NavigaTE Explainer

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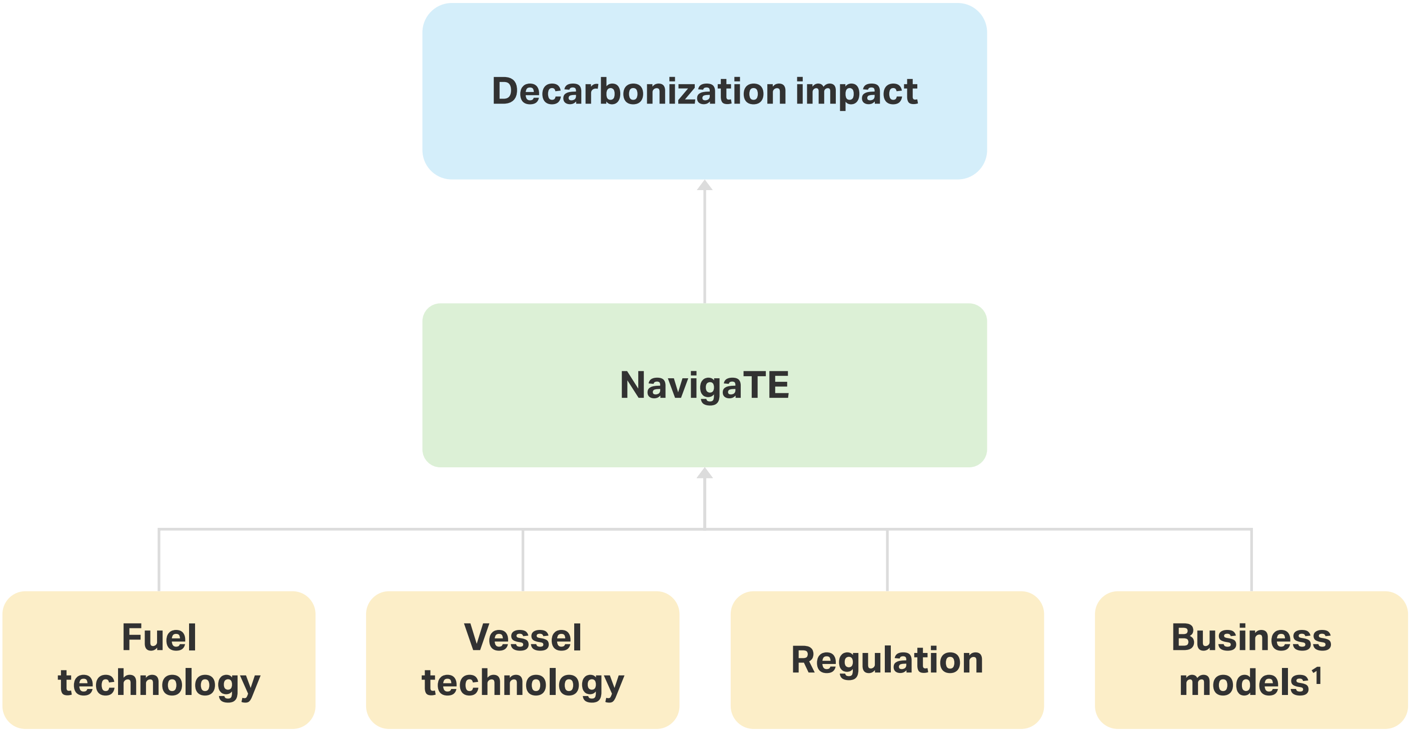
NavigaTE introduction

The NavigaTE model was built to provide data-driven insights to help decision makers

The impact of various elements on decarbonization is quantified via NavigaTE



To enable data-driven insights regarding the transition towards zero carbon shipping, the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping has developed a techno-economical model.

The model is known as NavigaTE.

The target of developing NavigaTE has been to integrate knowledge from across functional disciplines within the shipping value chain.

By combining knowledge about specific technologies, regulations, and business models, it is possible to understand their combined impact on the decarbonization pathways via NavigaTE.

1: Including e.g., development in trade, cargo utilization, speed, etc.

NavigaTE models the shipping value chain from feedstock to onboard use

Feedstock

Fuel production

Bunkering & logistics

Onboard vessel

NavigaTE describes the **shipping value chain** from feedstock to fuel production, logistics, and vessels.

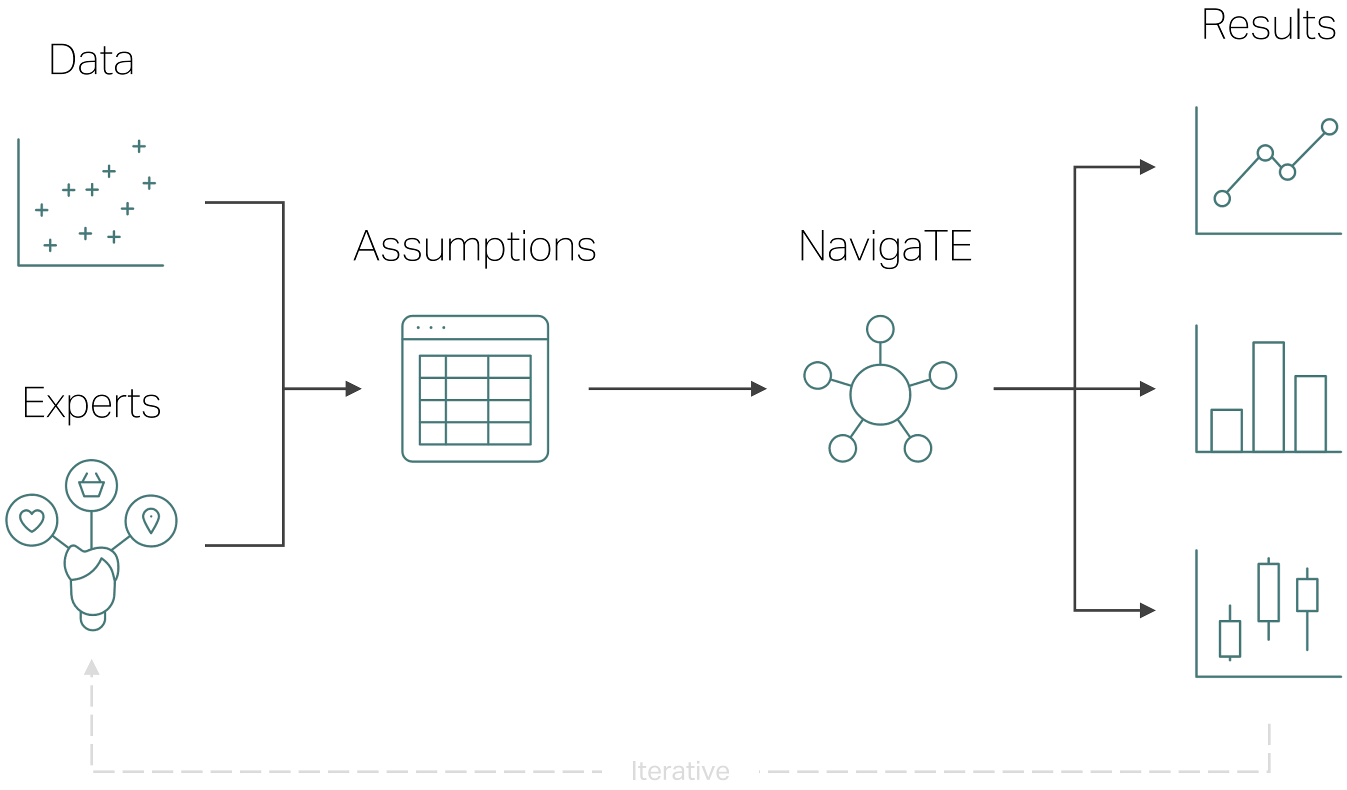
The model can be used for various tasks, including **global estimates** of fleet development, fuel uptake, impact of regulations, and the resulting expected emissions.

The model can go into **single-vessel-level detail** but does not aim to accurately describe the vessels with as much granularity as the models used by naval architects.

It is important to remember that NavigaTE is **only a model**. It uses general methods for predicting complex human behavior and does not account for all possible options. Therefore, the results should be interpreted **qualitatively, not quantitatively**.

The transition model workflow uses NavigaTE as one of four key steps

Illustrative transition model workflow around NavigaTE



To elaborate on how NavigaTE works, the **model workflow** around it must be understood.

The first step of the model workflow is to collect data. This data is collected from **industry partners**, **databases** and the **literature**.

The data is then quality-checked, analyzed, and condensed into a set of **model assumptions** by Center experts.

NavigaTE then **predicts how players** in the maritime value chain will **behave** given those **assumptions**.

The **results are analyzed** and put into a **broader context** by experts at the Center.

NavigaTE is a collection of equations; the simulator itself does not contain assumptions

Example of model choices and assumptions

Model choices

- Total cost of ownership approach
- Well-to-wake emissions scope
- Probabilistic approach to vessel selection algorithm[1]
- Linear programming used for the fuel selection algorithm[1]

Assumptions

- Renewable electricity cost
- Vessel lifetime
- Trade growth
- Cost of capital

Related to NavigaTE, a clear distinction is made between model choices and assumptions.

Model choices is a term used to describe choices made by the model developers in order to best describe decision making. This is essentially the equations used in the different calculations.

On the other hand, assumptions is a term used to describe the values and parameters passed to the simulator. These may vary for different scenarios.

Model choices are the focus of this document, which elaborates on the key model choices going into NavigaTE.

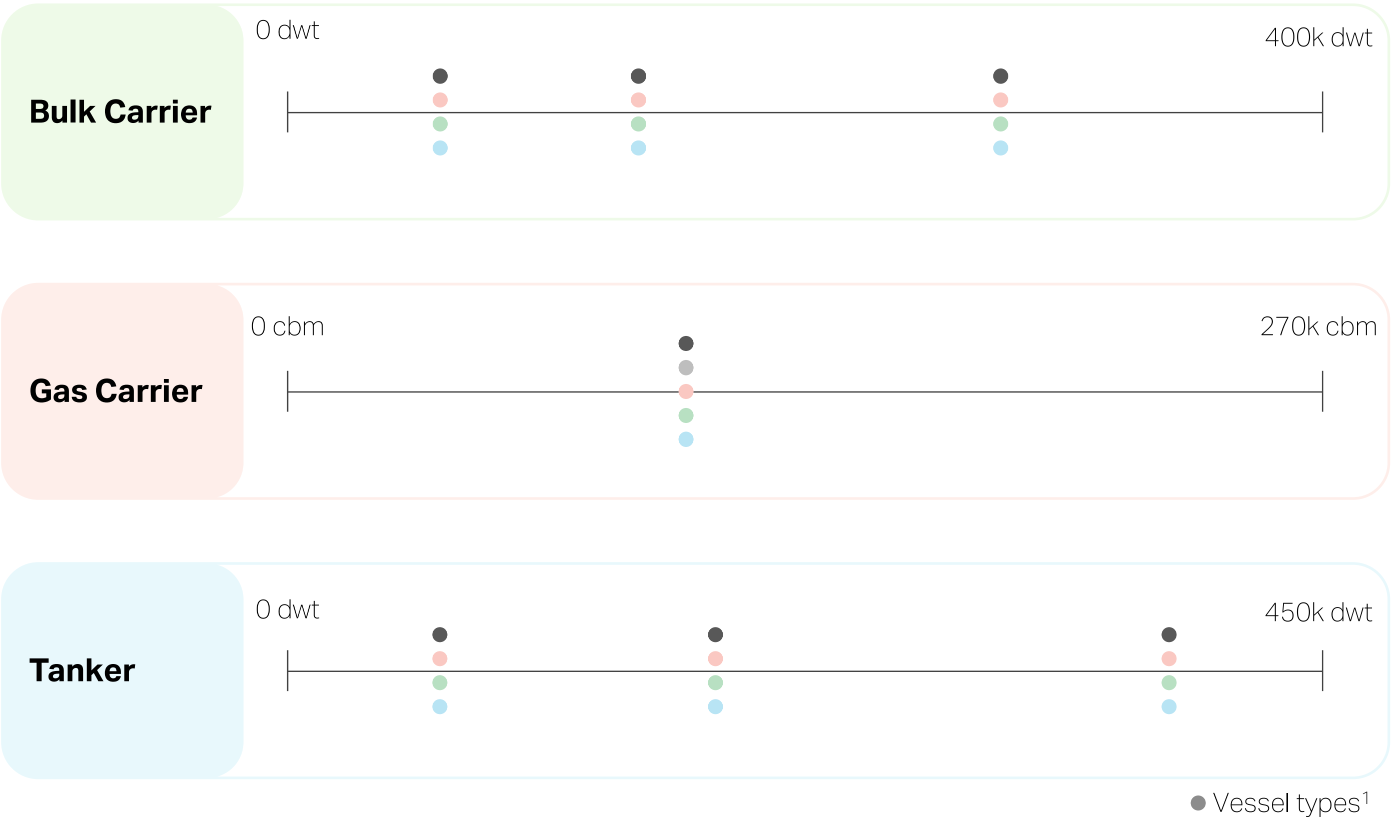
Assumptions about fuel- or vessel-related items are detailed in separate documents. However, for explaining some model choices, examples of assumptions are used in this document.

1: Both approaches will be detailed in later sections.

Vessel selection criteria

The entire fleet is represented by a set of segments, sizes and vessel types

Examples of representation of the fleet for three segments



1: Different vessel types can be used for the different segments based on assumptions. Examples includes ammonia-powered vessels not allowed for cruise and ferries or LPG-powered vessels only considered for the gas carrier segment.

The **global fleet** consists of approximately 100,000 commercial vessels.

However, modelling all vessels individually would significantly **increase computational** time **without adding value,** as many vessels are built similarly and can reasonably be **grouped**.

These groupings occur across **two categories** in NavigaTE, namely:

- Segment (container, bulk carrier, etc.)
- Size/nominal capacity

In the example, three segments are shown (bulk carrier, gas carrier, and tanker).

A segment+size combination is referred to as a **representative vessel**.

For each representative vessel, multiple technologies are considered. This difference is referred to as a **vessel type**[1] illustrated by the different colored dots.

For a representative vessel, different vessel types are used to model engine and fuel technology

Example of definition of vessel types

Vessel type	Fuel oil	Methane	Methanol	Ammonia
Engine technology	Internal Combustion Engine (mono fuel)	Internal Combustion Engine (dual fuel)	Internal Combustion Engine (dual fuel)	Internal Combustion Engine (dual fuel)
Fuel options	Fuel oils[1]	Methane & Fuel oils[1]	Methanol & Fuel oils[1]	Ammonia & Fuel oils[1]

1: Includes fossil fuel oils and bio/e-diesels

Each representative vessel is described by a set of vessel types. The entire representative vessel is defined by a distribution of these vessel types.

Technically, the vessel types within a representative vessel can vary on all parameters, but in practice most are kept constant and only the engine technology and fuel options are varied.

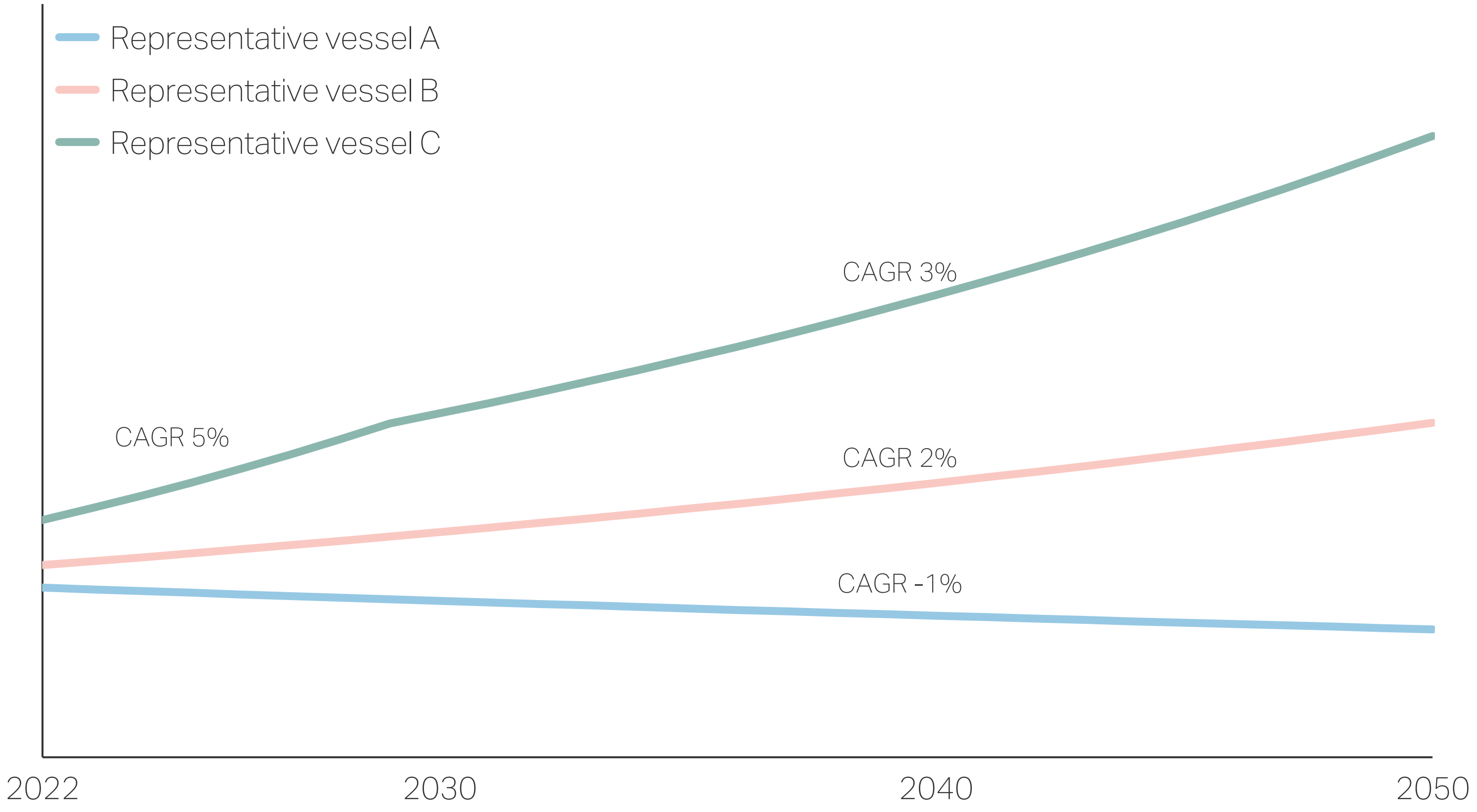
In this example, four vessel types are shown. All have an internal combustion engine as engine technology and fuel oil, methane, methanol and ammonia as fuel technology, respectively.

The model is provided an initial distribution of vessel types per representative vessel. Typically, this consists almost entirely of fuel oil vessels and a few methane vessels.

Over time, the vessel distribution may change as ship owners decide to build new/other types of vessels compared to the existing fleet.

Trade growth is used to simulate the development in number of vessels in the fleet

Example of trade growth for three different representative vessels



1: A trade growth of 0% can also be used.

For all representative vessels, a key element to determine is the **expected demand for shipping** for that given representative vessel.

The expected demand for shipping is guiding the **number of vessels** for each year in the simulation.

To model the expected demand for shipping, a **baseline** is established using real data.

This is combined with a **projection of trade growth** based on a forecast.

An **example** of the impact of trade growth is included in the illustration. Here, three representative vessels (A, B and C) are included with example assumptions.

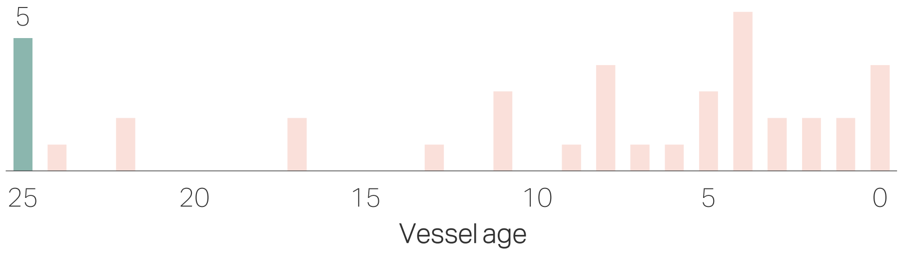
As seen, trade growth can both be **negative** (A) and **positive** (B and C).[1]

The trade growth can be a **fixed number** over time (A and B), or it can **change over time** (C).

For modeling the fleet turnover, scrapping and building of new vessels are considered

When to scrap a vessel

Number of vessels per age

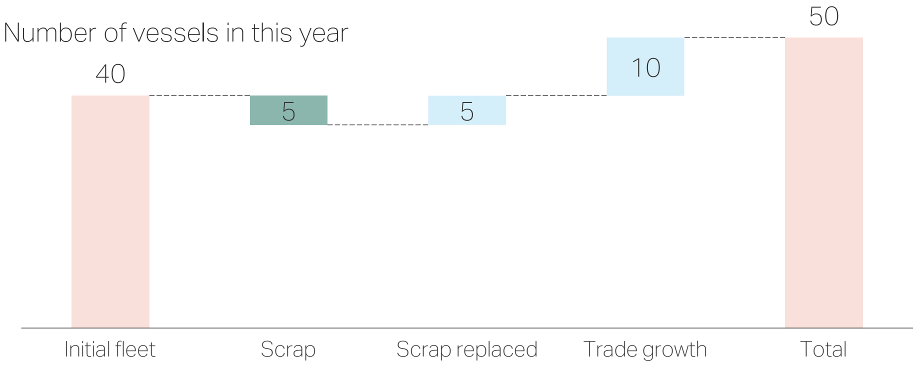


Lifetime (25 years)

5 vessels scrapped during this year

When to build a new one

Number of vessels in this year



15 new vessels built during this year

Two main elements are considered for modeling the fleet turnover: scrapping of vessels and building of new vessels.

For scrapping of vessels, the current fleet age distribution and an average vessel lifetime is considered. When a vessel exceeds the average lifetime (25 years), it is scrapped.

In the example shown, 5 vessels are 25 years or older in the model and these are scrapped.

The task of determining the number of new vessels to enter the fleet can be split in two elements: replacing the scrapped vessels and satisfying potential trade growth.[1]

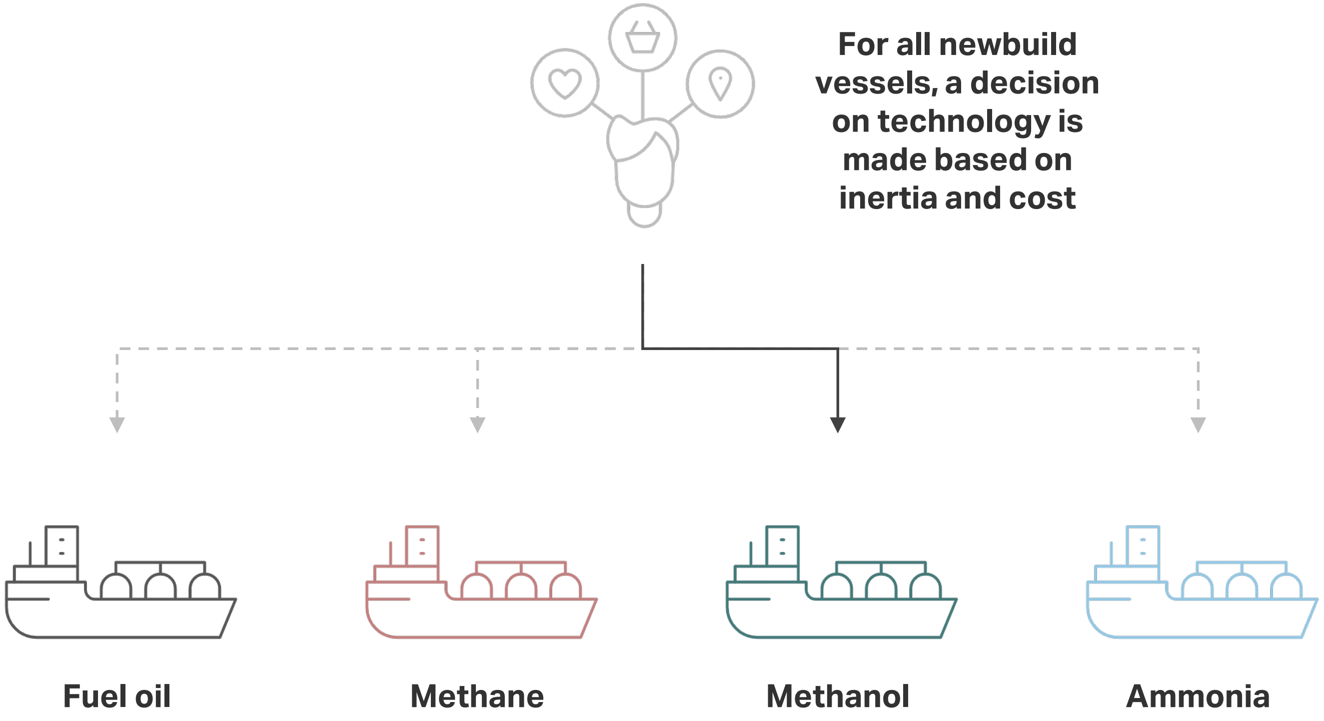
Both are considered for determining the number of new vessels to add to the fleet.

In the example, 5 vessels are built to replace the scrapped vessels and 10 additional vessels are built due to assumed trade growth.

1: If trade-growth is negative, not all the scrapped vessels will be replaced.
Note: This calculation is done per vessel segment and size.

The vessel type of the newbuilds depends on the orderbook, industry inertia, and cost

Decision regarding vessel technology for newbuild vessels



When newbuilds enter the fleet, their vessel type (fuel/engine technology) is determined by three different methods.

In the early years of the simulation, the vessels are selected from an orderbook[1] which is given directly as user input. This means that they are not modelled.

Once the orderbook is empty, NavigaTE starts modelling the vessel types that enter the fleet. This is done using two approaches sequentially.

First, a portion of the newbuilds are determined based on the historical distribution of vessels. This is called inertia.

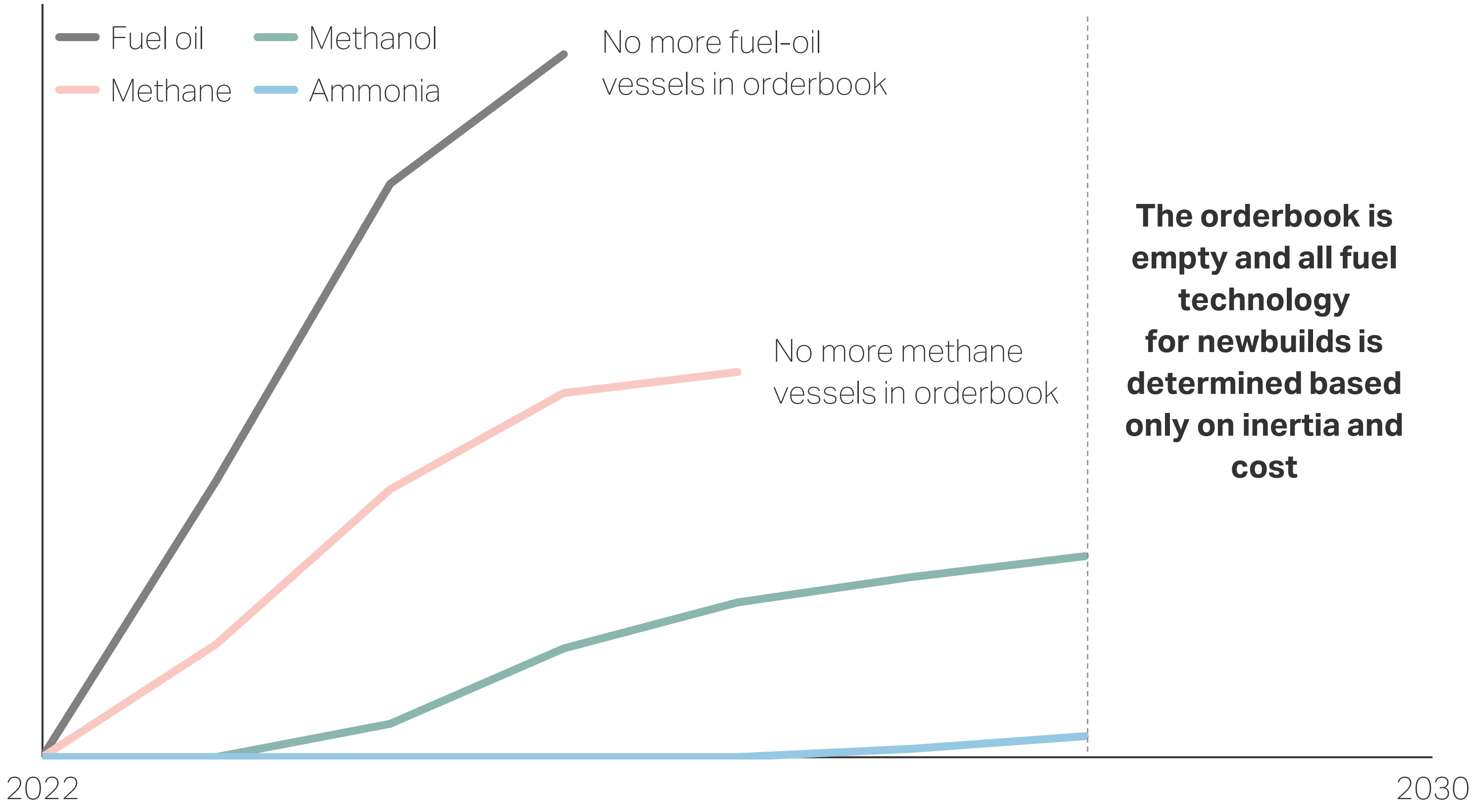
The remaining portion of newbuilds are determined based on a mathematical decision-making logic influenced by the cost of the individual vessel types.

These decisions are made for each individual representative vessel.

1: The orderbook is defined by the data available in Clarkson's.

The orderbook is the primary driver of the vessel types in the early years of the simulation

Cumulative number of vessels in the orderbook for a given vessel type



The orderbook in NavigaTE is defined by the cumulative number of vessels of each vessel type that should enter the fleet in a given year from the start of the simulation.

The number of vessels to enter the fleet per year is determined by the fleet turnover, not the orderbook.

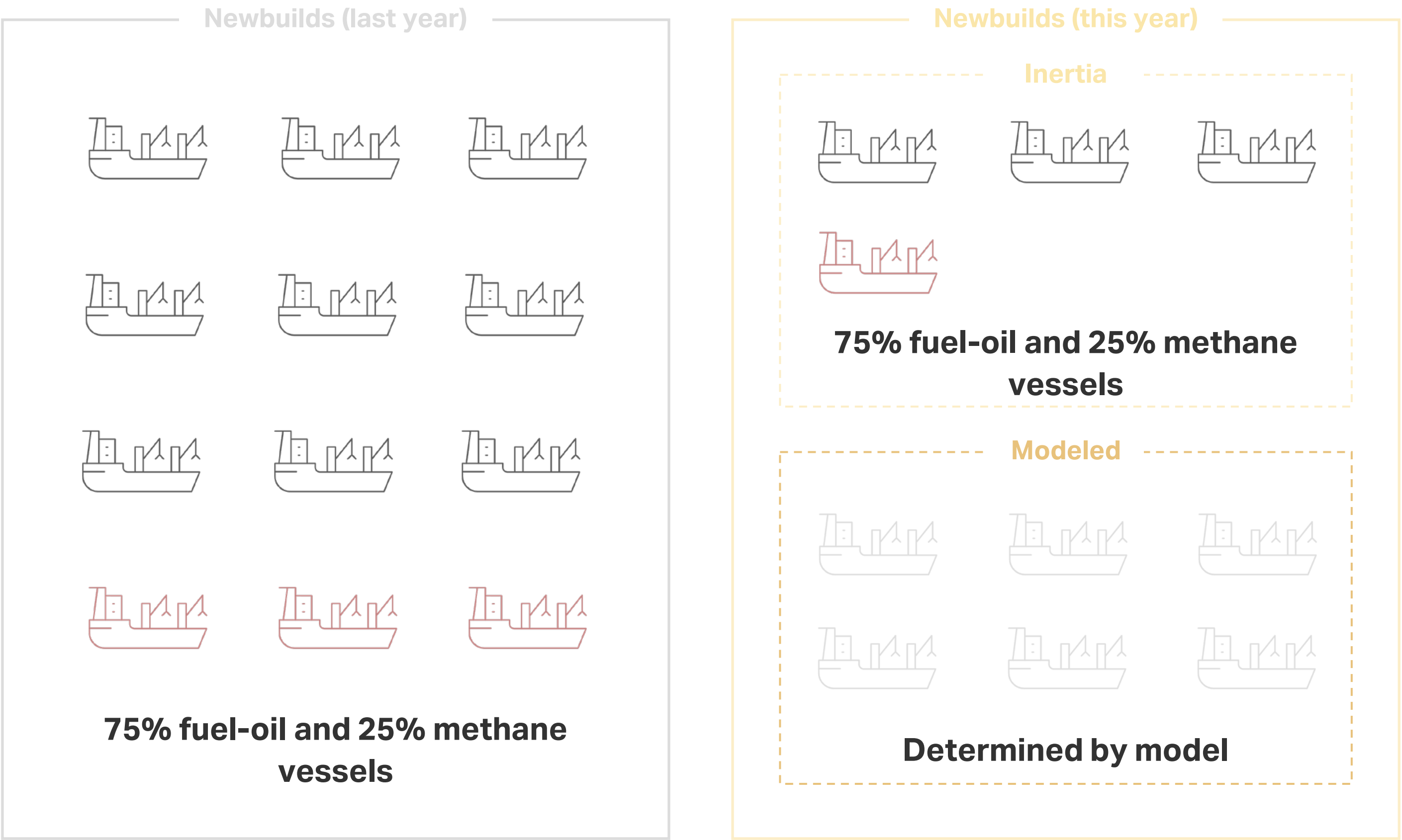
If there are sufficient vessels in the orderbook to satisfy the newbuild requirement, the vessel types are determined exclusively by the orderbook.

If there is an insufficient amount in the orderbook then the vessel types are determined by a mix of the orderbook, inertia and cost-based decisions.

This methodology ensures that 1) the entire orderbook can be used in the simulation and 2) the impact of the orderbook on the model results is highest in the early years of the simulation when the data is most complete.

Individual decisions are influenced by industry trends and the path taken by first movers

Illustrative example of impact from inertia in NavigaTE



Note: This is an illustrative example. The values for number of vessels and degree of inertia are not the values used in NavigaTE.

Inertia is defined in NavigaTE as an impact on decision making based on previous decisions.

The inertia in the model functions to mimic real-world factors that affect the speed of change adoption. For example, once companies make a strategic decision to focus on a specific fuel or vessel type, they are unlikely to make large changes to this strategy in the short term.

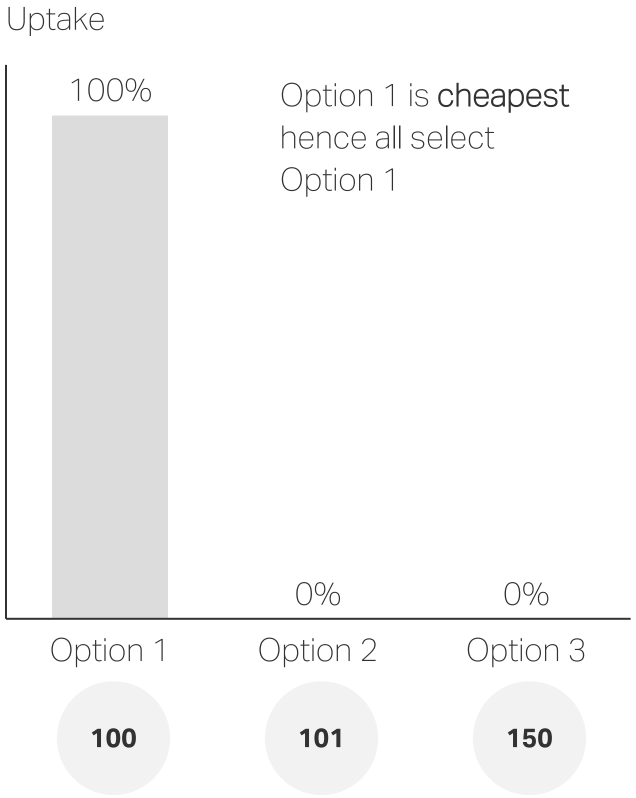
The result of adding inertia is that decisions made early in the transition have long-lasting future effects. In the model, these effects are represented by specifying that a share of the newbuilds will have the same distribution as in the previous year.

In this example, twelve newbuilds entered the fleet in the previous year: nine (75%) fuel-oil and three (25%) methane vessels. In the current year, ten newbuilds will enter the fleet. Assuming a 40% inertia, then four of those vessels will have the same 75%/25% split as the previous year.

The remaining six newbuild vessels will be determined based on cost.

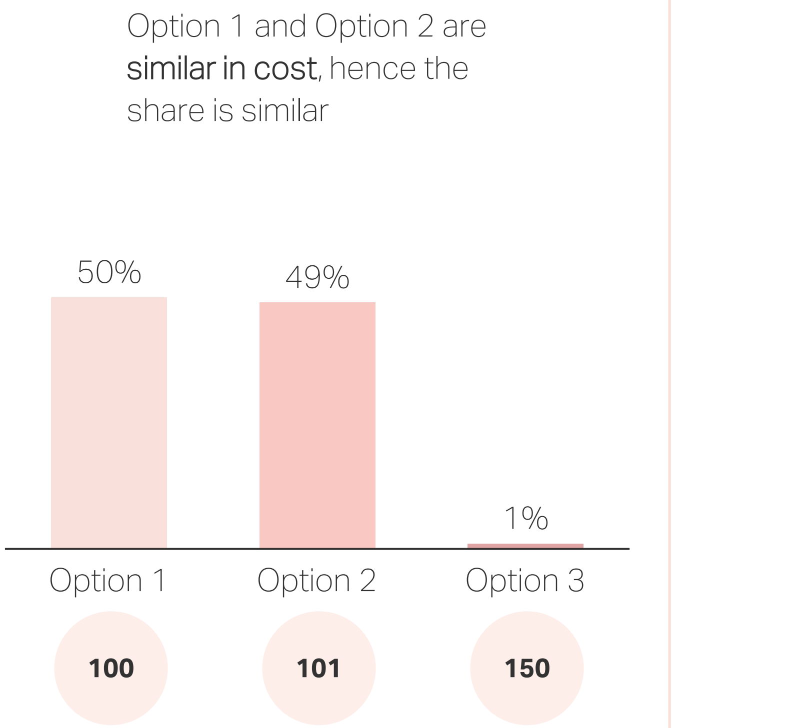
To decide which technology to install on a newbuild, a probabilistic approach is used

Cost-optimal approach



NavigaTE

Probabilistic approach



After considering the orderbook and inertia, the final element in vessel selection is considered. This is the cost-based element.

In a techno-economic model, there are two general approaches to modeling decision-making for a representative group of actors.

The simplest is a cost-optimal logic, where decisions are binary, i.e., the cheapest option available is selected by all actors.

The second is a probabilistic[1] approach. Here, it is assumed that decisions are influenced by cost, but also by factors such as corporate strategy, culture, etc. Therefore, options that are close to equal in cost will have a close to equal share.

The second approach (mathematically called a discrete choice model) is used in NavigaTE. This approach was selected because NavigaTE attempts to mimic decision making, not to find a cost-optimal solution.

1: Based on probability theory.

The net present cost for different vessel technologies depend on three key areas

Three pillars of calculating net present cost

Fuel	CapEx	Other OpEx
– Production cost – Fuel regulation cost	– Base – Machinery – Other	– Maintenance – Voyage cost – Crew cost – Other
40-70% of cost	**20-30% of cost**	**10-30% of cost**

In NavigaTE, the key decision-making parameter for selecting a vessel type is cost – specifically, the net present cost.[1]

All costs can be considered as three main pillars: fuel, capital expenditures (CapEx), and other operational expenditures (OpEx).

The impact on the net present cost per category varies with the segment, size, and vessel type, but some indicative numbers are included in the example.

The main cost pillar is fuel cost – especially in a decarbonized scenario, where this cost can be more than half of the overall cost.

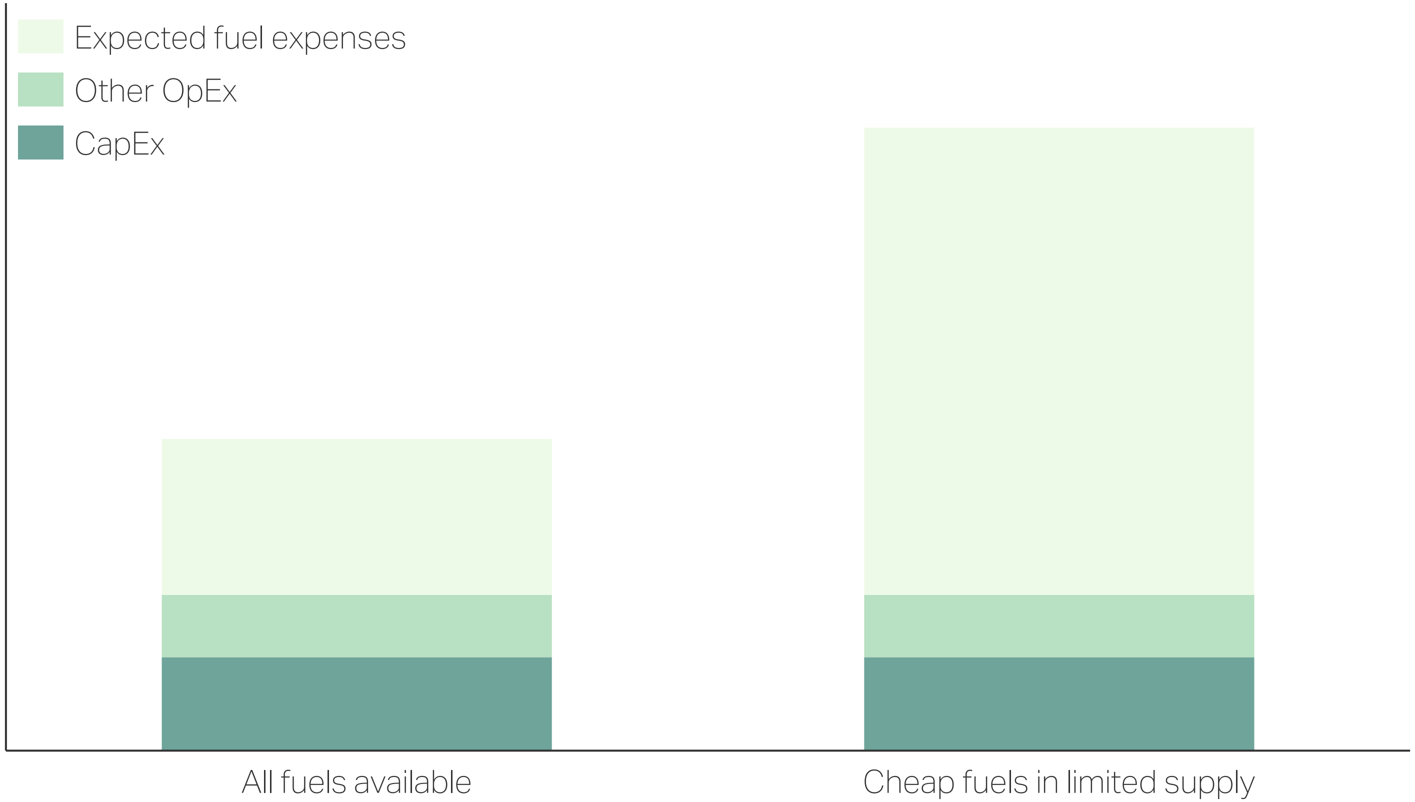
The remaining two cost pillars are smaller and roughly equal in size.

The net present cost is the sum of the discounted future cost-flows from the three pillars.

1: Same as net present value but without the without the positive cashflow.

Fuel availability impacts the expected net present cost

Example: Impact from limited fuel availability on expected fuel expenses



So far, only the actual cost has been considered. However, fuel availability is equally important to consider when predicting a vessel's future fuel-related expenses.

To account for fuel availability, an expected fuel cost is calculated. This impacts the decision of which type of vessel to build based on the expected availability of fuels.

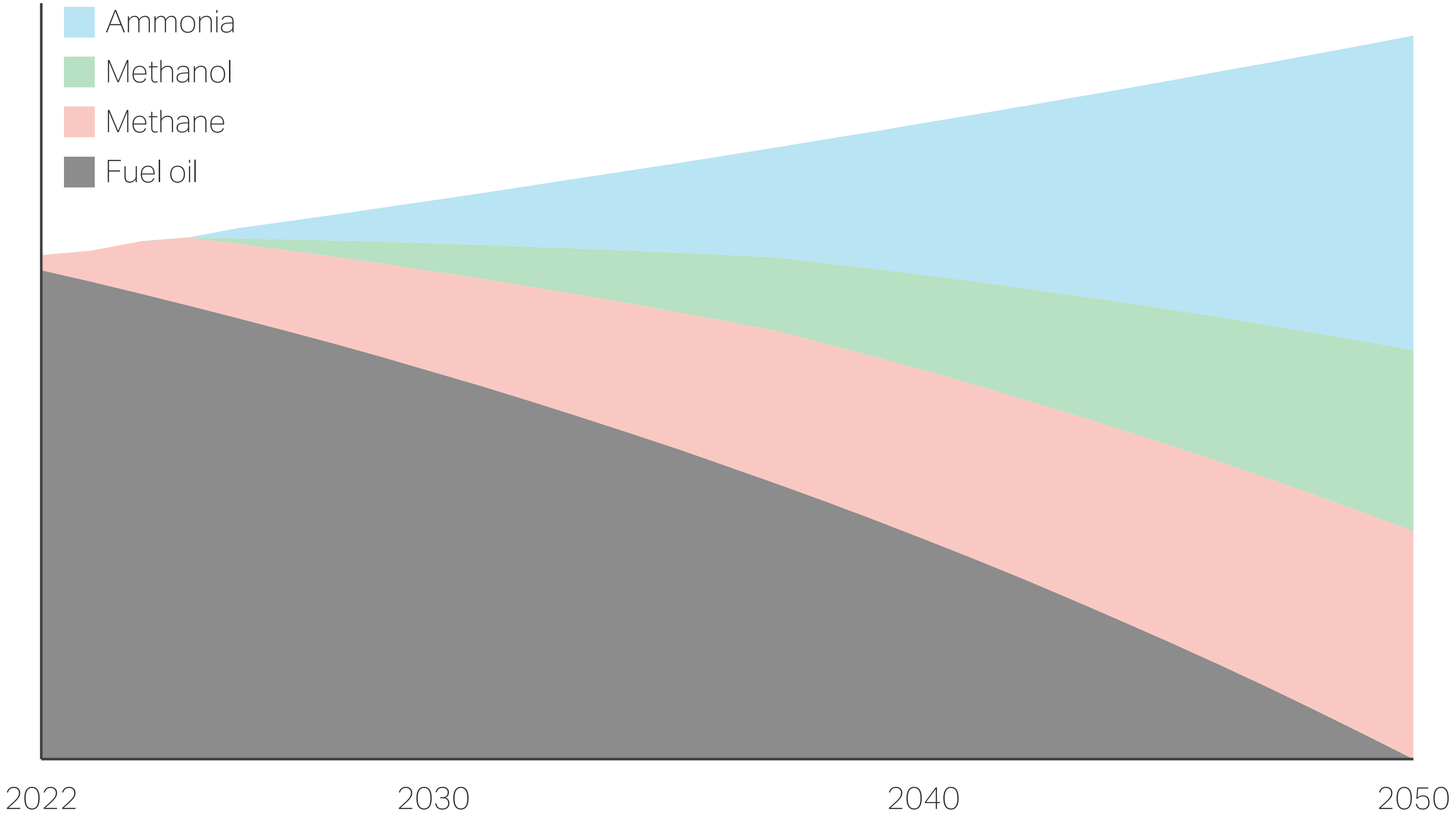
Based on the availability of fuels and the demand from vessels that can operate on that fuel, an expected fair share of the supply is attributed to each vessel.

The expected future expenses from fuel are then calculated assuming that only the fair share of the supply of each fuel is available to the vessel.

If the demand for a fuel is larger than the supply, this leads to higher expected future fuel expenses.

The vessel selection algorithm projects the fleet development down to vessel types

Example of fleet development for a representative vessel



The model starts with the **initial fleet**. This fleet develops based on **trade growth**, which guides the total number of vessels in the fleet per year.

The vessel selection algorithm is used to model decision-making regarding vessel types. The algorithm makes it possible to **project the expected fleet development** across vessel types.

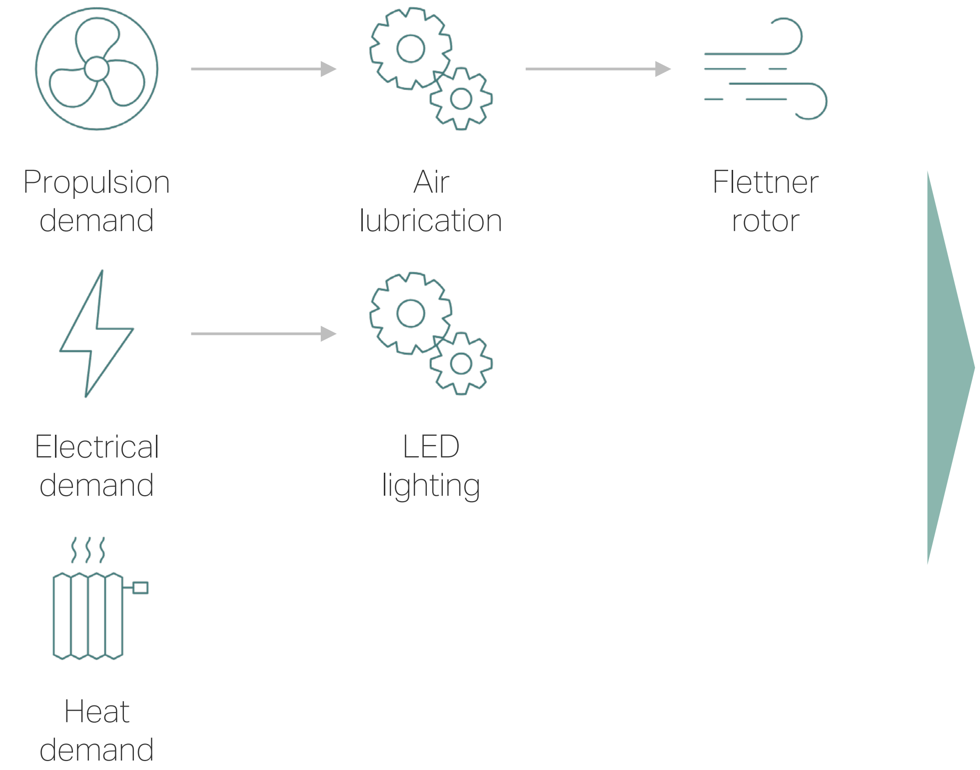
The example shows a scenario where **multiple vessel types** are projected towards 2050 based on the cost outlook and availability of fuels, the imposed regulatory framework, and the related vessel technology.

The expected fleet development depends on the **model choices** described in this section – but it is also highly dependent on the **assumptions** used for the simulations.

Energy efficiency

Energy efficiency technology reduces energy demand, resulting in a lower fuel spend

Example of installed technology reducing energy demands



The technologies will target either the onboard propulsion, electrical, or heat demand.

Depending on the business case for the technologies, it is not guaranteed all demands will be reduced.

The uptake of energy efficiency measures can occur both as installed technology on **newbuilds** or as **retrofits** onto the existing fleet.

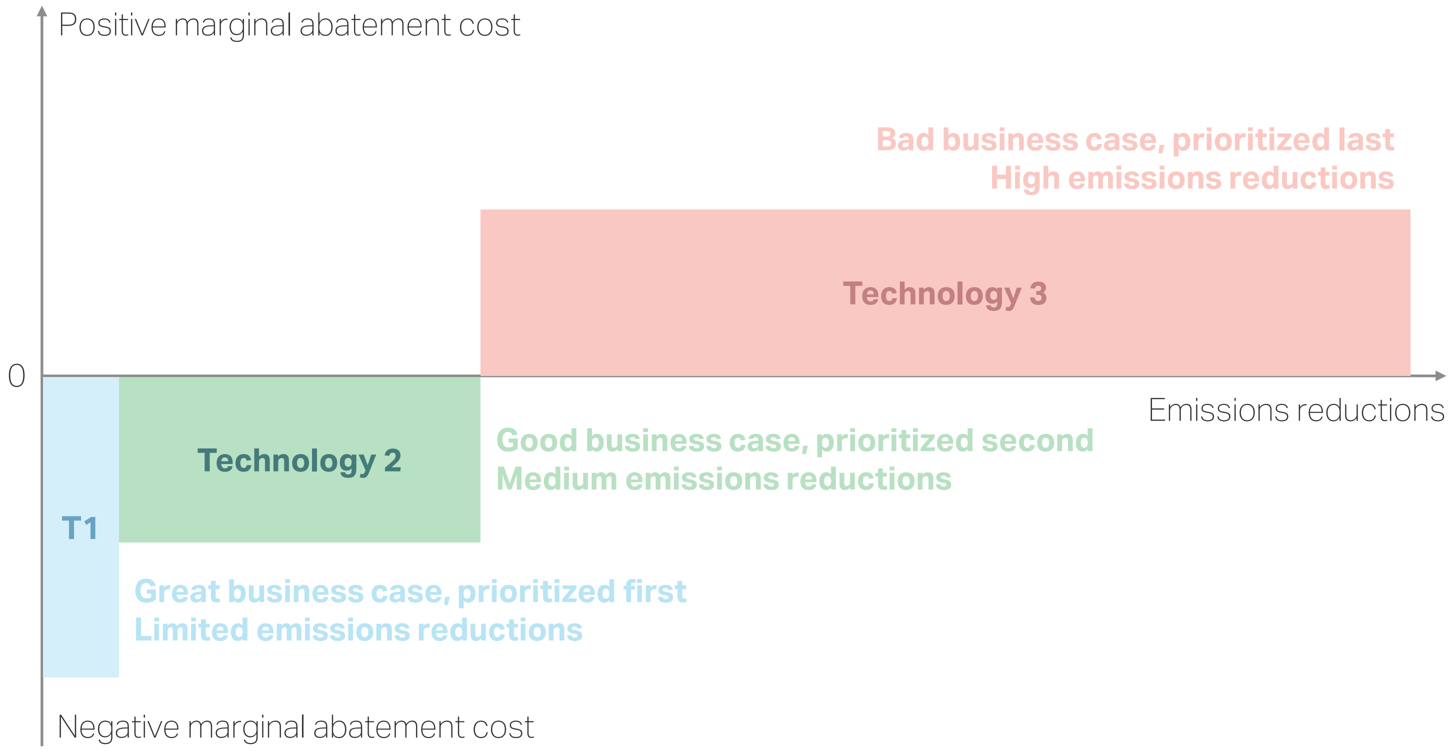
Energy efficiencies can be either **operational** or installed **technology**. They will have an associated CapEx, OpEx, and energy saving given in either percent saved (e.g., waste heat recovery systems) or installed capacity (e.g., rotor sails).

In the model, we differentiate between energy efficiency technology (e.g., air lubrication), which **reduces** the energy demand, and alternative power technology (e.g., rotor sails), which **satisfies** part of the energy demand by utilizing solar or wind power.

The impact of these two types of measures on the energy demand is modelled differently, but the method for determining their uptake is **similar**.

The uptake of energy efficiency technologies is based on a marginal abatement cost approach

Illustrative marginal abatement cost curve



For calculating the expected **uptake of energy efficiency technologies**, a marginal abatement cost approach is used.

This is illustrated by a **marginal abatement cost curve** (MACC). A MACC plots the expected emissions reductions compared to the expected marginal abatement cost of a given technology.

A **negative** marginal abatement cost indicates a **good business case** (as emissions are reduced while fuel costs are reduced as well).

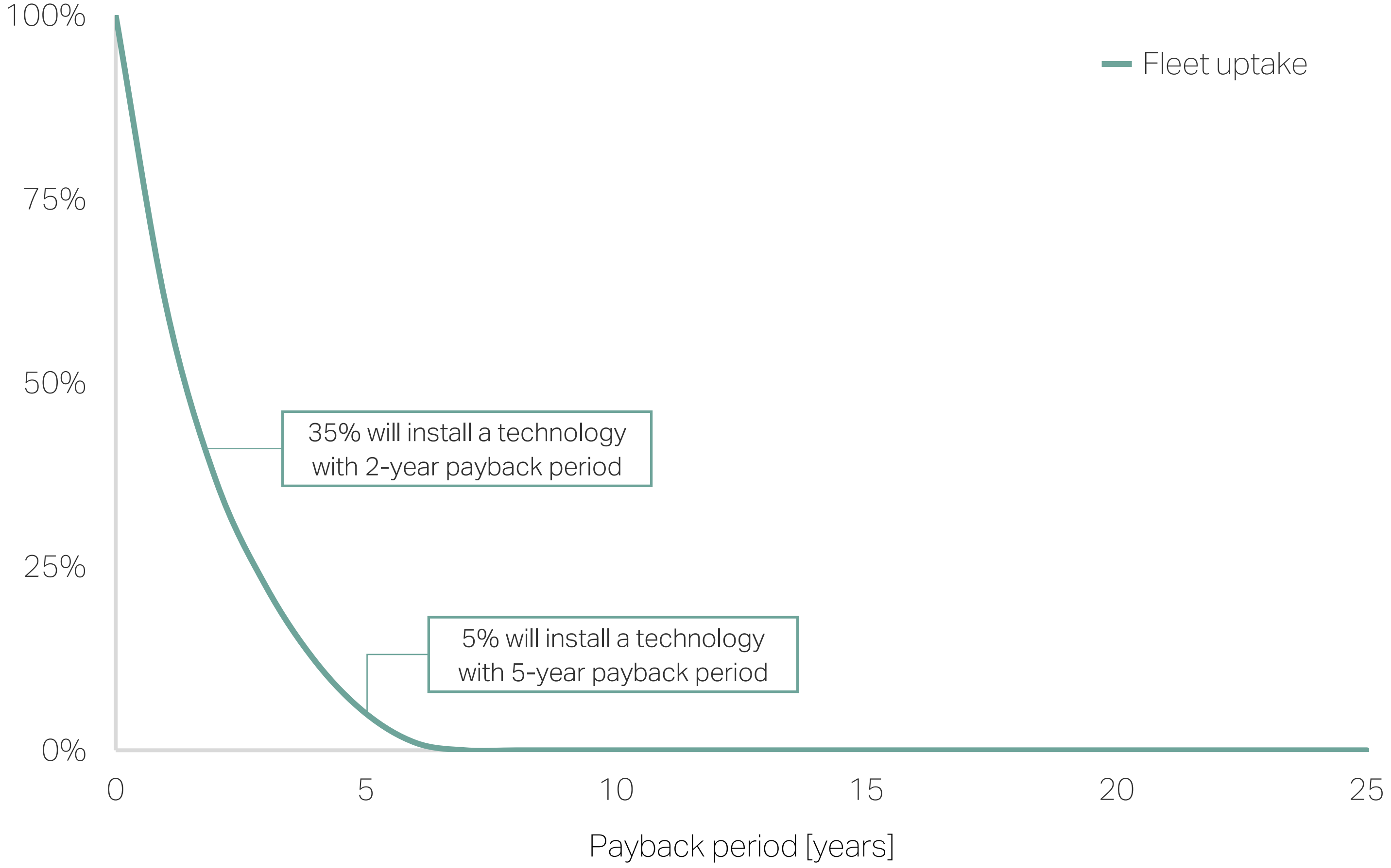
For all vessels, a **business case** for installing or retrofitting the technology is calculated. The business case is based on the expected fuel expenses and fuel regulation cost in the remainder of the vessel lifetime and the associated cost of the technology.

If the business case is considered **advantageous**, the energy efficiency will be adopted.

Notice that installing multiple efficiencies will yield **diminishing returns**.

Due to an inefficient business incentive structure, the adaptation is limited

Illustration of the fleet installing a technology as a function of payback period



Note: The uptake curve can be varied to test its sensitivity.

Based on the business case evaluation, the **payback period** of the investment is calculated. Using a user-supplied curve, the model looks up how large a **fraction of the fleet** will likely adopt a technology with a given payback period.

The business case evaluation is made for **every** technology, for every representative vessel type, and for every vessel age in the age distribution.

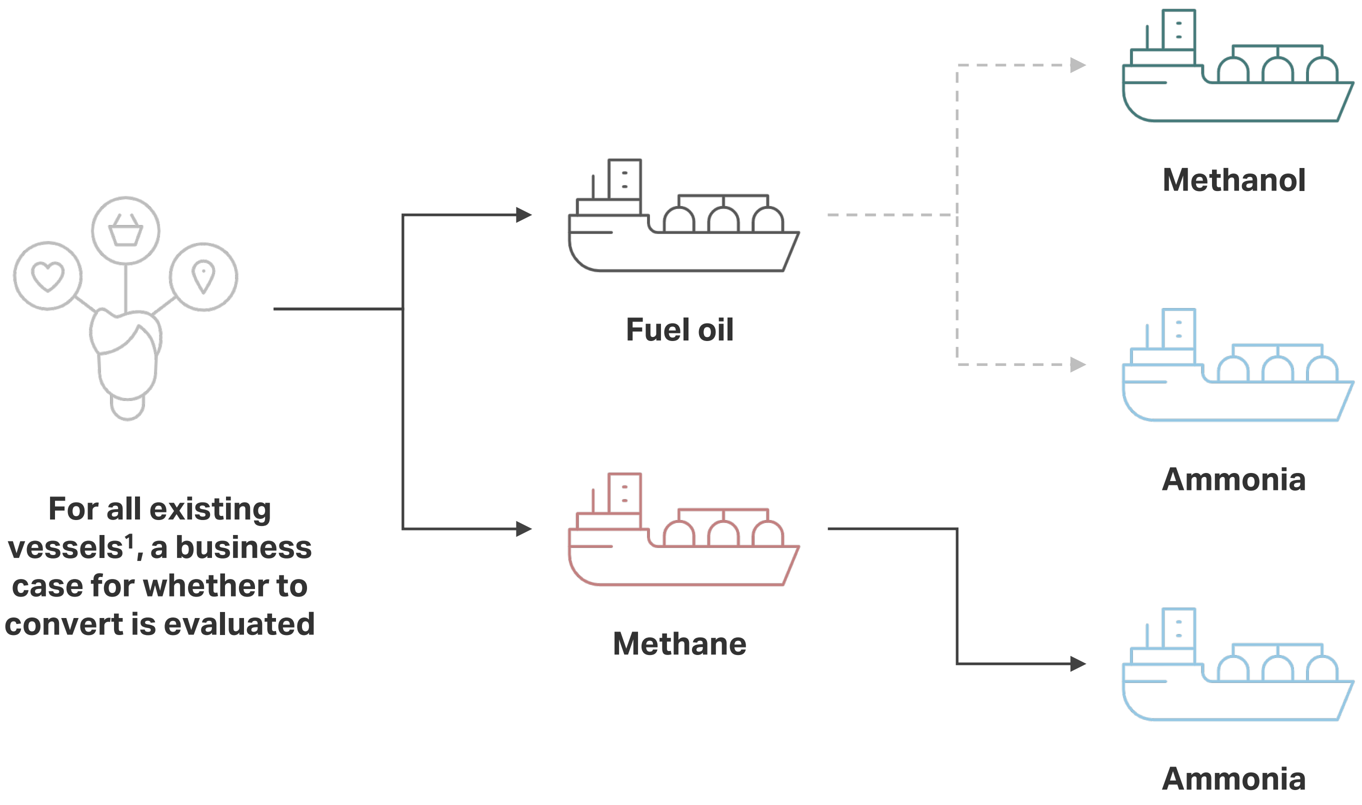
The likely uptake fraction is **impacted by the age** of the vessel. A technology with a 5-year payback period is more attractive for a new vessel than for a vessel that is 15 years old.

Retrofits follow the **drydock cycle** and consequently are only evaluated periodically. Further, the uptake of a specific technology may be **limited by supply** of that technology if the demand is high.

Fuel conversions

Vessels in the existing fleet can be converted to different engine and fuel technologies

Example of a decision regarding fuel conversion of existing vessels



It is possible to retrofit existing vessels to operate on a different fuel, by changing engine, tanks, supply system, etc. This is known as a fuel conversion.

The decision process for whether to convert a vessel follows the same principles as for installing energy efficiency measures. The expected future fuel saving is compared to the cost of conversion and a business case is evaluated.

For fuel conversion, multiple options can be possible for a single representative vessel. However, only one fuel conversion can be performed per vessel, i.e., it is not possible to complete a half methanol/half ammonia conversion.

In the example shown, a vessel owner owns a fuel oil vessel and a methane vessel. The fuel oil vessel can be converted to either methanol or ammonia. The methane ship can only be converted to ammonia. The owner decides not to convert the fuel oil vessel but does convert the methane vessel.

1: Currently limited to bulk carriers, containers and tankers due to limited data.

The business case depends on the potential fuel saving for the remaining lifetime

Example of a cash-flow from a fuel conversion business case

The business case for conversion is calculated based on the potential fuel saving from converting, offset by the cost of converting.

The fuel saving is calculated as the difference between the expected future fuel expenses of the two vessel types for the remainder of their lifetime.

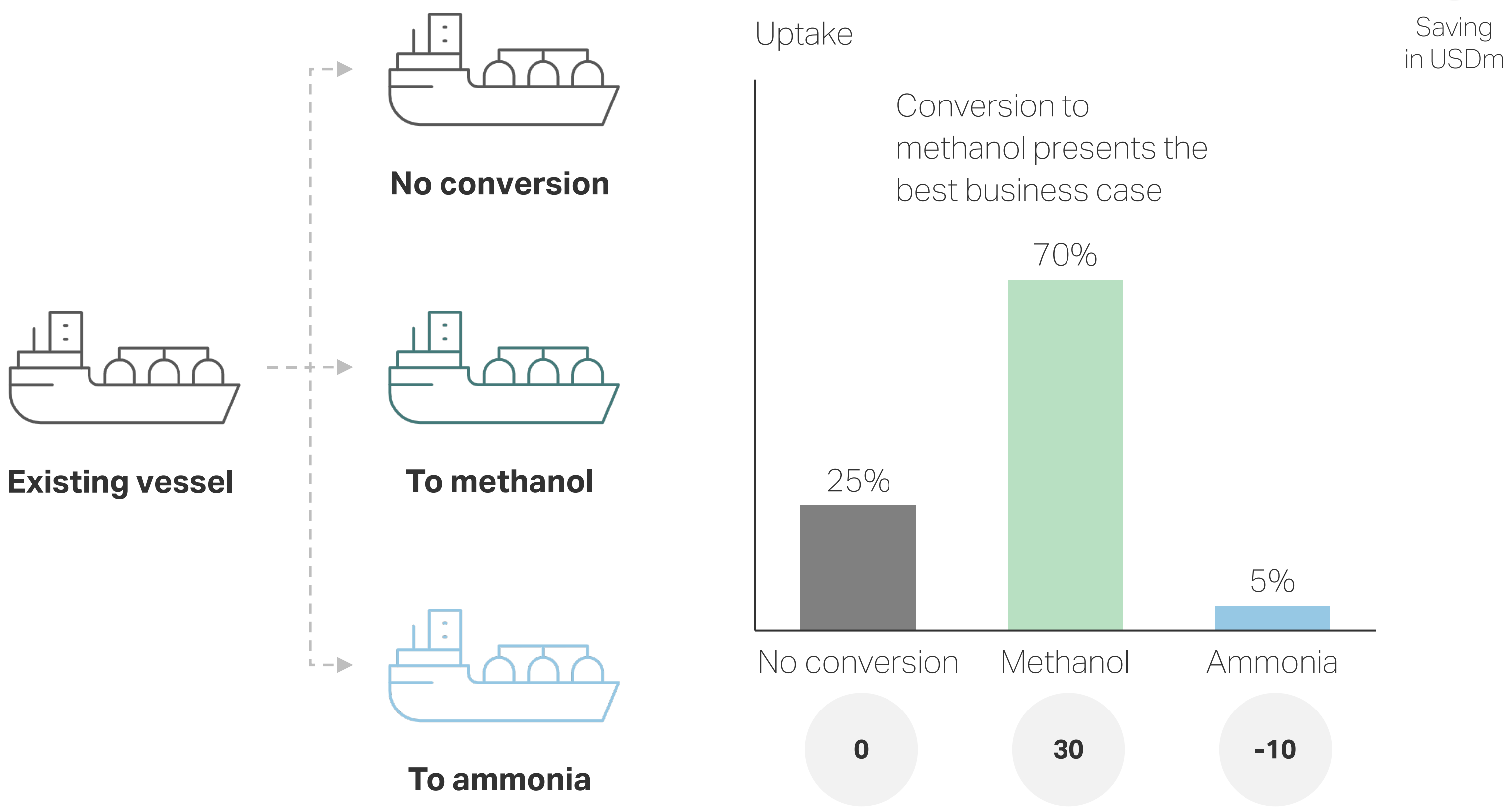
The cost of conversion is a user-supplied value which is considered a CapEx at the time of conversion.

The calculation also accounts for potential differences in OpEx between the original and new engine, supply system and tank technology.

Based on the saved expenses from fuel and the cost of conversion, the business case is calculated as a net present cost using the same discount rate as for newbuilds.

The number of conversions follows the same probabilistic approach as for newbuilds

Example distribution of fuel conversion options



Fuel conversions are based on the same decision logic as newbuilds. Namely, the uptake of each option is determined based on a discrete choice model using the business case as input.

A business case is positive if it results in lower future expenses and negative if it results in higher future expenses.

All evaluations are compared to a 'do-nothing case', namely the zero-cost option of not converting the vessel.

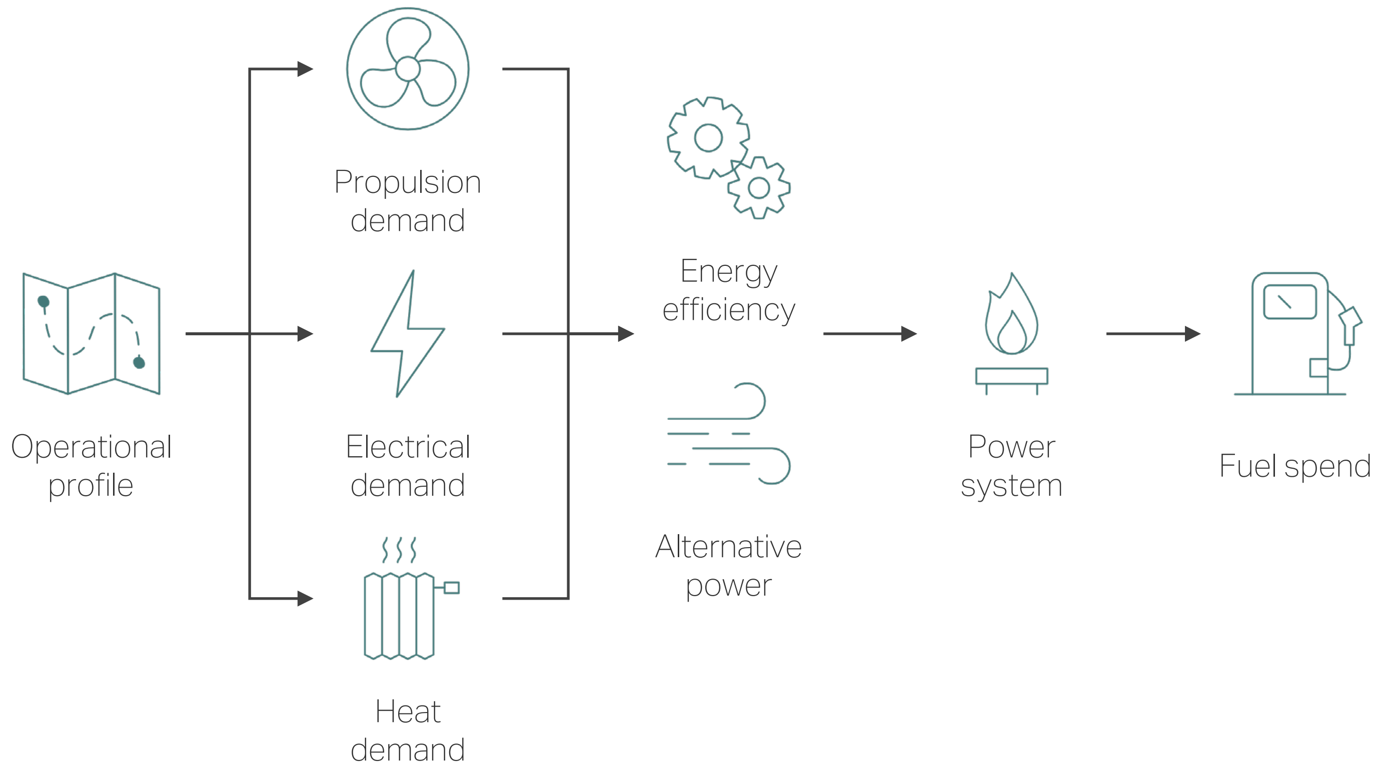
Even if there is a negative business case for a conversion, a small part of the fleet will still convert. This is consistent with newbuilds, where a portion of the decision-makers opt for more expensive options.

The uptake of fuel conversion may be further limited by technical constraints such as yard capacity.

Fuel selection criteria

Each vessel must bunker enough fuel to satisfy its required fuel spend

Flow diagram for how the required amount of fuel spend is derived



A vessel's operational profile details the **speed** and **distance** of each leg of its voyage, time spent at sea, time spent in port, etc.

This operational profile is translated into a raw **propulsion** demand necessary to move the vessel, a raw **electrical** demand for hotel load, refrigeration, etc., and a raw **heat** demand necessary to e.g., heat heavy fuel oil in the supply system or for general heating onboard.

The raw energy demand can be reduced by installing **energy efficiency** technology or **alternative power** sources[1].

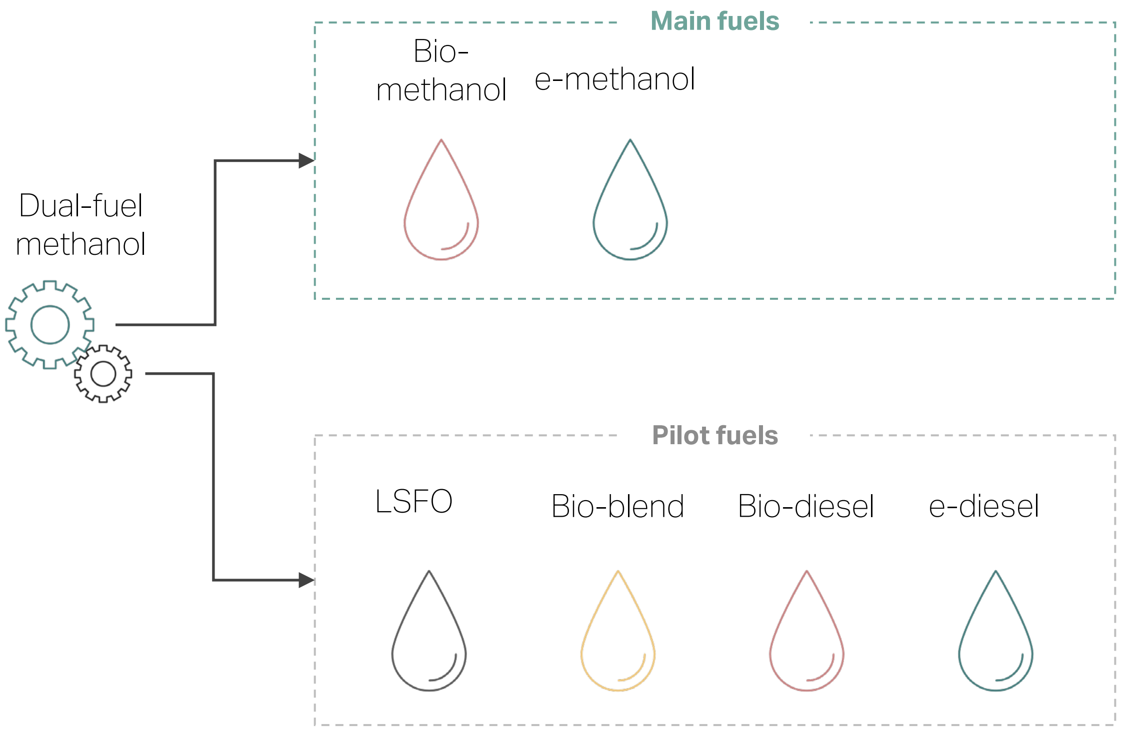
Different energy efficiency technologies and alternative power sources **impact** either the propulsion, electrical, or heat demand.

The remaining demand must be satisfied by the power system (engines, boilers, etc.) via the **fuel spend**.

1: E.g., wind-assisted propulsion. Energy efficiency is elaborated in a separate section.

The power system is tied to fuel type, not a specific fuel production pathway

Illustration of the fuels that can be used by a dual-fuel methanol engine



The power system is the unit that converts **fuel** into **energy**. An example of this could be a system composed of a main engine, an auxiliary engine, and a boiler.

NavigaTE differentiates between fuel types and fuels. A **fuel type** is essentially the **molecule**, e.g., methane or methanol.

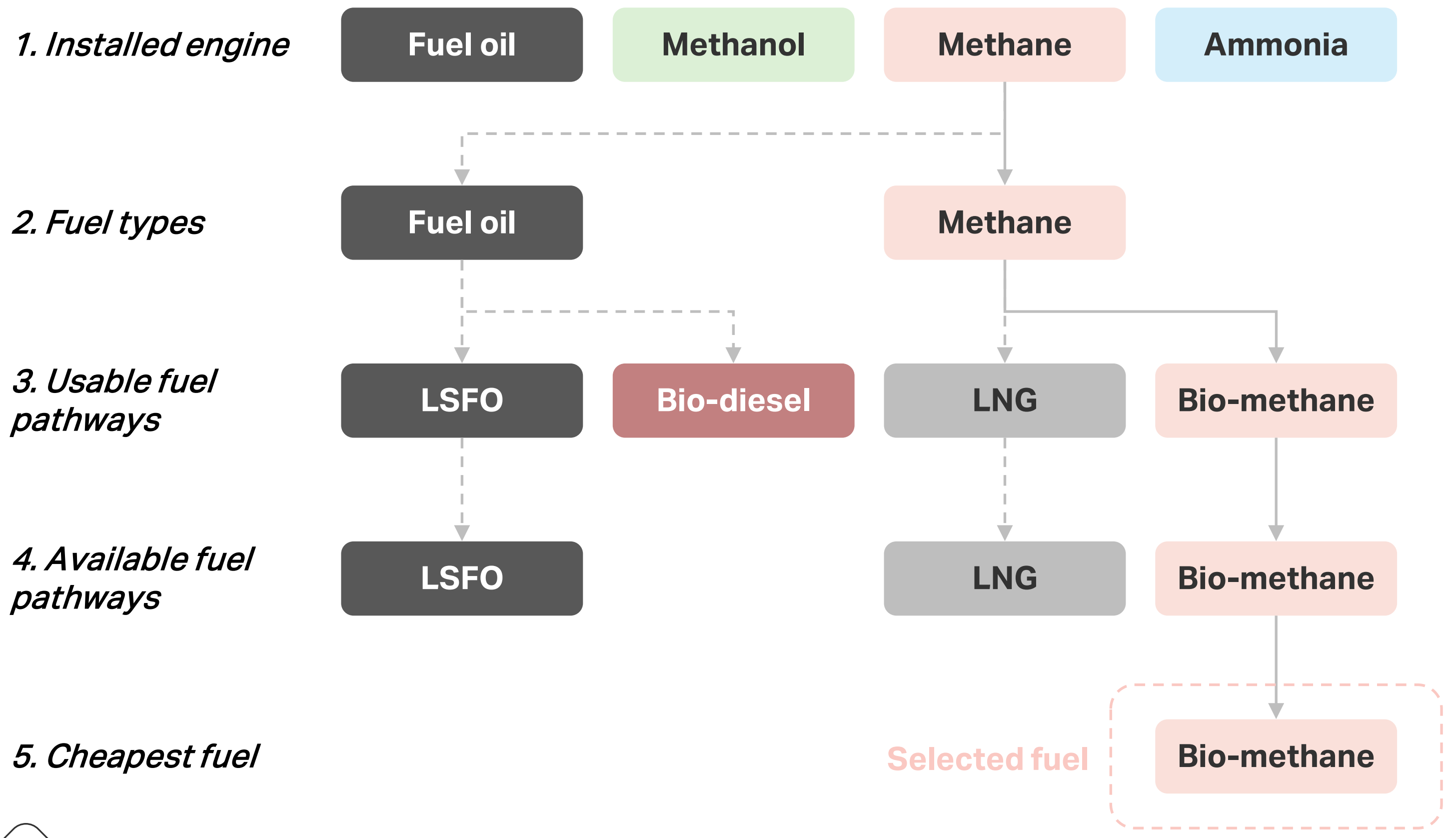
By contrast, a **fuel** distinguishes between different **production pathways**. An example of a fuel would be bio-methanol or e-methanol.

Fuels are differentiated from fuel types because different production pathways results in **different** costs and well-to-tank emissions. However, the engine technology onboard the vessels is **agnostic** to how the fuel was produced, and only cares what molecule it is.

Hence, a dual-fuel methanol engine can **operate on any fuel** which has the fuel type methanol. Further, dual-fuel engines may also operate on a wide range of pilot fuels.

The fuel selection criteria consider a range of constraints while minimizing cost

Simplified fuel selection example for a methane vessel



The **fuel options** for a vessel are defined based on the type of engine installed on the vessel. For mono-fuel engines there is a single option, and for dual-fuel there are two.

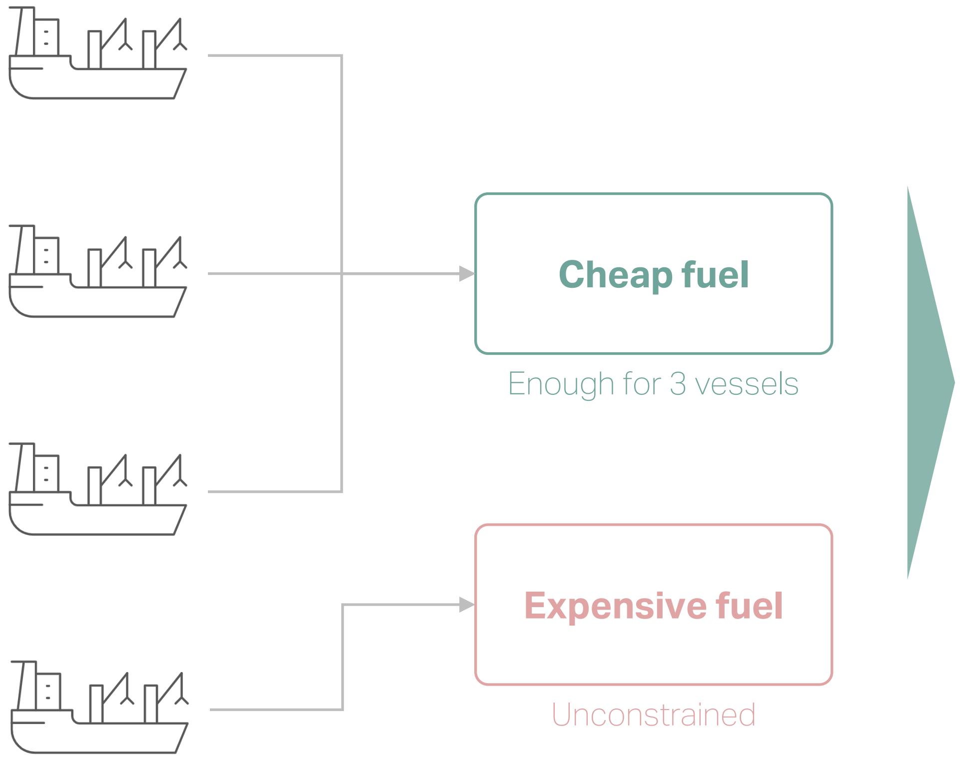
For any given fuel type, there are multiple **fuel pathways** that produce the specific molecule. For the fuel type 'methane', this includes e.g., liquified natural gas (LNG), bio-methane, and e-methane.

However, some of these fuel pathways may be **unavailable** for various reasons. They may be banned from a regulatory perspective, or they may be unavailable due to limited quantity.

Among the group of available fuels, the **cheapest** one is selected. Due to limited fuel availability, a single vessel may combine **multiple** fuels.

The fuel distribution is a result of the fuel selection algorithm

Example of fuel selection algorithm



Three ships will use the cheap fuel, but the last ship must use the expensive fuel.

The total fuel distribution will thus be 75% cheap fuel and 25% expensive fuel.

The fuel selection algorithm solves the total fuel consumption for all vessels simultaneously. Unlike the vessel selection, the bunkering selection is assumed to be cost-optimal (binary).

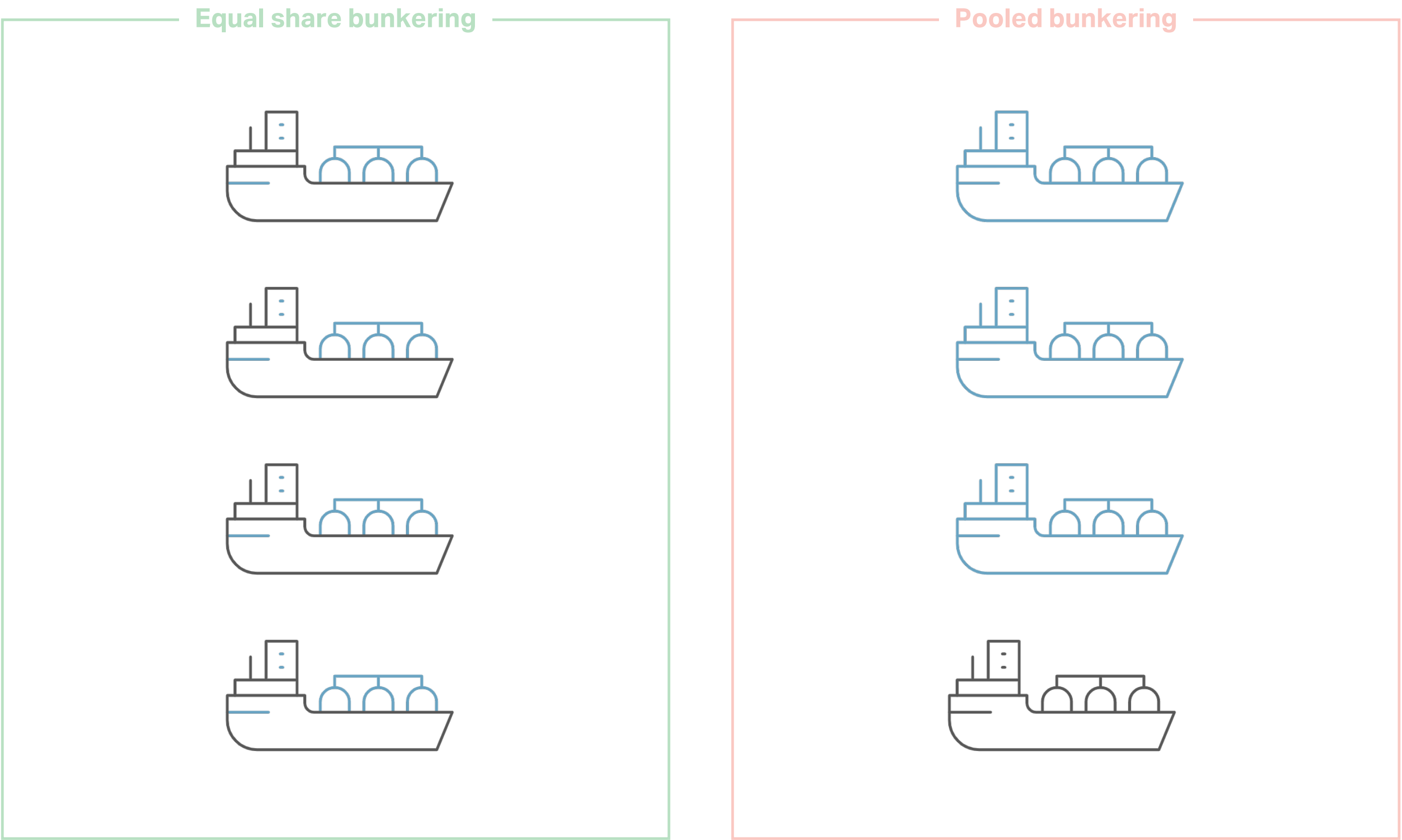
The bunkering selection in the model uses an optimization methodology known as linear programming. The total bunkering expenses are minimized subject to a set of constraints.

In simple terms, the algorithm selects the cheapest fuel that a vessel can use until that fuel is no longer available. Then the algorithm selects the second-cheapest fuel, and so on, until the total fleet demand for fuels is satisfied.

In practice, the algorithm is more complicated, as certain technical and behavioral limitations must be satisfied as well. Some of these limitations are explained in the following pages.

The availability of certain fuels may be limited, impacting the fuel selection

The logic of shared fuel (when limited) for a representative vessel type



Fuel availability constraints can be applied to individual fuels, e.g., bio-methanol or blue ammonia.

These constraints act as hard barriers, meaning that if more vessels request a specific fuel than is available, some vessels will have to use a different one.

This can be thought of in two different ways:

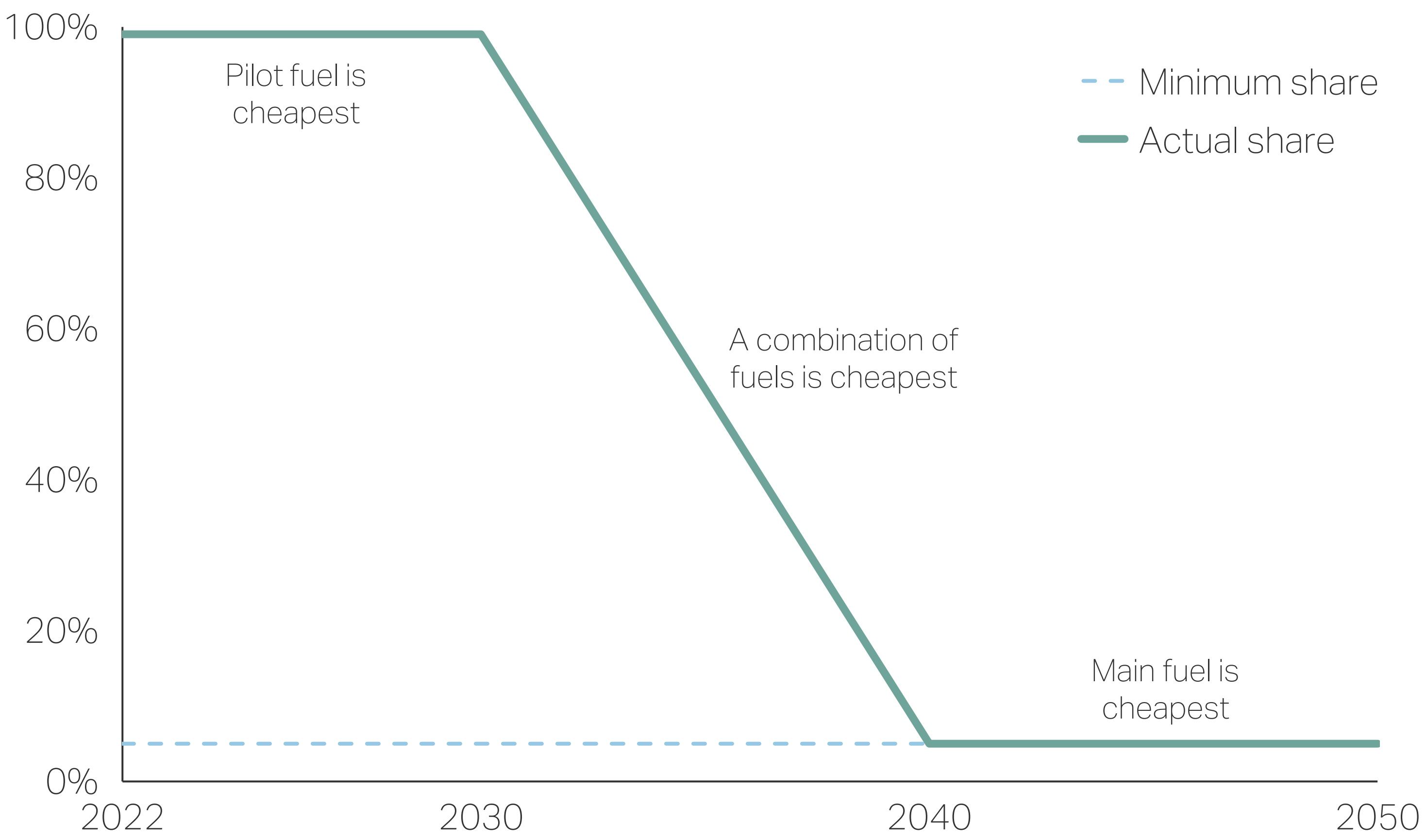
- The first option is that the vessels satisfy an equal share of their energy demand with the requested fuel. The remaining energy demand is satisfied by another fuel.
- Alternatively, a fraction of the pool of vessels satisfy their full energy demand with the requested fuel, and the remaining vessels use a different fuel.

Mathematically, the outcome is the same. However, for logical consistency with regulations, the first logic is assumed.

See the "Fuel availability" section for how the availability constraints are derived.

Dual-fuel engines can operate variably between main fuels and pilot fuels

Example of a vessel's pilot fuel share changing over time



For dual-fuel engines, a minimum amount of pilot fuel is required in the combustion process.

From an engine perspective, the share of pilot fuel can vary, since the engine can function on anywhere between the minimum amount of pilot fuel and the maximum amount of pilot fuel (100%).

A vessel's ability to operate on a high share of pilot fuel is defined by not only the engine, but also the size of the pilot fuel tanks and the bunker frequency.

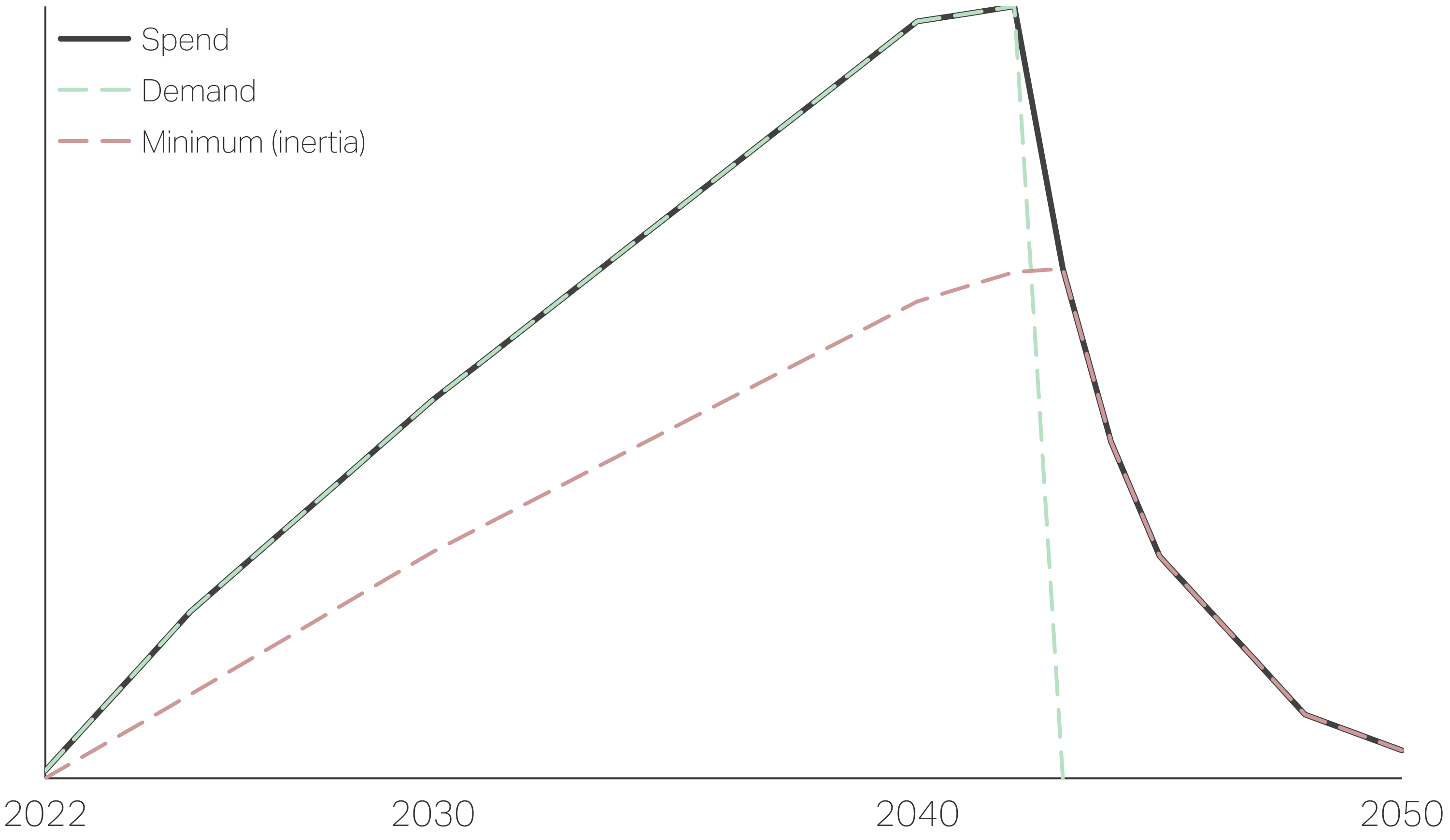
The choice to operate fully on pilot fuel or fully on main fuel depends on which is cheapest if they are both available.

For some cases – for example, if one of the fuels is in limited supply – it might be best to use an intermediate share of pilot fuel.

The share of pilot fuel used is automatically determined by the algorithm based on what is cost-optimal yet feasible.

The fuel selection is also influenced by historical bunker decisions with lasting effects

Fuel spend, fuel demand, and minimum possible spend due to inertia



In NavigaTE, the use of fuels in **previous years** has a lasting effect on the fuel distribution. This concept is called **fuel inertia**.

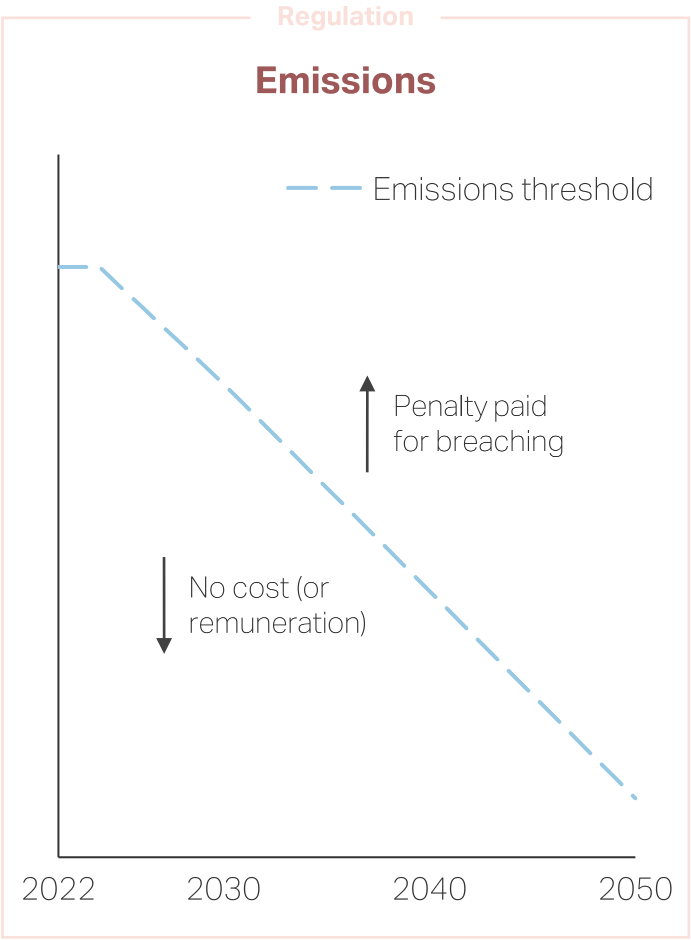
There are **two main rationales** for the fuel inertia in the model. The first is **resistance to change**. Namely, that organizations are risk-averse and prefer to do what they are used to.

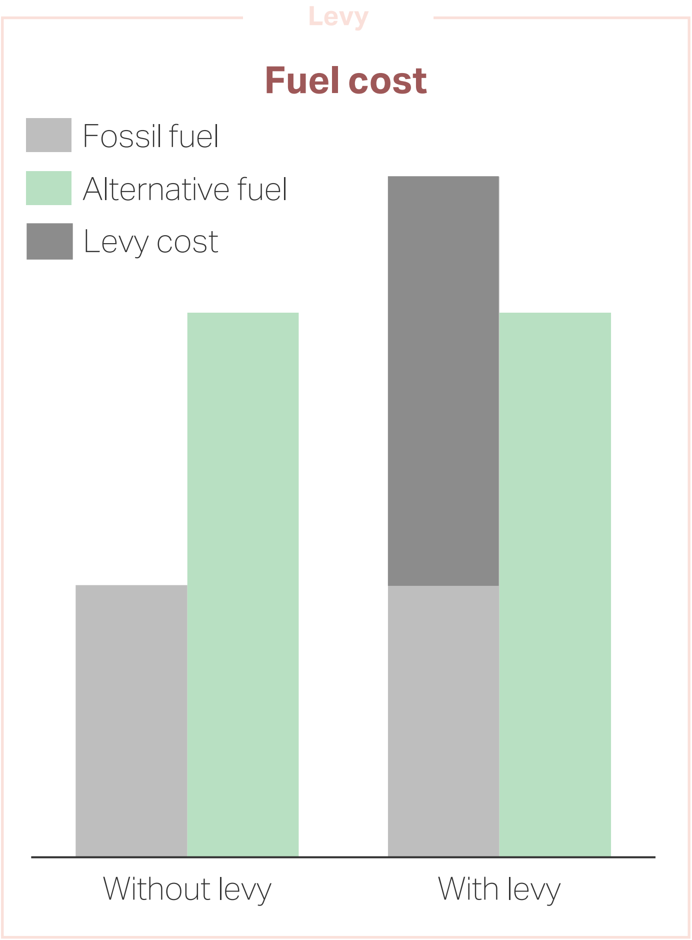
The second is **fuel offtake agreements**. Especially for alternative fuels, fuel producers will sign long-term offtake agreements to hedge their investment.

Modeling-wise, this means that the bunkered amount of a given fuel **may only decrease by a fraction** relative to the previous year.

This means that if **demand** for a specific fuel **disappears**, then there is a **lower bound** on how quickly the fuel spend can ramp down.

Policy may impact bunker decisions either through regulations, levies, or bans





NavigaTE allows for three kinds of policy instruments: **regulations**, **levies**, and **banning** vessel types or fuels.

A **regulation** is modelled as a **cap** on an emissions-related measure[1] with an associated **penalty** if a **threshold** is breached. It may also be implemented as an emissions trading scheme (ETS) with remuneration below the threshold.

A **levy** is tax **paid at the time of bunkering**. It is calculated as an **additional cost** of the fuel which is proportional to the emissions factor. It may also be used as a subsidy that subtracts from the cost.

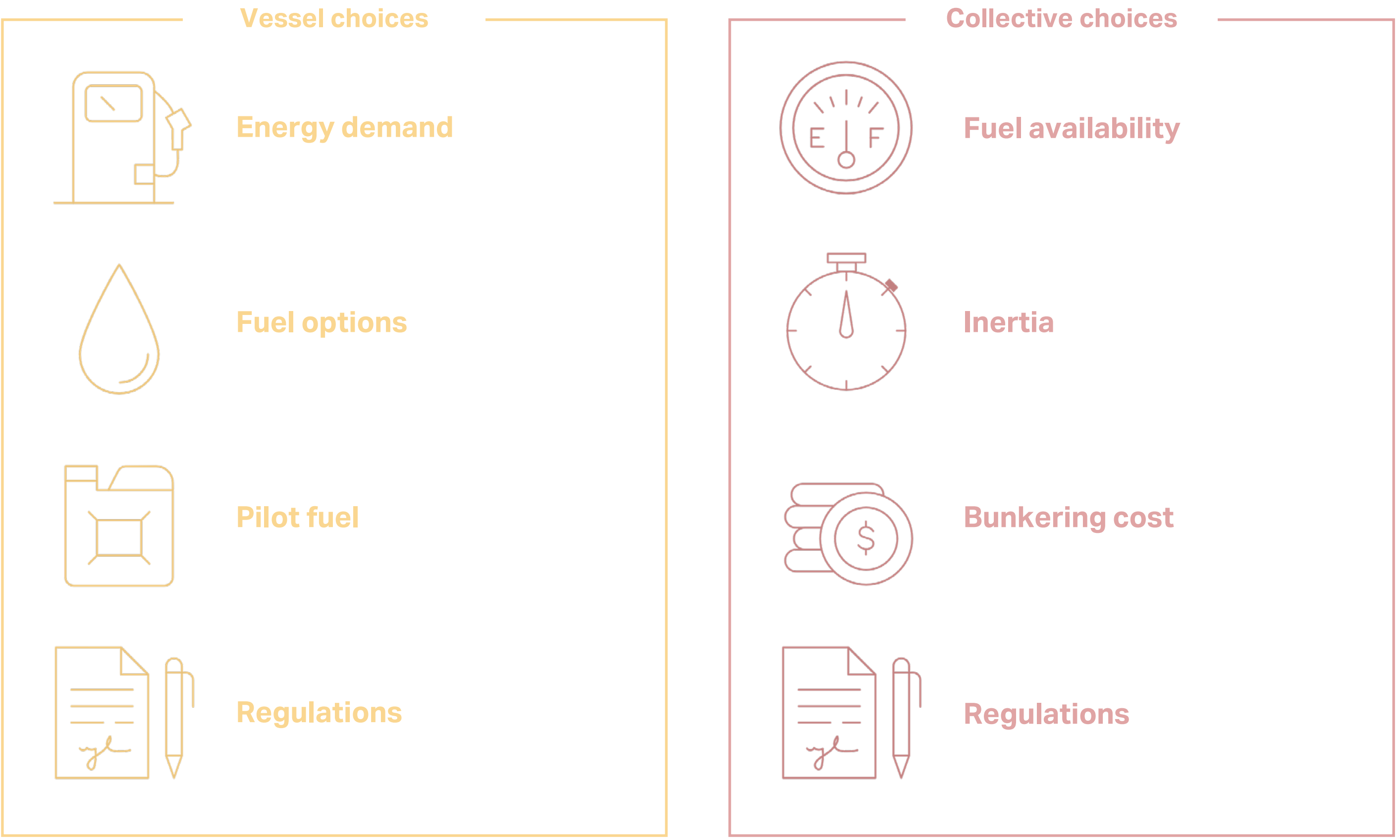
A **ban** on either **vessel types** or **fuels** disallows the use of either going forward. For fuels, this means they can no **longer be bunkered**.

For vessel types, a ban means they cannot be **introduced as newbuilds**. The vessels already in the fleet are not affected.

1: This includes absolute emissions, emissions intensity, carbon intensity indicator (CII), and more.

The fuel selection depends on both individual vessel choices and collective choices

Example of governed by individual vessels and collectively

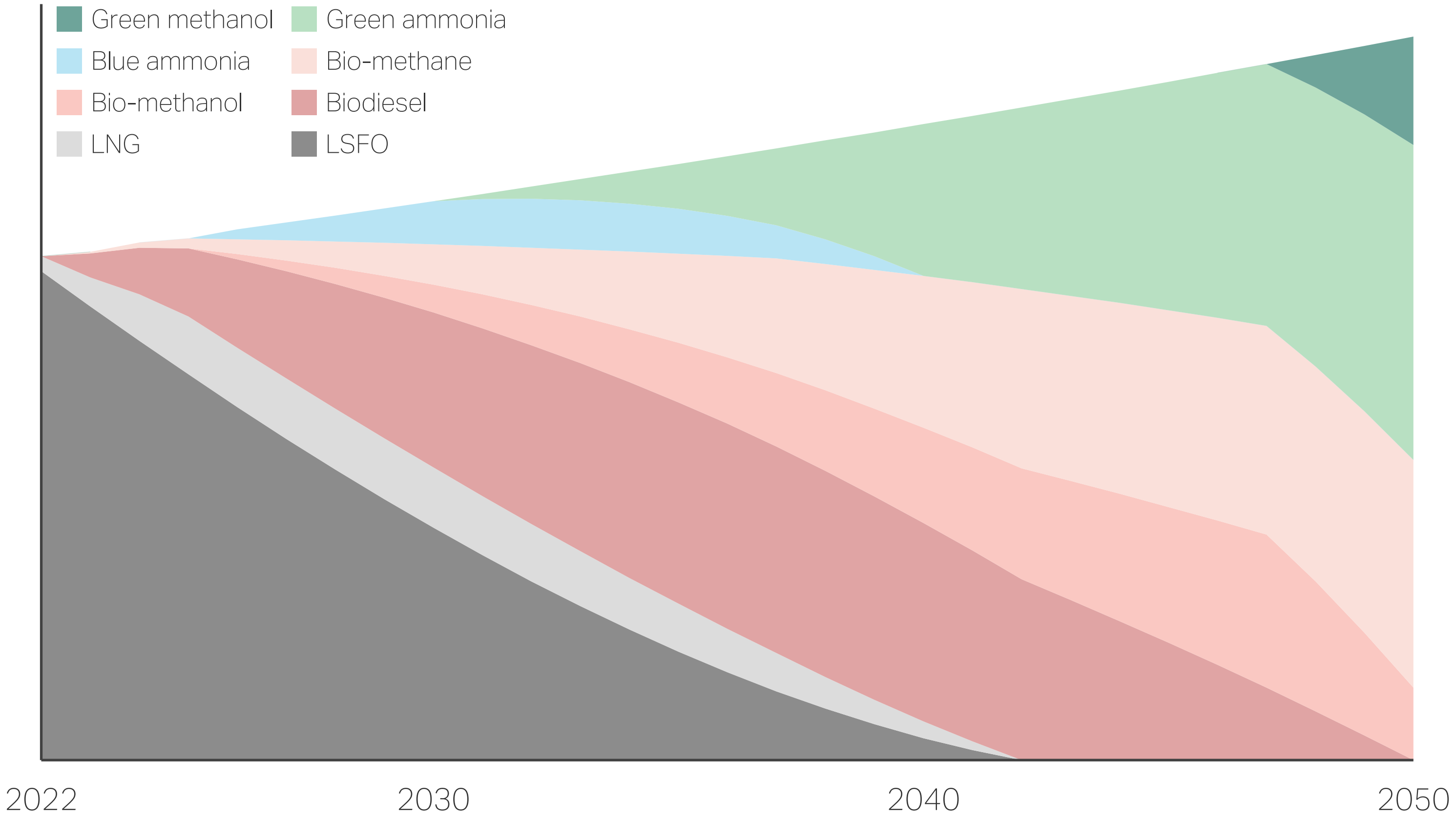


Two types of requirements guide the fuel selection: Individual vessel requirements and collective requirements. Examples of both types are:

- Technical requirements, such as meeting the energy demand, possible fuel options based on engine technology, and the share of pilot fuel used, are specific to each individual vessel.
- The fuel availability (maximum bunkering) and inertia (minimum bunkering) for each fuel must be adhered to by the collection of vessels.
- The fuel selection algorithm strives to minimize the cost of bunkering for the collection of vessels, not for each individual vessel.
- Regulations can be applied at both an individual vessel level and a collective level.

The fuel distribution is the result of the decisions of the fuel selection algorithm in each year

Example of a fuel distribution



As the simulation progresses through time, a bunkering decision for each individual vessel is made for a **given year** (also impacted by the collective requirements).

As the fleet composition, fuel costs, fuel availability, and other factors **change over time**, so does the fuel selection.

The bunkering decision is cost-optimal in each **individual** year of the simulation, but not necessarily **across** all years.

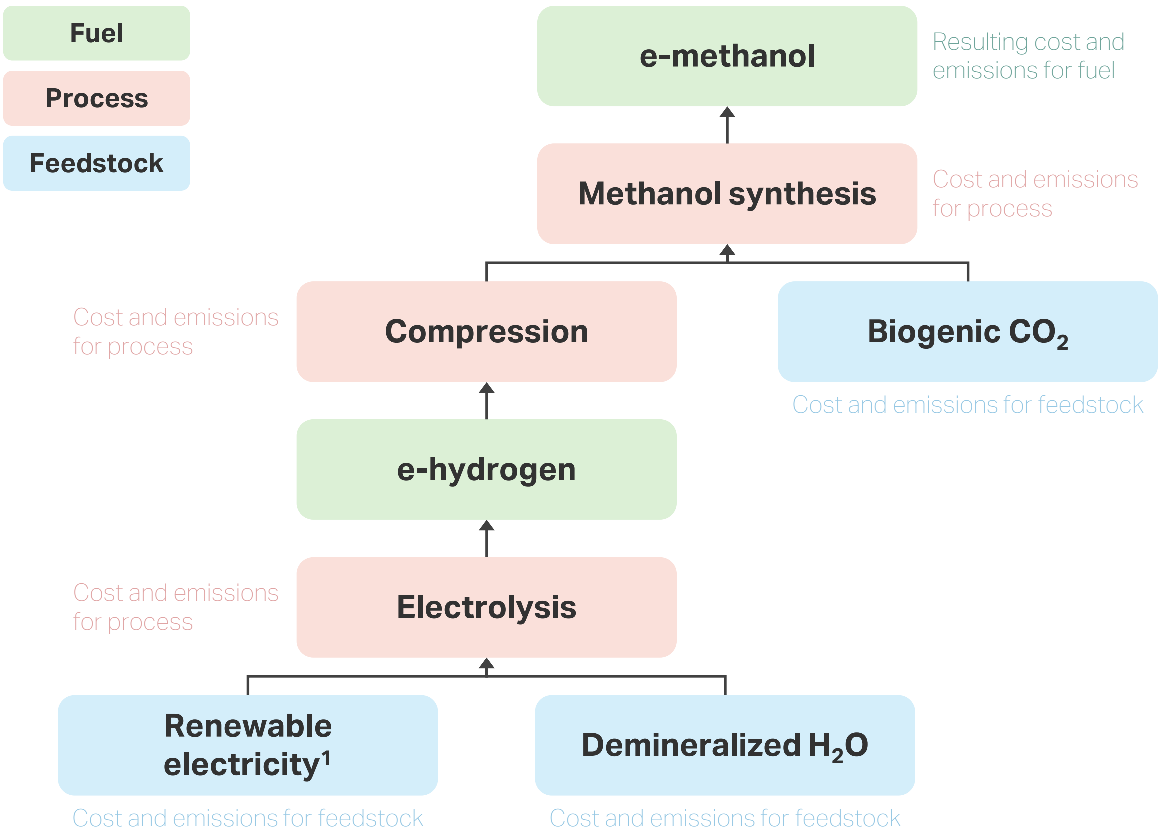
This contrasts with the vessel selection algorithm, which uses a probabilistic approach instead of a **cost optimal** approach. A cost-optimal approach is used for the bunkering due to the **short investment horizon**.

As an **analogy**, people are likely to behave in cost-optimal way when deciding where to buy gasoline for their car. On the other hand, when selecting between a petrol car and an electric car of similar costs, the decision might be impacted by other factors such as convenience, flexibility, and resale value.

Fuel cost and emissions

The cost of fuels are modelled bottom-up considering the cost of individual components

Bottom-up calculation for production of a fuel (e-methanol example)



The cost of fuels and the well-to-tank emissions are modelled using a bottom-up approach. This approach comprises three main elements: feedstock, processes and fuels.

Feedstock refers to components in the chemical process of fuel production which are assumed to be available in the market, e.g., water or biogenic CO_2. A feedstock may have a cost and emissions associated with it.

Processes are the chemical processes of producing a fuel. These have an associated CapEx and OpEx for the plant, as well as an energy demand and associated emissions.

Fuels are the outcome of a process. They may be intermediate fuels used as feedstock in other processes or bunker fuels[2]. Their cost and emissions are the aggregate of those from the feedstock and processes used in producing them.

1: Renewable electricity is currently considered a feedstock based on an assumption of mega-plants with stand-alone electricity generation.
2: A bunker fuel is a fuel that can be used onboard a vessel.

Some parameters are modelled across multiple regions while others are global

Examples of current split between regional and global parameters

Regional parameters

- Renewable electricity cost
- Biomass cost
- Fossil fuel cost
- Fuel availability

Global parameters

- Production facility costs
- Process efficiencies
- Emissions
- Finance[1]

For all fuel calculations, a regional split can be considered.

However, parameters can also be used across some or all regions by e.g., having global parameters.

In the current version of NavigaTE (version 2.0), examples of both can be found.

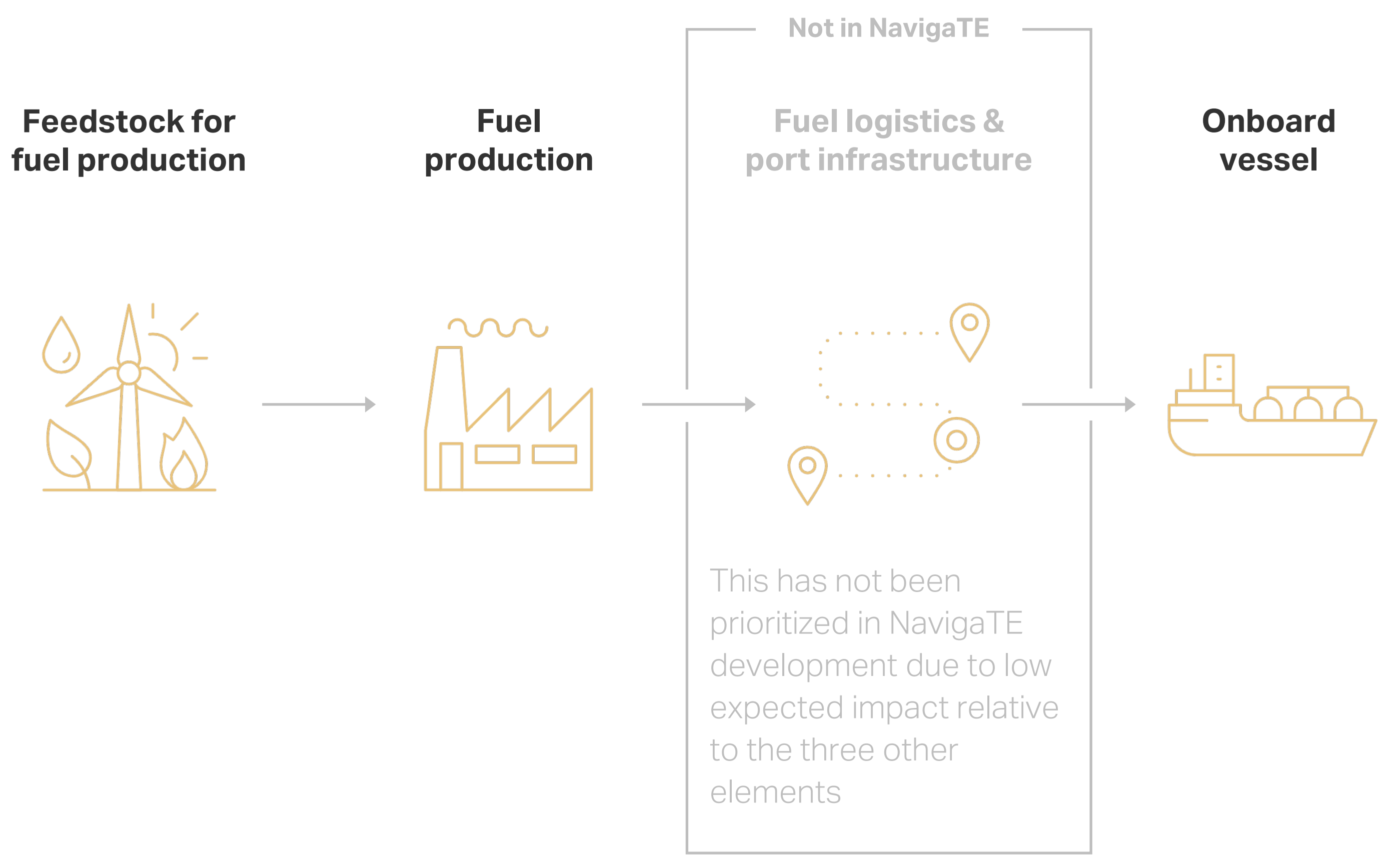
Regional parameters include feedstock costs (e.g., renewable electricity cost and biomass cost), fossil fuel costs, fuel availability assumptions and more.

Global parameters include parameters related to fuel production facilities (costs and efficiencies), emissions factors, finance, and more.

1: Finance includes e.g., cost of capital and lifetime of plants

Fuel logistics and port infrastructure are not considered in NavigaTE for now

Maritime value chain – and the elements included in NavigaTE



The maritime value chain related to emissions can be split into four key categories.

Feedstock for fuel production, fuel production, and fuel use onboard vessels are the three most important parameters to describe.

The fourth category – fuel logistics & port infrastructure – is also a key element to understand.

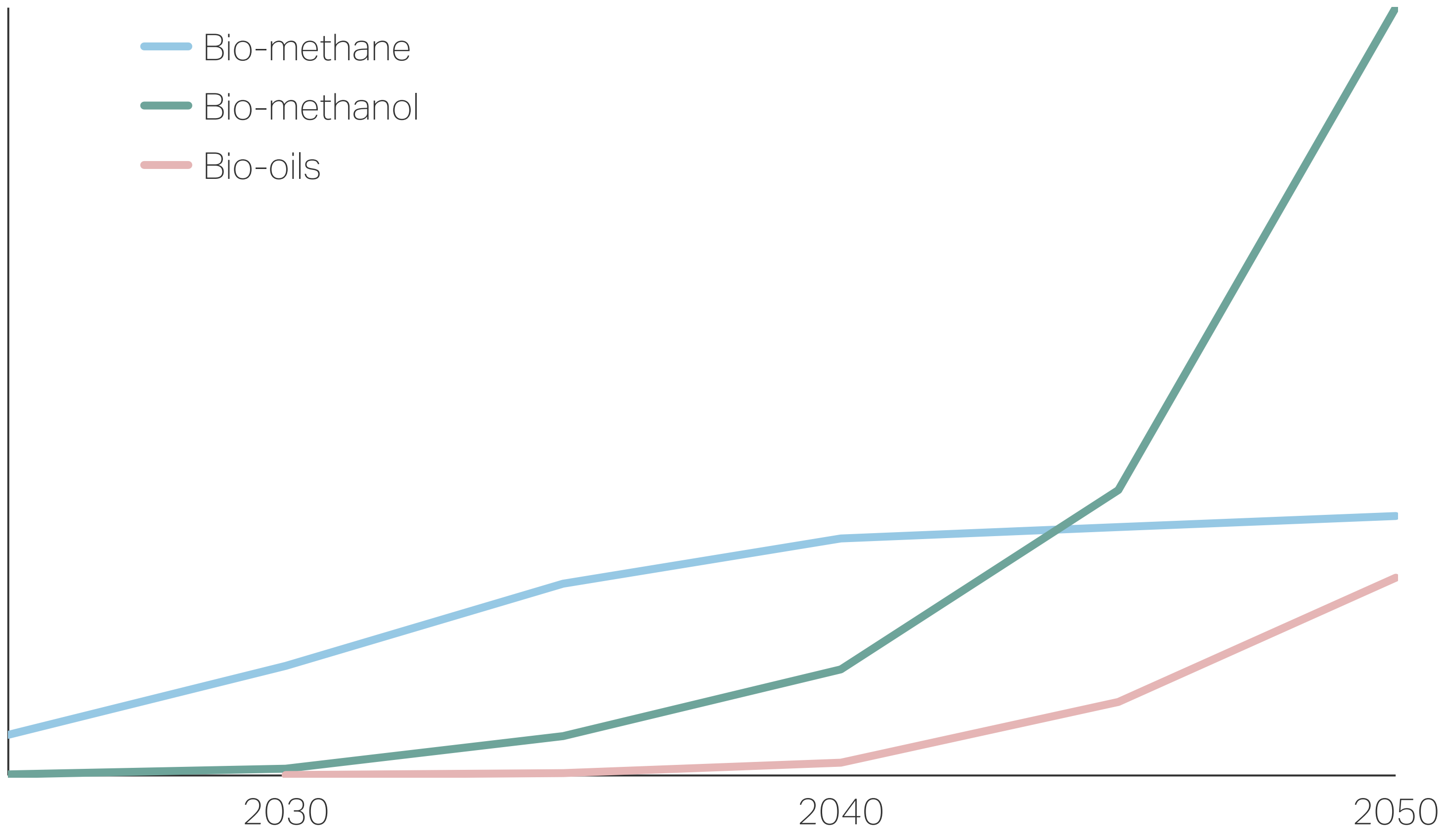
However, due to prioritization, fuel logistics and port infrastructure has not been modelled in detail the current version of NavigaTE (version 2.0). Bunkering of fuels is assumed to be included in the fuel costs.

This prioritization is based on rough calculations on the expected impact of decision-making in each category for the global fleet transition.

Fuel availability

Availability of fuels is included in NavigaTE and can be implemented in multiple ways

Example of user-provided fuel availability constraints (EJ/year)



The availability of any given fuel is determined by the fuel production capacity. This may further be limited by the market share of that production capacity that is available to shipping.

Fuel availability constraints act as a limit on the amount of that fuel that can be bunkered. If the limit is reached, the algorithm must select a different fuel for the remainder. The constraints thus will not enforce a specific fuel mix but instead limit the availability of some fuels.

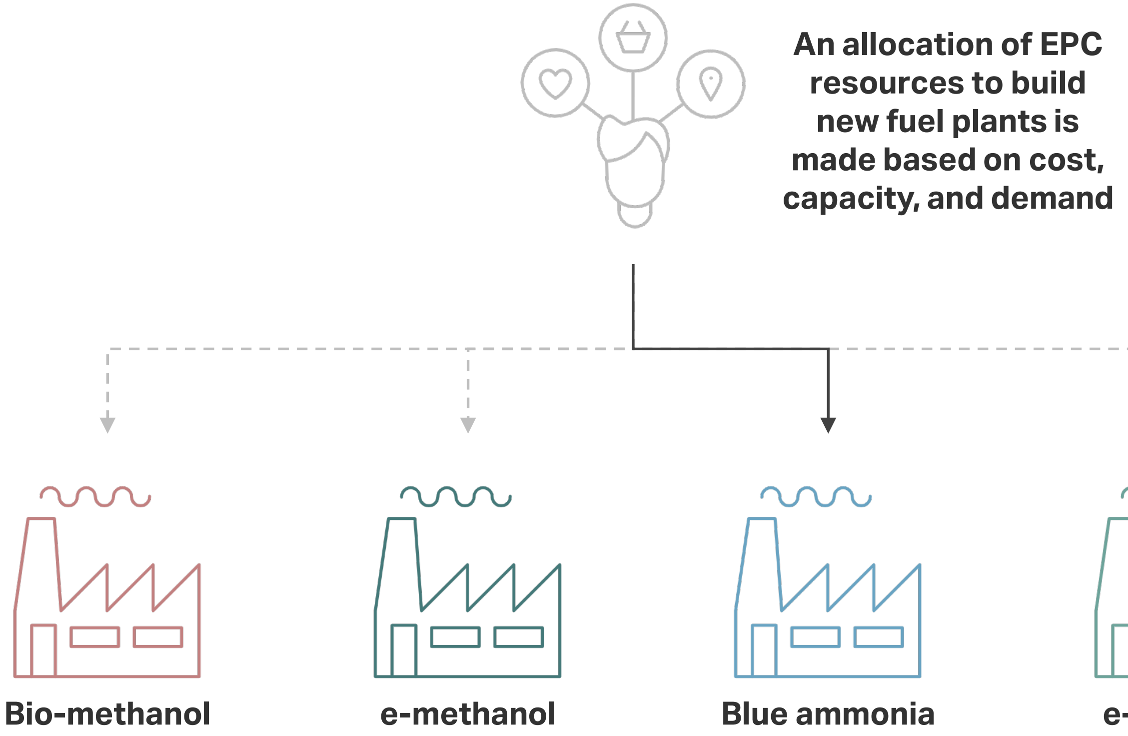
Fuel availability constraints can either be provided as a user-supplied forecast or used as a dynamic, model-updated constraint.

Static constraints are user-provided forecasts of the fuel availability in any given year. The availability can change over time, as shown in the example.

Dynamic model-updated constraints are explained on the following page.

Dynamic constraints ramp up fuel production based on plant capacity, cost and demand

Decision regarding fuel production ramp-up



Model-updated constraints are **dynamically calculated constraints** that accounts for multiple elements:

- Engineering, procurement and construction (EPC)
- Plant capacity
- Fuel cost
- Current supply and demand

A single EPC contractor can only build a **limited number of plants**. The plants also have **different capacities** and produce fuels with **different costs**. For these reasons, it is important to **prioritize** the EPC resources.

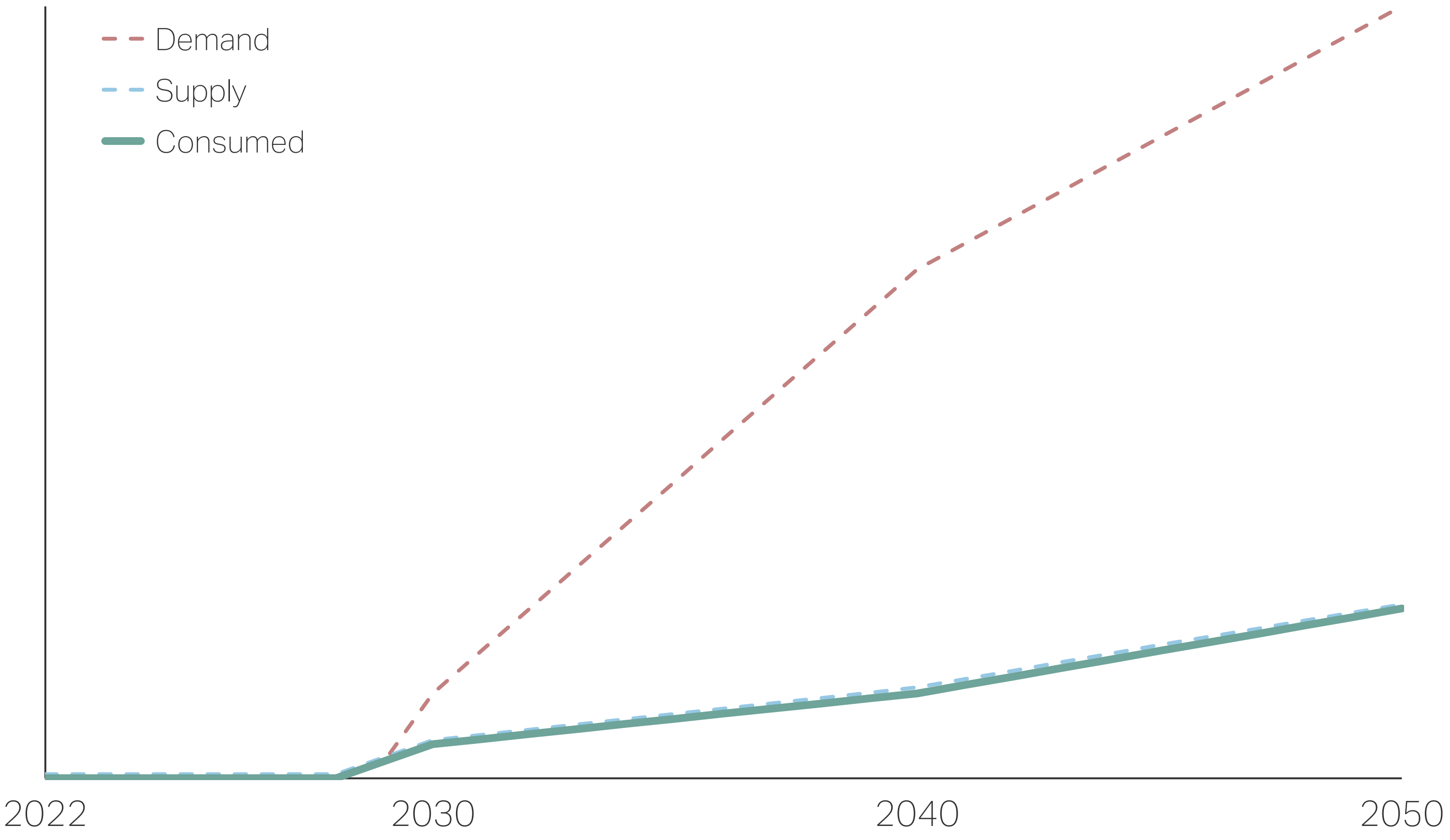
The **cheaper** the fuel is and the **larger** the plant is, the **more** EPC contractors are allocated. Further, the NavigaTE model accounts for the **supply-demand gap** and if there is a **recent demand** for the fuel.

The allocation is made using a **discrete choice model**, similar to how the newbuild vessel types are chosen.

Identifying bottlenecks

The consumption of a fuel can be constrained by the supply of that fuel

Demand, supply, and consumption for a single fuel pathway (supply-constrained)



The consumption of a given fuel can be constrained in multiple ways. This example considers the first type of constraint: supply constraint.

The fuel is supply-constrained if there are more vessels demanding the fuel than there is fuel production capacity available.

This could be a scenario where 100 vessels would prefer to use a specific fuel but there is only enough of that fuel for 10 vessels.

In the example to the left, a sudden increase in demand (red line) is seen around 2030.

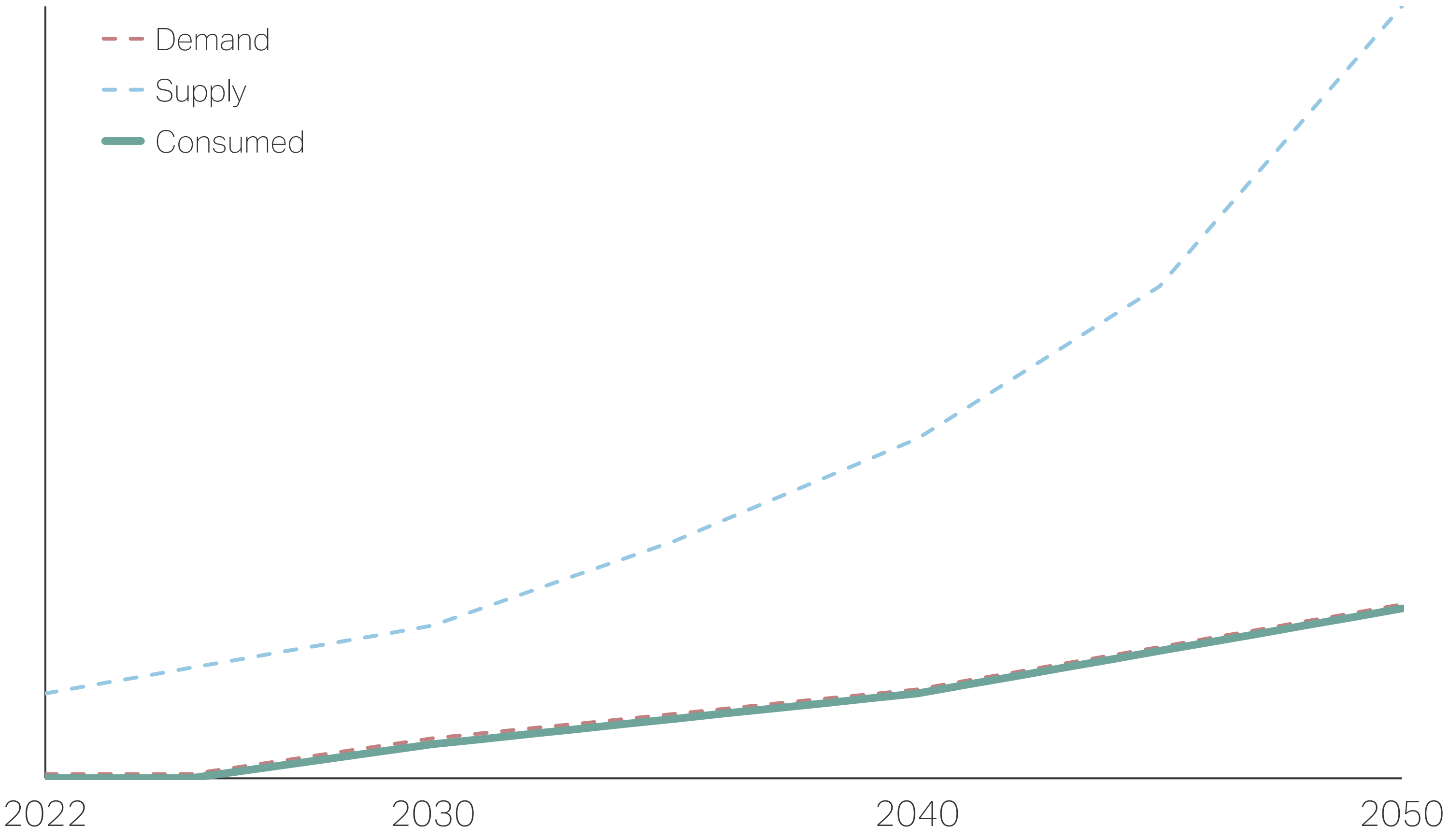
This means the model will consume all available fuel (green line) after the demand is seen.

The supply of the fuel (blue line) limits the consumption of the fuel to less than what is demanded.

Some of the vessels will thus have to use a different fuel from what is preferred.

On the other hand, fuel consumption can also be constrained by the demand of the fuel

Demand, supply, and consumption for a single fuel pathway (demand-constrained)



Another constraint on fuel consumption is demand constraint.

The fuel is demand-constrained if there are fewer vessels demanding the fuel than there is fuel production capacity available.

This could be a scenario where 10 vessels would prefer using a specific fuel but there is enough fuel for 100 vessels.

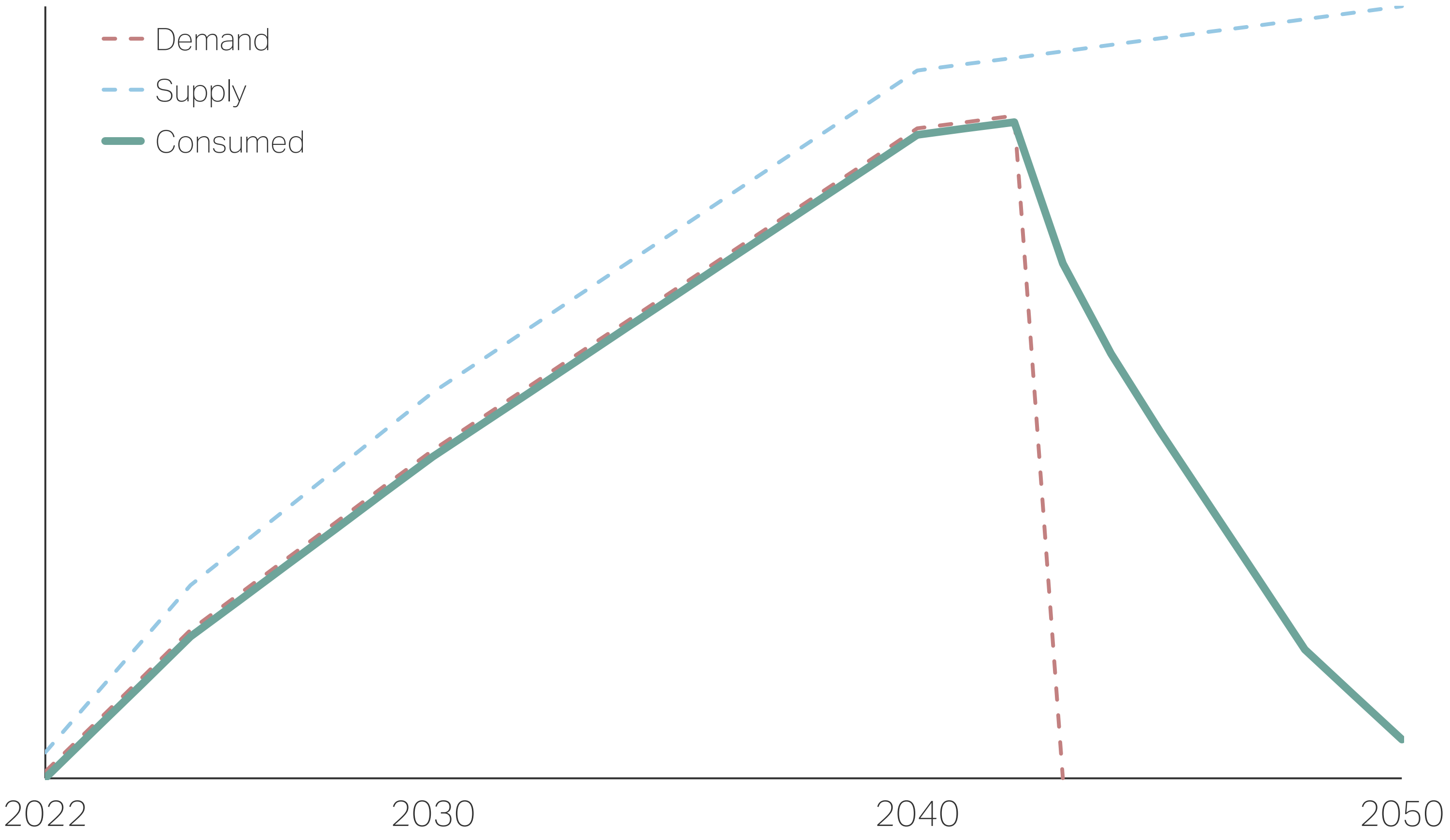
In the example to the left, the demand (red line) is always significantly lower than the supply (blue line).

This means the model will consume the fuel for all vessels demanding it (green line) but with a significant excess supply available.

All vessels can use the fuel – and potentially even more vessels would be able to if the demand increased.

The last possible constraint is an inertia constraint, avoiding discrete changes

Demand, supply, and consumption for a single fuel pathway (inertia-constrained)



The last type of constraint on fuel consumption is an inertia constraint.

An inertia constraint is added to the model to avoid discrete changes in fuel consumption from one year to the next.

The fuel is inertia-constrained if a sudden drop in demand for a specific fuel is seen.

This could be a scenario where two fuels cross in the fuel cost curves, hence replacing the demand for one fuel completely by demand for another fuel.[1]

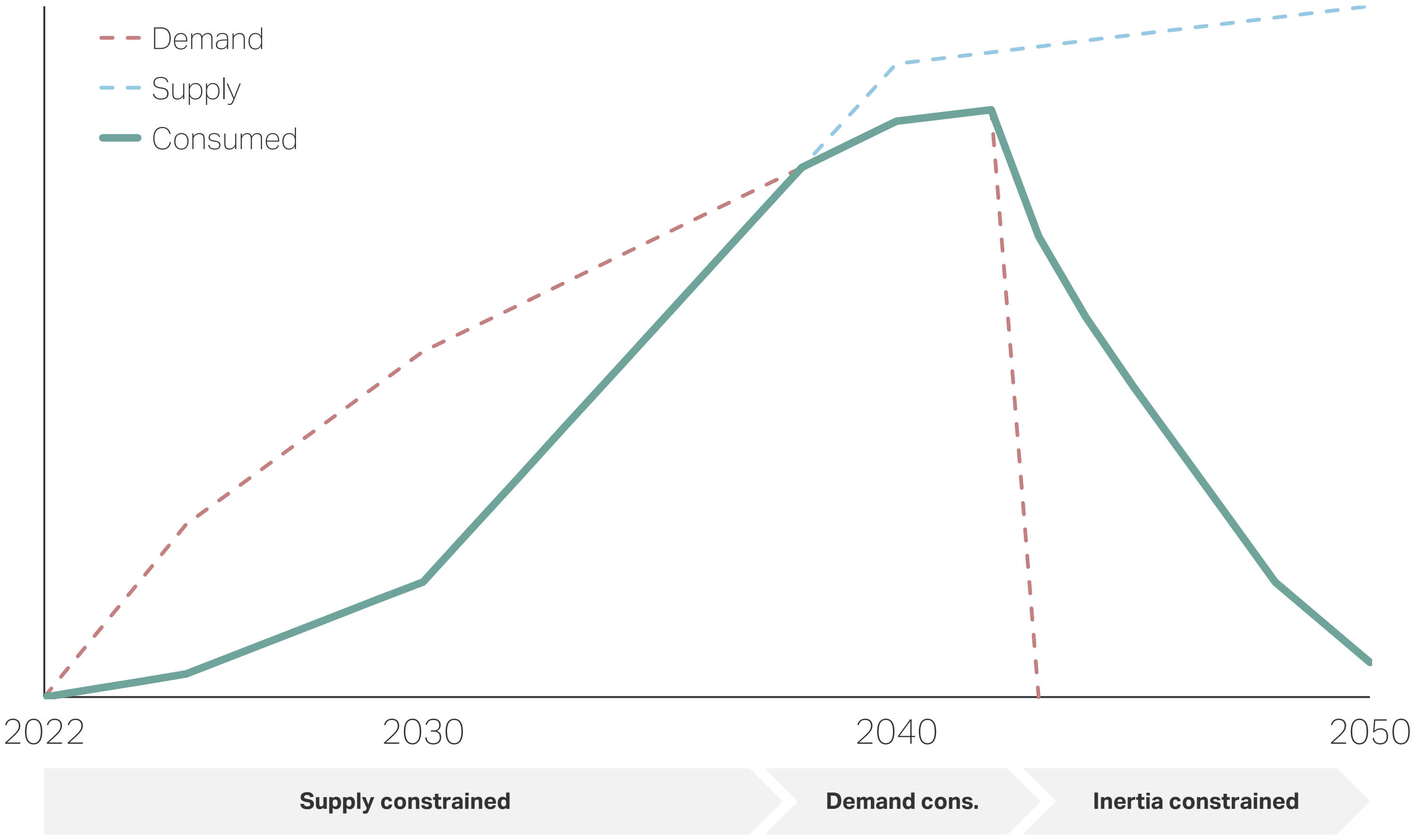
In the example to the left, the demand (red line) is always lower than the supply (blue line). However, unlike the demand-constrained scenario, the fuel consumed (green line) does not follow either of the two other lines in the final years.

This is because the inertia constraint does not allow a sudden drop in fuel consumption below a certain threshold, even if demand drops dramatically.

1: An example of this could be blue ammonia vs e-ammonia, where at some point the cost curves can cross.

In a simulation, it is possible to see a combination of all three types of constraints

Demand, supply, and consumption for a single fuel pathway (all constraints)



In most simulations using NavigaTE, a **combination** of all three types of constraints are guiding the fuel consumption at different times.

In the example on the left, the consumption is initially **supply**-constrained. This could be due to lack of ramp-up in fuel production capacity.

It is then followed by a period where the fuel consumption is **demand**-constrained, as there are not enough vessels to use all the fuel supply.

The last years are **inertia**-constrained, where the supply is high, but the demand drops to zero.

Due to the inertia constraint, the decrease in fuel consumption for this fuel in the final years is **gradual** instead of discrete.


End of
presentation