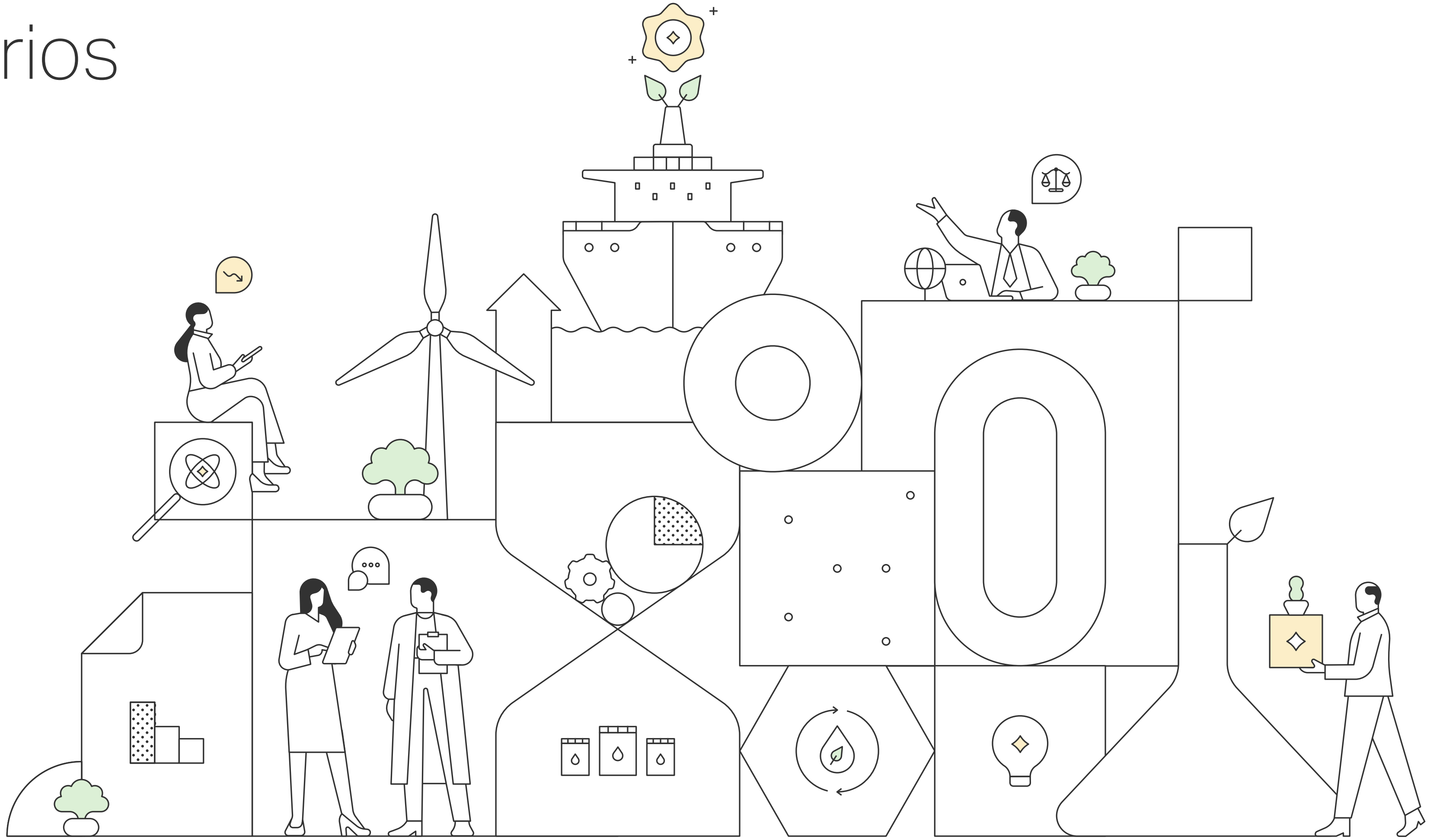
Position Paper
Fuel Option Scenarios

October 2021



Mærsk Mc-Kinney Møller Center
for Zero Carbon Shipping

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Certain information set forth in this document contains “forward-looking information”

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Objective and Scope

The purpose of this paper is to provide supporting documentation to the 2021 Industry Transition Strategy, detailing particularly assumptions and aspects on the cost, availability and uptake of future fuels. It is not the purpose of the paper to predict the future fuel blend but rather to make plausible that already today, we can identify plausible/possible ways of decarbonizing, noting that the future will be different and most likely include solutions that are more cost-effective than assumed in the present paper.

Several fuels are assumed support the transition. The present analysis only includes a sub-set of possible known fuels, and more fuels could develop in the future. The real future fuel blend will be – among other aspects such as national and global politics - dependent on future fuel pathway constraints on primary energy, technology maturation, and technology cost down. The fuel blend will also depend on regulation and on-board energy efficiency. This paper investigates scenarios related to these selected techno-economic fuel pathway constraints

This report should NOT be used to identify one scenario as a prediction of the future. Rather the different shown scenarios and sensitivities should be considered as a portfolio of results helping to illustrate possibilities, implications, sensitivities, limitations, dependencies and that the future fuel blends could look very different depending on the many socio-techno-economic developments along the way. Specifics around individual fuels are covered in the respective separate fuel position papers

Uncertainties in data and scenarios

The techno-economic model, NavigaTE, is used to model the fuel options and the presented scenarios. NavigaTE and the underlying data is documented separately.

Navigate is based on the principle that a vessel owner will shift to the fuels with the lowest Total-Cost-of-Ownership (TCO) for the vessel ownership and operation, therefore the fuel cost becomes a deciding factor. The estimated costs of fuels are based on methods, data and assumptions of high quality but they are still highly uncertain. For example, there are significant uncertainties related to the improvement of technology performance and cost (learning curves). While it takes significant developments to enable the new pathways and reach the assumed learning curves, further radical innovations could increase the competitiveness of certain fuels beyond assumed developments.

Cost estimates are based on fuel production from large-scale, stand-alone, un-subsidized fuel plants. However, during the first decades of ramp-up it can be expected that significant volumes of fuel can be produced, realizing favorable synergies from other processes or achieving subsidies or special opportunities thereby reducing the fuel production cost as well as the price. The assumed fossil fuel cost is based on market price (forward curve) while the alternative fuels costs are based on the production cost (including return on investments). Supply-demand in-balances are not modelled, and sector-competition is implicitly modelled in the assumptions about scale and availability.

Due to the high uncertainties on cost of future fossil respectively green fuel, the shown carbon tax levels are correspondingly uncertain.

Agenda

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Executive Summary

1

Industry can draw close to zero CO_2-eq emissions in 2050 and with it have nearly all energy demand met by alternative fuels.

2

To cover demand e-fuels, blue fuels, and biofuels will all be used and needed alternative fuels. Uptake of each fuel varies with each scenario.

3

Bio-methane, -methanol & -oils could play significant roles in the maritime industry's decarbonizing – though their uptake depends on highly uncertain factors including cross-sector competition, the speed of production increase, global biomass availability and the critically important ability to control methane slip.

4

Among e-fuels, e-ammonia and e-methanol are top candidate alternative fuels. Critical challenges for each are the regulatory and safety hurdles associated with ammonia and the future cost and availability of biogenic CO_2 for carbon-containing e-fuels, such as e-methanol.

5

Blue fuels may serve as potential transition fuels, depending on the development and acceptance of carbon capture and storage, success in management of methane leakage, and also depending on the pace of cost decrease of renewable electricity for producing e-fuels.

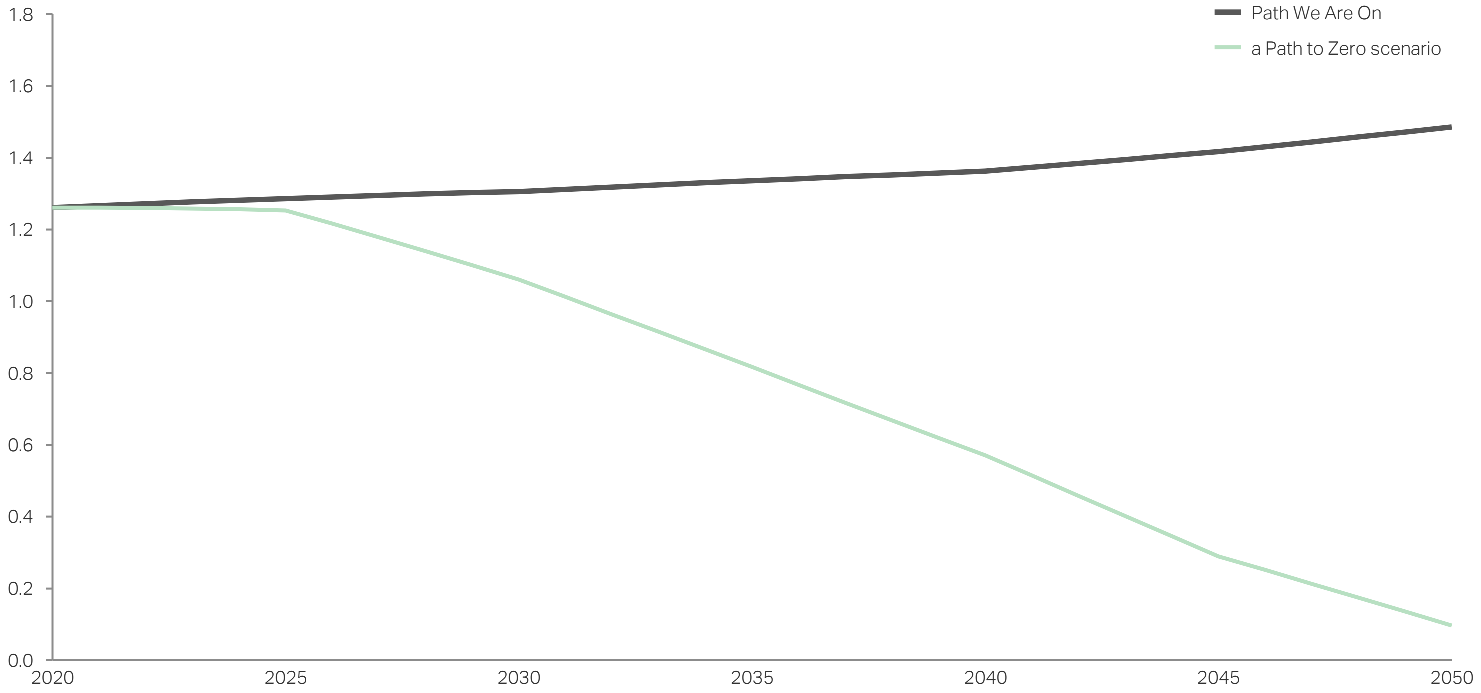
6

Onboard vessel solutions are needed to enable and enhance the utilization of low emission fuels and achieve decarbonization.

Agenda

The marine industry can approach zero CO_2-eq emissions in 2050...

Industry emissions towards 2050 in different scenarios
WTW Maritime Emissions GtCO_2–eq/year

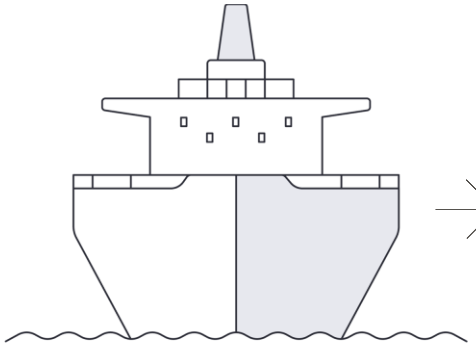


Source: NavigaTE
1) The Path We Are On models future maritime emissions based on current outlooks on e.g., growing global trade volumes, current vessel fleet composition, technological developments and existing industry-wide CO2 abatement initiatives. More information on The Path We Are On is available in the Center's Industry Transition Strategy document.
2) Full list of critical levers assumptions provided in the appendix while more information on each critical lever is found in the Center's Industry Transition Strategy document.
3) Please refer to the Center's Industry Transition Strategy document.

- In the Path We Are on, maritime will likely emit more GHG in 2050 than today.[1)]
- If activating critical levers[2)] in five different areas the industry can drive maritime fleet to zero CO_2-eq emissions by 2050. We call this "a Path to Zero".
- In a Path to Zero, we model the most positive and realistic outlooks on all critical levers.
- All being important in a Path to Zero a flat global carbon tax of USD ~230/tCO2-eq (or a sequenced tax level between USD 50-150/tCO_2-eq in an "earmark and return scheme") is needed.
- Further studies are ongoing to explore opportunities for further 2030 and 2040 reductions[3)]

… and how we get there depends on key market, regulatory and technical developments

We have considered key fuel pathway[1)] uncertainties that could critically impact the development of the marine sector's pathway to reaching zero by 2050



Biofuels availability to shipping

Renewable electricity cost development

Safety case for ammonia

Main scenario

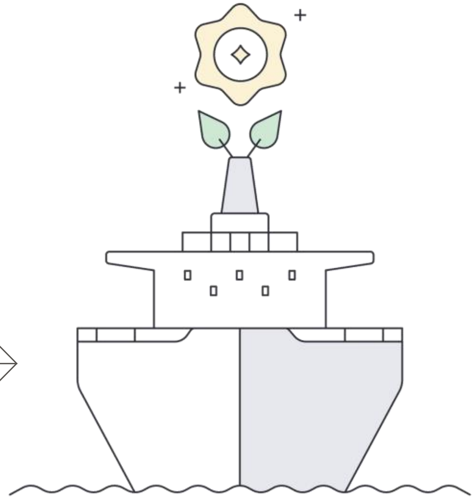
"A Path to Zero"

Alternative scenarios

Reaching zero with:
Scarce / Abundant biofuels

Reaching zero with:
More / less costly electricity

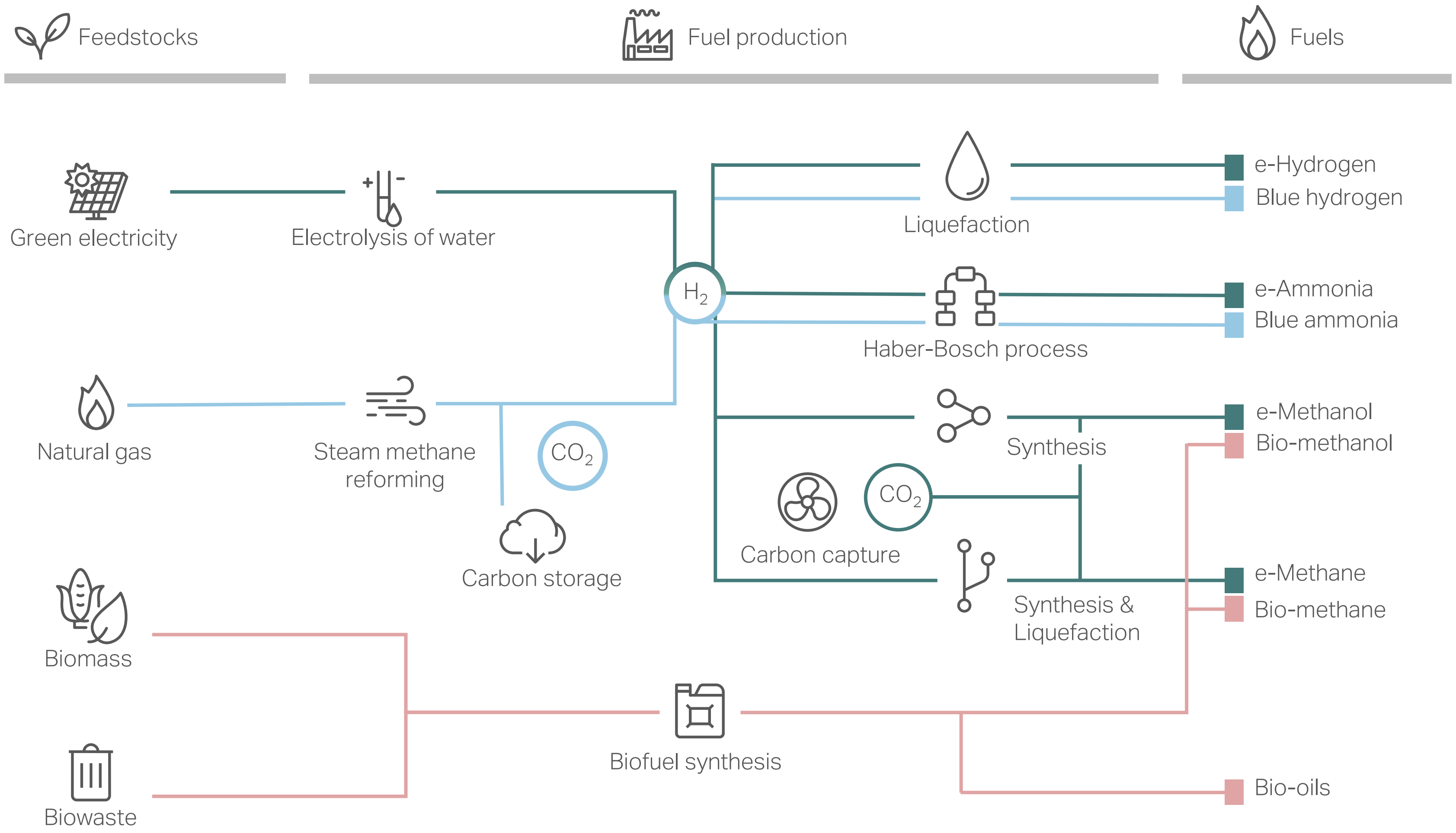
Reaching zero with:
No ammonia acceptance



Alternative possible fuel composition outlooks

1) With reference to Industry Transition Strategy and appendix, other than fuel pathway critical levers also include energy efficiency levers, financing, willingness to pay, and regulation.

The cost and scalability of future decarbonized fuels is highly uncertain

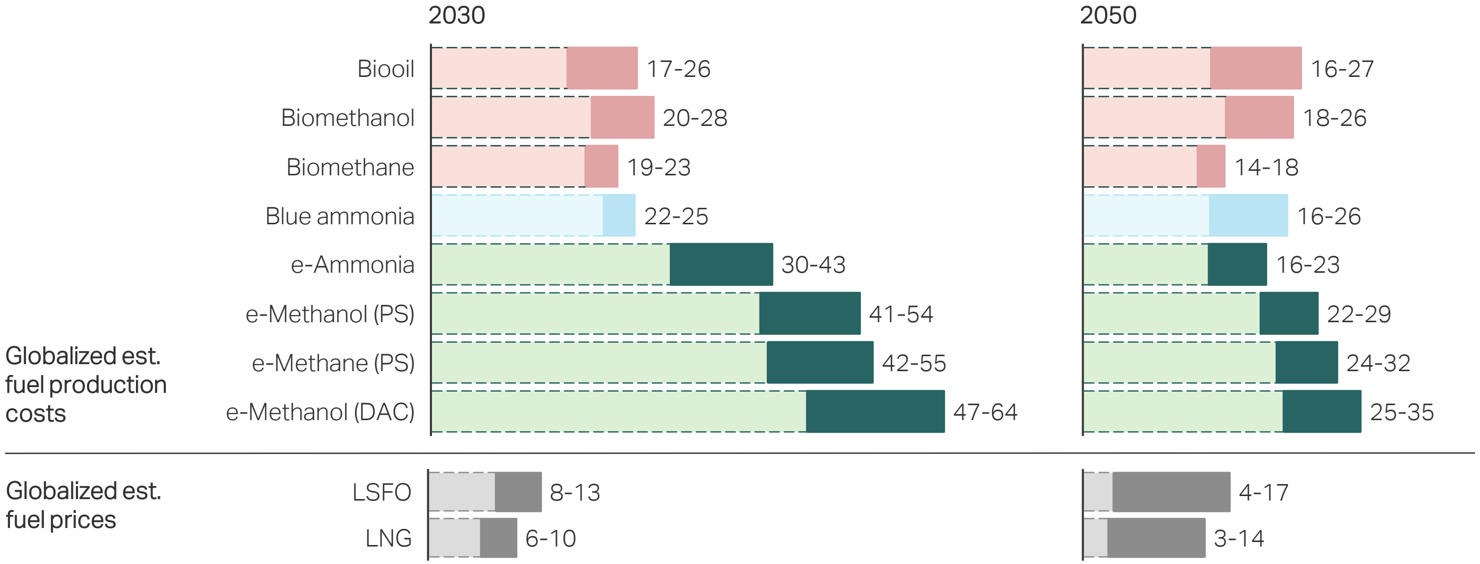


1) Hydrogen is deemed irrelevant for deep sea shipping and is not further analyzed in this document.

- Currently, we have at least five candidate groups for future alternative fuels: hydrogen, ammonia, methanol, methane and bio-oils
- Each group in turn contains different types of fuels, distinguished by the feedstock and fuel production processes used.
- Renewable energy is used to produce e-fuels, fossil feedstocks are used as a basis to produce blue fuels, while bio-oils include a range of techniques that convert biological material into an oil-like substance
- Carbon dioxide and capture thereof may be regarded as an additional feedstock for methane and methanol influencing cost and scalability

Fuel prices cannot be predicted but data, assumptions, and analyses can indicate levels and realistic ranges of production cost

Fuel costs[1)] (USD/GJ) decline over time, though there remains uncertainty on absolute fuel cost levels



Source: NavigaTE. The illustration illustrates the cost of fuels based on a global weighted average for non-subsidized, stand-alone, commercial scale plants. These fuel costs should not be interpretated as a prediction of fuel prices.
1) Production, logistics, and storage at port. 2) Assumptions provided in the appendix. 3) Assumptions related to cost of renewable energy is outlined in the appendix.

Alternative fuel costs will decline, but which pathways are optimal depends on uncertainties in the cost development:

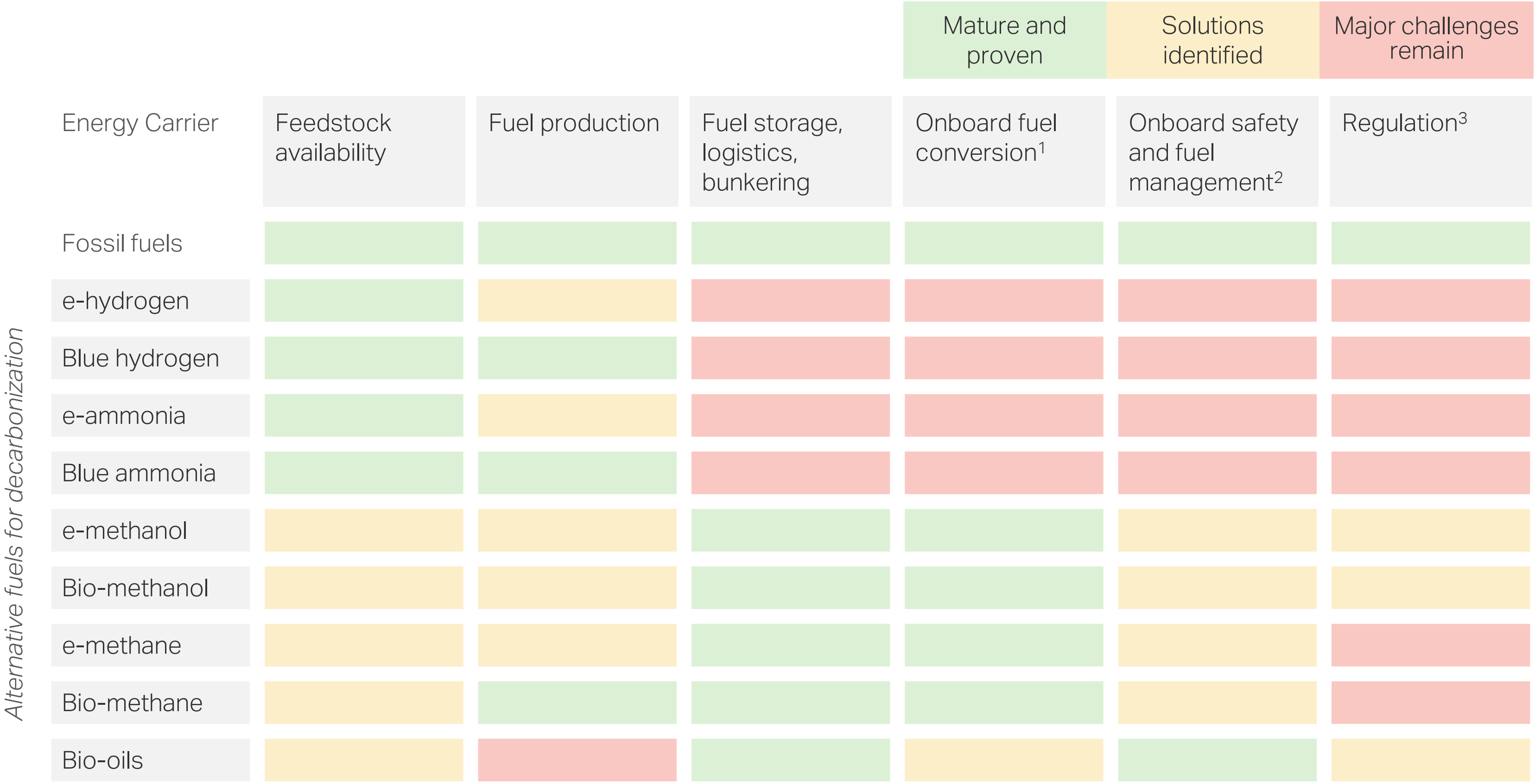
– **Biofuels** will be cost competitive, but scaling constraints will affect global supply, maritime availability, and price. Illustration presents a +/- 40% sensitivity on the cost of biomass.

– **Blue fuels** represent a cost competitive alternative until lower electricity costs makes e-fuels attractive. Illustration presents low/ high natural gas price outlook[2]).

– **E-fuels** will become more cost-effective as electricity costs decline throughout the period. Illustration presents a sensitivity between lower quartile costs with critical levers activated vs. median costs without critical levers[3]).

– **LFSO/LNG:** Illustration presents low/ high natural gas and low/ high LSFO price outlook[2]).

Alternative fuels present challenges beyond just cost reduction, in any path to decarbonization



Even though the analysis of different fuel pathways may be largely a technoeconomic assessment, progress towards decarbonization will only be possible by addressing the other various challenges associated with each fuel. A successful approach to navigating the industry transition must entail:

- Supporting the regulatory framework to enable and steer the transition
- Ensuring safety for onboard use
- Achieving the required technological readiness for fuel production– and for vessel operation on alternative fuels
- Scaling up the infrastructure and operations along the supply chain: production, logistics, storage, and bunkering.

Source: MMM Center for Zero Carbon Shipping
Note: Emissions reduction impact from direct electrification of ships and nuclear-powered vessels is not modeled in NavigaTE 1.0
1 Considers onboard fuel supply and storage, fuel conversion and emissions control systems
2 Considers fuel toxicity, flammability and explosiveness
3 Includes regulatory framework supporting onboard regulatory aspects, and market mechanisms supporting adoption

Even with the projected levels of fuel cost and its uncertainty, it is possible to decarbonize shipping in multiple scenarios. The example below is assuming that ammonia is enabled to become a fuel.

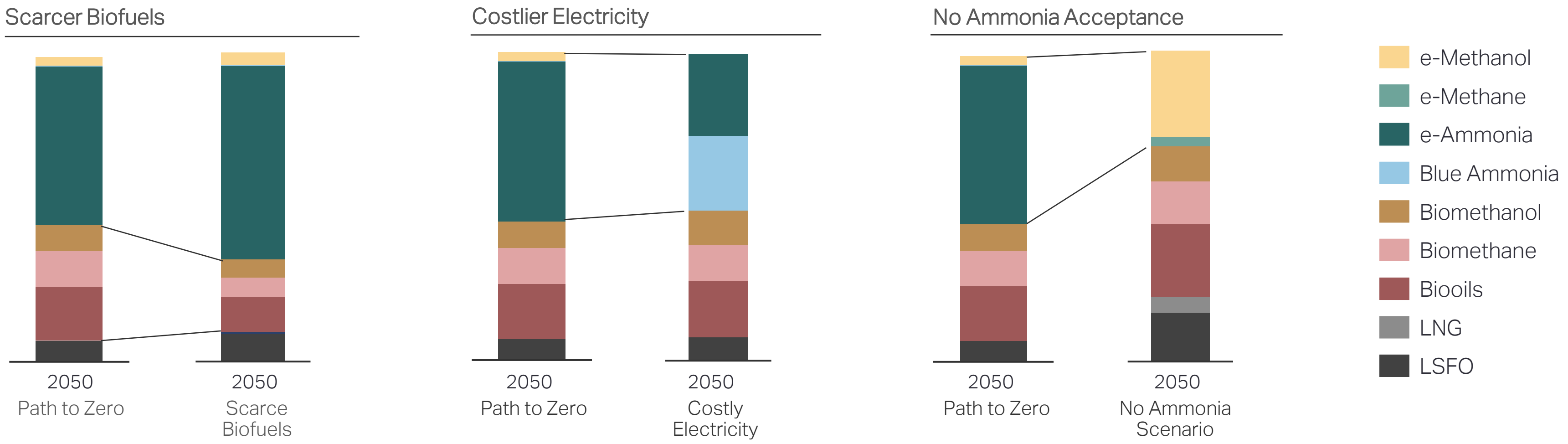
Fuel composition & energy demand in the "a Path to Zero" in EJ/year

Full list of critical levers provided in the appendix. Critical levers are fully described in the Industry Transition Strategy. 2) Refer to section titled Scenarios altering the Path to Zero fuel blend.

The "A Path to Zero" scenario:

- Assumes an optimistic-reasonable scenario through activation of all critical levers[1)]
- Medium biofuel availability (not the scarcer case), low-cost electricity (not the more costly case), ammonia acceptance, and blue fuels acceptance.[2)] Carbon taxed as needed.
- Energy efficiency investments are intensified, decreasing energy demand towards 2050 even as total volume transported by the maritime industry increases.
- Ammonia plays a central role, first as blue ammonia and later as green ammonia. Assume ammonia safety risk is mitigated.
- Biofuels play a role as their value chains reach necessary scale: bio-methane with a primary role from 2030s, and bio-methanol and bio-oils impacting the fleet mix from 2040s
- Fossil fuels would be nearly phased out by 2050

There are multiple viable pathways to decarbonize by 2050, and several fuel blend combinations could deliver the solution



Less biomethane and bio-oils, more electro-fuel

+$15/ton CO2 tax eq.1)

More blue ammonia, less electro-fuels

+$45/ton CO2 tax eq.1)

E-methanol and e-methane, instead of e-ammonia

+$70/ton CO2 tax eq.1)

1) Additional CO2 tax required to achieve the same emissions level as in Path to Zero, while still enabling uptake of more costly alternatively fuels in the respective scenarios where constraints on scarcity of biofuels, more costly electricity, and no uptake of ammonia are applied.

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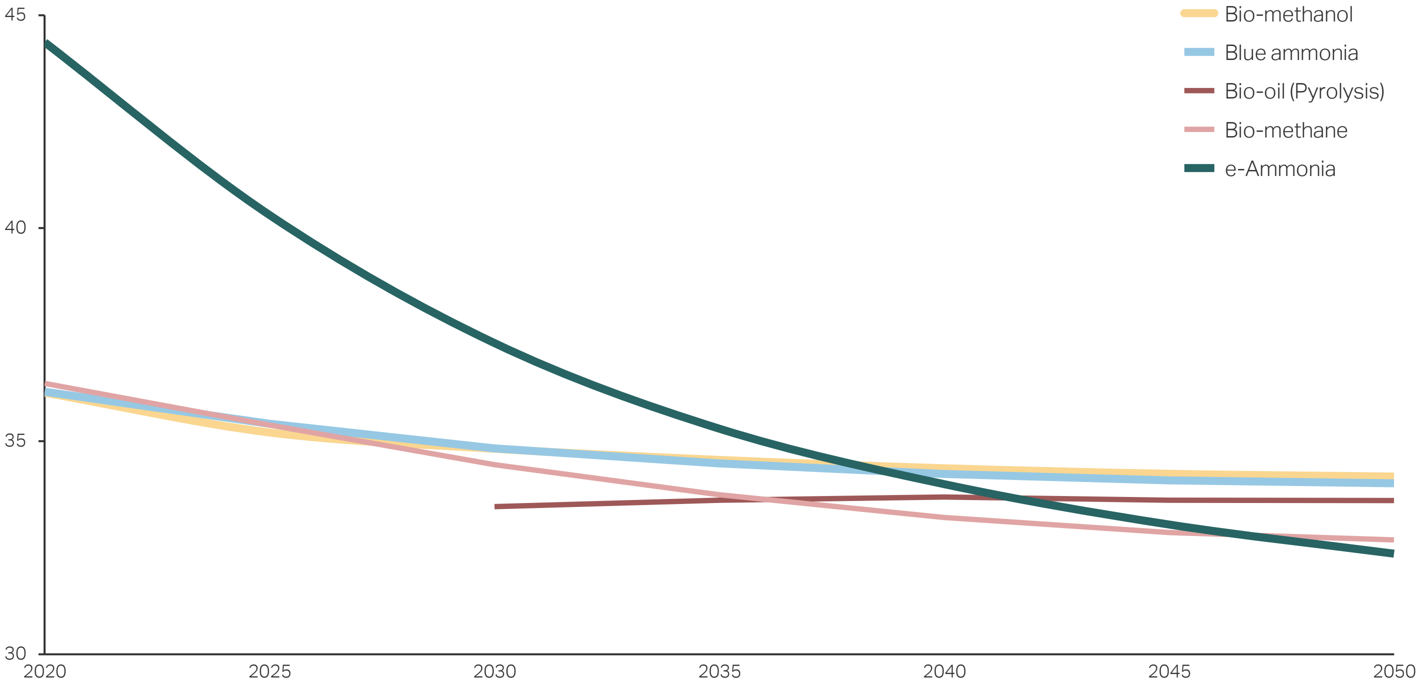
Biofuels availability

Biofuels' role in the maritime industry is mainly limited by its availability

Total cost[1] of ownership[2] in USDm/year for operating on alt. fuels



1) The underlying fuel costs are provided in appendix. 2) Container vessel (~8,000 TEU) with a 25-year lifetime and a representative operational profile, low-cost scenario for electricity prices, and all energy efficiency levers with <10 years payback on.

Highlights from NavigaTE analysis

Bio-fuels are cost competitive with other alternatives until 2040/45
Compared to other alternative fuels, operating vessels on biofuels are projected to result in lower cost of ownership until 2040/2045 (see chart). Specifically, operating a medium sized container vessel on bio-oils or liquid bio-methane results in lower cost of ownership than blue- and e-fuels until 2040/2045, after which green ammonia reaches as low cost as liquid bio-methane. Bio-methanol shows similar operating costs as blue ammonia.

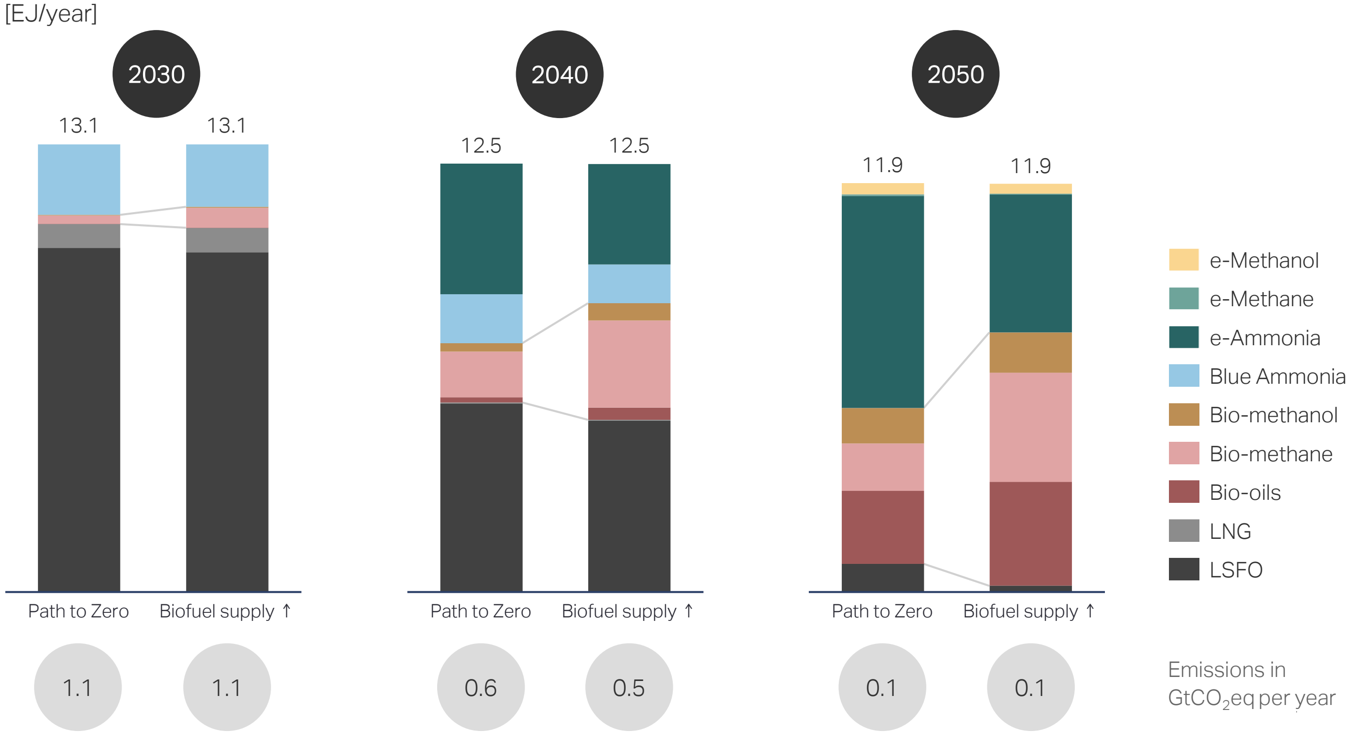
The uptake of biofuels is limited by supply
Bio-fuel uptake in shipping is not limited by cost, but rather by the availability of bio-fuels for the shipping industry at scale. This availability is driven by the maturity of biofuel conversion technologies, roll-out speed of conversion plants and competition for biofuels and biomass between industries. To map their impact, two scenarios were assessed:

1. **Double bio-fuel availability:** Can be envisioned if: global sustainable biofuel demand >200 EJ, other industries demand less carbon-based fuels than expected, or the roll-out speed of biofuel conversion technologies is faster than predicted

2. **Half bio-fuel availability:** Can be envisioned if: global sustainable biofuel demand is less than 200 EJ, other industries demand more carbon-based fuels than expected, or the roll-out speed of biofuel conversion technologies is slower than predicted

Double biofuel availability to the maritime industry increases its uptake, resulting in lower emissions at same CO_2 tax

Impact on the fleet fuel mix



Highlights from scenario analysis

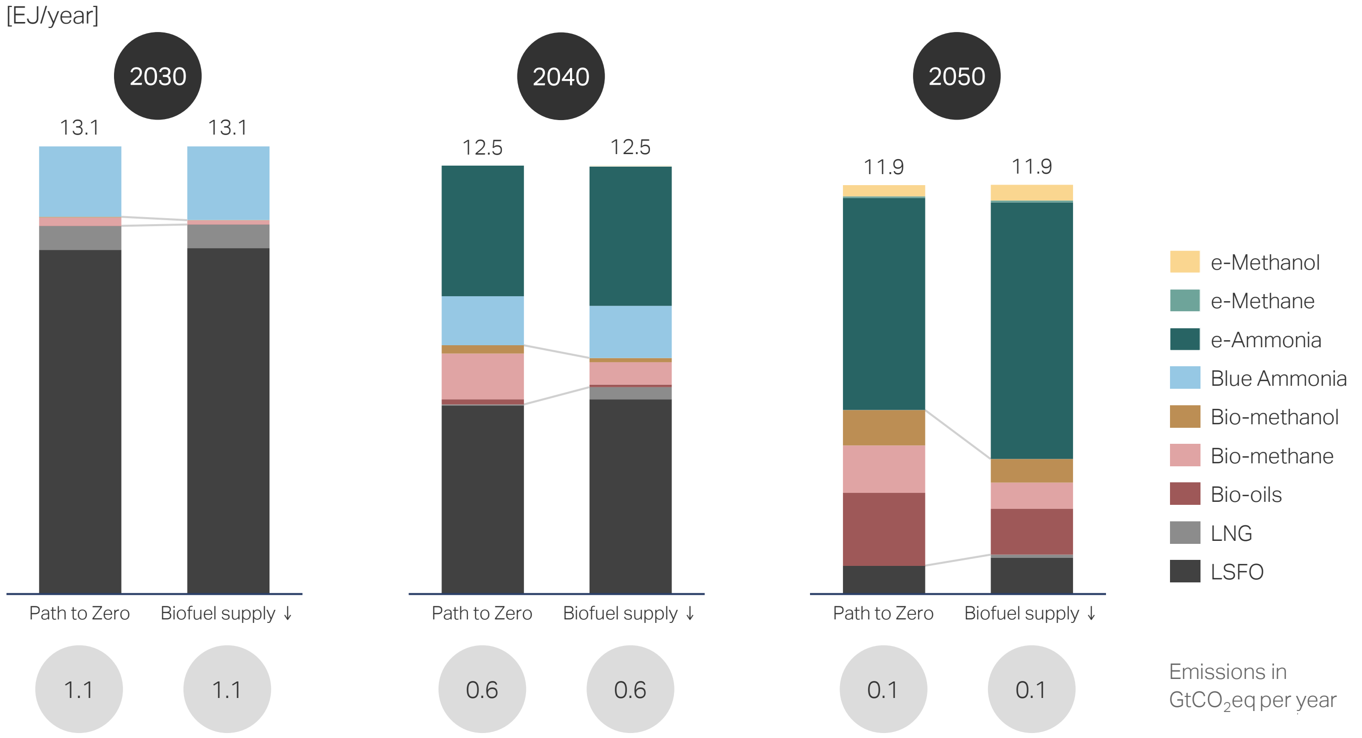
Biofuels could play a larger role if supplies are available
With double biofuel availability, the uptake of bio-fuels in shipping increases significantly. Specifically, biofuel's share of the total energy demand from shipping increases from 2 to 5% in 2030, from 13% to 26% in 2040 and from 35% to 56% in 2050. The highest increase in uptake happens for bio-methane and bio-oils, while bio-methanol uptake primarily increases in 2040.

Increased biofuel use primarily decrease green and blue fuel use
Higher availability of biofuels results in a 4% point drop in the use of LSFO in the fleet in 2040 (42 to 38% of fleet energy demand). This is caused by the existing LSFO vessels that cannot utilise the new fuels. Bio-oils, which can be used in these vessels directly, are still not available in sufficient scale to decrease replace LSFO. Instead, the increased biofuel uptake results in less green ammonia (29% to 22% in 2040 and 50% to 33% in 2050) and blue ammonia (11%-9% in 2040).

Increased biofuel uptake reduces fleet emissions
When the use of bio-fuels in the fleet increased from improved availability, the fleet's total emissions decreased by 8% in 2040 and 40% in 2050 compared to the Path to Zero case. Thus, a slightly higher emission reduction is achieved at the Path to Zero. Also, a higher emission reduction will be achievable than in the Path to Zero case, as the biofuels have lower cost of operation until 2040/2045.

Conversely, half biofuel availability decreases its uptake resulting in higher emissions at same CO_2 tax

Impact on the fleet fuel mix



Highlights from scenario analysis

Biofuels could play a smaller role if supply is lower than predicted
If supply of biofuels for shipping is half of the uptake of bio-fuels decreases 2% to 1% in 2030, from 13% to 7% in 2040 and from 35% to 21% in 2050.

Low biofuel uptake results in higher fossil, blue and e-fuels use
At lower biofuel availability, the use of LSFO increases from 44% to 45% in 2040, and from 7% to 9% in 2050. In addition, LNG remains in the fuel blend at 3% in 2040 compared of 0% in the Path to Zero case. Green ammonia and blue ammonia are both used to a slightly higher extent in 2040, and green ammonia at a significantly higher extent in 2050 (61% instead of 50%).

Reduced biofuel uptake increases fleet emissions
At lower biofuel availability the fleet's total emissions increase by 7% in 2040 and 10% in 2050 from the Path to Zero case. Thus, a slightly lower emission reduction is achieved at the same level of carbon tax, and a slightly higher carbon tax is necessary to reach the same decarbonisation target: an extra +$15/ton CO_2 would be needed. Also, a lower emission reduction will be achievable than in the Path to Zero case, as the biofuels have lower cost of operation until 2040/2045.

To be part of the solution, rapid development in biofuel supply and sustainability control must occur

Biofuel sustainability must be tightly controlled

Feedstocks used for biofuel production must be sourced sustainably

The sustainability of biofuels is highly dependent on the origin of the biomass used. While a bio-oil based on used cooking oil, and one based on palm oil, are similar on the molecular level, the use of land space differs. Producing palm oil results in direct or indirect deforestation releasing high amounts of CO_2 to the atmosphere. Thus, the bio-oil from used cooking oil has low emissions in its production, while the palm oil bio-oils has high emissions. Recognizing the difference between these feedstocks is a challenge. A vessel-operator needs robust and widely recognized standards and systems for documenting the sustainability of the bio-fuel production cycle. The road transport and aviation industries have developed some of these systems already, which the maritime industry could benefit from modifying and adopting.

Controlling methane loss throughout the value chain will be critical, especially for bio-methane

Methane loss to the atmosphere from production and through use can jeopardize the sustainability of bio-methane. Leak levels from production of bio-methane can vary significantly from plant to plant, and from country to country. If bio-methane is to play a role in the decarbonization of the maritime industry, it is critical that regulation drives both production plants, distribution network owners and vessel owners to minimize methane loss rates.

1) Standard plant sized (kton fuel/year): Bio-methane: 10, HTL oil: 92, Bio-oils: 75-200 depending on technology, Bio-methanol: 150

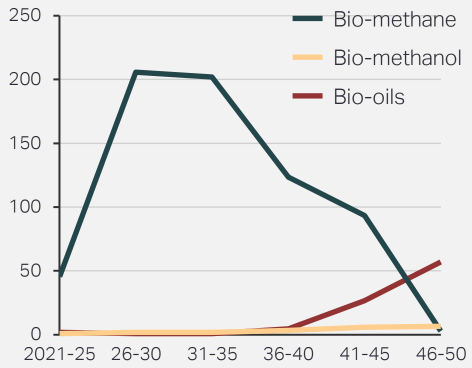
Biofuel supply for shipping must increase at unprecedented speeds

Three major risks were identified when accelerating the biofuel value chain for the maritime industry: Roll-out of conversion plants, competition of biomass and competition for biofuels

Roll-out of conversion plants must accelerate rapidly

To reach biofuel supplies predicted in the Path to Zero scenario, the roll-out of conversion plants supplying the maritime industry must accelerate rapidly. 200 new bio-methane plants supplying shipping must be built per year between 2025 and 2035, while bio-oils would require 30-60 new plants supplying shipping per year after 2040 to meet demand.

New plants supplying shipping, per year
[Number of new standard sized[1] plants]



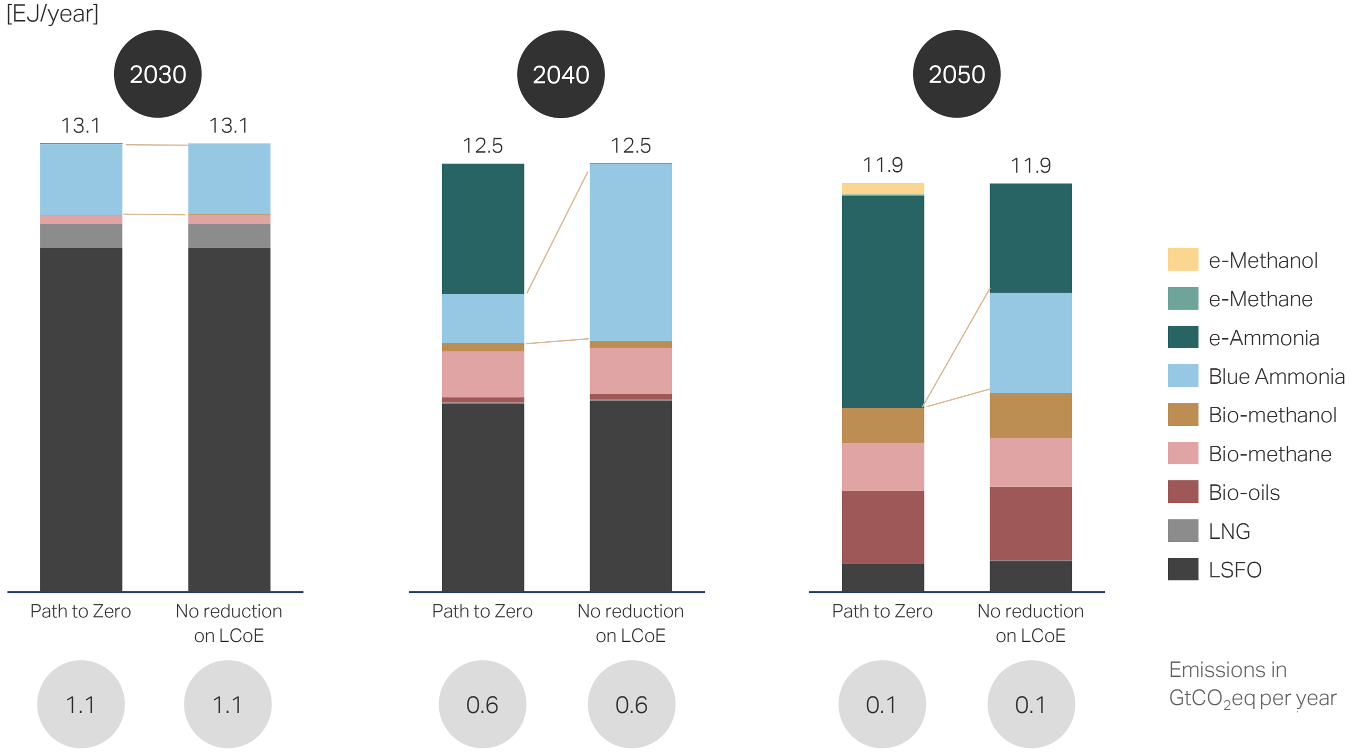
Competition of biomass and biofuels could reduce supply for shipping

Most industries are moving towards zero emissions by 2050. Their energy demand exceeds the amount of global sustainable biomass projected to be available. Thus, the competition for biomass and biofuels could drive prices to levels which are unsustainable for the maritime industry.

Effect of renewable electricity cost on green / blue fuels

Blue ammonia could play a more prominent role in the transition with a higher renewable electricity cost

Impact on the fleet fuel mix



1) Corresponding to activated critical lever as per Industry Transition Strategy. Critical levers are listed in appendix.
2) From 2030, required storage capacities for blue ammonia start with 0.2 GtCO2eq per year and range up to 0.5 in 2045 of the alternative scenario.

Highlights from scenario analysis

Carbon taxation promotes blue ammonia during the transition period
Although blue ammonia carries an emissions penalty from methane leaks in upstream production, using it as a fuel nevertheless results in less net emissions than fossil fuels. Therefore, carbon taxation has a net positive effect on the uptake of blue ammonia, especially during the early industry transition.

The role of blue ammonia strongly depends on electricity cost
The Path to Zero scenario features low-cost scenario for supply of renewable energy[1] and results in moderate uptake of blue ammonia. In contrast, medium-case RES costs (more expensive renewable electricity) would significantly expand the role for blue ammonia. Without low-cost RES, the emissions reduction would be less effective than in the main scenario. In that case, achieving the same emissions target would require a tax that is $45/ton CO_2 higher than the tax in A Path to Zero. Blue ammonia's role could also get amplified if it was not possible to globally supply enough RES to meet demand from all industry sectors.

Regulatory risk: Carbon Capture and Storage[2]
A key uncertainty for blue ammonia's role is the political acceptance of CCS as an effective practice. The positive climate impact of blue ammonia hinges on the assumption that stored CO_2 is permanent. However, certifying blue ammonia as a low emissions fuel will require the establishment of standards to certify that stored carbon is not escaping over time or otherwise having a negative impact on climate. Further, methane emissions associated to upstream natural gas production must be mitigated.

Whereas a faster decline in renewable electricity cost would limit the role of blue ammonia in the transition

Impact on the fleet fuel mix

Highlights from scenario analysis

Carbon taxation limits blue ammonia in the long run
While carbon taxation promotes blue ammonia during the transition, it does carry an emissions penalty due to methane leakage in upstream production. Therefore, carbon taxation also makes blue ammonia more expensive than it would be otherwise, which can make it less attractive whenever greener options are economical.

The role of blue ammonia strongly depends on electricity cost
Two assumptions are made in the low-cost RES scenario: (1) the required buffering capacity is assumed as half of the baseline amount, and (2) the marine industry would be able to secure renewable energy from the countries having the lowest quartile of costs. These effects would make electro-fuels less expensive and therefore better able to compete against blue ammonia, resulting in less blue ammonia in the mid-transition fuel mix. Regardless of whether the scenario is low- or medium-, RES costs will gradually decrease over time, leading to electro-ammonia outcompeting blue ammonia in the long-run.

Regulatory risk: Carbon Capture and Storage
A key uncertainty for blue ammonia's role is the political acceptance of CCS as an effective practice. The positive climate impact of blue ammonia hinges on the assumption that stored CO_2 is permanent. However, certifying blue ammonia as a low emissions fuel will require the establishment of standards to certify that stored carbon is not escaping over time or otherwise having a negative impact on climate. Further, methane emissions associated to upstream natural gas production must be mitigated.

Blue ammonia can be overall beneficial for the transition, but its acceptance may be challenged at various levels

Blue Ammonia – Benefits

Blue Ammonia

Blue ammonia has been proposed as a more cost-effective, near-term solution for the marine industry's transition to low emission fuels. Since it is produced in the same way as conventional ammonia, the only time constraint to its implementation is validating and certifying that CO_2 from the process is permanently stored.

Potentially near-term reduction of carbon footprint

Since the technologies for blue ammonia production are established, it may be possible to supply blue ammonia within the 5-10 years that it will take before demand takes off. Since blue ammonia is up to 80-90% less carbon intensive than fossil alternatives, it represents a potential near-term solution to decarbonization.

Blue ammonia can accelerate the green transition

In all RES cost scenarios, electro-fuels will be too expensive to produce in the near-term. Therefore, the fleet uptake of ammonia fuel could be laboriously slow, if new-builds do not foresee any advantage of purchasing ammonia-ready vessels. Therefore, in the medium term, the lack of affordable green ammonia will hinder the transition. However, if blue ammonia would become an option near the start of the transition, then the vessels and logistics infrastructures could benefit from a head-start to improve the economics of ammonia in the maritime industry. In this case, greener ammonia could be adopted sooner, and in larger quantities.

…. and Risks

Safety and Environmental risks

The largest barrier to utilizing blue ammonia in shipping is that – blue or not– onboard usage of ammonia poses significant safety and environmental risks that need to be addressed. Beyond toxicity hazards, ammonia furthermore awaits the technology readiness for propulsion, especially the development of an engine capable of running on ammonia without N_2O slip.

Upstream Production risks

Since blue ammonia is produced from natural gas, its upstream emissions can be nearly as significant as for LNG. Methane is a potent greenhouse gas, and there are emissions that may be difficult to control from exploration, drilling, pipelines, etc.

Regulatory risks of CCS

CO_2 storage is a technology that is generally considered to be mature enough to scale commercially. However, there is currently no global standard for CO_2 crediting, and there is potential skepticism about the long-term efficacy of storage. Certification schemes must be developed in conjunction with ongoing validation that storage does not leak.

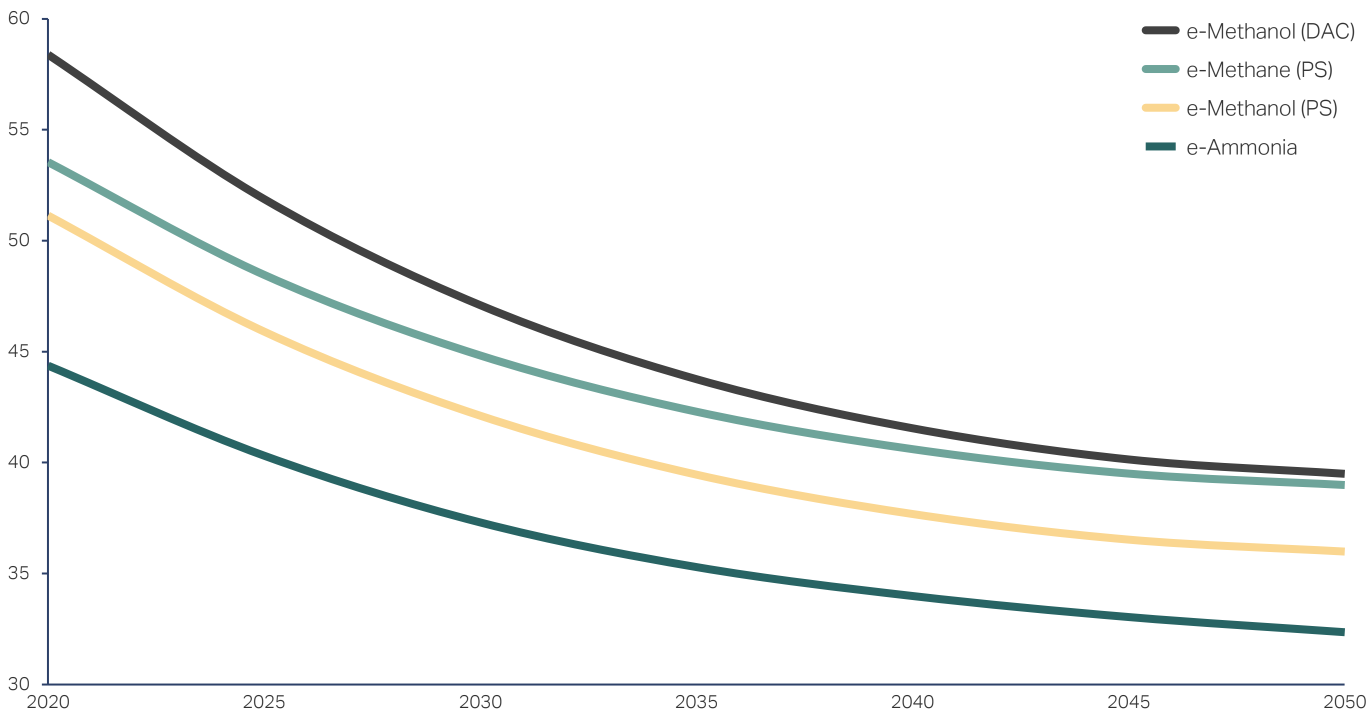
Political view on the fossil fuel industry

Public sentiment may be disinclined to support policies for a product that extends the lifetime of fossil industries – especially if the CO_2 is used to recover more oil and gas.

Altered hierarchy of e-fuels

Ammonia is the cheapest e-fuel and the only relevant blue fuel; without ammonia other e-fuels may play a larger role

Total cost[1] of ownership[2] in USDm/year for the cheapest e-fuels



1) The underlying fuel costs are provided in appendix. 2) Container vessel (~8,000 TEU) with a 25-year lifetime and a representative operational profile, low-cost scenario for electricity prices, and all energy efficiency levers with <10 years payback on

E-fuels share a similar cost decrease due to declining electricity cost

The projected e-fuel costs depend similarly on the decreasing cost of renewable electricity prices. Extra cost differences are due to CO_2 costs and potential technology optimizations (in the case of e-diesel).

Ammonia is the least costly energy-dense e-fuel

Ammonia is made from N_2 feedstock, which is readily available and cheaper to obtain than the CO_2 that is needed for carbon-based fuels. However, ammonia has slightly lower energy density than the carbon-containing options, and it faces significant safety and regulatory hurdles.

E-methanol is the second least-costly alternative maritime e-fuel

If ammonia should fail to overcome the barriers to its implementation, the next most cost-effective e-fuels are e-methanol and e-methane. These two options have very similar costs of production, but their effective total costs of usage depend on ship storage and consumption: bunkering, onboard storage, operational characteristics, and shipping route. As with ammonia, both methane and methanol require more space onboard than LSFO: e-methane requires energy intensive cryogenic storage, and e-methanol is less energy-dense. All considered, e-methanol is likely the more cost-effective option for a larger portion of the fleet, although e-methane may still find use.

The availability of Point Source CO_2 is a key cost determinant of carbon-containing e-fuels

As shown in the fuel options cost curve, carbon-containing electro-fuels will be more costly to produce than ammonia, since CO_2 feedstock is required. This CO_2 is only emissions neutral if secured from a biogenic source or by direct air capture, and it is not as easily extracted as N_2. This is because CO_2 utilization carries costs related to capture, compression or liquefication, and transportation. Furthermore, demand for biogenic CO_2 will face competition from other industries, including CCS and carbon credits.

Point source CO_2 must be biogenic for low emission fuels

From an LCA perspective, the capture and re-use of non-renewable CO_2 does not result in a net positive climate impact. Capturing a carbon atom of fossil origin will render a carbon credit to the operator who does the capturing. But if downstream fuel-producers utilize such captured carbon, they must either (a) pay for the value of the credit or (b) bear the burden of its later re-emission as CO_2. I.e. the carbon credit cannot be claimed by both the upstream and downstream industries. Therefore, captured non-biogenic carbon is taken on loan: it merely serves as a temporarily energy storage medium, before being re-emitted as CO_2 with a net-negative climate impact.

Biogenic CO_2 is difficult to capture and utilize today, but it may become easier in the future

The amount of biogenic CO_2 produced today could theoretically supply all that shipping would need. However, most biomass power plants are small or remote, and therefore the CO_2 capture and transport costs are prohibitive– this effectively means there is a shortage. Moreover, most of today's biogenic CO_2 is uneconomical to capture because it is emitted in low concentrations.

Despite the near-term undersupply of biogenic CO_2, it is envisioned that more biogenic CO_2 will be available in the longer term. This is because bio-methane will likely emerge as a new and widespread resource, replacing natural gas in grids, thereby increasing the biogenic CO_2 availability while also decreasing the costs of capturing and transporting it.

Direct Air Capture is cost-prohibitive in the near-term; demand will depend on availability of point sources.
Direct air capture is a technology for removing CO_2 at its low concentrations in ambient air. The result is direct depletion of the greenhouse gas from the atmosphere. DAC is currently at an early stage of commercial readiness, with focus on reducing operating cost. Due to its dependence on low-cost renewable electricity, it may not be economically feasible – compared to point source capture - until late in the industry transition.

Various CO_2 dynamics will be interlinked: carbon taxation, carbon crediting, point source CO_2 price, and demand for DAC
In a future with international CO_2 taxation, it is likely that *carbon credits* will be recognized for removing atmospheric CO_2. The ability to globally trade such credits will trigger a demand for *emissions offsetting*. I.e., it may well cost less for hard-to-abate sectors to buy carbon credits rather than pay a high emissions penalty.
Two methods for removing and permanently storing CO_2 are DACCS (DAC + Carbon Storage) and BECCS (Bioenergy + Carbon Capture and Storage). The costs of these processes may become lower than some of the CO_2 tax levels being considered. *Therefore, BECCS/DACCS costs may potentially determine the maximum* effective *CO_2 tax.*

Another consequence of such CO_2 trading is that the CO_2 tax level will determine the CO_2 feedstock price for e-methanol etc. To be used for carbon-based electro-fuels, its value as a feedstock would need to be higher than its value in BECCS/DACCS.

Without blue ammonia the transition would be delayed or require a higher CO_2 tax

Impact on the fleet fuel mix

Highlights from scenario analysis

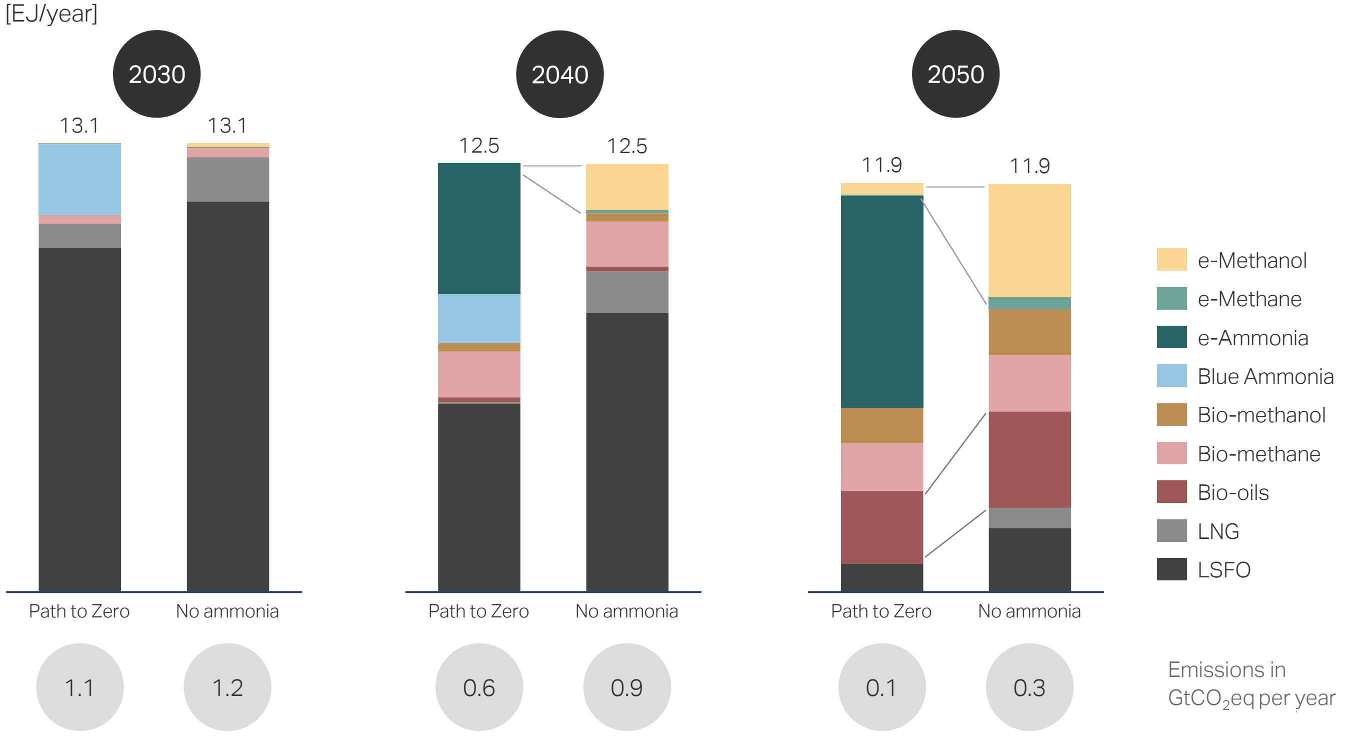
Blue ammonia may promote future uptake of electro-ammonia
Electro-ammonia will be too costly to produce in the short-term, limiting its utilization in the early transition. And if low emission ammonia production is not cost-effective, then the maritime industry will not have a reason to convert to ammonia-powered vessels. Therefore, blue ammonia may be an attractive transition fuel: the industry can prepare vessels and infrastructure for later operation on renewable ammonia.

The absence of a blue ammonia option could hinder the green transition
Comparing scenarios with / without available blue ammonia, it can be seen that removing blue ammonia decreases the future demand for total ammonia (blue + green). While this is not surprising for those years when blue ammonia would otherwise have been an affordable option, less total ammonia (and other e-fuels) is also demanded in 2050– a year when blue ammonia would not otherwise impact the fuel mix. Furthermore, the scenario of no blue ammonia also results in higher LSFO usage.

Removing the blue ammonia option could be compensated by higher tax
If blue ammonia is not available for the industry transition, then it is possible to find a carbon tax level that will nevertheless yield the same future consumption of fossil fuels. Analysis shows that, by increasing the tax burden by an additional \$30-\$40/ton CO_2 beyond the Path to Zero case, the future consumption pattern of fossil fuels can match the levels reached by allowing for blue ammonia. The resulting fuel mix is also similar: green ammonia then replaces the blue ammonia content of the Path to Zero case.

Without both blue and green ammonia the transition would be delayed even more or require an even higher CO_2 tax

Impact on the fleet fuel mix



Highlights from scenario analysis

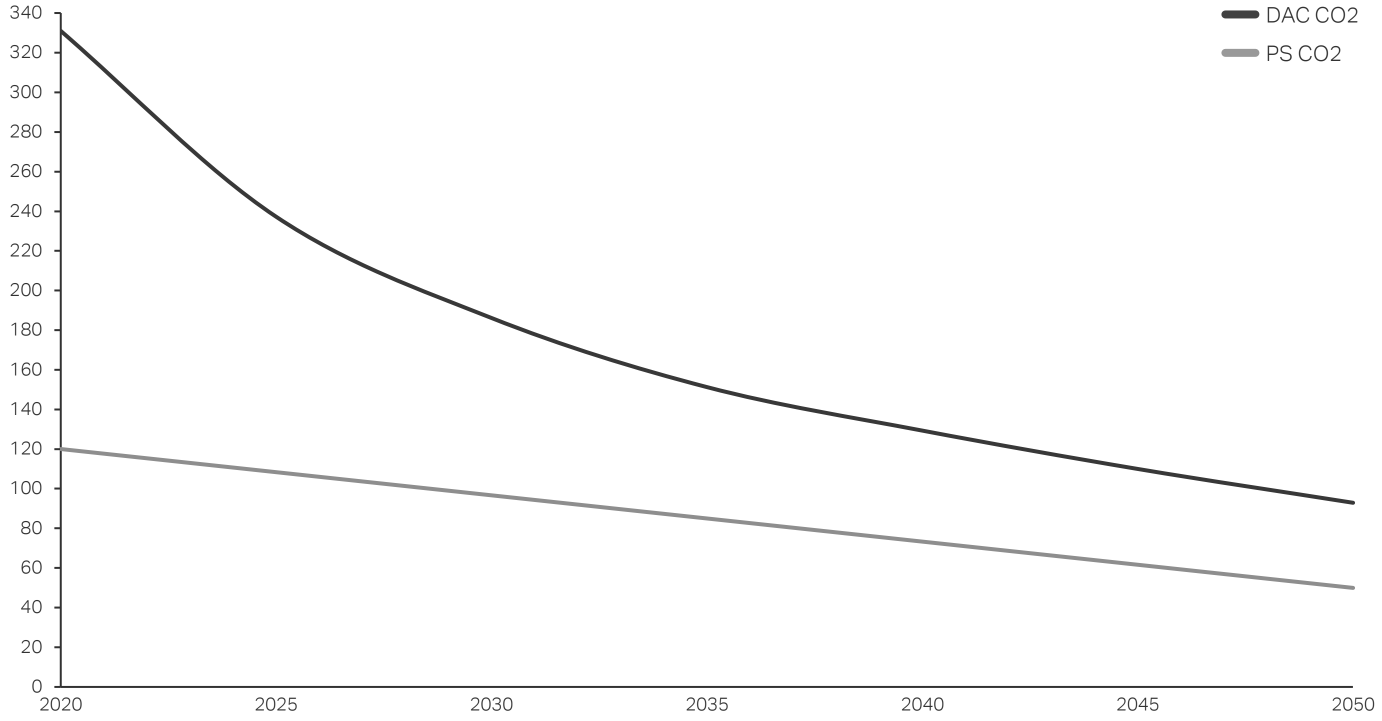
Ammonia has the potential to accelerate the transition, at a lower tax rate than non-ammonia fuels
Ammonia is the cheapest of the energy-dense e-fuels to produce, mostly because the nitrogen feedstock is more affordable than the biogenic CO_2 that is required to make carbon-containing e-fuels. Therefore – if able to overcome technological, regulatory, and safety barriers– ammonia could make the industry transition achievable at a lower tax level.

E-methanol, and possibly e-methane, play a larger role if ammonia is not viable
In the event that ammonia becomes unfavourable, its portion of the fuel mix would need to be substituted by other low emission fuels. Analysis shows that this gap would be filled by e-methanol, a small amount of e-methane, and some biofuels (especially bio-oils). Compared to the scenario where ammonia is available, the transition to these fuels would occur later. Furthermore, a scenario without ammonia results in a higher LSFO consumption.

Significantly higher tax could compensate for absence of ammonia
If ammonia is not available for the industry transition, then by increasing the carbon tax level by an additional $70/ton CO_2 beyond the Path to Zero case, it is possible to maintain the same future fossil fuel consumption achieved in that case. Then e-methanol (and a portion of e-methane) would replace the entire e-fuel supply.

Prohibitive DAC cost developments in near future mean biogenic CO_2 sources are the source of carbon for carbon-based e-fuels

Cost of CO_2 (biogenic point source or direct air capture) in USD/tCO_2



CO_2 is costly for carbon-based e-fuels

The cost of CO_2 will significantly contribute to the cost of e-methanol and e-methane – even with decreasing prices for both biogenic point source (PS) CO_2 and direct air capture (DAC) CO_2.

For one ton of methanol, ~1.5 ton of CO_2 is needed, resulting in an additional cost of USD 75-180 per ton of methanol in 2050.

The availability of PS CO_2 may be limited by competing demand from other industries.

If CCS and carbon trading are recognized by regulatory bodies, then there may be high demand for PS CO_2, for the purpose of offsetting. In that scenario, the carbon tax/credit level could set the market price of CO_2– making carbon fuels even costlier.

Agenda

Agenda

NavigaTE Model Assumptions

Energy & Fuels Key input data (1/3)

Cost of renewable electricity – mid case	Unit	2020	2025	2030	2035	2040	2045	2050
Europe	USD/MWh	65	60	55	51	47	43	40
Middle East	USD/MWh	65	58	52	47	42	38	34
Asia	USD/MWh	84	76	69	62	56	51	46
Americas	USD/MWh	53	50	47	45	42	40	38
Africa	USD/MWh	72	64	57	51	45	40	36

Cost of renewable electricity – low case	Unit	2020	2025	2030	2035	2040	2045	2050
Europe	USD/MWh	55	44	36	32	30	28	26
Middle East	USD/MWh	42	34	28	25	23	20	19
Asia	USD/MWh	82	54	43	36	33	29	27
Americas	USD/MWh	39	35	29	26	23	22	21
Africa	USD/MWh	79	45	35	30	27	25	23

Cost of carbon capture and storage	Unit	2020	2025	2030	2035	2040	2045	2050
Cost of CO_2 point source	USD/ton	120	108	97	85	73	62	50
Cost of CO_2 capture, blue fuels	USD/ton	25	25	25	25	25	25	25
Cost of CO_2 storage	USD/ton	50	50	50	50	50	50	50
Cost of direct air capture[1] CO_2	USD/ton	331	237	186	151	129	110	93

Electrolyser efficiency (LHV basis)	Unit	2020	2025	2030	2035	2040	2045	2050
Alkaline	%	59%	61%	62%	63%	65%	66%	68%
PEM	%	51%	53%	54%	56%	58%	60%	63%
SOEC	%	75%	76%	78%	79%	80%	82%	83%

Electrolyser market share	Unit	2020	2025	2030	2035	2040	2045	2050
Alkaline	%	80%	70%	50%	25%	5%	0%	0%
PEM	%	20%	25%	33%	37.5%	40%	30%	20%
SOEC	%	0%	5%	17%	37.5%	55%	70%	80%

1: DAC is modelled is the fuel module

Energy & Fuels Key input data (2/3)

LSFO and crude oil prices[1]	Unit	2020	2025	2030	2035	2040	2045	2050
Crude oil price	USD/bbl	73	61	59	59	59	59	59
LSFO price	USD/ton	561	466	452	452	452	452	452

Woody biomass cost[2]	Unit	2020	2025	2030	2035	2040	2045	2050
Europe	USD/ton	95	100	105	110	114	119	124
Middle East	USD/ton	111	115	119	123	128	132	136
Asia	USD/ton	68	73	77	82	87	91	96
Americas	USD/ton	85	89	94	98	102	107	111
Africa	USD/ton	116	121	126	132	137	142	147

Organic wet waste cost[3]	Unit	2020	2025	2030	2035	2040	2045	2050
Europe	USD/ton	50	50	50	50	50	50	50
Middle East	USD/ton	50	50	50	50	50	50	50
Asia	USD/ton	50	50	50	50	50	50	50
Americas	USD/ton	50	50	50	50	50	50	50
Africa	USD/ton	50	50	50	50	50	50	50

Natural Gas price[4]	Unit	2020	2025	2030	2035	2040	2045	2050
Europe	USD/ton	319	335	351	368	386	405	425
Middle East	USD/ton	95	100	105	111	117	123	130
Asia	USD/ton	375	390	406	422	439	457	475
Americas	USD/ton	133	140	147	155	163	171	180
Africa	USD/ton	201	230	263	301	344	393	450

Biofuel availability[5]	Unit	2020	2025	2030	2035	2040	2045	2050
Bio-methane	EJ/year	0.11	0.29	0.78	1.36	1.68	1.76	1.84
Bio-diesel (HtL)	EJ/year	-	-	0.00	0.01	0.04	0.20	0.55
Bio-crude (HtL)	EJ/year	-	-	0.00	0.01	0.05	0.32	0.87
Bio-diesel (Pyr)	EJ/year	-	-	0.00	0.01	0.05	0.31	0.85
Bio-crude (Pyr)	EJ/year	-	-	0.01	0.04	0.22	1.26	3.39
Bio-methanol	EJ/year	0.00	0.01	0.05	0.28	0.75	2.02	5.44

1) Forward 10yrs, as of June 2021 extrapolated 2,3) Outcome of center analysis of biomass availability and price 4) TTF forward, HH forward, IHS, WoodMackenzie, and BNEF 5) See section "Biofuel supply constraints" for references

Energy & Fuels Key input data (3/3)

Well-to-tank methane slip GHG potential (100y)[1]	Unit	2020	2025	2030	2035	2040	2045	2050
LNG[2]	gCO2eq/MJ	4.5	4.5	4.5	4.5	4.5	4.5	4.5
Blue ammonia[3]	gCO2eq/MJ	2,4	2,4	2,4	2,4	2,4	2,4	2,4
E-methane[4]	gCO2eq/MJ	1	1	1	1	1	1	1
Bio-methane[5]	gCO2eq/MJ	9,0	7,7	6,5	5,2	4,0	2,7	1,5

LSFO and LNG price, scenarios	Unit	2020	2025	2030	2035	2040	2045	2050
Crude oil, baseline	USD/bbl	73	61	59	59	59	59	59
LSFO, baseline	USD/GJ	13.2	10.9	10.6	10.6	10.6	10.6	10.6
LSFO, low	USD/GJ	13.2	9.0	7.9	6.9	5.8	4.7	3.6
LSFO, high	USD/GJ	13.2	10.9	13.2	14.3	15.4	16.3	17.2
LNG, baseline	USD/GJ	8.2	8.2	8.3	8.4	8.5	8.6	8.8
LNG, low	USD/GJ	8.2	6.8	6.2	5.4	4.6	3.8	3.0
LNG, high	USD/GJ	8.2	8.2	10.3	11.3	12.3	13.2	14.2

1) IPCC report 5 methane emission factors used: 28 gCO2eq/MJ for 100y 2,3,4) Sphera 2021: 2nd Life Cycle GHG Emission Study on the Use of LNG as Marine Fuel
5) Sphera 2021 + partner & industry dialogue setting methane leak in production today at 1.4%, reducible by 90% by 2050

Critical Levers

Most probable and realistic outlook on critical levers

1 Policy and regulation

- IMO members can reach consensus on a **carbon pricing** scheme starting in 2025. Inspired by current EU ETS pricing levels we use 2020/21 **average of ~USD 50/ton CO_2 as benchmark**
- Further regulatory tightening of **energy efficiency measures** continues. Specifically, we model **continuous efficiency improvement and successful regulatory enforcement on new designs in an EEDI phase 4 post 2030 and a continued tightening of carbon intensity during operations (CII) until 2030.**

2 Tech advancements on ship

- Shipowners look for business cases with **further efficiency penetration of known measures**. Balanced between environmental and commercial necessity, investment pay-back periods may be extended from today's average of 2 years to 10 years.
- **New solutions development** in e.g. shipbuilding, propulsion, smart shipping, analytics, robotics, sensors etc., in conjunction with an increasingly skilled workforce may give significant energy efficiency improvements all the way up to 2050.

3 Energy & fuel advancements

- Energy & fuel advancements to scale the production and drive cost-down of different fuel types can drive decarbonization.
- For e-fuels, dedicated renewable energy access is available. We model a scenario where **renewable electricity costs continue with significant declines towards** 2050.
- For biofuels, technological advancements continue, however supply will be **constrained** by **biomass availability** and **cross-sector competition**

4 Customer demand/pull

- Customer willingness to pay (WTP) differs across products; the closer the end-user to the supply chain, the higher WTP premium. In maritime terms, this would imply more appetite to pay green premiums in some vessel segments (e.g., containers) than others.
- Each sector is thus modelled separately but weighed together by segment size. Our outlook suggests maritime customers paying an average **green premium of 12% on 50% of total global ton-miles** in 2050

5 Finance sector mobilization

- Major financial institutions are reallocating own- and customer portfolios with the aim to reduce carbon footprint. Applied to the industry weighted cost of capital (WACC) at 7% we add discounts for green financing, rewarding those having clearly defined abatement targets. We use an **average discount up to 250 basis points (2.5%) in 2050** for vessels sailing on alternative fuels.

Source: MMM Center for Zero Carbon Shipping.
Note: These projections and outlooks are subject to significant uncertainty, predominately linked to the evolution of global environmental regulation and enforcement, global trade developments and the cost and competitiveness development of alternative fuels. More information on each individual lever is presented in the Deep-dives section.

Biofuel Supply Constraints

We have identified 3 main constraints for the supply of biofuels for the maritime industry

Availability of sustainable biomass

- A limited amount of biomass can be sourced for biofuels without compromising sustainability, food production and biodiversity
- This sets a maximum volume of biofuels available for all industries

Maximum throughput of biofuel value chains

- Most biofuel value chains are still immature
- Rapid scaling is needed to support decarbonation of the global industries
- The speed of scaling will determine the timing of biofuel availability

Competition for biomass and biofuels between industries

- Many global industries are decarbonizing towards 2050
- This creates competition for sustainable biomass and biofuels
- This may limit the availability of biofuels for shipping

Maximum biofuel supply is limited by the amount of sustainable biomass

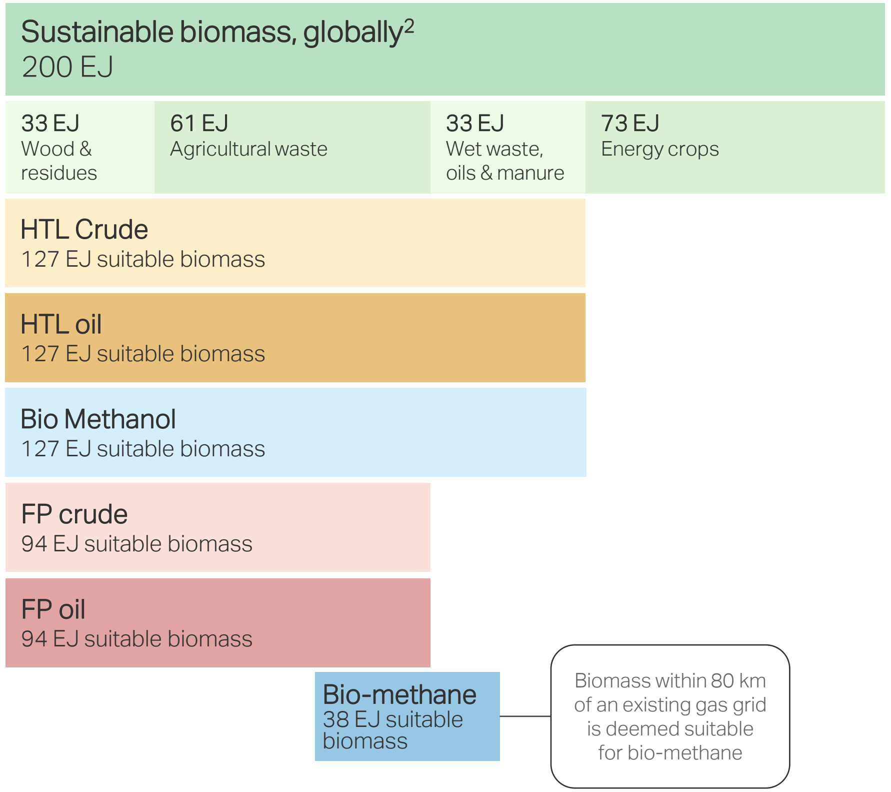
Availability of sustainable biomass

Maximum throughput of biofuel value chains

Competition for biomass and biofuels between industries

Global maximum biofuel supply is limited by the amount of sustainable biomass suitable for the conversion technology

- Availability is debated among scientists, but we see 150-200 EJ sustainable biomass available[1]
- Energy crops is left out from the analysis, due to their debatable sustainability from land use, resulting in 120 EJ
- Individual biomass pathways have different suitable biomass, which defines their maximum supply
- Only biomass within 80 km of an existing gas grid is deemed suitable for bio-methane, due to the cost of laying new pipelines. Access to liquefaction and certificate scheme will be required.



1) Chum et al (2011)≈ 100-300; Lauri et al (2014 ≈ 165; IEA (2017) ≈ 145; Wenzel et al (2014) ≈180; NREL (2021) ≈ 160-180
2) Split of biomass from internal center study

Supply of the value chains limited by maximum roll-out speed of conversion plants

Availability of sustainable biomass

Maximum throughput of biofuel value chains

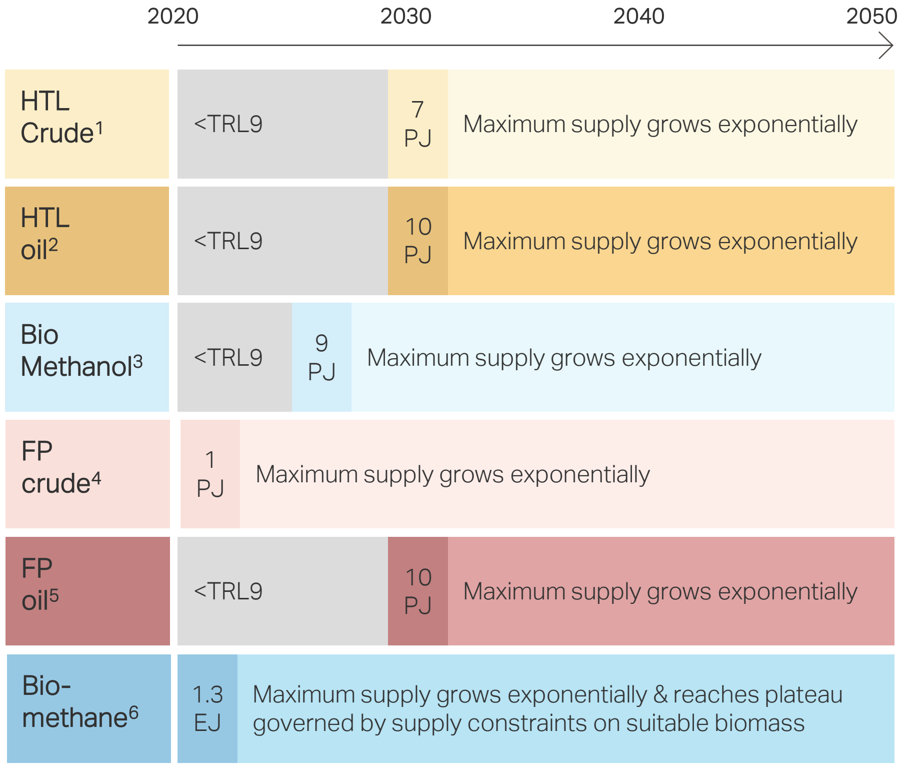
Competition for biomass and biofuels between industries

Maximum supply of the value chains limited by maximum roll-out speed of conversion plants

The supply for shipping is limited by how fast supply chains can be scaled. We deem that the rate limiting step in all value chains is the construction of new conversion plants. The scaling rate can be split into two phases:

Phase 1: Restricted by technical immaturity (<TRL 9)
When technologies are immature, conversion plants will not be built in high numbers and large scale due to technical risk – supply is greatly limited.

Phase 2: Restricted by maximum roll-out of conversion plants
Recently matured technologies will roll-out slowly due to remaining commercial risk, and limited suppliers. When assessing historical roll-out speeds of biofuels that are technical and commercial mature and granted government support, these followed exponential growth until reaching a maximum limit, thus forming an S-curve. In our outlook we simulate a fast roll-out of the first projects by using the fastest growth rate observed, that of US Biodiesel from 2003-2016[7]. This bounds the initial roll-out from 0-5% to the maximum potential. To represent a slower global roll-out after 5%, the growth rate of global ethanol from 2003-2016[7] was used from 5%-100%.



1) Projected 3 plants at 100kton/yr in 2030 2) Projected 2 plants at 80/yr in 2030 3) IRENA / ETSAP 4) Combined current production of Ensyn, Empyro, Savon Voima and Green fuel Nordic in 2020 5) Projected 3 plants at 70kton/yr in 2030 6) IEA bio-methane forecast 7) US Biodiesel followed logarithmic growth by formula 10^(log(x)+0,152). This is the highest growth observed, between Global ethanol (0,086), Global biodiesel (0,110), Latin America ethanol (0,027) and EU Biodiesel (0,130).

Biofuel supply for the maritime industry is approximated by biofuel competition with other industries

Availability of sustainable biomass

Maximum throughput of biofuel value chains

Competition for biomass and biofuels between industries

Maximum fraction of biofuel supply for the maritime industry is approximated by biofuel competition with other industries

To simulate competition with other industries, we set a maximum supply of biofuels which the maritime industry could obtain. The maximum biofuel supply for shipping was set to 16% of a maximum sustainable biofuel supply. The 16% fraction stems from shipping capturing twice as much biofuels as their current fraction of the global non-electrifiable energy demand (average of low and high scenario - see table on the right). This is achievable if the maritime industry takes a first mover role into biofuels, is facing higher willingness to pay, or faces stronger regulatory incentives than the other industries with non-electrifiable energy demands.

One exception to this is for bio-methane where 8% was used instead of 16. Drivers that could push the maritime industry to reach a higher fraction of bio-methane than its relative need may be counteracted by the higher cost of maritime use due to the requirement for liquefaction, the loss of methane and additional emissions from methane slip.

Demand for carbon-based fuels [EJ][1]

	Low scenario	High scenario
Shipping	Up to 20	Up to 20
Plastics	60	120
Peak heating	30	50
Buildings	30	40
Industry	20	40
Aviation	15	20
Cement	0	30
Electricity balancing	10	20
Steel	5	20
Road transport	5	10
Total	175	370

5-11% of total

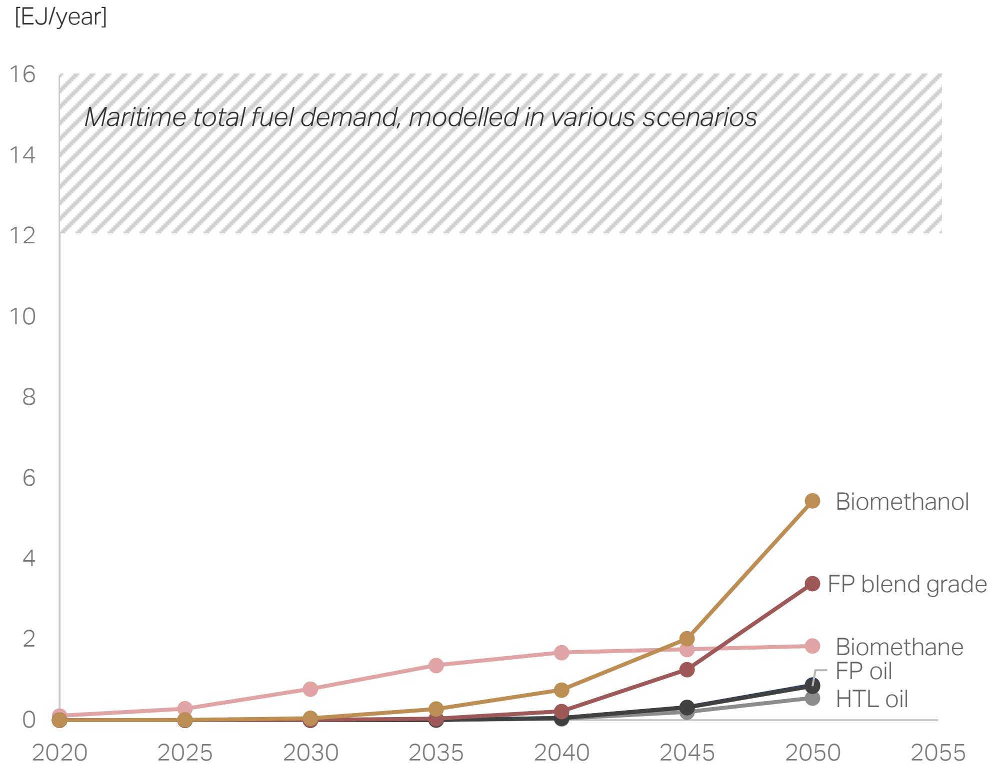
1) Results of the "Biomass availability study" conducted by the center, Maersk and University of Southern Denmark.

Based on this analysis, bio-methane could reach significant supply for the maritime industry before 2030 – other biofuels from 2040

Highlights from supply analysis

- Bio-methane is available today and is scalable to supply 6% of the fleet in 2030 - maximum supply limitations may be reached at 10% of the maritime industry's energy demand
- Bio-methanol is in limited supply today and could scale to supply 2% of fleets energy need in 2035 (0.3 EJ), and 40% in 2050
- Bio-oils could reach scales able to impact >1% of the fleet fuel mix from 2040:
  - FP crude is available in very limited supply today, but could scale faster than the other bio-oils, thus reaching 1.5% of fleets energy need in 2040 (0.2 EJ) and 25% EJ in 2050 (3 EJ)
  - The remaining bio-oils, FP oil and HTL oil and crude, could start scaling near 2030 when technical maturity is reached and then reach 2% of the fleets energy needs in 2045 (0.3 EJ) and 6% in 2050 (0.8 EJ), individually
- FAME & HVO have been excluded in the first version of the position paper due to low supply of waste feedstocks[3] and the debatable sustainability of food-based bio-fuels

Maximum supply constraints of biofuels for shipping



1) Assuming 200 EJ of sustainable biomass available globally and an energy conversion of 60%. 2) Based on internal study identifying the amount biomass needed to cover the non-electrifiable energy need of global sectors. Sectors (EJ): Shipping (30), Aviation (30), Road transport (30), Electricity balancing (30), Peak load heating (50), Industry (50), Plastic (90), Cement (30), Steel (20). 3) Maximum supply of 2nd generation FAME/HVO for shipping assessed to 0.2 EJ / 2% of shipping's energy demand. See appendix for documentation

Renewable Energy Cost and Availability

Renewable Energy Source supply can probably meet demand

Certainty of demand is key to ensuring low supply risk

There is a good outlook for RES availability as seen from today…

High capacities: To reach IEA targets, Renewable Electricity must increase by >1000 GW in annual capacity addition– required by all industries beyond marine.

Achievable targets: Industry sentiment is optimistic that RES supply can meet the expected, substantial demand. (Photovoltaics, Wind turbines, and upstream mining, etc.)

Demand first: The key requirement to achieving scale is certainty of demand via planned supply chain investment.

… despite some potential barriers that will need to be addressed in providing e-fuels for shipping…

Land permitting: Policies to remove barriers of obtaining and reforming land

Electrolyzer permitting: Standardized regulations to enable approval of electrolyzer installations

Labor supply: Labor additions on >25% CAGR will be required for maintenance, including re-training of oil&gas sector, in geographical regions requiring maintenance of new RES infrastructure.

Demand from other sectors: Competition for renewable electricity supply will come from other industries having higher willingness to pay.

… and there remain potential risks to RES availability that have not been fully evaluated.

Green construction: Future availability of green steel, required for the construction of all infrastructure in the transition (RES construction, chemical plants, CO_2 pipelines, fuel storage, shipbuilding, etc.)

Battery materials: Supply of lithium / cobalt / nickel for utility-scale batteries will be challenged by exponentially increasing demand in the short-term. Long-term increased supply (for load buffering of RES) will depend on the development of recycling.

Recycling: Supply of RES infrastructure does not yet consider LCA optimization, e.g., recyclable materials (wind turbine blades, batteries, etc.)

Background: Defining the Cost of electricity

LCoE (levelized cost of electricity) best indicates the potential to supply

Different definitions of "cost" can potentially confuse the assessment of renewable energy outlook

Spot prices, Marginal Costs, and Levelized costs
Different information sources sometimes use varying definitions to "cost", potentially leading to confusion about the real costs of renewable energy.
For the purposes of evaluating electro-fuels production for the marine industry, it is important to keep a realistic view of production costs, especially when forecasting future costs– which may exist in different financial and political circumstances.

Prices versus costs
It is firstly important to distinguish costs from prices. By "cost" in this context, we refer to expense that is required in order to create supply, i.e., production cost. "Price" refers to cost experience by *the customer* rather than the producer, and it is largely determined by competing customers' willingness to pay– as well as by policies like subsidies and taxation.
Production costs are not necessarily reflected by price, since prices can be affected by temporary situations and by policy.

→

Marginal production costs / Operating costs
Marginal costs are sometimes quoted to emphasize the low costs of renewable electricity. An operating cost is the short-term level of expenses for maintaining ongoing supply– after the initial investment in energy infrastructure. Because it explicitly overlooks capital investment, the operating costs alone are not conducive to making economic comparisons.

Spot prices
The spot price is the price at which the fuel or electricity can be bought at a specific point of time. Spot prices can change for a variety of reasons, e.g., renewable energy is sometimes discussed as having a very low spot price during hours of peak electricity production.
Spot prices, or marginal costs, have low relevance for assessing large-scale electro-fuel production. The maritime industry requires such large scales of electricity that production must effectively use all spot prices– including both low price at peak hours and very high price at off-peak.

→

Subsidized prices
Already today, electro-fuels could be made at much lower prices than what is forecast… *if* government partially subsidizes the production.

Current price levels are sometimes reported with the intent of showcasing affordable technologies. However, the subsidized price of a fuel or electricity is not a sustainable price level to consider, in evaluating the future viability of supply.

Levelized costs
In order to comparably evaluate future costs, it is most informative to calculate the levelized cost, which includes all relevant costs to investment decisions– especially including the cost of capital, spread over the years of expected production. Meanwhile, extraneous factors, such as subsidies, are excluded.

By including all major cost contributions, the resulting numbers for can be compared against each other on a rational basis (e.g., wind versus PV or other), to inform about required investments and likely market developments.

Key Assumptions for Renewable Energy Costs

Assumptions for calculating representative costs

Dedicated electricity infrastructure, off-grid

E-fuels for the maritime industry would need to be produced in massive quantities, and in locations suitable for marine supply. Therefore, the maritime industry would require a dedicated supply infrastructure. Despite some P2X overtures that peak hours may provide nearly free cost, the maritime industry could not rely solely on peak hours, since e-fuel production requires full-day operation.

It is assumed electro-fuel production rates must be nearly constant

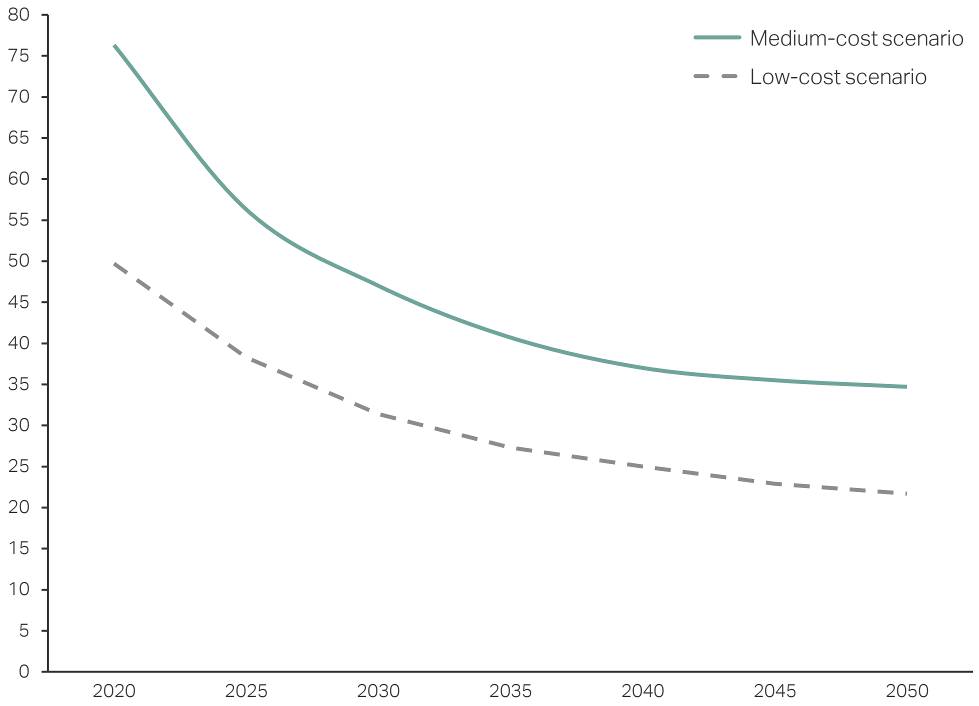
Chemical-producing plants are not able to shut-down and start-up daily. Even for hypothetical plant designs which might adapt their loads, a low plant uptime means a longer payback time on investment – for a high CAPEX engineered for peak capacity. Regardless, the economics of production would be significantly worsened due to intermittent operation.

Renewable electricity must also be supplied at constant rate

The aforementioned constraint on e-fuel production means that electricity must also be supplied at a constant rate. Therefore, intermittent power sources will require some form of load balancing, in order to achieve stable and economical plant operation. The practice of buffering– with batteries or other storage– is sometimes called “peak shaving”. We assume costs of RES production that include batteries [See details on supporting slide.]

In the low-cost scenario, the required buffering capacity is assumed to be half of the amount in the medium-cost scenario.

Cost in USD/MWh for Renewable Electricity with Battery



Key Assumptions for Renewable Energy Costs

Assumptions for calculating RES costs

Electricity prices are based on future forecasts, with batteries incorporated for buffering

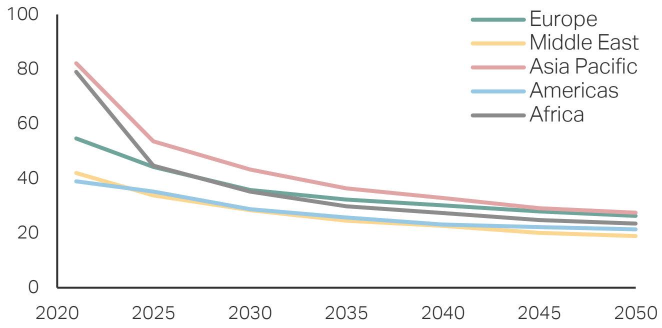
We used Bloomberg New Energy Finance (BNEF) as a source of forecasts for levelized electricity costs (LCoE). This information resource contains cost estimates of renewables energy sources combined with batteries, for multiple countries and for all years to 2050.

For certain countries that did not have battery costs included in the renewable electricity cost estimate, a scaling factor was applied in order to approximate the cost that would include batteries. This scaling factor is based on the global average ratio. On average for our medium-cost scenario, adding battery cost to photovoltaics results in 2.3x of the base cost; whereas for wind power, it results in 1.5x of base cost.

Country estimates converted to Region estimates

The NavigaTE model uses 5 geographical regions. For each region, it is assumed that the renewable electricity cost can be represented by the median of all constituent countries. The median is preferable to the mean because it more closely represents the lower-cost countries by excluding the most expensive regions which are outliers.

Cost development in USD/MWh for RES + Battery, by region
Low-cost scenario illustrated



Best technology chosen per region

The renewable energy costs were analyzed for both wind power and photovoltaic power. While each region might use either power source or a combination of both, we assume that the lower cost power option is chosen first. An associated assumption is that combined energy parks (PV + wind) would be designed economically, so that the marginal addition of the more expensive option would not increase the average electricity cost.

For displaying a global average, we choose a weighted average of the 5 regions 40/30/10/10/10, with highest weighting to the lowest cost region.

Vessel Considerations

Presented fuel options include relevant fuels for mainly oceangoing vessels and that can have a fleetwide impact

Our focus is currently on identifying main pathways for oceangoing vessels that account for the majority of fleet emissions

LPG: Not currently modelled

Ethane: Not currently modelled

Wind: Not a main source of propulsion power, but considered as an energy efficiency initiative

Energy carriers with main application to short-sea and coastal shipping are currently not modelled

Electrification: Onboard electrification with batteries is not included as it will not play a major role in the largest long-distance shipping segments

Hydrogen: Application of compressed and liquified hydrogen is mainly for short-sea shipping due to fuel storage and more frequent bunkering requirements

Potential game-changing or new developments will be incorporated once considered viable

Nuclear: Onboard nuclear power could be a game-changer, but is not currently included due to perception and safety challenges

Onboard CCS: Onboard carbon capture and storage (CCS) has the potential to reduce the emission intensity of carbon-based fuels and technical feasibility studies at the Center are in progress

Some engine-based vessel pathways require a pilot fuel, which can change the emission intensity of selected fuel combinations

Primary Fuel	Pilot fuel % (Diesel 2-stroke)	Pilot fuel % (Otto 2-stroke)	Pilot fuel % (Diesel 4-stroke)	Expected Range (pilot %)	Uncertainty
Bio-oils	-	-	-		-
LNG/methane	0.5-1.5	0.5-1.0	1-2	1-2	Low
Methanol	5	-	-	5	Medium
Ammonia	5-10	-	10-20	5-15	High

Main pilot fuel options
LSFO, MGO, FAME, HVO, bio-oils

Methane, methanol and ammonia engine-based vessel pathways require a pilot fuel

- To ensure proper ignition of some primary fuels in internal combustion engines, a pilot or secondary fuel is injected into the combustion chamber to ignite the fuel mixture. The amount of pilot fuel needed depends on the primary fuel's ability to ignite.
- Fuel cell vessel pathways do not use a combustion process and, therefore, do not require any pilot fuel to operate, however, depending on the fuel cell technology a reformer is needed to produce hydrogen.

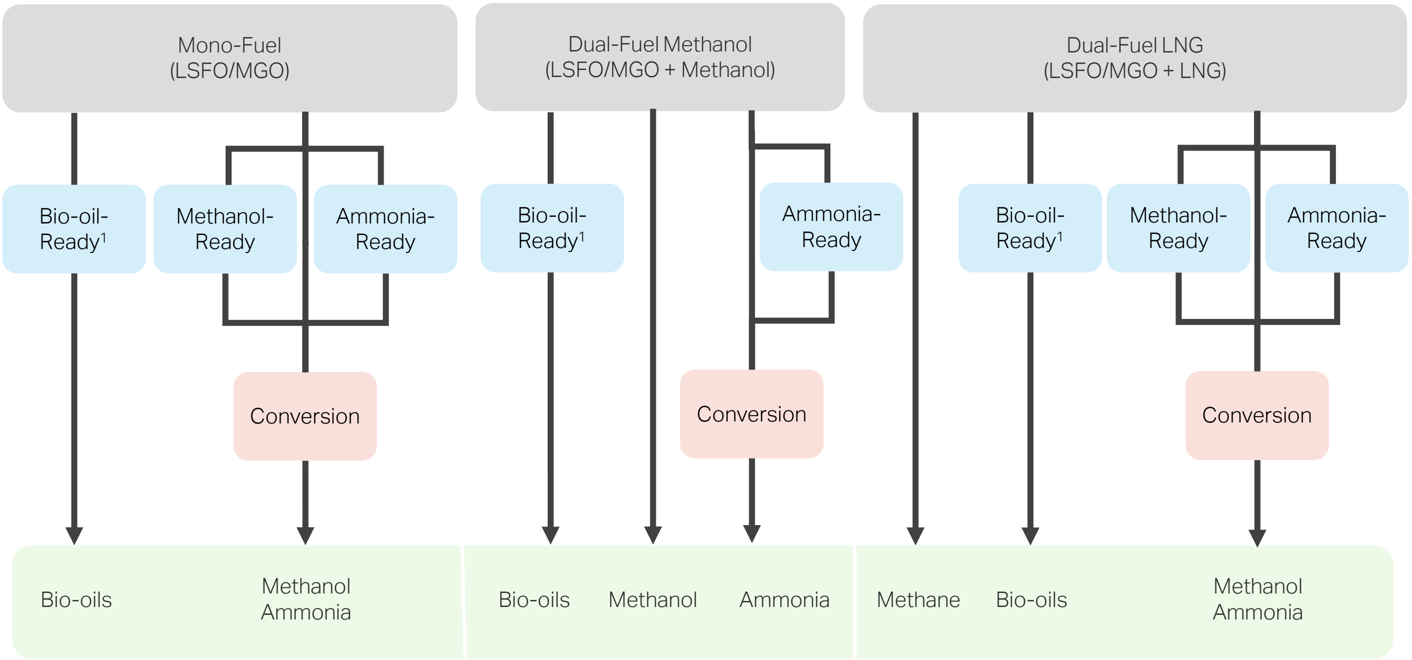
Uncertainty of pilot fuel percentages exists for the less developed engine technologies

- LNG/methane engines are the most developed with have the lowest pilot fuel percentage while ammonia engines are still under development with higher uncertainty

Pilot fuel options exist to reduce or achieve net-zero emissions compared to fossil-based fuels

- For example, ammonia combined with a bio-oil pilot fuel would produce zero well-to-wake emission intensity even if the bio-oil has tank-to-wake emissions
- Hydrogen and DME have been proposed as pilot fuels, but are not considered here due to high uncertainty and implementation risks

Vessel fuel flexibility via newbuild preparation, fuel conversion and dual-fuel engine configurations allow for multiple fuel pathways



Available Alternative Fuel Options

Newbuild preparation can be beneficial depending on the conversion timeline

- Preparation for alternative fuel options at the newbuild phase can maximize flexibility while minimizing risk and future conversion costs

Fuel conversion will be possible even without newbuild preparation

- To avoid the risk of stranded assets, conversion to methanol or ammonia will be possible, however, complexity and cost is uncertain

Dual-fuel LNG configurations can provide flexibility

- In addition to the potential to convert to ammonia or methanol, LNG dual-fuel configurations also allow for drop-in usage of bio- or e-methane
- Investment cost, total lifecycle emissions, and flexibility to be considered when making vessel decisions

1) Bio-oil-Ready requires less preparation compared to Methanol-Ready and Ammonia-Ready, which are much more extensive
Source: DNV "Maritime Forecast to 2050: Energy Transition Outlook 2021"

Onboard vessel implementation risks need to be mitigated for fuel pathway options to be become viable at large scale

Implementation risks address either uncertainty/lack of information or needed development in a particular area

- Risks can be seen for fuels like bio-oils where there is lack of information to confirm implementation is possible, for example, the impact of bio-oils on engines and fuel supply
- Other are related to known risks that need to be mitigated through the development of a technology, system or regulation

Low risk | Medium risk | High risk

	Fuel storage (incl. volume requirements)	Fuel supply system	Energy converters	Safety (toxicity, flammability, explosion)	Environment	Regulations	Emissions (tank-to-wake, air pollutants)
Methanol	2.5x volume*			Toxicity & low flashpoint			
Methane	2x volume* + cryo structure & auxiliaries					Methane slip unregulated	Methane slip
Bio-oils		Acidity & stability	Varying fuel properties				Increased NO_X
Ammonia	3.6x volume*	Corrosion	Engine development	Toxicity	Toxicity	No prescriptive rules	Ammonia, N_2O and NOx

*compared to LSFO

Onboard vessel risk mitigations to be completed along the critical paths to ensure viable fuel pathways

Methanol

Energy density & volume
- Additional storage capacity balanced with vessel requirements
- The use of structural tanks increases design flexibility

Safety
- Risk-based approach as done for LNG
- Leverage experience from chemical industry

Methane

Regulation
- Methane to be a regulated vessel emission

Emissions
- Onboard methane emission measurement
- Methane slip reduction technology
- Optimal vessel design and operation

Bio-oils

Fuel storage & systems
- Materials compatible with higher acid content
- Tank coatings to minimize bacterial growth and corrosion
- Drainage of excess water

Energy converter
- Fuel analysis to confirm compliance and adjust engine parameters
- High-quality fuel filter system

Emissions
- NO_X measurement for bio-oils and engines
- NO_X reduction technology

Ammonia

Energy density & volume
- Optimize speed and range requirements, bunker more frequently or accept cargo capacity loss

Safety
- Safety systems to address toxicity
- Use best practices from chemical industry and development of existing gas-fueled vessels
- Crew training programs

Emissions
- Ammonia slip, N_2O and NO_X reduction technology

Fuel supply & storage, Regulation, Energy converters
- Material selection
- Prescriptive rules for ammonia
- Engine development
- Use of carbon-neutral pilot fuels to minimize impact of higher pilot fuel need

Mitigation measures for the high and medium implementation risks are summarized

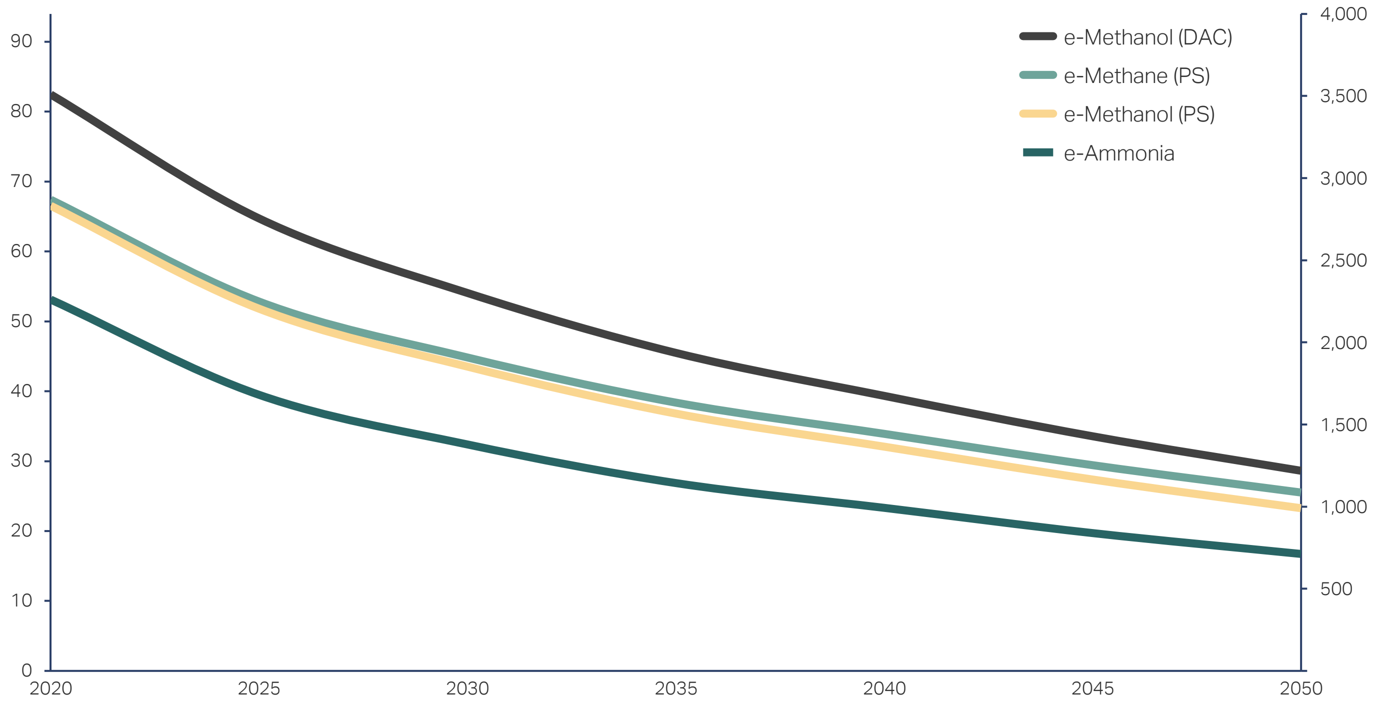
- Total well-to-wake life-cycle perspective is a critical regulatory, enforcement and emission control parameter
- Regulatory risk exists for all carbon-based fuels, even if they have zero well-to-wake emissions including short term measures like EEDI/EEXI/CII
- The soft elements like crew training and operational/risk management onboard will be equally important compared to hard engineering concerns especially for toxic and low flashpoint fuels
- Methanol and methane are lower risk pathways with conditioned methane regulation, enforcement and methane slip reduction critical for its justification
- Bio-oil mitigation measures address mainly the current uncertainty and lack of experience on potential onboard impacts
- Ammonia has the highest risk with critical mitigations measures needed due to lower TRLs across bunkering and onboard systems; safety and crew operational procedures and training critical

Note: The risks shown on this slide are only the medium and high implementation risks. Low risks are not shown.

Supporting data

Ammonia is the cheapest e-fuel and the only relevant blue fuel. Without ammonia, other e-fuels may play a larger role.

Cost2 in USD/GJ (left) and USD/tLSFOe1 (right) for the cheapest e-fuels



E-fuels share a similar cost decrease due to declining electricity cost
The projected e-fuel costs depend similarly on the decreasing cost of renewable electricity prices. Extra cost differences are due to CO_2 costs and potential technology optimizations (in the case of e-Diesel).

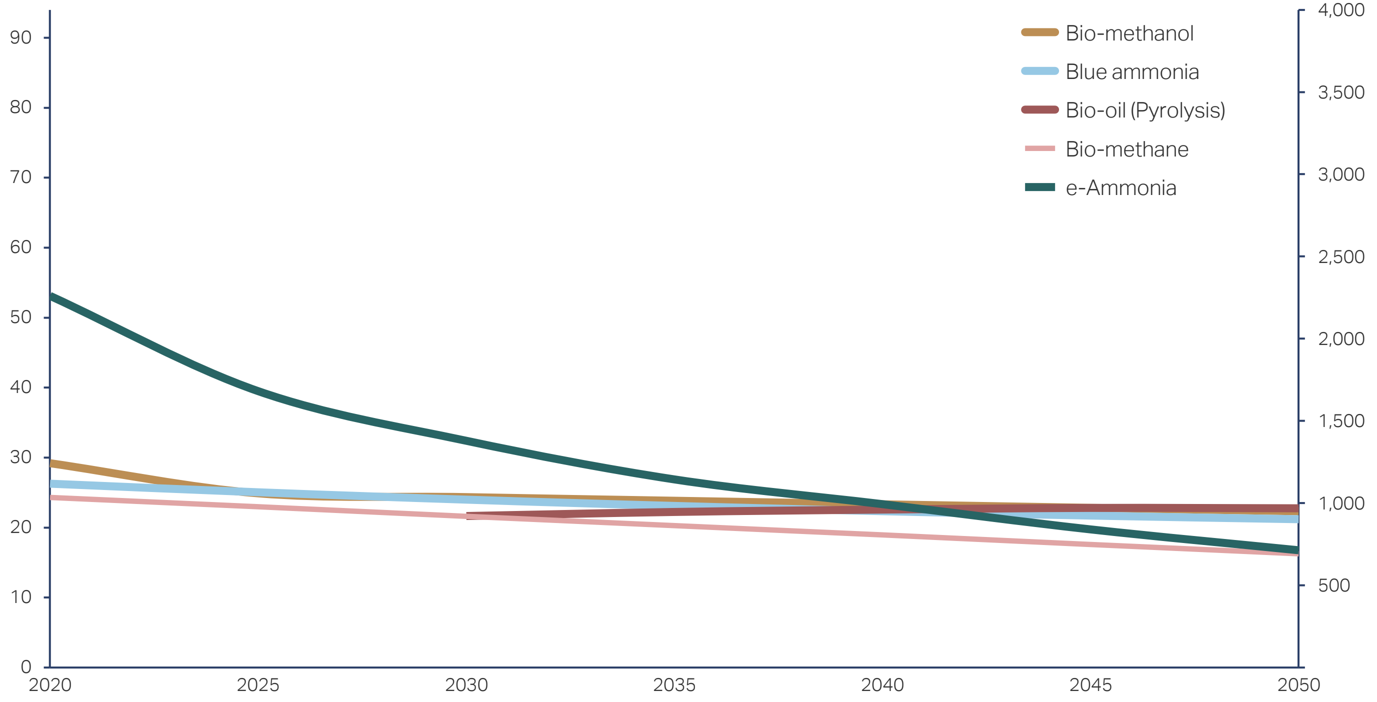
Ammonia is the least costly energy-dense e-fuel
Ammonia is made from N_2 feedstock, which is readily available and cheaper to obtain than the CO_2 that is needed for carbon-based fuels. However, ammonia has slightly lower energy density than the carbon-containing options, and it faces significant safety and regulatory hurdles.

E-Methanol and e-methane are produced with similar costs
Between the two options, methanol is slightly less expensive to produce, but e-methane costs declines more quickly because the electrolyzer + plant give more potential to optimize efficiency. Because e-methane and e-methanol are so close in cost, their relative usage will depend on each ship's design, operation, and route: e-Methane requires cryogenic storage, whereas e-methanol is less energy-dense. All considered, e-methanol is more likely to be the more cost-effective option, although e-methane may still find niche use.

1: LSFO equivalent (1 ton LSFO equals ~42 GJ of energy) 2) Low-cost RES scenario.

Biofuel's production cost is projected to be competitive with blue and e-fuels until 2040

Cost in USD/GJ (left) and USD/tLSFOe1 (right) for selected fuels



1: LSFO equivalent (1 ton LSFO equals ~42 GJ of energy)

Bio-fuels are cost competitive with other alternatives until 2040/45

Compared to other alternative fuels, biofuels are projected to be cheaper to produce until 2040/2045 (see chart). Specifically, production costs for bio-oils or liquid bio-methane is lower than blue- and e-fuels until 2040/2045. Bio-methanol shows similar production costs as blue ammonia. In 2050, green ammonia approaches as low cost as liquid bio-methane.

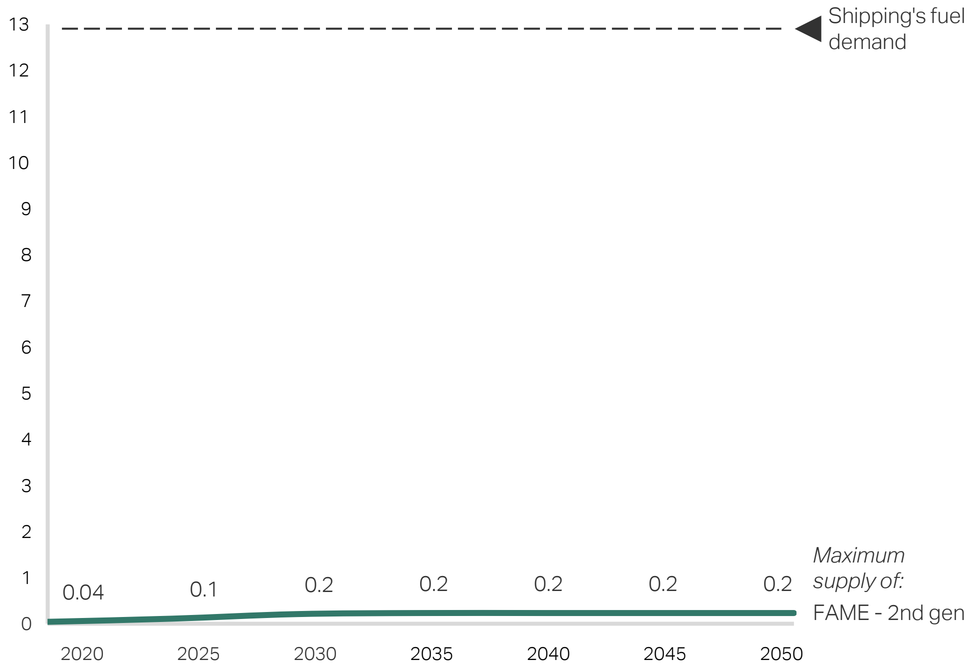
FAME from waste products (2nd gen) could support up to 2% of the maritime industry's energy need

Supply analysis conclusions

- FAME is produced from two sources today: Food oils (palm oil, soybean oil…) and waste oil (used cooking oil, acid oil…). FAME made from food oils, here named 1^{st} gen, is considered to have high emission factors due to using land space, which either directly or indirectly causes deforestation – therefore, we only consider FAME produced from waste (2^{nd} gen)
- Today, the global 2^{nd} gen FAME production is 0,3 EJ for all sectors[3]. To simulate competition with other industries, we set a maximum volume of FAME obtainable for the maritime industry. Maritime's current fraction of global non-electrifiable energy demand is 8%.[2] For the analysis, we used 16% which can be perceived from the industry taking a first-mover role into bio-fuels, being able to economize from customers' higher willingness to pay or being imposed stricter regulatory incentives than the other industries Thus, 0.04 EJ is available to shipping today (0.3% of the maritime industry's energy need)
- The maximum global potential of 2^{nd} generation oils converted to FAME is believed to be 1.5 EJ (~40 mt/year)[4], or 0,24 EJ for the maritime industry assuming a 16% availability (1.8% of the maritime industry's energy need)
- Considering the maximum roll-out speed, modelled by assessing historical biofuel roll-out speeds of technical and commercial mature technologies with government support,[1] FAME could grow to maximum supply of 0.2 EJ in 2030 for the maritime industry (1.8% of the maritime industry's need)

Fastest possible roll-out of 2^{nd} generation FAME supply available for the maritime industry, with unconstrained demand

[EJ/year]



1 The fastest growth rate observed, that of US Biodiesel from 2003-2016[2], was used for the early roll-out from 0-1,5 EJ for maritime of each biofuel. To represent a slower global roll-out after 1,5 EJ for maritime, the growth rate of global ethanol from 2003-2016 was used above 1,5 EJ. US Biodiesel followed logarithmic growth by formula 10^(log(x)+0,152). This is the highest growth observed, between global ethanol (0,086), Global biodiesel (0,110), Latin America ethanol (0,027) and EU Biodiesel (0,130) 2. Based on internal study identifying the amount biomass needed to cover the non-electrifiable energy need of global sectors. Sectors (EJ): Shipping (30), Aviation (30), Road transport (30), Electricity balancing (30), Peak load heating (50), Industry (50), Plastic (90), Cement (30), Steel (20) 3) UFOP (2020) Report on Global Market Supply 2019/2020 4) Ecofys (2019), ICAO (2018)