Managing the Transition to Zero-Carbon Marine Fuels

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January 2024
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Summary

In response to increasing policy commitments supporting and requiring the global shipping industry to decarbonize in line with the Paris Climate Agreement, ship and engine manufacturers and cargo owners are evaluating and beginning to invest in ships and services that can be fueled with alternative low- and zero-carbon fuels. The relative carbon intensity (CI) and costs of these fuels, such as ammonia and methanol, can differ substantially depending on the types of feedstocks and processes for producing them. There are also important differences in ship design needs to ensure that alternative fuels are safely and effectively onboarded, stored, and used.

This analysis looks at key factors for producing low-carbon alternative fuels and opportunities for managing the costs of transitioning to low-carbon marine fuels, with an initial focus on ammonia. To better understand how ship owners might plan their fuel capacity and flexibility to adjust to emission limits, CATF has developed a set of economic tools for estimating the cost of producing alternative fuels at the local or regional level, initially looking at ammonia (NH₃) fuel, and for comparing fuel costs and emissions from ships built or retrofitted with dual-fuel capacity. Consistent with ship and engine manufacturer’s projections and recent steps by the EU to adopt marine sector targets for reducing emissions by 80% by 2050, we have compared four container ship investment scenarios:

- A newly built vessel powered by low sulfur heavy fuel oil (HFO)
- A newly built vessel fully powered by NH₃ fuel with HFO pilot fuel
- A retrofitted dual-fuel vessel with full range capacity to run on NH₃ fuel
- A retrofitted dual-fuel vessel with reduced range capacity to run on NH₃ fuel

Capital costs are based on estimates from the Maersk Mc-Kinney Moller Center for Zero Carbon Shipping;¹ fuel costs are based on 2020 market prices and CATF estimates and held constant over time. The primary variable in the fuel cost tool is an escalating price on carbon emissions, based on projected EU carbon credit prices of approximately $100/ton in 2025,² increasing 4.25% annually.

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¹ Preparing Container Vessels for Conversion to Green Fuels | Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, September 2022.
² Analyst EU carbon price forecasts edge higher but risks remain, Reuters, January 25, 2023.
Our analysis shows that ammonia dual-fuel ship operators will have substantial flexibility in transitioning to lower-carbon fuels that would allow them to meet or exceed decarbonization goals, such as the EU marine sector targets. Ships built or retrofitted with dual-fuel capacity can run on a wide mix of conventional fuel oil and low-carbon ammonia—potentially 100% NH₃—and blend in lower carbon ammonia as supplies become available. Moderately low-carbon ammonia can be produced with natural gas with carbon capture and effective upstream methane leakage controls. Very low-carbon ammonia can be made with electricity generated with low-carbon emissions, if that electricity is additional to what otherwise would be produced for the grid and other demands for electric power.

Because of its higher ignition point, running the ship on full ammonia will require pilot fuel, such as marine fuel oil or hydrogen (using hydrogen would enable the lowest CI for an ammonia fueled ship). The table below shows the emission-reduction potential of different operational and ammonia fuel choices relative to the FuelEU Maritime requirements.

The EU’s emission reduction targets for shipping fuel and emissions, which will be fully phased into the EU’s emissions trading system (ETS) by 2026, will have a substantial impact on the economic competitiveness of low-carbon fuels, such as ammonia. With a projected carbon price of $100/ton in 2025 increasing 4.25% annually, the net present value (NPV) of the cost of marine fuel oil over the 30-year life of the ship could double to more than $390 million.

Under this scenario of a regulated market with a price on carbon, a new full ammonia ship seeking to minimize emissions can break even with the fuel costs of the HFO ship while reducing total emissions over the lifetime of the ship by 77%. Ship operators that retrofit to comply with the EU targets can reduce their lifetime emissions by half and at a lower overall cost. All three ammonia-fueled ships evaluated were able to comply with or outperform the new FuelEU Maritime targets at a cost equal to or below that of a conventional heavy fuel oil powered ship.³

³ These comparisons do not include projections for reductions in the costs of producing ammonia, especially using zero-emission electricity at scale, which could further reduce the cost of ammonia fuel relative to conventional marine fuel oil.
SECTION 1

Introduction

Given the 30-year operational life of a standard cargo ship and the uncertain timing and availability of low- or zero-carbon marine fuels, some major marine engine and ship manufacturers recognize the need to decarbonize shipping by mid-century and are shifting to dual-fuel engines and retrofit-ready ships. As a carbon-free, hydrogen based fuel that is already produced, transported and used globally in large volumes, ammonia is considered a leading alternative fuel—if testing demonstrates it can be used safely. According to the International Energy Agency, ammonia, along with hydrogen and related fuels will meet 80% of the ship fuel bunkering needs by mid-century. While ammonia is already produced globally on a large scale today, supplies of low-carbon ammonia produced with carbon capture or zero-emission electricity will take time to scale and for costs to come down. In the interim, shipping companies and cargo owners committed to low- or zero-carbon shipping or operating in carbon-regulated markets will likely face significant fuel cost impacts that will vary over time. This analysis looks at key factors for producing low-carbon alternative fuels and opportunities for managing the costs of transitioning to low-carbon marine fuels, with an initial focus on ammonia. Future analyses can look at other alternative fuels or different policy and market factors.

1. Managing the Transition to Zero-Carbon Marine Fuels

The vast majority of commercial ships built today will still be in operation in 2050, during the critical decades the marine sector needs to decarbonize in line with national climate goals of carbon neutrality by midcentury. The European Union recently adopted greenhouse gas (GHG) intensity limits for energy used on board by a ship of 80% below 2020 levels by 2050 and agreed to expand the bloc's emissions trading system (ETS) to the marine sector emissions. In the U.S., tax credits passed in the Inflation Reduction Act will significantly reduce the cost of producing low-carbon hydrogen and ammonia and a new federal hydrogen hub program will help scale hydrogen-based fuel infrastructure, including at ports. More recently, the International Maritime Organization updated its “ambition” for reducing shipping emissions to net-zero by “about 2050” and set in motion a process to adopt policies to support and reduce the carbon intensity of marine fuels to meet the net-zero goal.

To understand how ship owners and fuel providers might adjust to emission limits or penalties, CATF has developed a set of economic tools for estimating the cost of producing alternative fuels at the local or regional level, initially looking at ammonia fuel (NH₃), and for comparing fuel costs and emissions from ships built or retrofitted to use alternative fuels.

Propulsion Systems and Fuel Flexibility: To meet the challenge of building ships today that will likely need to use different fuels in the future, forward looking companies are rapidly shifting to dual-fuel engines and planning for secondary fuel storage capacity for alternative fuels, such as methanol and ammonia. Dual-fuel engines can run on a wide mix of two fuels to power the engine, typically with conventional heavy fuel oil (HFO) as the primary fuel and natural gas, methanol or ammonia as the secondary fuel. In the case of vessels

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4 Low-Speed, Dual-Fuel Portfolio Reaches Millennium Milestone, MAN Energy Solutions, November 2, 2022.
5 Energy Technology Perspective 2020, International Energy Agency, February 2021
7 Revised GHG reduction strategy for global shipping adopted (imo.org), International Marine Organization, July 2023.
that run on ammonia, which does not produce CO₂ when burned, shipboard carbon emissions can reach very low levels. New ships can be designed, and space can be planned, for future retrofits that enable ships to use alternative fuels. Key retrofits for making conventional engines ammonia-compatible include refrigerated storage tanks, fuel preparation, double-walled piping, and additional worker safety systems.

Ship engine manufacturers do not see major hurdles in scaling the use of alternative fuels, as they become more widely available. In September 2022, the Maersk Mc-Kinney Moller Center for Zero Carbon Shipping (MMMC) published an analysis of costs for preparing container ships to use alternative fuels, including different levels of preparation for future retrofits to the ship. MMMC estimates the costs will range from 16-24% of a $150 million, 15,000 TEU container ship (lower cost for a new build, higher total cost for retrofits). Ships are expected to retain their HFO fuel capacity when the ammonia fuel capacity is added, which will enable ships to run on HFO when ammonia fuel is unavailable.

**Carbon Intensity Flexibility**: Alternative fuels vary widely in carbon intensity. The net climate benefits from biomass-based fuels are limited given the global potential for adverse land-use impacts. For ammonia, the two major processes for producing it—steam reforming natural gas or electrolysis of water to produce hydrogen, which is then combined with nitrogen to make NH₃—could have significant differences in carbon intensity. Key factors impacting carbon intensity include methane leaks in natural gas production and distribution, carbon capture rates and availability of zero-emission electricity.

CATF’s ammonia cost tools estimate the carbon intensity and cost of producing ammonia from natural gas with carbon capture or electricity from low- and zero-carbon sources, based on local costs for each production pathway. For this analysis, we estimated the cost of producing ammonia for bunkering in major ports in the U.S. Gulf Coast and northern Germany, which in turn are used to estimate annual net fuel costs under different fuel use and supply choices.

**Shipping Speed Flexibility**: Shipping speed is not a factor in this analysis but is an important tool that ship operators have to limit fuel costs. Reducing shipping speed by 10% can reduce power needs and fuel use by approximately 20%. Increased use of so called “slow steaming” can directly reduce fuel oil and alternate fuel use as well as all associated emissions. Along with dual-fuel capability, ship operators are increasingly ordering ships optimized for slower speeds.

### 2. The Cost of Low-Carbon Ammonia Fuels

CATF’s ammonia fuel cost tool incorporates equipment capital, energy consumption, hydrogen storage and operational costs, and local or regional costs for natural gas, carbon capture and/or electricity. We assume fuel production will be near ports bunkering and supplying ammonia fuel, in this case Houston, Texas and Hamburg, Germany. Future analyses could be done for other regional shipping routes or networks of ports.

**Ammonia from Natural Gas**: The cost of producing ammonia from natural gas with steam reforming is strongly dependent on the price of natural gas in consideration. The figure below shows the sensitivity of the levelized cost of ammonia (LCOA) to the price of natural gas in U.S. dollars per MMBTU. Generally, there is a limited correlation between marine fuel oil or crude prices and natural gas prices. The cost estimates for ‘blue ammonia’ in the figure below do not include a carbon tax or tradable credit; they do include a CO₂ capture rate of 82% and a geologic sequestration cost of $30 per ton, which can vary depending on the location. For marine fuel cost analysis, we assume that the ammonia supplied to Houston would be produced from natural gas in the Gulf Coast region and that the ammonia supplied to Hamburg would be produced from natural gas in Norway.

The well-to-wake greenhouse gas emissions from natural gas-based NH₃ fuels will vary most significantly depending on the total emissions captured for sequestration (CCS) and the upstream methane...
emissions of the natural gas supply used to make the ammonia. In this analysis, focused on the Houston- Hamburg shipping route, we based upstream methane emissions on gas produced in the US Gulf region\(^\text{12}\) for ammonia produced and supplied in Texas and methane emissions associated with gas produced and processed into ammonia in Norway\(^\text{13}\) and supplied to Germany. The resulting average CI for natural gas based NH\(_3\) used on this shipping route is 45.6 kg/GJ, roughly half of the CI of conventional fuel oil.

Ammonia from Electricity: We estimate that a 70% efficiency electrolyzer operating at 50% capacity coupled with hydrogen storage would be needed to supply an electrolytic ammonia plant at 87% capacity.\(^\text{14}\) The sensitivity analysis below shows the dependency of the levelized cost of ammonia on the cost of electricity, which can influence the capacity factor of the electrolysis operations and the overall cost of ammonia produced with zero-emission electricity. As with gas prices, for this analysis, we base our electricity costs on the 2020 market rates in Texas and Germany. We also assume wind power to be the primary source of zero-emission electricity in both markets with estimated upstream (manufacturing) of 6.2 kg/GJ.

Our analysis shows that, unless the high electricity use and costs of electrolyzers comes down substantially, ammonia made from zero-emission electricity will be significantly more expensive than other fuels until higher carbon prices make them competitive in the late 2030s and early 2040s.

\(^{12}\) Benchmarking Methane and Other GHG Emissions of Oil & Natural Gas Production in the United States, CATF and CERES, June 1, 2023.


3. Phasing in Zero-Carbon Marine Fuels

To illustrate how the flexibility of dual-fuel ships and NH₃ fuel supplies of varying carbon intensity might help shipping companies manage costs over time, CATF has developed a marine fuel cost management tool to assess options for phasing in the use of alternative fuels. The tool looks at i) the timing of retrofits to incorporate dual-fuel engines and partial- and full-NH₃ fueling capabilities, ii) costs and emissions for conventional heavy fuel oil and low- and very low-carbon NH₃ fuel, and iii) the annual fuels costs and emissions over time under different fuel use and market scenarios, and the net present value of those ship investment and fuel choices.

The initial scenarios assessed here include the following key parameters:

1. CO₂ intensity (CI) of NH₃ supplies are estimated well-to-wake. “Moderate CI” NH₃ made from natural gas includes upstream emissions and NH₃ process emissions minus the level of CCS in case of steam methane reforming. “Very Low CI” NH₃ assumes electrolysis with zero-emission electricity. We are comparing alternative fuel CIs to an estimated 2020 baseline of 92.6 kg/GJ.¹⁵

2. Costs are in U.S. dollars ($/ton, $/GJ) with no inflation, based on actual and estimated 2020 costs of HFO, natural gas, carbon capture and electricity for NH₃ production. (Fuel costs are held constant over time. Future analyses could use projected reductions in fuel costs.)

3. Well-to-wake CO₂ emissions cost (under the EU ETS or carbon tax) is $100/ton in 2025 and increases 4.25% per year through 2055, assuming a 30-year operating life of the container ship. Future analyses could use alternative CO₂ price projections or credits or debits relative to new EU maritime fuel requirements, represented by the grey arrow in the charts below.

4. Incremental NH₃ fuel equipment and construction investment costs are estimated to be between $24-35M, consistent with an analysis by the Maersk Mc-Kinney Møller Center for Zero-Carbon Shipping.¹⁶

With these parameters, our base-case cargo ship is a 2025 conventional 15000 TEU (twenty equivalent unit) new build operating for thirty years on HFO.

¹⁶ Preparing Container Vessels for Conversion to Green Fuels | Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, September 2022.
**Figure 3: VLSHFO BAU: Fuel Cost and CO₂ Intensity**

Base case: Low sulfur heavy fuel oil new build, 92.6 kg/GJ carbon emissions, $392M lifetime fuel cost

Base Case emissions and fuel costs of a HFO container ship are shown above, relative to the FuelEU Maritime CO₂ intensity targets. The net present value (NPV) of fuel costs over the life of the ship would be $392M, roughly double the $200M cost of the same fuel without a carbon price.
**SECTION 2**

**Alternative Fuel Cases**

The alternative fuel cases examined here include additional capital expenditures for a dual-fuel engine capable of running on up to 92% ammonia, piping and safety equipment, and partial or full ammonia fuel storage capacity.

1. **Full Ammonia New Build**

   If sufficient moderately low-carbon ammonia supplies (Moderate CI NH₃) are available in 2025, the least expensive investment for a ship buyer wanting to minimize emissions would be a “new build” ship that is fully powered by ammonia, at an estimated incremental cost of $24M (or 16% over the $150M for conventional container ship). Primarily because of ammonia’s lower energy content relative to HFO, a full ammonia fueled cargo ship will require approximately three times more space for fuel storage and processing than a conventional HFO fueled container ship, resulting in a loss of up to 4% of cargo capacity. This includes space for refrigerated fuel tanks, fuel preparation, and air separation/nitrogen production equipment.

   Due to ammonia’s higher ignition point, operating ships on full ammonia will require approximately 8% pilot fuel. Conventional HFO or diesel could be used as pilot fuel, resulting in on-board CO₂ emissions. Alternatively, hydrogen derived from ammonia through the use of on-board ammonia cracking equipment (such as being developed by Amogy¹⁷) could serve as pilot fuel or be...

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**Figure 4: Full NH₃: Fuel Cost and CO₂ Intensity**

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used in fuel cells with no on-board CO₂ emissions. The Full Ammonia New Build starts with Moderate CI NH₃ for three years, then blends in Very Low CI NH₃ until 2032, after which only Very Low CI NH₃ fuel is used.

**Key Results:** 77% lifetime CO₂ reduction, 86-93% reduction in 2050 with very low CI NH₃; lifetime fuel cost same as HFO Base Case.

If the Full Ammonia New Build ship operator chose instead to minimize costs while staying within the FuelEU Maritime targets, the ship could run on Moderate CI NH₃ until 2043 before transitioning to Very Low CI NH₃. Doing so would save more than $27M (7%) in total fuel costs but would limit lifetime emission reductions to 60% below the same for a conventional HFO ship.

2. **Full Ammonia Retrofit**

Under a Full Retrofit scenario—in which the engines are modified, alternative fuel storage and handling equipment, and other relevant systems, are added to a vessel so that the vessel can run entirely on ammonia—a ship operator delays the transition to NH₃ fuel until retrofitting in 2032. Under an escalating price on carbon emissions, by 2030 the net cost of natural gas-based ammonia (with CCS) is lower than HFO and the dual-fuel ship operator might choose to switch from low to high ammonia blends as fast as possible, becoming fully ammonia fueled in 2034. The hypothetical ship operator switches to Very Low CI NH₃ in 2044, when that fuel is more cost effective under a higher carbon price. Reductions in the cost of ammonia made with zero-emission electricity would encourage an earlier shift towards Very Low CI NH₃.

**Key Results:** 52% lifetime CO₂ reduction, -86-93% by 2050; lifetime fuel cost $11.7M below HFO case.

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3. Reduced Range Retrofit

Under a Reduced Range Retrofit scenario (illustrated below), a ship operator minimizes fuel costs as it attempts to comply with EU emission reduction targets. A partial retrofit to the ship would add two thirds the ammonia fuel tank capacity of a full ammonia retrofit, reducing the range the ship while running on ammonia and requiring either more frequent ammonia fueling stops or greater HFO use. More frequent fueling stops and potentially longer routes could result in more fuel use by Reduced Range Retrofit ships (as compared to full dual-fuel-capable ships).

Under this scenario, the ship operator delays the retrofit for eight years and operates substantially longer in conventional dual-fuel operation, starting with a low-NH₃ blend for six years and not reaching full ammonia operations until 2042, while staying close to the EU target levels.

**Key Results:** 40% lifetime CO₂ reduction, -86% by 2050; lifetime fuel cost $14.7M below HFO case.

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**Figure 6: Partial NH₃: Fuel Cost and CO₂ Intensity**
Ammonia Safety in Shipping

Ammonia production as well as various related technologies, such as the Haber-Bosch process, have been demonstrated at scale through use in the fertilizer industry for over 100 years. In 2021, the ammonia market was estimated to be around 178 million metric tons, with 80% of worldwide production used in the agriculture sector. About 10% of ammonia produced around the world globally is transported by sea, giving the existing shipping industry experience with ammonia handling and transportation.

The primary safety hazard for ammonia is its toxicity, though under certain conditions it is also flammable. Both of these hazards are well understood due to the long history of ammonia plants operating globally. In the marine transportation sector, cargo operators and crews have been trained to safely handle ammonia, which has allowed vessels for bulk transport of ammonia to operate safely for decades.

Existing safety measures for carriers of liquified gas such as ammonia include actions against leakage, firefighting procedures, gas freeing, ballasting and cargo cleaning, minimum allowable cargo tank steel temperature, emergency procedure and training of personnel. Specifically, for anhydrous ammonia, ships require toxic vapour detection, as well as the regular inspection and maintenance of equipment, training of personnel in the use of protective clothes, warning signs and emergency procedures to mitigate ship damage and injury in case of leakage.

<table>
<thead>
<tr>
<th>Concentrations</th>
<th>Exposure Time</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 - 20 mg/m³ (15-30 ppm)</td>
<td>Immediate</td>
<td>Smell of ammonia is noticeable</td>
</tr>
<tr>
<td>70 mg/m³ (100 ppm)</td>
<td>Immediate</td>
<td>Nose irritation / burning sensation in the eyes</td>
</tr>
<tr>
<td>200 - 350 mg/m³ (280-400 ppm)</td>
<td>0.5 - 1 hour</td>
<td>Tolerable</td>
</tr>
<tr>
<td>1200 mg/m³ (1700 ppm)</td>
<td>&lt; 30 minutes</td>
<td>Severe coughing attack</td>
</tr>
<tr>
<td>2500 - 4500 mg/m³ (3500 - 6400 ppm)</td>
<td>0.5 - 1 hour</td>
<td>Dangerous, less than 1/2 hour exposure may be fatal</td>
</tr>
<tr>
<td>3500 - 7000 mg/m³ (5000 - 10,000 ppm)</td>
<td>10 - 15 minutes</td>
<td>Serious edema, strangulation, asphyxia, rapidly fatal</td>
</tr>
<tr>
<td>&gt; 7,000 mg/m³ (&gt; 10,000 ppm)</td>
<td>Immediate</td>
<td>Fatal</td>
</tr>
</tbody>
</table>

A key requirement of storing and using ammonia as a marine fuel is reducing human contact with ammonia as much as possible. Given its toxicity, for ammonia fuel to be viable, vessels, including engines, piping, and tankage, as well as onshore fuel bunkering facilities must be purposed built then demonstrated, such that they do not pose any additional risk to personnel or environment. Safety guidelines for ammonia fuel aboard ships are under development by the International Maritime Organisation (IMO). Additionally, testing and validation of ammonia fuel marine engines is now underway while dual-fuel ships that can be fueled with ammonia are in the design phase.

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20 Why the shipping industry is betting big on ammonia, https://spectrum.ieee.org/why-the-shipping-industry-is-betting-big-on-ammonia.
SECTION 3

Key Findings

Fuel flexibility enables ammonia fueled ships to comply with near-zero emission targets. The potential for dual-fuel ships to blend in and shift over time entirely to alternative fuels, such as ammonia, will enable ships to comply with declining emission reduction targets. This table shows emission reduction potential of various levels of moderate and very low CI ammonia fuels relative to the FuelEU Maritime emission reduction targets. It is important to note, however, that the feasibility for ships to meet and exceed emission reduction targets will be highly dependent on the availability of alternative fuels along most major shipping routes.

<table>
<thead>
<tr>
<th>FuelEU Maritime emission reduction targets; ship potential by NH3 fuel type</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Year</strong></td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>NH3 Moderate CI</td>
</tr>
<tr>
<td>NH3 Mod/V.Low Blend</td>
</tr>
<tr>
<td>NH3 Very Low CI</td>
</tr>
</tbody>
</table>

Varying ammonia fuel costs and carbon intensities provides additional flexibility. Natural gas-based ammonia with CCS is roughly half of the CI of conventional heavy fuel oil. The carbon intensity of ammonia made with zero-emission electricity can be 93% lower. The ability to blend ammonia fuels of varying cost and carbon intensity provides additional flexibility for managing fuel costs and emissions.

<table>
<thead>
<tr>
<th>Fuel + CO2 ($2020)</th>
<th>Mkt $/ton</th>
<th>kg/GJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>VLSHFO BAU</td>
<td>$630</td>
<td>92.6</td>
</tr>
<tr>
<td>Full NH3 New Build</td>
<td>$338</td>
<td>45.6</td>
</tr>
<tr>
<td>Full NH3 Retrofit</td>
<td>$461</td>
<td>19.7</td>
</tr>
<tr>
<td>Partial NH3 Retrofit</td>
<td>$584</td>
<td>6.2</td>
</tr>
<tr>
<td>CO2 (tax, ETS, etc.)</td>
<td>$100</td>
<td>4.25%</td>
</tr>
<tr>
<td>Pilot fuel (LSHO)</td>
<td></td>
<td>8.0%</td>
</tr>
</tbody>
</table>
New build and retrofitted ammonia fueled ships can operate at lower costs than conventional HFO ships with substantial emission reductions. Under a policy requiring the marine sector to reduce the carbon intensity of marine fuels and/or pay for excess emissions, moderately low-carbon ammonia will be cost competitive with conventional marine fuel oil. All three ammonia ship options analyzed—new build, full retrofit, and partial retrofit—were able to operate at the same or lower total fuel costs compared with conventional fuel oil, while achieving 41-77% lower lifetime emissions.

<table>
<thead>
<tr>
<th>Cap+OpEx, CO₂&gt;30 yrs</th>
<th>NPV $M</th>
<th>CO₂ MT</th>
<th>Net $M</th>
<th>Net CO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>VLSHFO BAU</td>
<td>$392</td>
<td>3.35</td>
<td>$ -</td>
<td>-</td>
</tr>
<tr>
<td>Full NH₃ New Build</td>
<td>$392</td>
<td>0.76</td>
<td>$ (0.0)</td>
<td>-77%</td>
</tr>
<tr>
<td>Full NH₃ Retrofit</td>
<td>$381</td>
<td>1.61</td>
<td>$ 11.7</td>
<td>-52%</td>
</tr>
<tr>
<td>Partial NH₃ Retrofit</td>
<td>$378</td>
<td>1.99</td>
<td>$ 14.7</td>
<td>-41%</td>
</tr>
</tbody>
</table>
SECTION 4

Conclusion

With increasing pressure and requirements for the marine sector to reduce its considerable and growing emissions in line with the Paris Climate Agreement, shipping companies and manufacturers must prepare for a future with low-carbon marine fuels, including by building ships to be dual-fuel ready. CATF’s analysis of four ship scenarios (one fossil fueled, three fueled partially or fully with ammonia) shows that investments to build or retrofit ships with dual-fuel capacity will provide ship operators with significant flexibility for meeting existing and future carbon emission regulations. With sufficient supplies of ammonia fuel—beginning moderately low-carbon ammonia made natural gas with carbon capture and transitioning to ammonia made with very low carbon renewable electricity—a full ammonia new build could deliver an 77% reduction in lifetime emissions at the same lifetime cost as a conventional heavy oil fueled ship that has to pay for its emissions. Moreover, new ships can be prepped for future retrofits to run on alternative fuels. In a regulated market with a price on carbon, such as the EU’s emissions trading system, all three ammonia-fueled ships evaluated were able to comply with or outperform the new FuelEU Maritime targets at a cost equal to or below that of a conventional heavy fuel oil powered ship.