Mærsk Mc-Kinney Møller Center
for Zero Carbon Shipping

Transition Outlook

Modeling shipping's decarbonization potential under four global scenarios

Enabling the transition, November 2026

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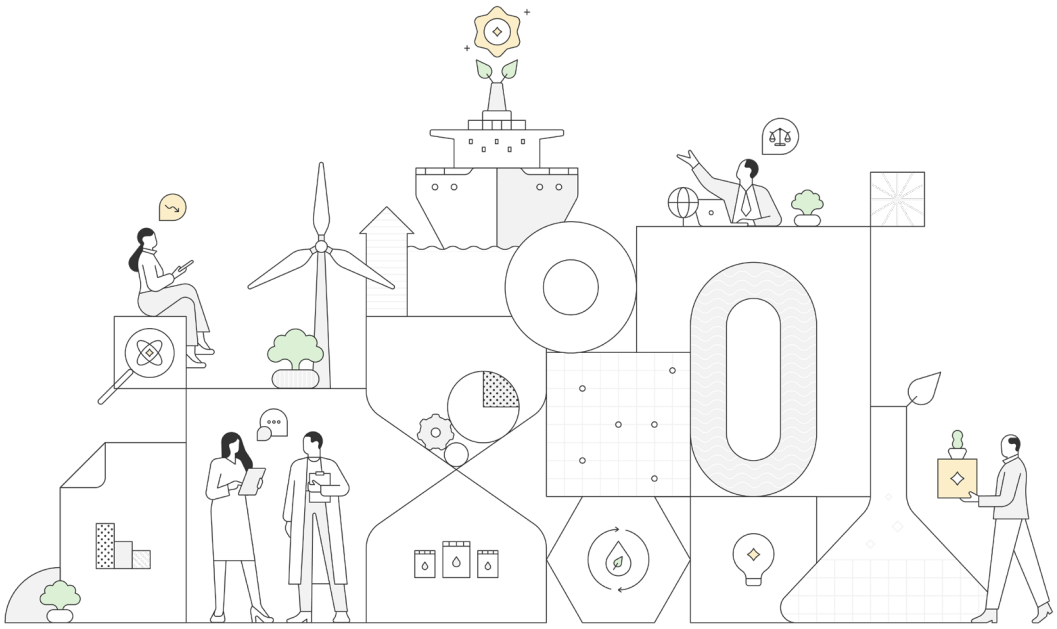

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Preface

Six years ago, the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) was established with a mission to accelerate sustainable decarbonization of the global shipping industry. Since then, this mission has only become more urgent, with our planet still at risk of abrupt or irreversible climate changes. At the same time, the incentives to invest in low-emissions technologies and fuels are growing, as countries aim to capture economic opportunity and reduce dependence on fossil energy sources. Shipping's energy transition faces both a challenge and an opportunity.

This report asks a simple question: if the global shipping industry faced a binding incentive to decarbonize, could it technically achieve net-zero? Building on data about today's technologies and tomorrow's energy supplies, we conclude that the answer is yes.

We reach this conclusion by studying a range of plausible global scenarios. Across these, we vary factors that collectively make it harder or easier for the industry to decarbonize, like how much low-emissions fuel the world will make and how much of it can be used to power shipping. By looking across these scenarios for paths converging to net-zero, we can move from asking if the transition is possible to uncovering insights about how it can unfold.

We find that decarbonization would require us to deploy energy efficiency measures at scale, use direct electrification wherever possible, invest early in dual-fuel vessels, and use a mix of low-emissions energy sources – ranging from sustainable biofuels in the nearer term to scaling ammonia in the future.

Achieving our goal ultimately means using lower-emissions energy that is more expensive than the fossil energy we rely on today. In part, this is because fossil fuels don't pay for the climate-related damage they cause. With that said, if the industry converges towards net-zero using the pathways we model, the increase in shipping costs in 2050 is smaller than many might assume.

These findings rest on modeling a simplified version of the world. The inputs to our analysis reflect what we know today about important but uncertain factors like future energy costs, resource availability, and technology scalability. We assume incremental technological developments, but do not include radical breakthroughs that cannot yet be anticipated. If more low-emissions energy becomes available sooner or costs less, we can cut emissions even faster and more cheaply. As we learn more, especially about which energy sources scale and at what cost, our paths to zero will shift.

All in all, this paper substantiates that the known technological solutions are sufficiently mature and available to enable decarbonization towards 2050. Decarbonization is technically possible. But if it were easy, or cheaper than business as usual, our work would already be done.

In the short time since the MMMCZCS was established, most of the necessary technical solutions and frameworks for decarbonization have been developed and demonstrated. The industry has developed standards and frameworks to regulate the use of new fuels. Many new fuel types are being produced and used at full scale, with the first large commercial ships running on ammonia as a fuel in 2026 – just an idea on paper six years ago. Energy efficiency has proven its value and has even greater potential yet to be fulfilled. With effective global regulatory frameworks, these solutions can be brought into industry-wide use: the sooner the better.

Executive summary

Decarbonizing shipping is difficult. It is a hard-to-abate sector because reducing emissions beyond what can be achieved with energy efficiency or direct electrification requires switching to energy sources that have lower emissions but are more expensive than fossil fuels.

However, "hard" does not mean "impossible" or "infeasible." This analysis shows that, under a credible global decarbonization incentive and robust life-cycle emissions accounting, strong emissions reductions are feasible without extreme increases in unit transport cost. This conclusion is based on modeling a transition toward net-zero greenhouse gas (GHG) emissions from shipping by 2050, across four scenarios for how the global energy system could develop.

Our analysis is not a forecast, but a test of what the transition looks like when certain prerequisites are in place. Our model, Navigate, combines tens of thousands of data points and assumed values for critical inputs such as the scalability, cost, and emissions intensity of fuels. This enables us to simulate the evolution of the global fleet and the production and use of new fuels, giving a higher market share to cost-efficient and scalable technology options.

We consider four different scenarios, each reflecting different global developments. What is held constant across all scenarios is shipping's incentive to reach net-zero by 2050. The key insights we find across the scenarios are:



Energy efficiency is the most cost-effective lever.

Efficiency measures replace up to 35% of energy consumption by 2050 across all scenarios, with the lowest abatement cost among all decarbonization solutions. Capturing the full potential requires both technical measures (e.g., hull coatings, air lubrication, waste heat recovery) and operational measures (e.g., speed management, just-in-time arrival).



Direct electrification offers some of the lowest abatement costs.

Shore power and battery-electric propulsion for short-sea and regional shipping are robust decarbonization strategies across all four scenarios. Direct electrification avoids fuel conversion losses, making it one of the most efficient pathways in both cost and energy terms, where operationally feasible. Making it available to shipping at scale will involve substantial infrastructure build-out.



Early investments in dual-fuel propulsion offer lower total transition costs compared to waiting or retrofitting later.

Across all scenarios, the model shows that the cost of the transition is minimized if all new vessels built from 2030 onwards can operate on low-emissions fuels. Delaying this inflection point to e.g., 2035 forces additional expensive retrofit catch-up to reach the 2050 target – and even then, puts net-zero by 2050 at risk. The orderbook decisions made today will determine whether 2050 targets remain achievable through natural fleet renewal, or will require scrapping stranded assets.



Shipping's decarbonization uses a diverse mix of energy sources.

The fuel mix remains diverse throughout the transition. The amount of suitable biomass, and shipping's access to it amid cross-sector competition, is uncertain: greater access raises the share of biofuels and lowers the share of other fuels. Under our conservative assumptions that suitable

biomass is contested, low-emissions ammonia and biomethane would see high uptake in 2050 across all four scenarios. Biomethane has one of the lowest abatement costs and enters the mix early, but its supply is limited; ammonia's availability could grow over time, provided upstream emissions are tightly controlled. A significant share of 2050 demand is met by other pathways – ethanol, methanol, diesels, other carbon-bearing e-fuels, and electrification – and fossil fuels phase out gradually.



Life-cycle emissions control determines whether the fuel transition delivers real emissions reductions.

The same fuel molecule can carry a very different well-to-wake GHG footprint depending on its production pathway. The pathways in this report assume credible life-cycle emissions accounting and enforcement, covering e.g., blue ammonia upstream emissions, biofuel feedstock sustainability, and renewable electricity and biogenic CO_2 for e-fuels. Without this control, the emissions reductions that fuel switching can theoretically deliver are unlikely to materialize.



Transport costs rise moderately across all scenarios.

Across the four scenarios, total transport expenses per cargo mile (including vessel investment costs, fuel costs, and emissions compliance costs) rise to 1.2-1.4x by 2050 compared to today across the three largest segments: bulk, container, and tanker. This is equivalent to a compound annual growth rate (CAGR) of 0.7–1.4%. The cost premium of low-emissions fuels and more efficient vessels is moderated by the fact that most of the cost of owning and operating is broadly similar across propulsion systems. More coordinated scenarios carry lower investment risk and therefore lower transport costs.

These findings rest on a few prerequisites that apply across all four scenarios. These define the conditions under which the model results hold, and outside of which they do not:

Prerequisite 1: A decarbonization incentive reaches the global fleet.

We impose an incentive to reach net-zero by 2050 across all scenarios. This means there is a sufficient cost of emitting GHGs so that there is a business case for using efficiency improvements and lower-emissions energy. Without such an incentive – whether through regulation, carbon pricing, customer pull, or equivalent – fossil fuels remain the cheapest option, and the fuel-switching dynamics we describe do not materialize.

Prerequisite 2: Emissions are tracked accurately and on a well-to-wake basis.

The incentive in Prerequisite 1 must apply to the actual GHG footprint of each fuel, from production to combustion. Without credible well-to-wake accounting, low-emissions fuels lose their advantage as sources of emissions abatement, and reported emissions diverge from real-world climate impact. Fulfilling this prerequisite will require a shift from current practice.[1]

Prerequisite 3: Trade growth is the same across scenarios.

We assume the same trade growth across scenarios in each year. This trade growth varies across segments in the range of 1-2.5% CAGR from 2026 to 2050. Holding trade growth constant lets us focus on technical and systemic requirements and compare pathways on a like-for-like basis. We do not model feedback in which changes in fuel costs change trade demand.

Prerequisite 4: The dual-fuel ramp-up depends on industrial capacity for scaling fast.

To realize the modeled pathways, an entire industry needs to implement large-scale changes on a relatively short timeline. We have aimed to model some of the most important constraints in the capacity expansion of fuel production and infrastructure. Further constraints in shipbuilding, equipment manufacturing, and other supplies are not modeled. These could also impact the speed of the transition.

Our overall conclusion is clear: given an incentive to decarbonize, radically cutting emissions from shipping is feasible under realistic assumptions about the cost and availability of low-emissions energy.



01 Introduction: Decarbonization in a changing world

1.1 Why we need this analysis

Decarbonizing maritime transport by 2050 requires two shifts: reducing total energy demand through energy efficiency solutions, and replacing fossil fuels with low-emissions energy sources.

While shipping can increase uptake of energy efficiency solutions independently of other sectors, replacing fossil fuels does not depend on shipping alone. The pace of renewable electricity expansion, the availability of suitable biomass, the scaling of hydrogen-derived fuels, and the stability of capital markets all shape how this replacement can happen, and when.

Accordingly, instead of showing what the transition looks like under just one of many possible future worlds, this analysis outlines maritime decarbonization's pathway across four substantially different scenarios for how the global energy system could develop.

The framing constraint for our analysis is the presence of a sufficient incentive that makes it attractive for shipping to use lower-emissions but higher-cost abatement options, beginning with biofuels and transitioning to more expensive energy sources over time. In parallel, the incentive drives increasing adoption of energy efficiency measures over time. We describe this as "holding the net-zero by 2050 ambition constant."

This approach allows us to cleanly identify developments that appear consistently across the four scenarios we model – in other words, the elements of the maritime transition that hold regardless of which world materializes. These common features are the developments that shipowners, energy producers, and other industry stakeholders can use to ground their decisions without committing to a single forecast. While the four scenarios we model cannot encompass every possible future, they do cover a range of realistic possibilities.

1.2 Current context for the transition

Over the past five years, the industry's understanding of maritime decarbonization has matured. For the purposes of our current analysis, we can identify seven key system-wide developments that describe the world as it stands today. Some of these features are enablers, raising the feasibility of the transition; others are rate-limiters, raising the cost or lowering the pace at which we can achieve hard-to-abate decarbonization at scale.

Technical and business solutions are available or fast maturing. Engine and infrastructure solutions for low-emissions maritime operation have moved from concept to commercial availability. Low-emissions methanol and methane solutions operate commercially,[2] and a wide range of energy efficiency technologies are available to the industry.[3,4] Developers have trialed ammonia-fueled operations, and the first ammonia-fueled deep-sea vessel entered commercial operation in 2026.[5] Credible insetting of maritime emissions exists, and other business frameworks to support decarbonization are available or being developed.[6]

Renewable electricity and electrification have scaled rapidly. Solar energy, wind energy, and battery deployment have expanded faster than anticipated.[7] Falling costs reinforce electrification across much of the global economy,[7] strengthening the case for investing in infrastructure to facilitate direct electrification in transport and industrial segments, and reshaping which sectors compete with maritime for limited fuel supplies.

Energy resilience is a structural driver of renewable energy expansion. Energy security and industrial competitiveness have become central to energy policy worldwide.[8] Many governments increasingly see decarbonization of power production as a path to energy resilience and

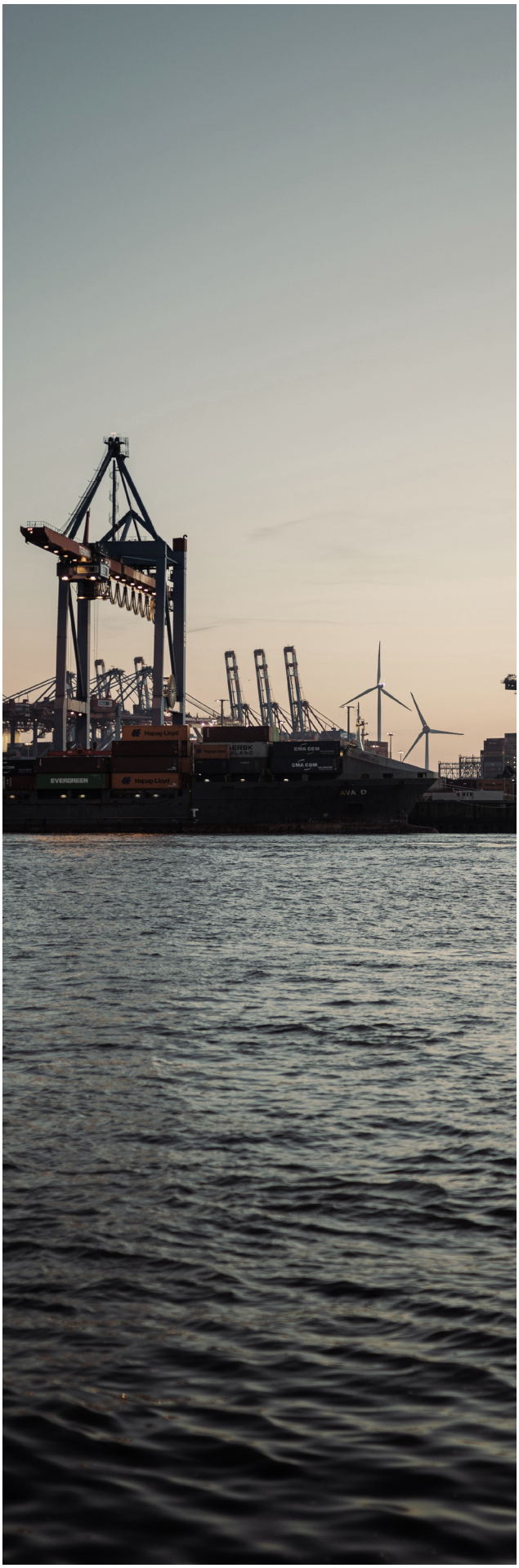
strategic autonomy.[9] Renewable energy expansion now looks like a durable trend, no longer dependent on climate ambition alone.

Hydrogen and e-fuels face scaling challenges. Technology pathways for hydrogen and e-fuels are viable, but large-scale deployment has moved more slowly than previous projections suggested.[10] Investment decisions are waiting for credible demand signals and durable policy frameworks.[11]

Biomass is finite and likely contested. Waste-based biomass and biogenic carbon are scarce resources, in demand by multiple hard-to-abate sectors.[12, 13] This means that biofuels and carbon-bearing e-fuels could face greater feedstock availability challenges than other fuel pathways. Industry currently treats these fuels as strategic and scarce, sharpening cross-sector competition.

The financing landscape has shifted. Higher interest rates and greater project risk scrutiny have raised the cost of capital for low-emissions fuel and infrastructure projects, affecting deployment timelines for capital-intensive investments across the energy transition.[14]

The voluntary market is limited. Despite growing awareness and the impact or potential impact of regulation, current and forecast voluntary demand for low-emissions shipping services appears too limited to be a significant driver of decarbonization.[15]



02 Analytical approach: scenarios and method

This section sets out how we define the four scenarios for how the global energy system could develop, varying the conditions outside the industry's control. The system-wide developments listed in Section 1.2 are the shared starting point for all four scenarios, and hold regardless of which scenario materializes.

2.1 The value of scenario analysis

The question we seek to answer is not only whether shipping can decarbonize, but also how it can decarbonize as the surrounding world evolves differently. Across all four scenarios, we assume that the maritime sector pursues net-zero GHG emissions by 2050. Holding the decarbonization objective constant allows us to isolate the conditions that enable or constrain the transition.

Beyond this, the future is uncertain. Will governments coordinate climate policy globally, or will regions pursue divergent approaches? Will renewable electricity and green hydrogen scale fast enough to displace fossil fuels across hard-to-abate sectors by 2050? And will competition for biomass rule out biofuels for shipping? The answers to these questions and others will jointly determine the availability, cost, and characteristics of the energy available to the shipping industry.

We therefore use scenarios not as predictions, but as lenses for testing robustness. Each scenario represents a plausible future for the global energy system, shaped by forces largely outside maritime's control.

Running the same maritime decarbonization analysis across all four scenarios lets us identify the pathways that keep appearing regardless of scenario conditions. We consider findings that hold across all four scenarios to be robust. Findings that change across scenarios reveal where uncertainties outside the sector's control matter most.

2.2 Building four global scenarios

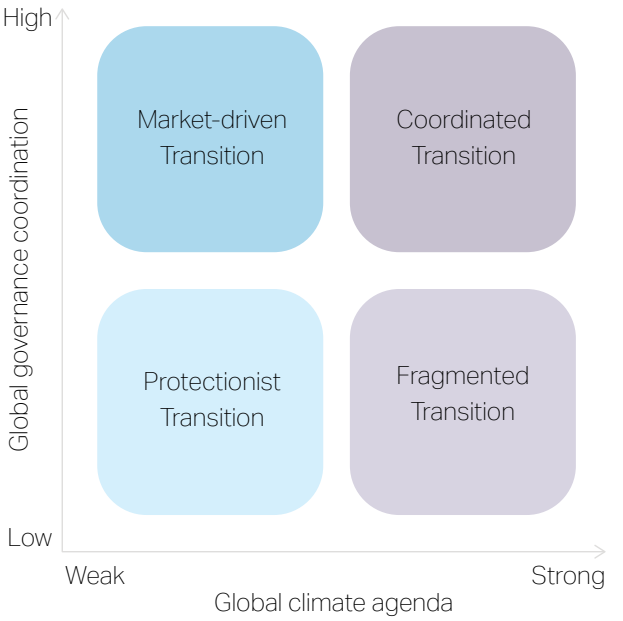
We examine four scenarios defined along two global change dimensions: the strength of the global climate agenda, and the degree of international governance coordination (Figure 1). Both dimensions describe developments outside maritime's direct influence, yet both profoundly shape the conditions for maritime decarbonization.

Global climate agenda reflects the strength of national commitments, regulatory frameworks, and policy instruments aimed at reducing GHG emissions. A strong climate agenda drives demand for low-emissions energy across sectors. A weak climate agenda means the energy transition continues, but is driven by market competition and energy security rather than climate considerations.

Global governance coordination reflects the degree of international cooperation in implementing climate and energy policies, standards, and infrastructure. High coordination enables aligned markets and globally compatible regulatory frameworks. Low coordination leads to fragmented regional approaches with uneven infrastructure development.

These two dimensions intersect to produce four scenarios, each a distinct combination of climate ambition and coordination. Together they span a wide range of plausible futures, from aligned global climate action to fragmented, security-first approaches.

Figure 1: Four global scenarios describing the broader developments that shape maritime decarbonization.



In turn, each scenario implies a different combination of the states of three boundary conditions: biomass availability, low-emissions hydrogen industrialization, and investment certainty. These boundary conditions determine whether and how the maritime sector can decarbonize.

We identified these conditions by testing a long list of model assumptions in dedicated sensitivity analyses, identifying those with the greatest influence on the shape and cost of the transition, and bundling the most influential into three areas:

- **Biomass availability for shipping** determines the maximum uptake of biofuels and depends on cross-sector competition for biomass. When biomass availability is high, it can cover a large share of shipping's energy demand. When biomass availability is low, cross-sector competition limits shipping's access to energy from this feedstock. Variation in this condition changes which fuels dominate the modeled maritime fuel mix.
- **Low-emissions hydrogen industrialization** determines the availability and cost of hydrogen-derived fuels (e-ammonia, e-methanol, e-diesel, blue ammonia) and depends on the development of the market for hydrogen-derived fuels outside of shipping. When low-emissions hydrogen industrialization is high, this hydrogen and its derivatives scale rapidly enough to play a key role in supplying maritime. When it is low, deployment lags and costs remain elevated, leading to lower use of hydrogen derivatives in shipping.
- **Investment certainty** determines the cost of capital and the pace at which new vessels can be deployed. It depends on the perceived risk in investments in decarbonization solutions. Stable policy and financial conditions increase investment certainty, enabling rapid capital deployment, while high uncertainty raises the cost of capital and slows infrastructure buildout. Investment certainty therefore shapes how quickly the fleet and its supporting infrastructure can transition.

These boundary conditions determine the characteristics and feasibility of the maritime transition. (For our definitions of the fuel pathways referred to throughout this report, see the **assumptions appendix**).

Putting together these global change dimensions and boundary conditions, we can describe four scenarios (Figure 2). Each of these scenarios represents a plausible set of energy system conditions that maritime may need to navigate as it transitions to net-zero.

By fixing the ambition, we can see what paths toward net-zero would look like in each scenario, including how much harder or costlier it becomes when the surrounding conditions are unfavorable. The results should therefore be read as conditional: this is what the transition would require if the industry pursued it.

Figure 2: Four global scenarios that could shape the maritime transition to net-zero.

Market-driven Transition

Climate ambition is weak, while international cooperation focuses on trade stability and cost-effective energy supply chains.

Medium investment certainty
Projects that compete on cost attract capital, but low-emissions projects must do so without strong climate-driven demand.

Low hydrogen industrialization
Low-emissions hydrogen industrialization advances slowly, pulled by industrial uses rather than fuel switching.

High biomass availability
Limited cross-sector competition leaves shipping with high access to biomass.

Coordinated Transition

Governments align regulatory frameworks and industrial policies to drive global decarbonization.

High investment certainty
Investment certainty is high, as coordinated rules give capital markets a clear long-term direction.

High hydrogen industrialization
Low-emissions hydrogen industrialization scales rapidly under combined climate demand and stable financing.

Medium biomass availability
Cross-sector competition for biomass is strong, but coordinated allocation gives shipping a medium share.

Protectionist Transition

Both climate ambition and international coordination are weak.

Low investment certainty
Governments make energy decisions based on national security and economic competitiveness, leading to low investment certainty for cross-border transition projects.

Low hydrogen industrialization
Low-emissions hydrogen industrialization stalls outside of strategic national programs.

Low biomass availability
Biomass mobilization is limited and prioritized for domestic energy security, leaving shipping with low biomass availability.

Fragmented Transition

Climate ambition is strong, but countries pursue decarbonization through regional and national targets.

Medium investment certainty
Investment certainty is moderate, dampened by inconsistent rules across regions.

Medium hydrogen industrialization
Low-emissions hydrogen industrialization advances unevenly, with production hubs in some regions and supply gaps in others.

Low biomass availability
Cross-sector competition for biomass is strong, and weak coordination leaves shipping with low access.

2.3 The modeling environment

We model the maritime transition using Navigate,[16] an open-source integrated assessment model that simulates how the global fleet may evolve under different conditions. Navigate simulates fleet evolution (e.g., vessel ordering, fuel uptake, technology adoption) over time, under the boundary conditions defined by each scenario set out above.

We assume that shipping operates much as it does today, and that the transition draws on technologies that already exist or have a clear line of sight to commercial availability within a few years. This means that we do not include, for example, potential future breakthroughs such as fusion energy or fully autonomous vessels. Some incremental technologies, such as onboard carbon capture and storage (OCCS) and onboard nuclear propulsion for commercial use have also not been included in this analysis. Their exclusion reflects the current boundary of our modeling, not a judgment on these technologies' potential. For business models, we hold vessel utilization, trade routes, and ship sizes broadly constant; we do not, for example, reduce the number of ballast legs.

We model a decarbonization incentive as a global fuel standard: the well-to-wake GHG intensity of the energy the fleet uses must decline over time, reaching net-zero by 2050. The rate of reduction is dynamically determined based on fuel scalability and the cost of emissions set sufficiently high to incentivize all fuel pathways. We do not replicate the detailed mechanics, rates, or penalty levels of any specific regulations, nor the regional measures and customer pull that may also incentivize the transition.

When this decarbonization incentive exists, economically rational operators adopt lower-cost abatement options first, subject to availability constraints. As such, the abatement cost curve or merit order is the core logic driving our results. Specifically, the merit order describes how the cost of avoiding one tonne of CO_2eq compared to the fossil fuel baseline differs across measures and fuels. This logic explains why energy efficiency always appears first (lowest cost, no supply constraint), why biomethane is attractive but with uptake varying by scenario (low cost, limited supply), and why low-emissions ammonia emerges as a primary scalable fuel (low or moderate cost, few supply constraints).

Underlying this merit order logic are energy costs, such as the cost increase required to reduce (abate) emissions from moving from a cheaper fossil fuel to a relatively expensive and lower-emissions energy carrier. By their nature, our inputs mainly comprise modeled production costs. Given our long-run horizon, we do not simulate short-run price dynamics, applying the logic that long-run prices reflect marginal production costs.

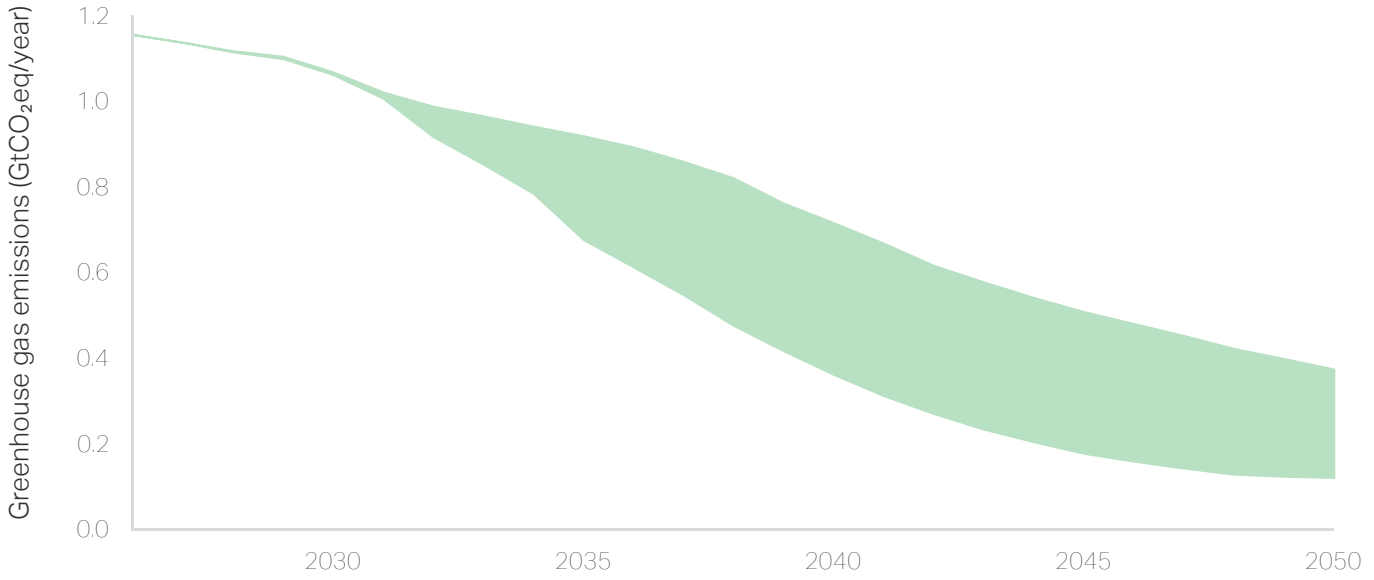
Because it becomes increasingly costly to abate the last few tonnes of GHG emissions, our model accepts some residual emissions from shipping (in the range of 10-32% across simulations – see Figure 3). These reflect a combination of "actual" residual emissions (e.g., from fuel production and transport) and artifacts caused by the model's granularity limits. To reach net-zero in 2050, shipping can address these residual emissions through e.g., offsetting outside the shipping sector, or using higher-cost abatement solutions within the sector. As an indication, we can estimate that abating these residual emissions using direct air capture and permanent storage of carbon – the option with the highest abatement cost in our model – would add around 5% to our estimated impact on overall shipping costs in 2050 (see Section 3.6). This additional cost would be reduced if cheaper abatement or offsetting solutions become available.

The merit order should not be read as a deterministic optimization. Navigate is a simulation model, not a cost-minimizing model: at each decision point, solutions gain market share in proportion to their cost-competitiveness (a discrete-choice logic). Lower-cost options are adopted more and earlier, but no single option "wins" outright. Further documentation for Navigate is available on the Center website.[16]

03 Cross-scenario insights

Across all four scenarios, a consistent set of developments appears as part of the trajectory towards maritime net-zero by 2050. We consider these robust developments, because they emerge regardless of how the surrounding world develops.

Figure 3: Modeled GHG emissions over time (5th-95th percentile range of uncertainty, across all scenarios).



3.1 Energy efficiency is the foundation

Energy efficiency is the most robust decarbonization lever in the analysis. Across all four scenarios, our analysis shows energy efficiency measures replacing up to 35% of onboard energy consumption by 2050, with little variation between scenarios. In absolute terms, this is ~7 EJ of avoided energy. In other words, we estimate that the fleet would require ~19 EJ in 2050 without these energy efficiency measures; with energy efficiency implemented, this is reduced to ~11.5 EJ (see **assumptions appendix** for further detail).

The underlying economics are intuitive: most energy efficiency measures have the lowest abatement costs among all decarbonization solutions.

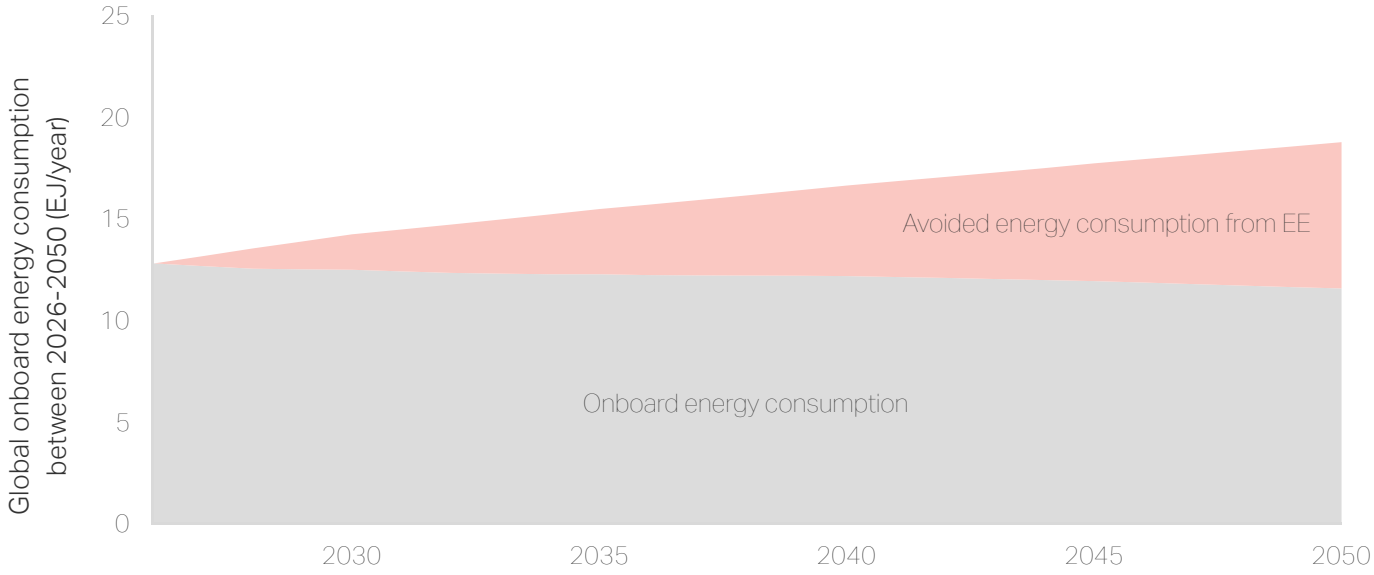
As a result, they appear first in the merit order regardless of scenario conditions, because they reduce total energy demand without requiring new fuel supply chains. Every unit of energy saved through efficiency is a unit the industry avoids having to produce, transport, and bunker as low-emissions fuel.

Energy consumption per voyage can be reduced using both technical solutions (e.g., hull coatings, air lubrication, propeller optimization, waste heat recovery) and operational solutions (e.g., speed management, just-in-time arrival, voyage optimization). Both types are needed to achieve the full 35%.

The uptake of energy efficiency solutions is consistent across all four scenarios because the net-zero goal we hold constant makes it the lowest-cost lever in every scenario. Energy efficiency regulations[17] could accelerate the same result.

On this basis, energy efficiency is a no-regret decarbonization investment, regardless of how the surrounding world develops. At the same time, realizing this potential will require aligned incentives that allow vessel owners and charterers to share costs and benefits.[18]

Figure 4: Energy efficiency uptake over time, measured in avoided onboard energy consumption relative to total fuel consumption. Energy efficiency uptake does not vary across scenarios.



3.2 Direct electrification offers some of the lowest abatement costs

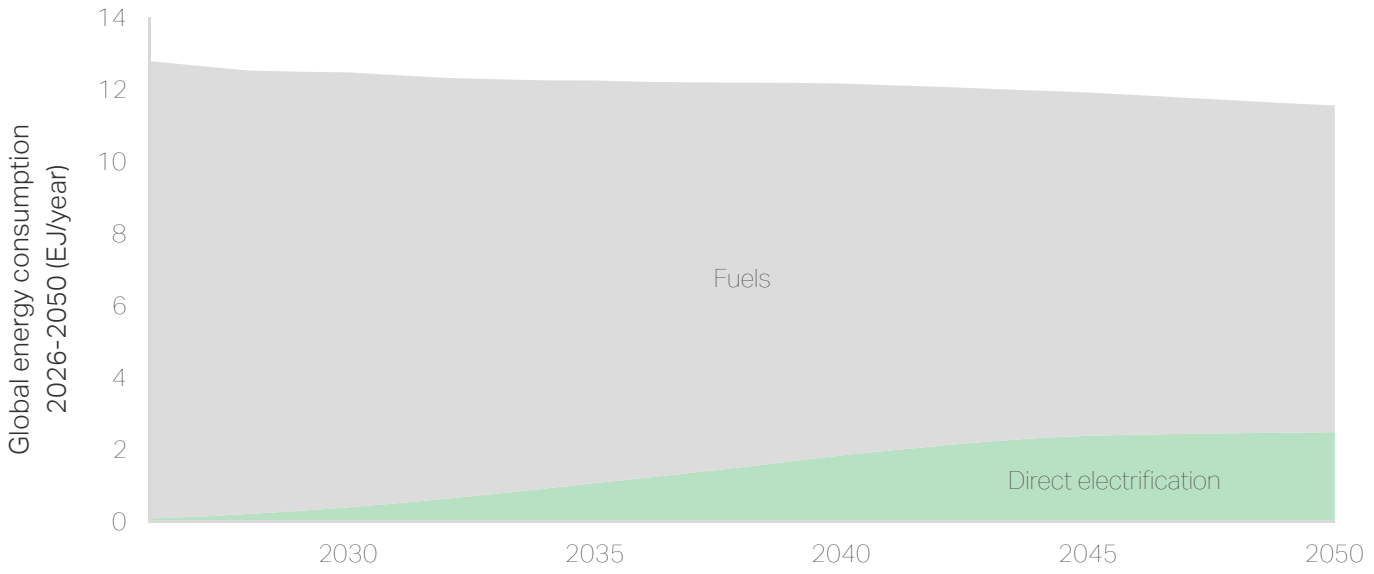
Shore power and battery-electric vessels are robust decarbonization investments across all four scenarios, with very little dependency on how the global energy system develops.

Shore power accounts for approximately 10% of energy consumption in 2050 across all scenarios in the model. It replaces onboard diesel generators while vessels are in port, directly electrifying auxiliary systems such as heating, cooling, and lighting.

Battery-electric propulsion and battery-hybrid systems could account for roughly 10% of total energy consumption in 2050. Batteries are more energy-efficient than combustion engines because direct electrification avoids fuel conversion losses. Battery-electric propulsion makes a compelling case on both cost and emissions for vessel segments with short voyages and frequent port calls (e.g., ferries, container feeder vessels, tugs). These segments represent up to 20% of maritime shipping's yearly fuel consumption today.[19] Deep-sea vessels can use onboard battery systems for parts of their operation, such as harbor navigation.

The underlying assumptions on direct electrification carry uncertainty due to the high pace of battery technology development. Therefore, the specific shares here are indicative. Enabling this decarbonization pathway will require relevant solutions, such as port charging infrastructure, to be built out. However, the direction is clear: electrification is adopted where operationally feasible.

Figure 5: Direct electrification and shore power uptake compared to global fleet onboard energy consumption (EJ/year). Direct electrification and shore power are expressed in chemical energy equivalents of fuel replaced, to account for differences in conversion losses across technologies.



3.3 Earlier investments in dual-fuel capability offer lower total transition costs

Most vessels ordered today will still be in service in 2050. This lock-in means that near-term vessel orders have a substantial long-term impact on whether the fleet can tackle emissions through switching to lower-emissions fuels in the future. As a result, across all four scenarios, nearly all fleet newbuilds entering service from 2030 onward are electric or capable of operating on alternative fuels. (Note that this is the common cost-minimizing path across our scenario modeling; the current orderbook should not be expected to mimic this.)

Natural fleet renewal is the lowest-cost mechanism for transitioning the fleet to operation on lower-emissions fuels. Building fuel flexibility into a newbuild rather than retrofitting later acts as a hedge against uncertainty regarding fuel availability. It preserves the option to switch fuel as the supply picture becomes clear, at a far lower cost than converting an existing vessel. Where full dual-fuel capability is not ordered from the outset, designing the newbuild so it can be converted later captures much of the same flexibility, and still avoids the high cost of retrofitting a vessel built without conversion in mind.

If the industry delays this shift to dual-fuel newbuilds even marginally to 2035, the fleet needs expensive retrofits to catch up. Even then, it may not be feasible to retrofit a sufficient share of the fleet to achieve net-zero by 2050.

Delaying the shift to dual-fuel newbuilding not only delays the transition but also raises its cost. This is our most time-sensitive finding: decisions made today determine whether 2050 is reachable mostly through natural fleet renewal, or if it requires disruptive, costly catch-up in the future.

A large share of newbuild orders today is already dual-fuel, predominantly methane.[20] The trajectory described here would broaden that shift across the deep-sea fleet. For this analysis, we consider ammonia, methane, and methanol/ethanol as fuel options for deep-sea newbuilds ordered from now.

For further insight into fuel retrofits and the role of optionality in vessel design, see our previous publications on retrofitting an 82,000 DWT bulk carrier for methanol dual-fuel capability, [21] preparing tanker vessels for conversion to green fuels, [22] and preparing container vessels for conversion to green fuels.[23]

3.4 The fuel mix remains diverse throughout the transition

Shipping does not converge on a single fuel. Today, different shipping companies, fuel producers, and ports are investing in a range of fuel pathways. These long-lived assets will shape the world in which shipping operates in 2050. Meanwhile, the global geography of fueling infrastructure means that different fuels will dominate availability in different places.

The amount of suitable biomass — and the share of it available to shipping — is a key uncertainty in this analysis, and ultimately a key determinant of the modeled fuel mix. Additional biomass potential likely exists beyond the supply that we model.

For example, forthcoming work by the Center examines the potential of crop-based biofuels with a low risk of indirect land use change and an enhanced sustainability profile. This new research, focusing on a small number of pathways, suggests a potential on the order of 5-6 EJ of crop-based biofuels.

If this full amount were available to shipping (in other words, if there were no cross-sector competition), it would be equivalent to roughly 40% of shipping's projected energy demand in 2030. We have taken a conservative approach, assuming that biomass will be contested, with shipping only getting a fraction of the market (depending on scenario).

As such, our modeling can offer high-level insights across the scenarios set out in Section 2.2. These insights are not predictions, and they should be interpreted in light of our modeling assumptions outlined in the **accompanying appendix.**

Fossil fuels phase out gradually in the modeled scenarios. Conventional fossil fuel oils and liquefied natural gas (LNG) remain part of the energy mix through most of the transition across all four scenarios. The pace of the phase-out follows the pace at which alternative fuel production can scale. As the decarbonization incentive tightens and availability of low-emissions energy increases, fossil energy loses cost-competitiveness.

As we move toward 2050, our analysis shows high uptake of the ammonia and biomethane fuel pathways in all scenarios. The proportions of biomethane and ammonia vary across scenarios depending on the biomass availability condition. Because biofuels come before ammonia in the abatement cost merit order, the more biofuels shipping can access, the less ammonia is used.

Among the low-emissions fuels we consider in our modeling, biomethane has one of the lowest abatement costs. Biomethane can also scale more quickly than many of the other pathways we consider, and we therefore see it entering the modeled fuel mix relatively early – from 2030 onwards across all scenarios. However, biomass availability is limited, and shipping will have to compete with other hard-to-abate sectors for access.

In contrast, ammonia's availability could increase over time. Two production pathways – blue ammonia (using natural gas with CCS) and e-ammonia (using renewable electricity and nitrogen from air) – could plausibly scale to volumes capable of powering important shares of shipping's energy demand.[24, 25, 26]

Our modeling requires accurate emissions tracking and a global fuel standard that incentivizes blue ammonia producers to tightly control upstream emissions (see Section 3.5). If this control is in place, blue ammonia precedes e-ammonia in the abatement cost merit order; if not, the positions of these two pathways are reversed. An additional near-term factor when it comes to low-emissions ammonia is the time needed to scale up its industrial production.

While we see biomethane and ammonia accounting for important shares of shipping's energy demand in 2050, a significant share must be addressed by other pathways. These include ethanol, methanol, diesels, other carbon-bearing e-fuels, and electrification. Each of these pathways will likely face constraints in terms of operational feasibility, feedstock availability, and/or cross-sector competition. These constraints are reflected in our assumptions and therefore the modeling results. For example, we see higher uptake of ethanol, biomethanol, and biodiesel in scenarios with higher biomass availability.

In summary, the interplay between ammonia and biomethane is important, but other fuels will also play a critical role in the fuel transition. A key insight here is that the composition of the fuel mix depends on a condition – biomass availability – that shipping does not control.

3.5 Life-cycle emissions control is crucial

Controlling upstream fuel emissions is essential across all four scenarios. The same fuel can carry vastly different well-to-wake GHG intensities depending on its production pathway.

Three areas deserve close attention:

Blue ammonia: The well-to-wake emissions intensity for blue ammonia depends mainly on the extent of methane leakage in the natural gas supply chain and the effectiveness of carbon capture and storage. If producers fail to control these upstream emissions, blue ammonia's climate benefit erodes sharply.

Biofuels: The sustainability of biomass sourcing determines whether biofuels deliver genuine emissions reductions. Without sustainability certification that ensures the adoption of best practices for land use and prevents adverse environmental impacts from biomass production, biofuel uptake may not translate into real-world decarbonization.

E-fuels: Production of e-fuels must be powered by renewable electricity that is not diverted from electricity grids. For carbon-based e-fuels such as e-methanol, the carbon input must be biogenic CO_2 with credible sustainability certification.

Therefore, the decarbonization incentive modeled here covers well-to-wake emissions and not just tank-to-wake. If regulation lacks credible life-cycle emissions accounting or enforcement, shipping's actual emissions will almost certainly exceed its reported emissions. The resulting gap between reported progress and real climate impact would substantially undermine the transition pathways we consider.

For more details on the emission factors used in our modeling, see the **assumptions appendix**.

3.6 Transport costs do not increase dramatically

Our analysis finds that the total transport expenses per cargo mile – including vessel investment costs, fuel costs, and emissions compliance costs – increase gradually year-on-year toward 2050. In 2030, transport costs are not significantly affected, as modeled uptake of alternative fuels is still limited.

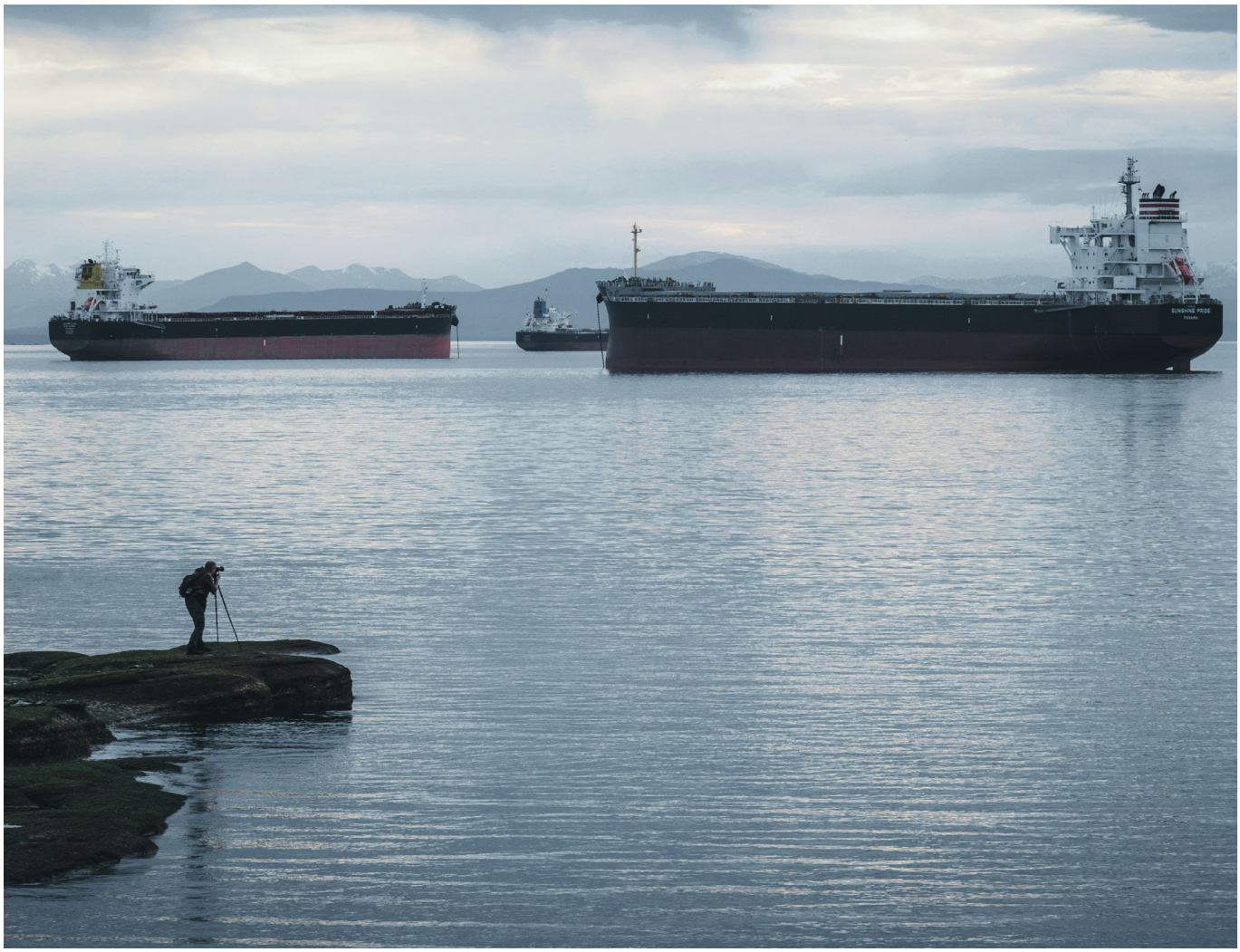
By 2050, modeled total transport costs have increased to 1.2-1.4x compared to today across the three largest segments: bulk, container, and tanker. This is equivalent to a CAGR of 0.7–1.4%. This increase is driven by low-emissions fuels and energy reaching full uptake in the model. While our assumptions call for these energy sources to become less expensive over time, we assume that they are still more expensive than fossil energy in 2050. At the same time, increased energy efficiency drives transport costs down.

Modeled transport costs do not increase equally across the four scenarios. Of these, the Coordinated scenario has the lowest transport costs, and Protectionist has the highest transport costs. However, even where costs are similar across scenarios, this does not imply equivalent emissions reductions — some scenarios deliver more decarbonization for a comparable cost.

Note that because our framework involves global, fleet-level modeling, we do not investigate the distribution of these costs across individual countries. We also hold vessel sizes and operating patterns constant over time, meaning that this trajectory reflects the cost of the energy transition rather than radical changes in ship size or how vessels are operated. For instance, we do not consider a scenario where the industry improves energy efficiency by avoiding all ballast legs.

The transition to low-emissions fuels and more efficient vessels carries a cost premium compared to the fossil baseline. However, this premium is moderate relative to total transport costs.

This is for two reasons. First, shipping can provide substantial transport work per unit energy, which moderates the impact of increased energy cost on the cost of transport work. Second, shipping's cost structure does not hinge entirely on energy. Much of the cost in the industry is related to investments in and operation of vessels, which are relatively consistent across energy sources and propulsion systems. Fuel cost is therefore a key factor in choosing which fuels and technologies to adopt, but relative fuel costs have a muted effect on relative total costs of ownership.



04 Closing perspective

The analysis presented here assumes an incentive for shipping to apply energy efficiency improvements and use lower-emissions (but more expensive) fuels. We characterize this as a shared net-zero objective by 2050 for shipping. We do not assume any particular form of this incentive – it could include regulation, carbon pricing, customer pull, or an equivalent mechanism.

Our findings should therefore be read as conditional: they describe what the transition can look like when the industry must decarbonize.

> We conclude that, given a sufficient incentive, shipping's decarbonization can be achieved within reasonable technical limits — and at a lower cost than might be anticipated.

Without this incentive, fossil fuels remain the cheapest option, and the dynamics described in this analysis are unlikely to materialize.

Across all four scenarios, this analysis identifies a consistent set of developments needed for deep decarbonization by 2050. These requirements — findings that arise uniquely from cross-scenario analysis — hold regardless of whether the world coordinates on climate, fragments into regional approaches, relies on market signals, or retreats into energy security priorities:

- Fleet ordering choices made between now and 2030 determine whether shipping's fuel transition is achieved through lower-cost natural renewal or through expensive retrofits and early retirements.
- Energy efficiency, direct electrification where operationally feasible, and dual-fuel ammonia and methane vessels appear to be robust investments regardless of which scenario materializes.
- Shipping's energy demand in 2050 is met using a wide range of energy sources, with biomethane and ammonia playing prominent roles. Multiple other pathways – including ethanol, methanol, diesels, other carbon-containing e-fuels, and direct electrification – make up the remaining share.
- Adequate control of GHG emissions across the fuel life cycle, supported by credible well-to-wake emissions accounting, is essential.
- Transport costs rise to 1.2-1.4x by 2050 compared to today across the three largest segments: bulk, container, and tanker. This is equivalent to costs rising by 0.7-1.4% per year.

In summary, shipping's energy transition is feasible, but fragile. The pathways are credible; the requisite technologies are mature or fast-maturing; and the costs are real, but arguably not extreme. The remaining work is execution – and the sooner the better. The decisions made in the coming years on fleet renewal, fuel production investment, regulatory frameworks, and organizational development will determine whether decarbonization proceeds through orderly renewal or requires costly, disruptive catch-up.

05 Acknowledgements

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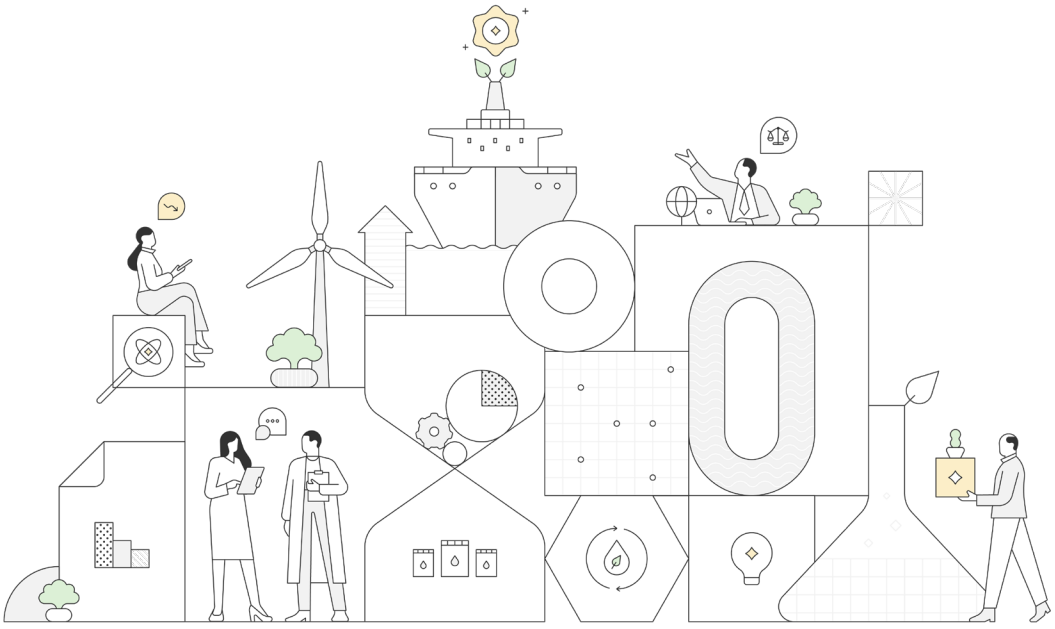

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