01 – INTRODUCTION

With the intense global focus on climate challenges, various industries need to transition towards reduced or net-zero emissions. The transportation sector constitutes an important contributor emitting 25% of the global GHG emissions. Within transportation, the shipping industry accounts for 3% of the global emissions and belongs to the hard-to-abate category as direct electrification is only an option for a low percentage of the total shipping emissions.

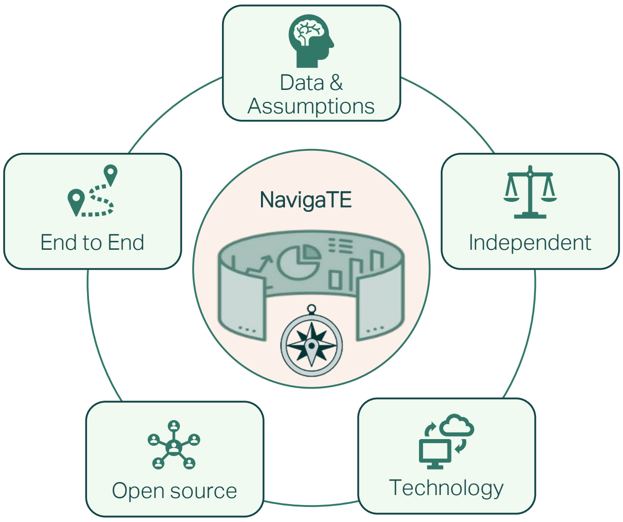
Industry analyses and reports are frequently published containing projections of possible journeys towards reduced or net-zero emissions for the shipping sector. Different model approaches, data and assumptions lead to different projections. Both in terms of the degree of decarbonization reached by 2050 as well as the uptake of different alternative fuels in each analysis.

Clarity is needed for investors and asset owners to make informed decisions. Regulators need an unbiased view of the cost gap between current fossil fuels and alternative fuels – for example when exploring an appropriate market-based measure required to enable the transition.

A move towards alternative fuels is not done without a clear understanding of the outlook for such fuels in 10-20-30 years. It requires an understanding of feedstocks, production & conversion processes, transportation, and the required investments in vessels to utilize the alternative energy carriers.

Based on this, the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (referred to as the "Center") has developed the first version of a techno-economic model to facilitate the navigation of the maritime sector towards its ultimate goal: Full decarbonization. This model is known as NavigaTE[1] .

Figure 1
Illustration of the guiding principles behind NavigaTE



The motivation behind NavigaTE is illustrated in Figure 1 and elaborated below.

End-to-end view: The scope and target of NavigaTE is to model the entire maritime energy value chain for powering the vessel from feedstock/primary energy to the wake of the vessel.

Technology: Each step in the path from feedstock to application on the vessel is represented by model elements linked to a simplified description. This includes a reasonable and manageable number of parameters while still representing and anchoring in actual technology. In other words, a company producing an alternative fuel or operating a vessel should be able to see the key cost drivers of their technological domain reflected in the model while still being able to understand the model overall and maintain an overview.

Data & assumptions: The model elements must be supported by realistic and representative data and assumptions. We are working with our partners[2] , additional industry players and relevant organizations[3] to establish a set of assumptions and data with broad consensus.

Open source: Part of the NavigaTE model will be made available as a shared version allowing relevant industry players, regulators, and authorities to study the principles of the model as well as getting fully aligned with core assumptions/projections. This will form a starting point to an on-going process of refining and developing the model inputs jointly with all relevant stakeholders.

Independence: MMMCZCS is an independent research center whose objective is to help accelerate decarbonization of the maritime industry without any energy or technology bias.

When combining robust methodology, solid data, and transparency with independence, it is the ambition that the outcomes will assist in creating a consensus and de-risk decision making processes across industries.

1) The capitalized "TE" emphasizes the Techno-Economic approach. 2) Current list of partners as of October 2021: Alfa Laval, American Bureau of Shipping, A.P. Moller-Maersk, Cargill, Boston Consulting Group (BCG), bp, Environmental Defense Fund, Danish Shipping, Haldor Topsoe, MAN Energy Solutions, McKinsey & Company, Mitsubishi Heavy Industries, Mitsui & Co., NORDEN, NYK Line, Seaspan Corporation, Siemens Energy, Sumitomo Corporation, Stolt Tankers, Swire Group, TotalEnergies, UK Maritime and Coastguard Agency. 3) The Center will be cooperating with various industry organizations on joint assumptions and data for the underlying TCO principles thereby ensuring an even broader stakeholder group.

premium for green shipping or regulators imposing a price on carbon as a market-based measure.

Both the Total Cost of Ownership and Industry Transition Model takes various greenhouse gasses into account, not only CO_2. This is done by recalculating all emissions to their global warming poten-tial (GWP[4]), often referred to as CO_2-equivalent. Throughout this document all emissions are considered as CO_2-equivalent but will for simplicity be referred to as simply CO_2.

Note that the forecasted costs of fuels, as well as critical lever outlooks, are based on trusted methods, data, and assumptions. It should be emphasized that the actual future market price of the fuels can vary greatly, depending on factors such as subsidies, small-scale synergies with other processes and supply-demand imbalances.

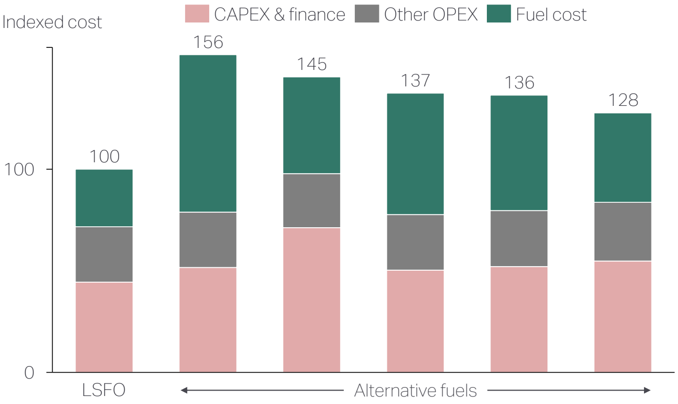
03 Total Cost of Ownership

The TCO model is a stand-alone module that calculates the total cost of ownership of a new build vessel for various combinations of vessel segments, fuels, and engine configurations as an input to the Industry Transition model. Additionally, the TCO model can be used as a separate tool for individual vessel analysis, allowing a potential vessel owner or operator to compare different options and combinations on a single-vessel level.

The vessel TCO is modelled considering all relevant costs with special emphasis on fuel cost based on a bottom-up fuel model, powertrain technologies, operating profiles, and energy efficiency measures, described in more detail in the following chapters.
An example of a TCO comparison between different operating configurations is shown in Figure 3.

Figure 3

TCO comparison towards the end of the transition between a baseline vessel using low-sulfur fuel oil (LSFO) and vessels operating on alternative fuels. The annual TCO for a new build vessel is calculated for a 25-year period over time as the sum of costs related to capital expenditures (CAPEX), operational expenditures (OPEX), and cost of capital.



The vessel TCO costs are split in the following cost categories: CAPEX, OPEX, and cost of capital:

For instance, the CAPEX increases when transitioning from LSFO to hydrogen due to costs related to a different engine design, tank systems and stricter safety measures.

COST CATEGORIES

CAPEX

The CAPEX includes:

- Vessel configuration CAPEX – see section 3.1, including:
  - Ship baseline
  - Propulsion and auxiliary power machinery (fuel dependent)
  - Tank & fuel system (fuel dependent)
- Efficiency levers – see section 3.3

COST OF CAPITAL

The cost of capital model considers the share of debt, cost of debt and cost of equity from which the weighted average cost of capital WACC is calculated.

OPEX

The OPEX is calculated per year and can be split in three main categories:

Fuel cost:

- Based on vessel energy demand (fuel consumption) including efficiency measures - see section 3.2 and 3.3 as well as fuel delivered costs - see section 3.4
- Fuel cost can be further modified by including a CO_2 pricing for the fuel well-to-wake calculated in the model - see section 3.5

- Maintenance – based on vessel configuration - see section 3.1
- Other OPEX including loss of cargo space due to larger tank size, port and canal fees and cost associated with efficiency levers.

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[4] https://www.epa.gov/ghgemissions/understanding-global-warming-potentials

3.1 Newbuild Vessels

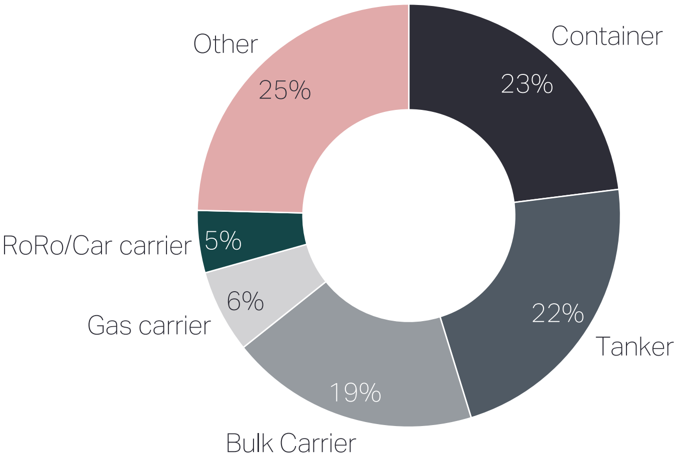
The TCO model includes a variety of shipping segments, and for each segment three generic sizes small/medium/large are defined. The vessel segments are as follows:

Vessel segments:

- Bulk Carrier
- Tanker
- Container
- Gas Carrier
- Ro-ro/Car Carrier
- Other Cargo
- Offshore
- Ferry
- Cruise
- Tug

Given that container, bulker, and tanker segments are responsible for more than 60% of maritime CO_2 emissions (c.f. Figure 4 below), a higher focus has been put on the description of those segments than less emitting contributors such as e.g. local ferries. An example of this includes not considering the cross-over between direct electrification vs. conventional/hybrid vessels for near-coastal operation to be captured accurately by NavigaTE 1.0.

Figure 4
Well-to-wake emissions split per segment for 2020.



A vessel can be further configured with the following equipment:

Vessel configuration:

Main propulsion and auxiliary power type, size, and fuel:

- Main Engine for a specific fuel (incl. dual fuel engines)
- Fuel Cell
- Battery

Tank & Fuel Supply:

- Fuel tank size. Cost is fuel dependent
- Fuel supply system. The cost is fuel dependent and the supply system size scales with main propulsion size

Depending on the size of the tank a cost associated with the loss of cargo space can be calculated for the various types of vessels. The lost cargo space can be due to requiring a larger tank to keep the same operational profile when using a fuel with lower energy density than the current fuels.

The estimates are made for the total TCO of a vessel rather than incremental TCO relative to a baseline vessel to show the complete picture of the vessel.

3.2 Vessel Operating Profile

The operating profile of the vessel is defined by number of sailing days, days in port, speed and draft profile, average auxiliary power use and boiler use. The bunkering region of the vessel can be defined, affecting fuel costs.

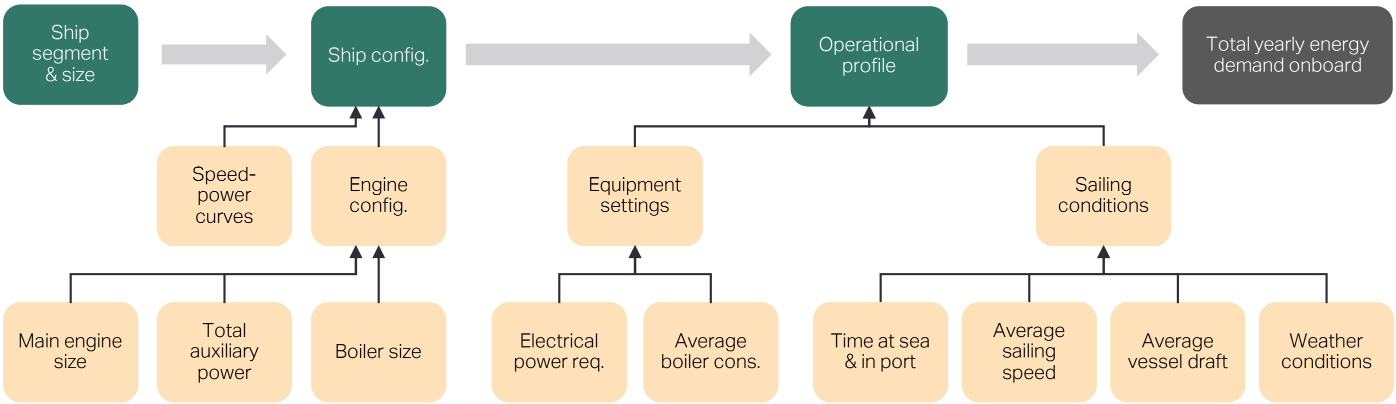
Based on the operating profile, the vessels energy demand can be derived as:

- Propulsion power demand – derived from configurable number of sailing days, speed and draft profile, and speed-power curves corresponding to an average in docking condition with some impact from weather
- Auxiliary power demand – derived from configurable number of sailing days/port days and average auxiliary power use
- Boiler power demand - derived from configurable number of sailing days/port days and average boiler consumption

The bottom-up approach grants sufficient granularity to study the

Figure 5

Illustration of model for vessel operations and power demand.



impact of replacing individual elements of a vessel with more energy efficient technology. As an example, the implementation allows for estimating the impact of changing from an auxiliary internal combustion engine to a fuel cell and what impact that has on the cost and emissions.

3.3 Energy Efficiency Measures

The model includes several efficiency levers, see Figure 6, that can be configured on the vessels. Each efficiency lever has a defined associated CAPEX, OPEX, potential energy efficiency benefit, lifetime and applicability for a given vessel type and size.

A vessel configured with a selection of efficiency measures, will have an updated TCO with the additional CAPEX and OPEX of the efficiency measures together with the expected benefit on fuel consumption (power demand) of those measures.

The portfolio of efficiency levers has been grouped into categories with 2-, 5- and 10-years payback time respectively. This is used to study the impact of implementing the low hanging fruits versus the impact of strong regulatory demands.

Figure 6

All energy efficiency levers including current penetration in the current fleet

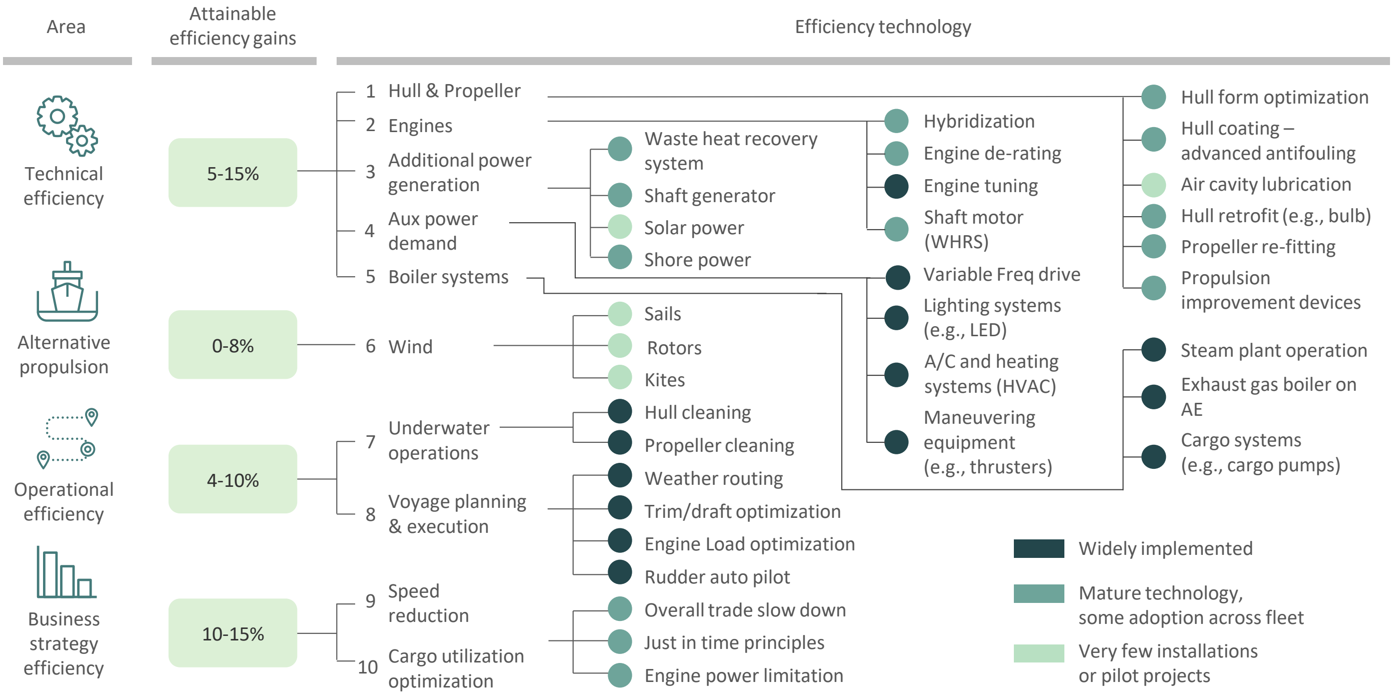
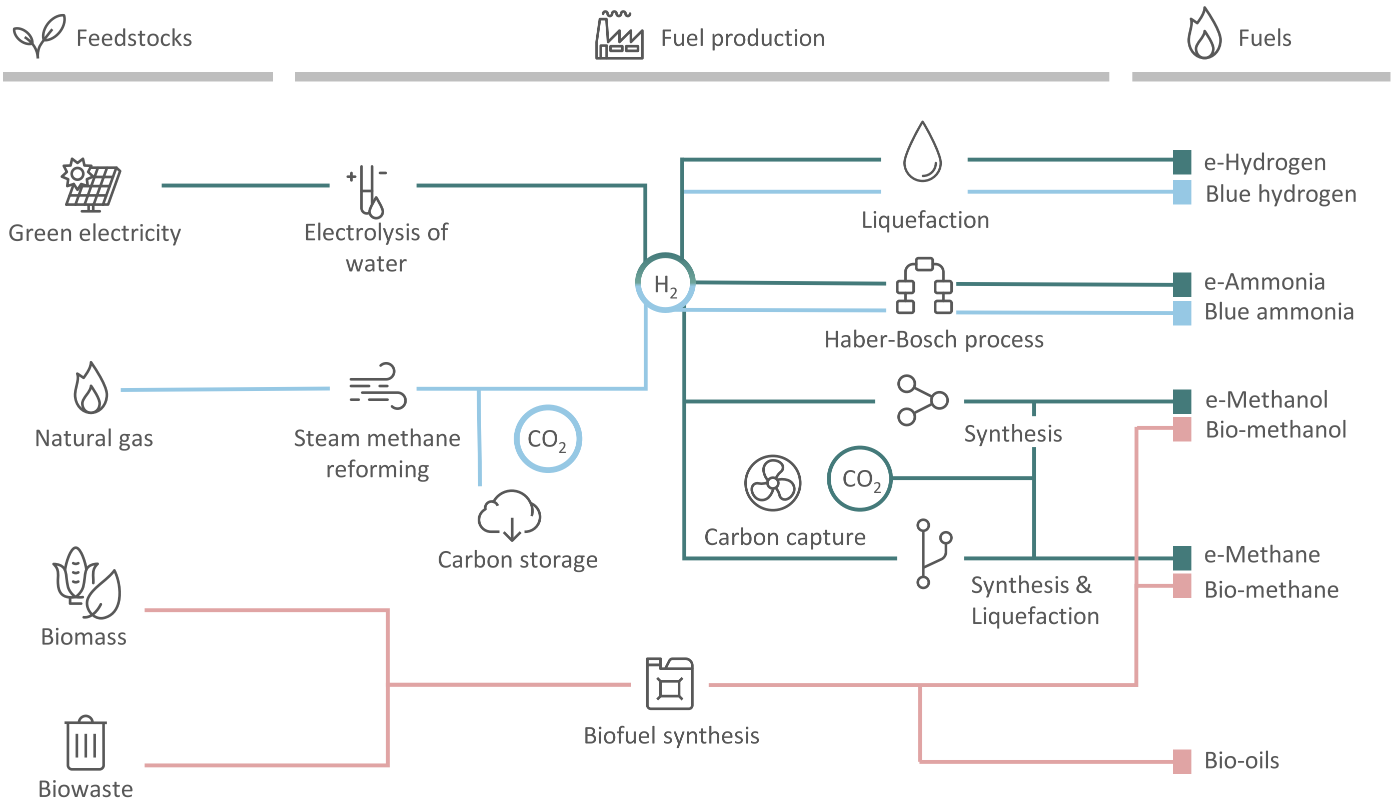


Figure 7

Schematic view of selected fuel production pathways in NavigaTE.



3.4 Fuel Cost Model

The fuel model in NavigaTE calculates the expected fuel production cost via a bottom-up approach for all considered fuel types including all necessary process steps to produce the fuels from the relevant feedstocks. The production cost also includes logistics cost to the port.

A schematic overview of included production pathways is presented in Figure 7, and Table 1 summarizes all the fuels.

Table 1 below summarizes the fuels included in the model.

The main feedstocks are the boundary of the fuel model and are not modelled. These include renewable electricity, natural gas, biomass, and organic waste and additionally nitrogen and point source captured CO_2.

Every feedstock and process flow in the model has an associated cost and GHG footprint depending on scope. Every process step in the model has an associated CAPEX, conversion amounts of inputs/feedstock to obtain outputs, other OPEX (non-feedstock related) and a GHG footprint depending on scope, see Figure 8 below.

Table 1

Included fuels

- LSFO (HFO)
- LPG
- LNG
- Grey Hydrogen
- Grey Ammonia
- Grey Methanol
- Blue Hydrogen
- Blue Ammonia
- e-Hydrogen
- e-Ammonia
- e-Methanol (PS)
- e-Methanol (DAC)
- e-Methane (PS)
- e-Methane (DAC)
- e-Diesel (PS)
- e-Diesel (DAC)
- e-DME
- Bio-diesel (Pyrolysis oil)
- Bio-diesel (HTL oil)
- Bio-methane
- Bio-methanol

Figure 8

Generalized process flow.

Feedstock parameters:

- Cost
- CO_2 footprint
- Primary Energy Efficiency

Process parameters:

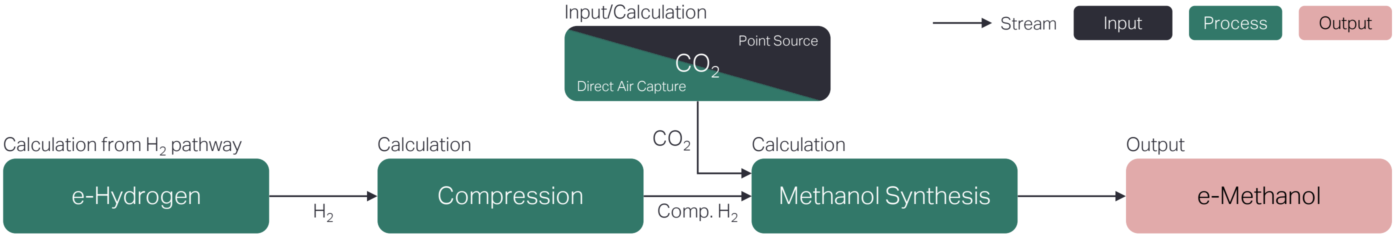
- CAPEX
- Other OPEX (non-feedstock)
- Conversions
- CO_2 footprint

Output parameters calculated:

- Cost
- CO_2 footprint
- Primary Energy Efficiency

Figure 9

Example process for electro-methanol.



Production pathways for various fuels are set-up as a series of connected processes, see Figure 9 below.

Feedstock and process parameters vary depending on the timeframe within 2020-2050 to capture introduction and improvements of new technologies over time, and different regions (Europe, Middle East, Americas, Asia and Africa) to capture regional differences in e.g. availability and cost of feedstock. The database of parameters for the feedstock and processes have been a consolidated input from literature and Center partners, expert knowledge, and review.

The fuel production cost for each pathway is split in three categories:

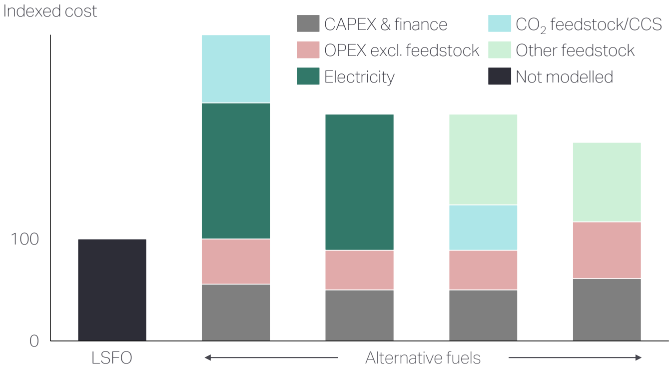
- Capital expenditures (CAPEX)
- Feedstock
  - Electricity
  - CO_2
  - Other (natural gas, biomass and more)
- Other operating expenditures (OPEX)

An illustration of this split is shown in Figure 10, where e-fuels, blue fuels and biofuels are represented.

To obtain a delivered fuel cost to the vessel, fuel logistics costs are added to the production cost. The fuel logistics costs include storage and transportation. Storage cost is modelled as the allocated CAPEX for the storage facility for the typical storage duration and where applicable, energy costs to keep the stored fuel in liquid form or fuel loss costs for fuels where reliquification is not practical. Transportation cost is modelled assuming sea transport for a typical transportation distance.

Figure 10

Illustrative breakdown of fuel production cost for various fuel types.



04 Industry Transition

The target of the Industry Transition (IT) model is to estimate the evolution of the global fleet of vessels from 2020 towards 2050, and the transition towards alternative fuels. Combined with additional analysis, this will provide a science-based, independent view of what it takes to decarbonize the maritime industry. It will outline relevant levers within e.g. technology, regulation and financing that will have the greatest positive impact on the transition. Further, it will point at immediate actions that will help unlock and accelerate the transition.

A simplified illustration of two fuel split scenarios is included in Figure 12.

Figure 12. shows two scenarios. One shows the path we are on (left) and one shows a path to zero (right). The scenario towards zero includes activated levers on energy efficiency and a price on CO_2 thereby enabling uptake of alternative fuels while at the same time reducing the total energy demand from 16 to 12 EJ. The current fossil fuel consumption in 2020 is equivalent to 13 EJ[5].

The IT model includes a global fleet composition, assumptions for trade growth, vessel scrap rates and energy efficiency development of the fleet, which is elaborated in Section 4.1. The model flow is illustrated in Figure 13.

As new build vessels enter the fleet, the fleet fuel uptake is calculated based on the differences in total cost of ownership (TCO described in section 3) between all vessel/fuel combinations considered, see Section 4.2.

An additional element is the introduction of critical levers, enabling to investigate the effect of various technological, commercial, financial, and regulatory developments and initiatives on the global fleet development, together with other assumptions and constraints. This is detailed in Sections 4.3 and 4.4.

It was highlighted earlier that the segments with relative low CO_2 emissions were captured with lower level of detail in NavigaTE 1.0. Consequently, when modelling a transition close to net-zero, 0.1 Gton CO_2/year is considered within the model uncertainty as zero. This is considered acceptable as 0.1 Gton CO_2/year corresponds to less than 10% of 2020 emissions. The model does not yet have the required granularity and data implemented for all segments to claim reliable results for e.g. vessels with short-distance round-trip voyages.

Figure 13

Illustration of the model flow of the Industry Transition model.

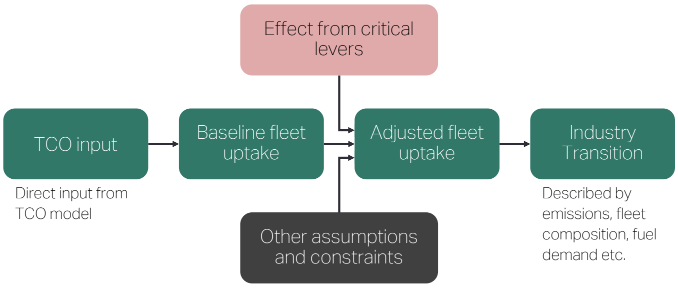
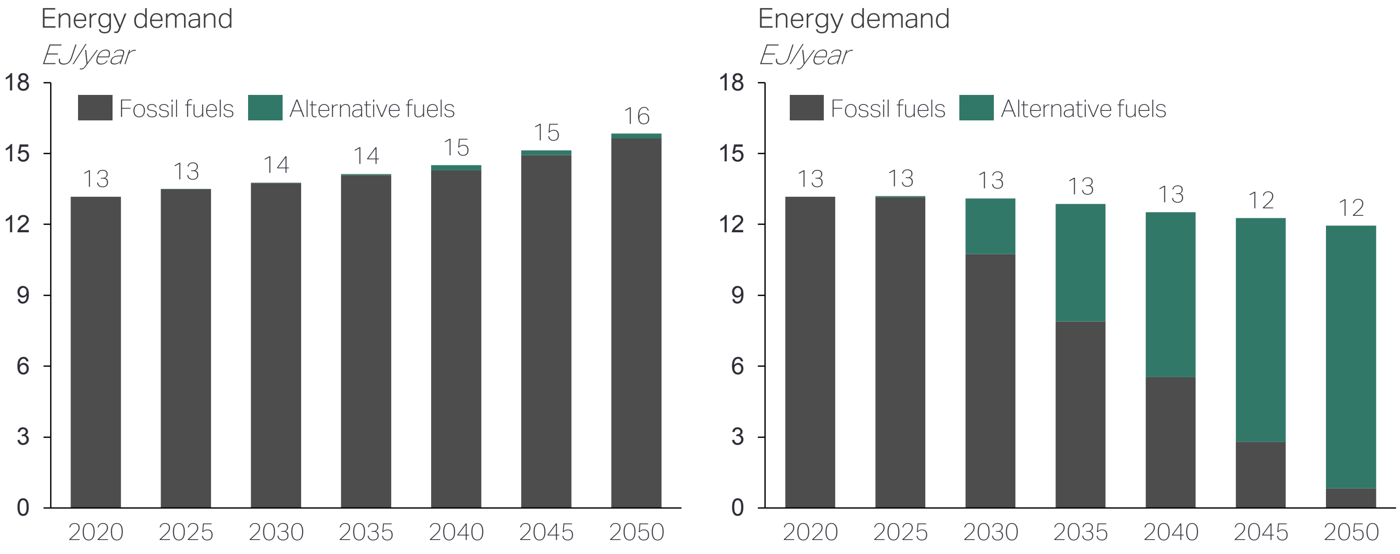


Figure 12

Example output of Industry Transition model showing two scenarios of fuel uptake.



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5) 1 EJ= 1018 J

4.1 Global fleet composition, trade growth, scrap rate, fleet energy efficiency

The modelled fleet is based on fleet data from the 4th greenhouse gas study by IMO. This is used as the baseline fleet. The baseline fleet evolves over time based on trade growth, scrap rate and energy efficiency uptake.

Trade growth

The expected trade growth is based on estimates on the global development measured in total ton-miles. The trade growth is translated into an increase in ton-miles needed. The assumed combined compound annual growth rate (CAGR) is 1.3% from 2020-2050 but varies for individual vessel segments.

Scrap rate and lifetime of vessels

The number of scrapped vessels is estimated based on a lifetime of 25 years as default but can be decided by the user. The scrapped vessels are assumed to be replaced with new vessels of the same segment on a 1:1 principle on ton-miles.

The model does not assume any fundamental changes in trading patterns, but rather focuses on how the industry is transitioning towards decarbonization via reduced use of fossil fuels and increased efficiencies.

Energy Efficiency Uptake in Industry Transition Model

The fleet energy efficiency is modelled to reflect the effect of increasingly more efficient new builds replacing the older less efficient retiring vessels. The base fleet efficiency is based on IMO4GHG consumption and emissions data combined with a historic fleet data base sample. For the new build vessels, the relative fleet efficiency improvement is considering current new build efficiency levels and the energy efficiency design index (EEDI), and carbon intensity indicator (CII) regulations agreed on already by the industry. Additional new build efficiency can be included in the model through the Critical Levers (see section 4.3) with stricter EEDI regulations or increased uptake of energy efficiency measures.

For vessels in the existing fleet, the impact of energy efficiency existing ship index (EEXI) and CII is included. The expected impact is based on a sample database from Clarkson's.

Apart from the impact of increased energy efficiency regulation, commercial and technological developments are also included in terms of energy efficiency. This is elaborated in Section 4.3.

Retrofits on existing vessels are not currently included in the model. The only impact on the existing fleet is from tightened regulation on energy efficiency such as EEXI and CII.

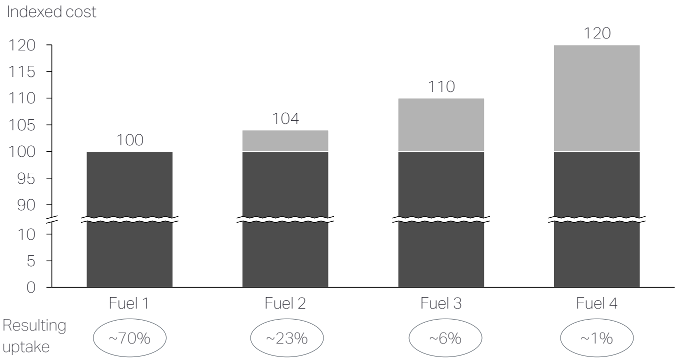
4.2 Fleet fuel uptake based on TCO input

New build vessels

New vessels will be added to the modelled global fleet to replace scrapped vessel and account for potential trade growth. The selection of a fuel-powertrain combination for the added vessels is based on a comparison of the TCO for the different fuels and powertrain options for the vessel. A fleet uptake curve is included in the model to determine the uptake of the different fuels resulting in a distribution in the fuel uptake. An example illustrating this logic is shown in Figure 14.

Figure 14

Illustrative example of fuel uptake logic.



As the vessel configuration running fuel 1 is cheapest, this has the highest uptake but not the only fuel selected. A relative ranking is used with the fuel uptake curve, resulting in the split shown above. This is included to model complex decision processes where other factors than solely cost is accounted for.

Existing vessels - substitute fuels

For existing vessels, the model allows for substitute fuels. This means that a vessel intended to operate on one type of fuel is allowed to use another compatible fuel if this would be cheaper. An example of this would be a vessel built to operate on LSFO being operated on a bio-diesel. The model does not account for retrofits between different fuels with different properties.
To determine the uptake of the potentially cheaper substitute fuel, the same logic shown above in Figure 14 regarding the fuel uptake is followed.

4.3 Critical Levers

The final uptake of the various fuels can be impacted by a variety of critical levers. These can change the relative uptake based on changed total cost of ownership for the different combinations. Multiple critical levers are defined. The full list includes:

1. Policy and regulation
  a. Global carbon pricing (on well-to-wake emissions)
  b. Stricter energy efficiency regulations

2. Technological advancements on-board vessels
  a. Increased uptake of existing energy efficiency levers
  b. Development of new technologies increasing energy efficiencies

3. Energy & fuel advancements
  a. Lower renewable electricity prices

4. Customer demand/pull
  a. Consumer demand and willingness-to-pay for green transportation

5. Finance sector mobilization
  a. Lower financing costs for low-emission vessels

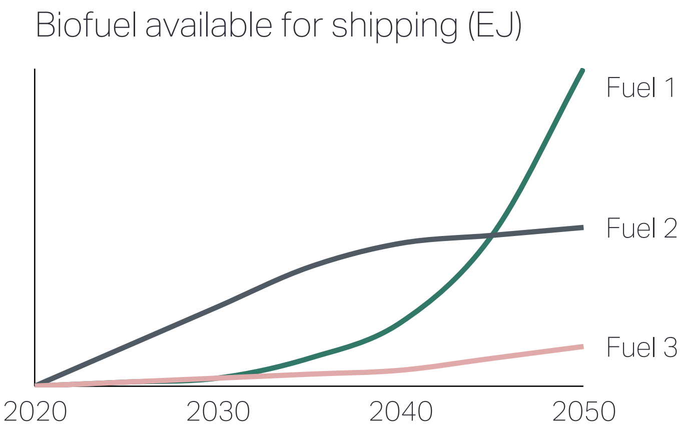
A further detailing of the critical levers – and their impact on different scenarios – is a significant part of the Center's upcoming Industry Transition Strategy.

4.4 Other Constraints & Availability

Fuel applicability
The model allows technologies to be selected to be only applicable for certain vessel segments and for certain years. An example could be ammonia not being available until 2030 and not being applicable to cruise ships and ferries due to safety concerns.

Constraints on fuel uptake
The model also includes the possibility to constrain the uptake of fuels. This includes constraining available biofuels based on a maximum capacity per year, which is defined based on technology readiness levels, scale-up speed, and biomass availability.
That means that a new build vessel in e.g. 2045 is unable to use the most attractive TCO option if that fuel is at a capacity limit seen from a global perspective. An example of this includes a constraint on biofuel capacity, illustrated in Figure 15.

Figure 15
Biofuel capacity constraint, illustrative example.



In the illustration, three different fuels are modelled with different availability development over time. For this illustrative example, fuel 1 has a slow ramp up initially but the availability of biofuels for shipping increases significantly over time. Fuel 2 reaches a plateau and fuel 3 never gains traction.

Scenarios leading to various fuel options towards 2050 are impacted by a combination of their attractiveness from cost of ownership (the TCO model) and their potential for impact via the rate of scale-up and ultimate availability (functionality in the transition model).

Future improvements of NavigaTE includes improved description of how the competition between different sectors will impact e.g. cost and availability of e.g. biomass, CO_2 point-sources and renewable electricity.

05 Summary and next steps

Since the launch of the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, NavigaTE has been scoped and developed and is now at a stage where it includes an combination of vessel technology, energy efficiency as well as conventional and alternative fuel types. These three elements are tied together in a transition model capable of simulating a maritime transition towards 2050 impacted by cost of technology options as well as critical levers required to close the fundamental cost gap existing between conventional fuels and the solutions needed for net-zero.

NavigaTE is a strong tool to study impact of a range of assumptions on the outcome towards 2050. The outcome being primarily the total greenhouse gas emissions, the impact from various fuel type uptake, cost/investment implications and the total energy requirement for the global fleet. Part of the NavigaTE model, the classic TCO-model, can be shared with organizations willing to cooperate regarding model functionality and improvement of the underlying data.

Initially, the model serves as a tool to support the analysis and scenarios of our first Industry Transition Strategy – including building scenarios for market-based measures. Following this, it will also be a highly useful tool for a prioritization of R&D activities, i.e. to be used as a measure of the impact/potential for new projects and to help focusing of capital on the most impactful paths and/or identifying bottlenecks for a transition.

Finally, the objective of the NavigaTE model is to support a structured, data-based discussion and collaboration with stakeholders in the eco-system to improve the common understanding of pathways and needed developments. The Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping is looking forward to a broad collaboration with all interested and relevant stakeholders to maximize the level of common understanding – and thereby de-risking strategic decision processes, increase comfort levels and getting out of the typical chicken-and-egg challenge.

06 Appendix

The NavigaTE model includes a range of data, parameters, and assumptions. The below sections highlight some of the model boundaries and key assumptions that have a significant impact on the results.

6.1 List of boundaries and key assumptions of the TCO-model

Fuel model:

- Levelized cost of renewable electricity per region and time.
- Assuming balanced electricity supply e.g. buffering capacity with batteries.
- Oil price – forward looking curve
- Natural gas price – following relative development of oil price
- Unsubsidized fuel production pathways
- First generation biofuels (FAME, HVO) not considered due to not being deemed sustainable for large scale supply
- Sustainable biomass considered from waste streams i.e., forestry residue, agricultural residue, organic wet waste
- GWP factors considered 100 years

Vessel technologies:

- Onboard carbon capture and storage not considered
- Onboard nuclear power not considered due to perception and safety challenges
- Retrofit not included
- Wind propulsion not considered as a main source of propulsion, but considered as an energy efficiency measure
- Powertrain technologies CAPEX, OPEX and fuel efficiency

6.2 List of boundaries and key assumptions of the IT-model

- Fleet baseline composition from IMO GHG 4th
- Global trade growth 1.3% CAGR
- Scrap rate at lifetime 25 years
- Retrofit of fleet not included
- No significant change of trade patterns, sizes, and types of vessels
- Renewable electricity supply assumed to cover demands in base case scenario
- Biomass availability
- New build vessels according to economic considerations, TCO
- Focus on ocean going vessel types accounting for the major share of GHG emissions – less detail on short sea going vessels (electrification, hydrogen)