondent projecting that it will choose to adopt a broad mix of fuels. Respondents also indicate that they expect to spread their own consumption across multiple fuel "families" (Exhibit 3). (The fuel families consist of fuels that ship engines can use interchangeably: for instance, one category comprises heavy fuel oil, marine gas oil, marine diesel oil, and biodiesel, while another category comprises LNG, biomethane/bio-LNG, and synthetic/e-methane/e-LNG.)

By 2050, 49 percent of respondents (weighted by fleet size), expect to adopt four or more fuel families within their own fleets, while another 43 percent expect to adopt three families. The most common scenario projected by 2050 (represented by 45 percent of respondents) is a fleet running vessels simultaneously on variants of fuel oil/biodiesel, methane, methanol, and ammonia. These outcomes would represent a significant increase in complexity over today's fleets, in which managing simultaneous consumption of more than one or two fuel families within a given fleet is rare, and typically manifests as a pairing of fuel oil/biodiesel and methane (in the form of LNG).

Exhibit 3

By 2030, most shipping company respondents expect to use three or more different fuel families, with a similar picture in 2050.

Expectations of fuel families,[1] by fleet,[2] %[3] of ships operated (n = 15)



[1]Fuel families are combinations of interchangeable fuels, such as heavy fuel oil, marine gas oil, marine diesel oil, and biodiesel; liquefied natural gas, biomethane, and synthetic/e-methane; biomethanol and synthetic/e-methanol; green and blue ammonia; green and blue hydrogen; nuclear; liquefied petroleum gas.
[2]Question: What is your expectation of your fleet's adoption of the following fuels?
[3]Weighted by fleet size.
Source: Survey of shipping companies conducted October–November 2022

A step change in fuel diversity

The picture observed at the individual fleet level is mirrored by the portrait painted of the industry as a whole. Asked for their projections about fuel usage across the entire industry, not just within their own fleets, respondents express a collective belief that, after fossil-based fuel oil, biodiesel and fossil-based LNG will be the most commonly adopted fuels by 2030 (Exhibit 4). In the longer term, respondents foresee a diminishing role for fossil-based fuel oil, coupled with the growing adoption of a dramatically expanded range of other choices.

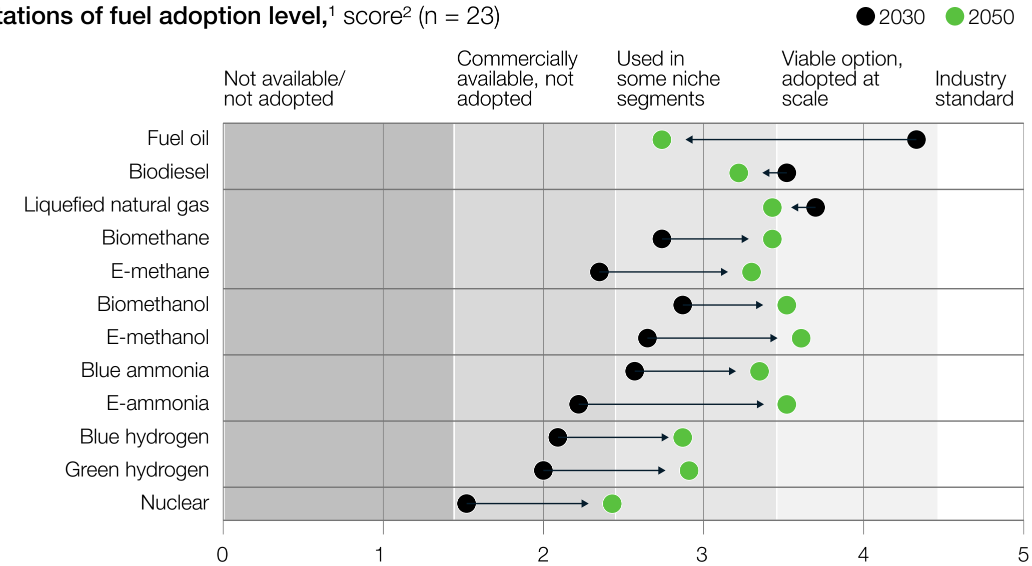
Respondents project that by 2050, biodiesel, LNG, biomethane, synthetic/e-methane, biomethanol, synthetic/e-methanol, and ammonia (both blue and green) could all experience significant uptake—for use in niche segments at the low end and for adoption at scale at the high end. No one fuel has a clear lead over the others, and only hydrogen and nuclear power lagged when it came to predictions about future fuel usage.

This expected proliferation of fuels and fuel families might not reflect a belief among respondents that the fuel consumption mix will be permanently diffused. It might, instead, reflect their ideas about how fuel

Exhibit 4

Shipping company respondents expect fossil-based fuel oil to remain industry standard in 2030 but foresee no industry standard by 2050.

Expectations of fuel adoption level,[1] score[2] (n = 23)



[1]Question: What is your expectation of the industry's adoption of the following fuels?
[2]Scored from 0 to 5, where 0 is no adoption and 5 is total adoption.
Source: Survey of shipping companies conducted October–November 2022

consumption will evolve. At any given point, many families could coexist—but some fuel choices might be in their infancies, while others are on their last legs. Indeed, a likely outcome is that ships built in today's fuel environment could still be in service more than two decades from now, sharing the water with ships built far in the future that incorporate newer fuel concepts and technologies.

When asked about engine types, there is comparatively clear agreement that ICEs—which today can run on fuel oil, methane (in liquefied form), and methanol, with ammonia ICEs available in the near future—will remain the dominant propulsion method for ships well out to 2050 (Exhibit 5). Fuel cell configurations (which use hydrogen or other alternative fuels to produce electricity that can propel ships) are expected to see significant development between 2030 and 2050, but only for use in niche applications.

Accelerating the transition

Making the leap to a greener-fuel future will require decades of work, but our respondents have indicated what they are looking for to accelerate the transition (Exhibit 6). More than 80 percent of respondents indicate that the following four developments would be most transformative:

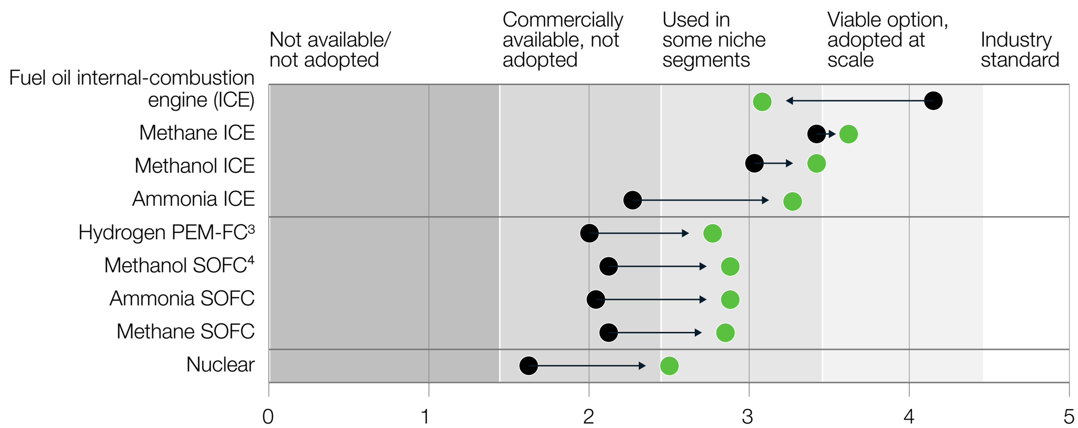
— greater availability of alternative fuels

— cost reductions for alternative fuels

Exhibit 5

Respondents foresee internal-combustion engines remaining the preferred technology for ships through 2050, with fuel cells moving into niche segments.

Shipping company expectations of engine technology adoption,[1] score[2] (n = 26)



[1]Question: What is your expectation of the industry's adoption of the following fuels?
[2]Scored from 0 to 5, where 0 is no adoption, and 5 is total adoption.
[3]Proton-exchange membrane fuel cells.
[4]Solid-oxide fuel cell.
Source: Survey of shipping companies conducted October–November 2022

— customer willingness to pay a "green premium"

— regulatory change

Survey respondents indicated that their top priorities are for fuel providers to bring alternative-fuel projects to final investment decisions and to commence commercial operations while bringing down the cost of those fuels as they scale. Dual-fuel engines can reduce the risk of a vessel not having access to a fuel that will enable it to sail, but shipping companies need greater clarity on when, where, and at what cost alternative fuels will be available. There is also a catalytic role that regulators could play by helping to underwrite and accelerate alternative-fuel providers' projects in a manner that would bolster the shipping industry's confidence in the future availability of fuels.

Another major factor identified by respondents was customers' willingness to pay a green premium (while there is a cost gap between greener fuels and fossil fuels). This willingness to pay could help defray some of the potential risk to shipping companies of adopting more expensive greener fuels faster than their peers.

For the same reason, the final factor—regulatory change—is critical: regulation creates a level playing field, so all shipping companies have the same incentives to adopt greener fuels within their fleets.

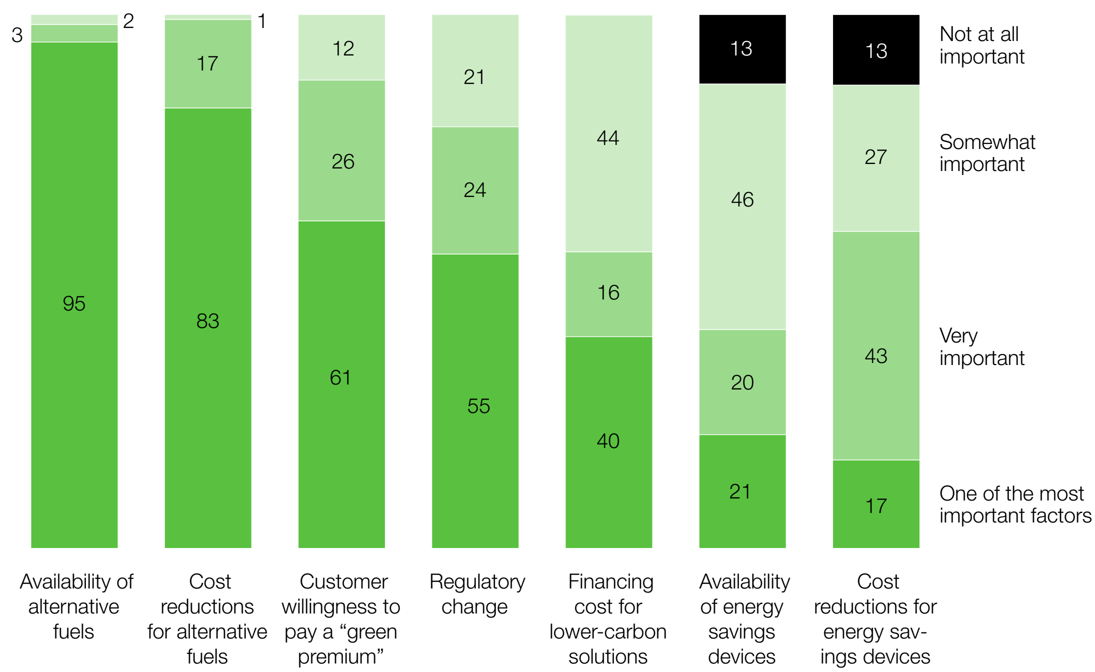
Implications of a multifuel future

Various players can glean different insights from these survey results. Here we offer potential takeaways for each group of stakeholders.

Exhibit 6

Fuel availability and cost, customer willingness to pay, and regulatory change are top priorities for shipping companies.

Factors influencing adoption of alternative fuels,[1] %[2] of ships operated (n = 15)



[1]Question: How important is it to resolve the following uncertainties in order for you to take (further) action on adopting alternative fuels?
[2]Weighted by fleet size.
Source: Survey of shipping companies conducted October–November 2022

Shipping companies. The most striking result from the survey is that shipping companies expressed a need to prepare for fleets that simultaneously run on three or more families of fuels. This implies a need to think strategically about when to introduce each fuel family to the fleet (a delicate balance of costs, decarbonization effects, and availability), how to create optionality in the fleet through dual-fuel and tri-fuel designs, and the reconsideration of networks and operating profiles to match the availability of fuels.

This need not cause paralysis. Mechanisms such as green corridors (specific trade routes established between ports equipped to handle future fuels), multiyear offtake agreements (contracts assuring stable demand for certain fuels), and public-sector partnerships could help reduce risk and thus encourage experimentation and adoption.

Meanwhile, if they have not already done so, shipping companies can immediately move to adopt efficiency-boosting techniques and technologies, which provide near-term benefit with little downside risk. Improving the efficiency of the fleet also hastens the day when greener fuels can be adopted at a competitive cost.

Shipping companies should strongly consider doing more to encourage among their customers a greater willingness to pay for green shipping services.

Crucially, shipping companies should strongly consider doing more to encourage among their customers a greater willingness to pay for green shipping services. More transparency about the life cycle greenhouse-gas footprint of different fuels might help give customers confidence to pay for greener services, potentially paired with a "book and claim" system to ensure integrity.[10]

Fuel producers. Future fuel scenarios will be determined by both the demand side and the supply side. Choices made by fuel providers will play a major role.

The speed of the shipping industry's adoption of alternative fuels will be a function of the cost gap between green and fossil fuels and the degree of availability of green fuels at a plethora of worldwide ports.[11] Of course, some fuel producers are already working hard to bring down costs and offer clarity about when and where new fuels will be available. There may be further scope for partnerships between multiple fuel producers and bunkering providers—offering joint road maps that delineate when and where certain fuel types will be available at which ports, thereby boosting shipping companies' confidence.

The central question for fuel producers, then, is how to scale their production in line with those aspirations. Many green-fuel projects expect multiple industries to provide the demand that will render them bankable, which may misalign project timetables with the shipping industry's needs. A closer dialogue between fuel producers and shipping companies can help, and fuel producers will likely need to work closely with first movers in the shipping industry to strike offtake deals that fairly balance risks and commercial terms between the parties.

Ports (and the bunkering companies that operate within them). Ports and bunkering providers might prioritize making individual fuels available in the near term—due to the existence of nearby production facilities, participation in green corridors that require use of particular fuels, or national decarbonization plans and incentives. And in the longer term, some ports might continue to specialize in specific fuels in service of individual shipping segments. But, based on these results, ports that wish to attract the greatest possible number of future vessels to their quays should prepare for the possibility that they'll need to offer a panoply of fuel types.

Policy makers and regulators. The single most important factor in fuel choice will likely be the rate of decarbonization required by regulators. To the extent that operating multifuel fleets creates duplicative investments in fuel supply chains, early clarity about target rates and levels of decarbonization can help decrease the risk of stranded assets.

[10] See, for example, "Accelerating maritime decarbonisation: A book and claim chain of custody system for the early transition to zero-emission fuels in shipping," Global Maritime Forum, March 2023.
[11] Fuel availability for shipping companies will also be a function of the demand for alternative fuels from other sectors, potentially with a higher willingness to pay than in the shipping industry.

Policy makers and regulators can also help close the cost gap between green fuels and fossil fuels (as recent policies in the United States and the European Union aim to do) and create a level playing field for all shipping companies as they endeavor to adopt green fuels (a goal the European Union has begun work on as the IMO considers global measures).

Other paths to a greener-fuel future could include a move toward well-to-wake carbon accounting of fuels (an approach that measures the greenhouse-gas footprint of both the production process and the consumption of fuels), and clearer safety, handling, and operating guidelines for less-developed fuel options (such as ammonia and nuclear).

This survey paints a striking multifuel portrait of the industry's future. The onus is on each shipping company to form its own view of its future fuel mix in line with its business strategy and decarbonization ambitions. We intend to monitor how views change over time—and to observe whether a multifuel future persists or eventually resolves with particular solutions.

In the world suggested by these survey answers, the role of first movers—and of entities that can galvanize entire value chains, from fuel production to a vessel's consumption—will be vital. Organizations that lead the way might provoke and shape others' actions, catalyzing investments that create their own momentum and, over time, perhaps result in the inevitability of a specific fuel scenario.