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Documentation and assumptions for NavigaTE 1.0

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for Zero Carbon Shipping

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Taking a Well-to-Wake perspective increases our understanding of value chain emissions.

The NavigaTE model utilizes a Well-to-Wake approach to assess the climate impacts of fuel pathways.

Well-to-Wake (WTW) evaluations form the basis for assessing climate impacts associated with greenhouse gases emissions in the maritime industry. The NavigaTE model, aims to harness the insights from such evaluations and provide an end-to-end analysis of marine fuel value chains.

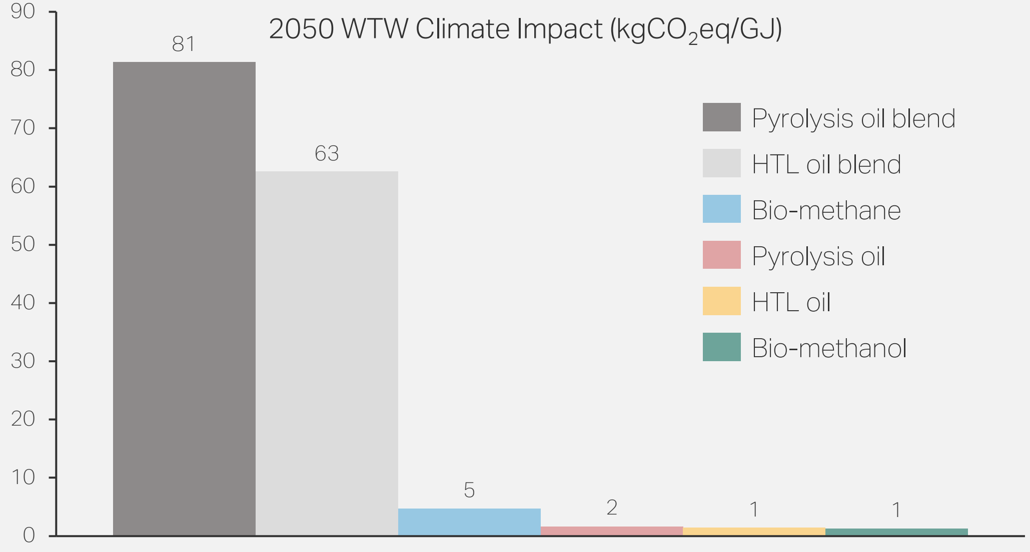
NavigaTE version 1.0 contains a framework for WTW evaluations with placeholders for further input and development. Emissions data has been collected from primary and secondary sources for energy intensive processes and implemented in the model. Fuel production in the model is assumed to be off grid with their own energy supply.

Our WTW evaluations aim to account for the energy expended and the associated emissions of fuel production and vessel types. Energy demand is expressed as MWh/ton of fuel. Greenhouse gas emissions are expressed as $kgCO_2eq/GJ$. The model is restricted to evaluating the climate impact of carbon dioxide (CO_2) emissions. Nitrous oxide (N_2O) emissions are assumed to be zero until accurate data is available from engine tests. Methane (CH_4) slip is accounted for methane derived fuels. Version 2.0 aims to build on this foundation, develop greater uniformity in our approach and deepen our understanding WTW climate impacts.

To support these endeavors, this paper describes the data inputs, assumptions, exclusions and the limitations of data set. Based on this work, recommendations have been formulated to frame the development of NavigaTE 2.0.

* WTW is reported per unit chemical energy in the fuel. The use of pilot fuel is outside of the system boundary; however, reference is made the use and climate impact of pilot fuel in our fuel options paper.

Biofuels summary



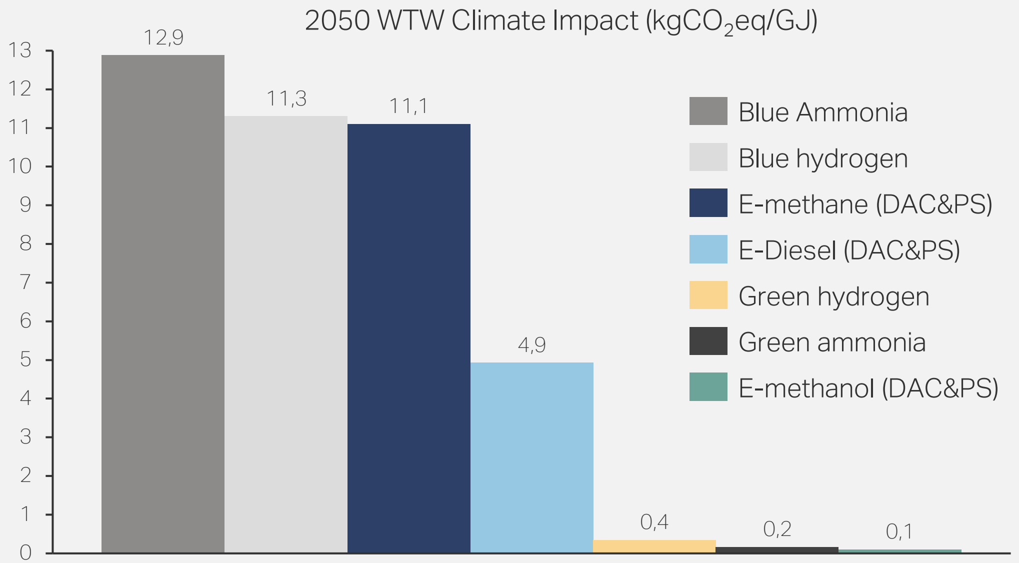
- The system boundary for biofuel pathways begins with collection of biomass and ends with onboard combustion.
- All biofuel pathways are expected to decarbonize via electrification of road transport for biomass collection.
- Biofuel pathways that rely on upgrading with low sulphur fuel oil generate the greatest emissions.
- HTL and pyrolysis oil blends where grey hydrogen is used as a feedstock to generate higher GHG emission. This explains the delta in the HTL and pyrolysis pathways.
- Biomass pre-treatment activities, green electricity consumption, and use of catalysts are excluded from the system boundary in NavigaTE 1.0

However, there are gaps in accounting for emissions associated with green electricity

Key NavigaTE updates

- Implement greater consistency by replacing emissions footprints with emissions associated with energy usage.
- Mature our feedstock scenarios and Include emissions associated with use of green electricity across all fuel pathways.
- Include emissions associated with energy use for the following processes;
    - Demineralized water generation
    - Fuel logistics with a particular focus on fuel storage
    - Include a GWP for 20 years.
- Further definition of the pre-treatment requirements for woody biomass prior to conversion and inclusion of the emissions generated.
- Mature our inventory and modelling of fugitive emissions and onboard GHG slips for the various fuel pathways and use scenarios including:
    - Refined calculation of onboard methane emissions due to methane slip and other emission sources
    - Potential N_2O emissions from ammonia-fueled engines
- Further definition of the feedstock sources for biofuel pathways that utilise food waste and plastic waste and allocation of the associated emissions.
- Inclusion of emissions related to pilot fuel ranges and options depending on fuel pathway and engine technology.

Blue and E-Fuel Summary



- The system boundary for e-fuels and blues fuels begins with supply of feedstocks such as green electricity and natural gas and ends with onboard combustion.
- Apart from blue fuels, NavigaTE assumes that distribution of fuels to the end-user produces most of the emissions.
- Emissions from e-fuel pathways assumes the consumption of green electricity to have 0 kgCO2/MWh.

* WTW is reported per unit chemical energy in the fuel. The use of pilot fuel is outside of the system boundary; however, reference is made to pilot fuel in our fuel options paper.

Appendix

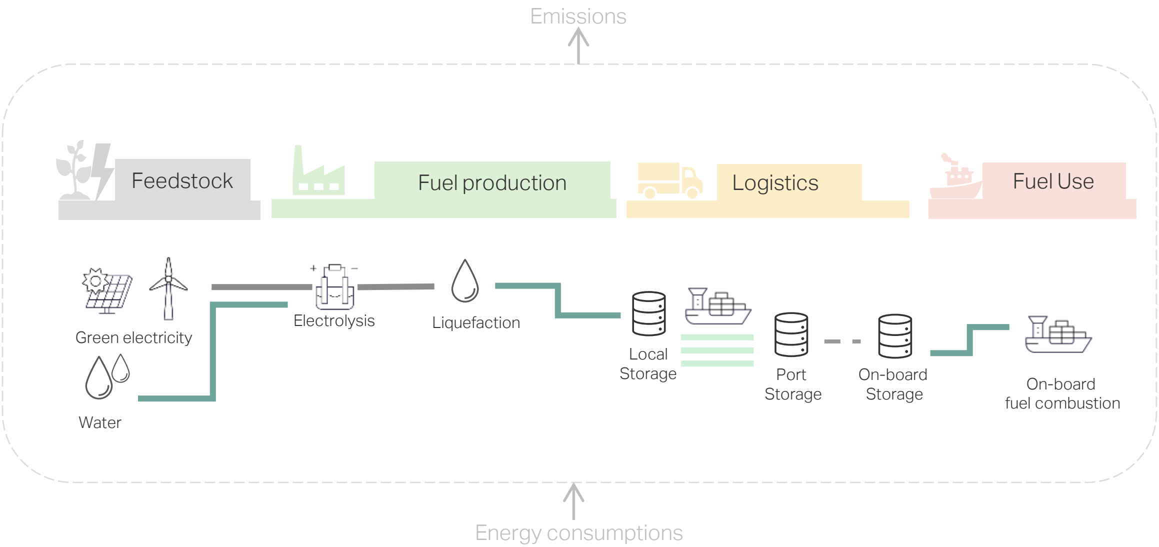
Hydrogen / Ammonia / E-diesel / E-Methanol / E-Methane / Bio-methanol / Bio-methane / Hydrothermal Liquefaction (HTL) Oil Blend / Hydrothermal Liquefaction (HTL) Oil / Pyrolysis Oil Blend / Pyrolysis Oil / Petroleum based fuels

Hydrogen

Green Hydrogen WTW Scope

System boundary

The system boundary includes the whole supply chain from fuel production up to the delivery of hydrogen to the hydrogen-fuelled vessels. The system boundary excludes emissions associated with the construction of pathway infrastructure. For this reason and limited impact categories, the WTW analysis is not meant to be interpreted as a full LCA.



Hydrogen WTW inventory development

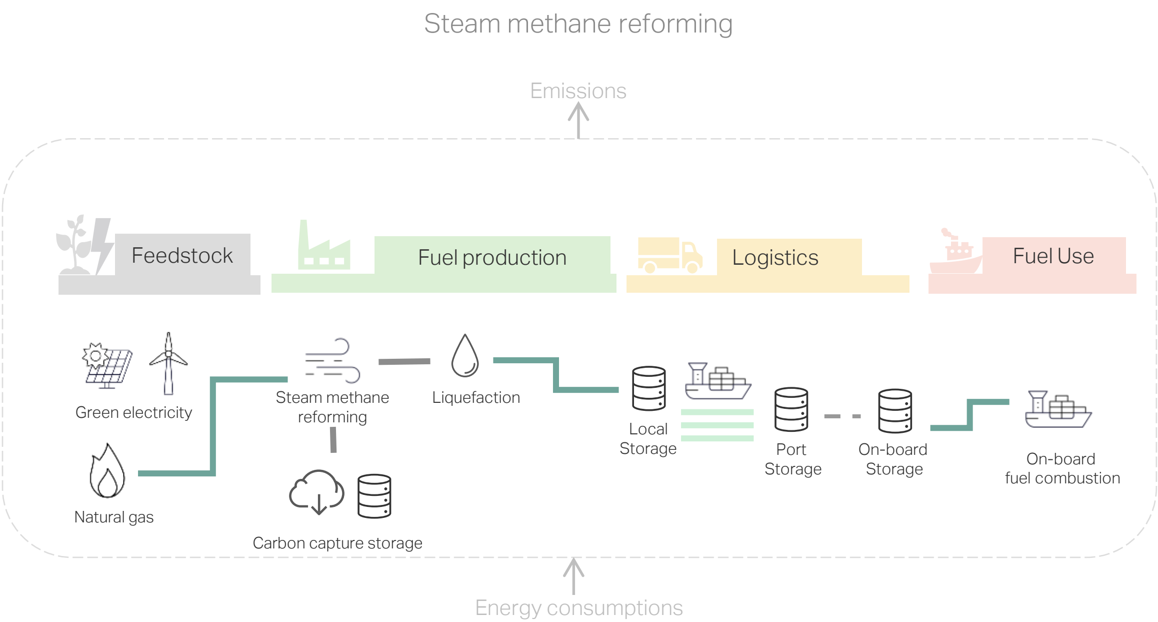
Data collection for green hydrogen relies on secondary data from literature. The average confidence level is reported as 4, this is indicative of solid analysis behind the values.

Unit Process	Subunit process	Parameter	Value	Unit
Feedstock production	Green electricity	Energy consumption	0	MWh/ton $_{H2}$
Feedstock production	Water	Energy consumption	0	MWh/ton $_{H2}$
Feedstock production	Energy consumption	CO2eq emissions	0	tonCO$_2$eq/MWh
Fuel Production	Electrolysis	Energy consumption	53,4	kWh/kg $_{H2}$
Fuel Production	Liquefaction	Energy consumption	10	MWh/ton $_{H2}$
Fuel Production	Energy consumption	CO2eq emissions	0	tonCO$_2$eq/MWh
Fuel Logistics	Local storage	Energy consumption	0	kWh/kg$_{H2}$
Fuel Logistics	Fuel transport	Energy consumption	0	Ton $_{fuel}$/voyage
Fuel Logistics	Port storage	Energy consumption	0	kWh/kg$_{H2}$
Fuel Logistics	Onboard storage	Energy consumption	0	Ton $_{fuel}$/kg$_{H2}$
Fuel Logistics	Energy consumption	CO2eq emissions	0,26	tonCO$_2$eq/ton $_{fuel}$
Fuel use	Onboard combustion	CO2eq emissions	0	kgCO$_2$eq/GJ

Blue Hydrogen WTW Scope

System boundary

The system boundary includes the whole supply chain from fuel production up to the delivery of hydrogen to the hydrogen fuelled vessels and on-board combustion.



Hydrogen WTW inventory development

Data collection for green hydrogen relies on secondary data from literature. The average confidence level is reported as 4, this is indicative of solid analysis behind the values.

Unit Process	Subunit process	Parameter	Value	Unit
Feedstock production	Green electricity	Energy consumption	0	MWh/ton $_{H2}$
Feedstock production	Water	Energy consumption	0,5	MWh/ton $_{H2}$
Feedstock production	Energy consumption	CO_2eq emissions	0,88	tonCO_2eq/ton$_{H2}$
Fuel Production	Electrolysis	Energy consumption	0	kWh/kg $_{H2}$
Fuel Production	Liquefaction	Energy consumption	10	MWh/ton $_{H2}$
Fuel Production	Energy consumption	CO_2eq emissions	0,39	kWh/kg $_{H2}$
Fuel Logistics	Local storage	Energy consumption	0	tonCO_2eq/MWh
Fuel Logistics	Fuel transport	Energy consumption	0	kWh/kg$_{H2}$
Fuel Logistics	Port storage	Energy consumption	0	Ton $_{fuel}$/voyage
Fuel Logistics	Onboard storage	Energy consumption	0	kWh/kg$_{H2}$
Fuel Logistics	Energy consumption	CO_2eq emissions	0	Ton $_{fuel}$/kg$_{H2}$
Fuel use	Onboard combustion	CO_2eq emissions	0,26	tonCO_2eq/ton $_{fuel}$

Hydrogen Assumptions

Supporting Assumptions

- The NavigaTE model assumes that fuel production utilizes green energy provided by wind and solar. For this reason, the emissions from this unit process are assumed as zero.
- Emissions from fuel logistics assume a tanker speed of 12 knots, 0,375 ton/m3/year and distance traveled of 3,734 km, a voyage duration of 7 days, and an overall capacity utilization of 40% to account for returning empty and loading/unloading operation.
- The density of green liquid hydrogen is 69 kg/m3
- TTW emissions are calculated based on the LHV and CO2 emission factors. See appendix – supplementary data.

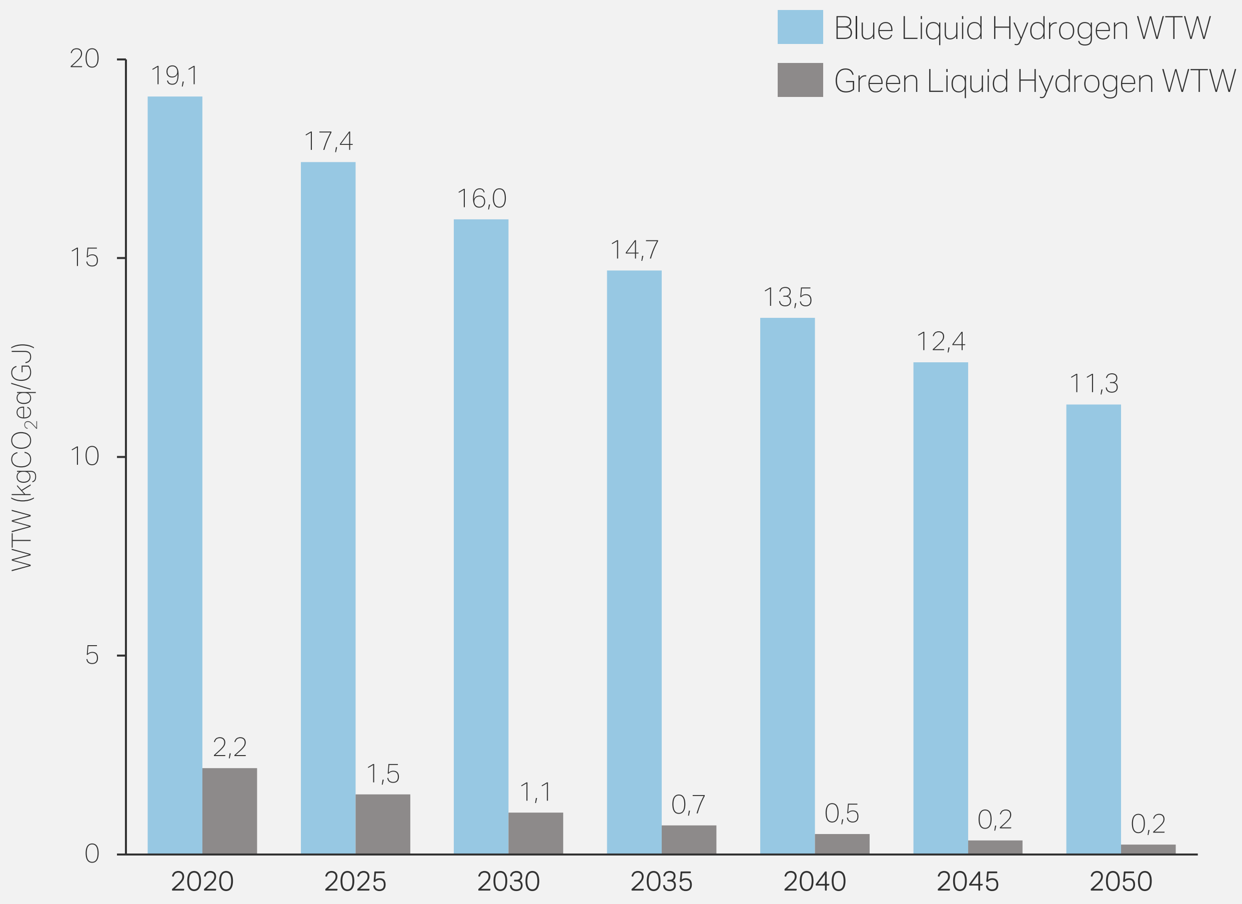
The WTW emissions reduction for blue hydrogen is attributed to:

- Decarbonization of fuel transport
- Feed stock efficiency increases leading to less natural gas input
- Improved efficiency of carbon capture from 89% in 2020 to 95% by 2050.

The WTW emissions reduction for green hydrogen is attributed to:

- Decarbonization of fuel transport
- System efficiency increases in electrolysis

Hydrogen WTW Emissions

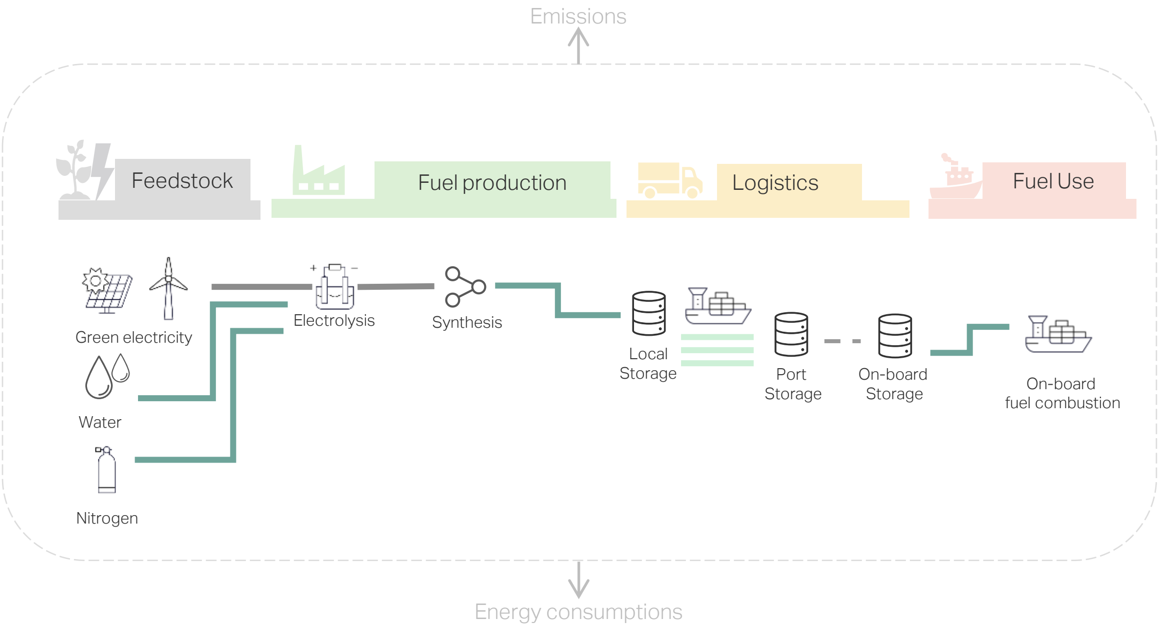


Ammonia

Green Ammonia WTW Scope

System boundary

The system boundary includes the whole supply chain from fuel production up to the delivery of ammonia to the ammonia fuelled vessels and on-board combustion.



Ammonia WTW inventory

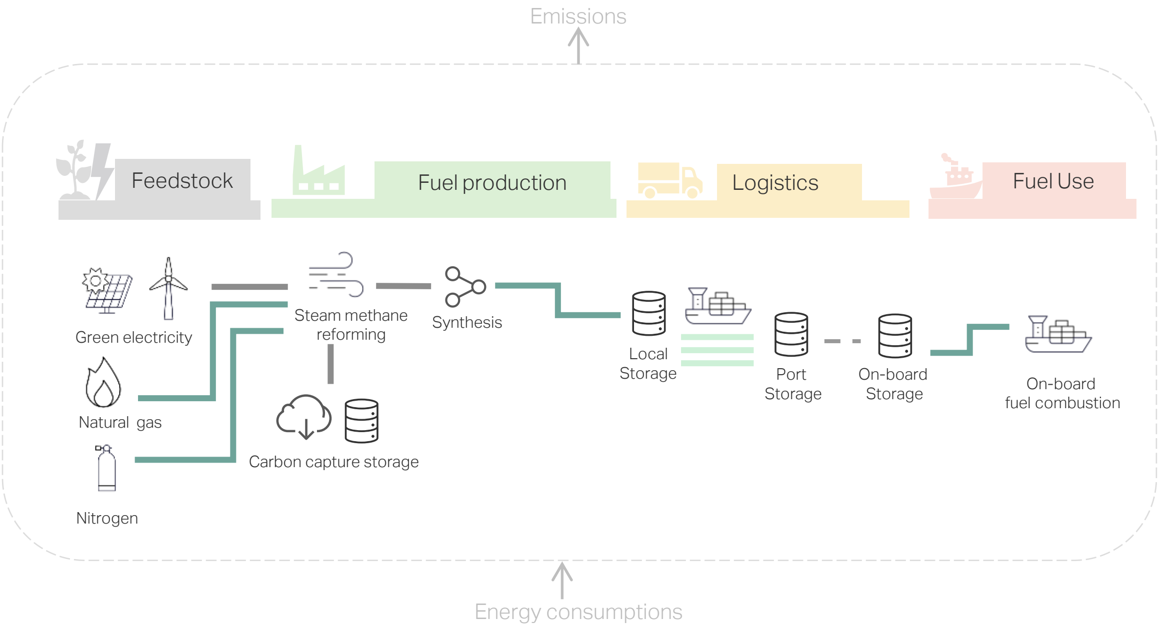
Data collection for ammonia relies on secondary data from literature. The average confidence level is reported as 4, which is indicative of solid analysis behind the values.

Unit Process	Sub unit process	Parameter	Value	Unit
Feedstock production	Green electricity	Energy consumption	0	MWh/ton $_{NH3}$
Feedstock production	Nitrogen	Energy consumption	0	MWh/ton $_{NH3}$
Feedstock production	Energy consumption	CO_2eq emissions	0	tonCO$_2$eq/ton $_{NH3}$
Fuel Production	Electrolysis	Energy consumption	53,4	kWh/kg $_{H2}$
Fuel Production	H2 Compression	Energy consumption	0	MWh/ton $_{NH3}$
Fuel Production	Synthesis	Energy consumption	0,44	MWh/ton $_{NH3}$
Fuel Production	Energy consumption	CO_2eq emissions	0	tonCO$_2$eq/MWh
Fuel Logistics	Local storage	Energy consumption	0	kWh/kg$_{NH3}$
Fuel Logistics	Fuel transport	Energy consumption	0	Ton $_{fuel}$/voyage
Fuel Logistics	Port storage	Energy consumption	1,3	kWh/ton$_{NH3}$
Fuel Logistics	Onboard storage	Energy consumption	0	Ton $_{fuel}$/kg$_{NH3}$
Fuel Logistics	Energy consumption	CO_2eq emissions	0,026	tonCO$_2$eq/ton $_{fuel}$
Fuel use	Onboard combustion	CO_2eq emissions	0	kgCO$_2$eq/GJ

Blue Ammonia WTW Scope

System boundary

The system boundary includes the whole supply chain from fuel production up to the delivery of ammonia to the ammonia fuelled vessels and on-board combustion.



Ammonia WTW inventory

Data collection for ammonia relies on secondary data from literature. The average confidence level is reported as 4, which is indicative of solid analysis behind the values.

Unit Process	Sub unit process	Parameter	Value	Unit
Feedstock production	Green electricity	Energy consumption	0	MWh/ton_{NH3}
Feedstock production	Natural gas	Energy Consumption	0	MWh/ton_{NH3}
Feedstock production	Nitrogen	Energy consumption	0	MWh/ton_{NH3}
Feedstock production	Energy consumption	CO_2eq emissions	0	$tonCO_2eq/ton_{NH3}$
Feedstock production	Blue hydrogen production	CO2eq emissions	2,03	$tonCO_2eq/ton_{NH3}$
Fuel Production	SMR	Energy consumption	0	kWh/kg_{H2}
Fuel Production	Carbon capture	Energy consumption	0	MWh/ton_{NH3}
Fuel Production	Synthesis	Energy consumption	0,46	MWh/ton_{NH3}
Fuel Production	Energy consumption	CO_2eq emissions	0	$tonCO_2eq/MWh$
Fuel Logistics	Local storage	Energy consumption	0	kWh/kg_{NH3}
Fuel Logistics	Fuel transport	Energy consumption	0	$Ton_{fuel}/voyage$
Fuel Logistics	Port storage	Energy consumption	1,3	kWh/ton_{NH3}
Fuel Logistics	Onboard storage	Energy consumption	0	Ton_{fuel}/kg_{NH3}
Fuel Logistics	Energy consumption	CO_2eq emissions	0,026	$tonCO_2eq/ton_{NH3}$
Fuel use	Onboard combustion	CO_2eq emissions	0	$kgCO_2eq/GJ$

Ammonia Assumptions

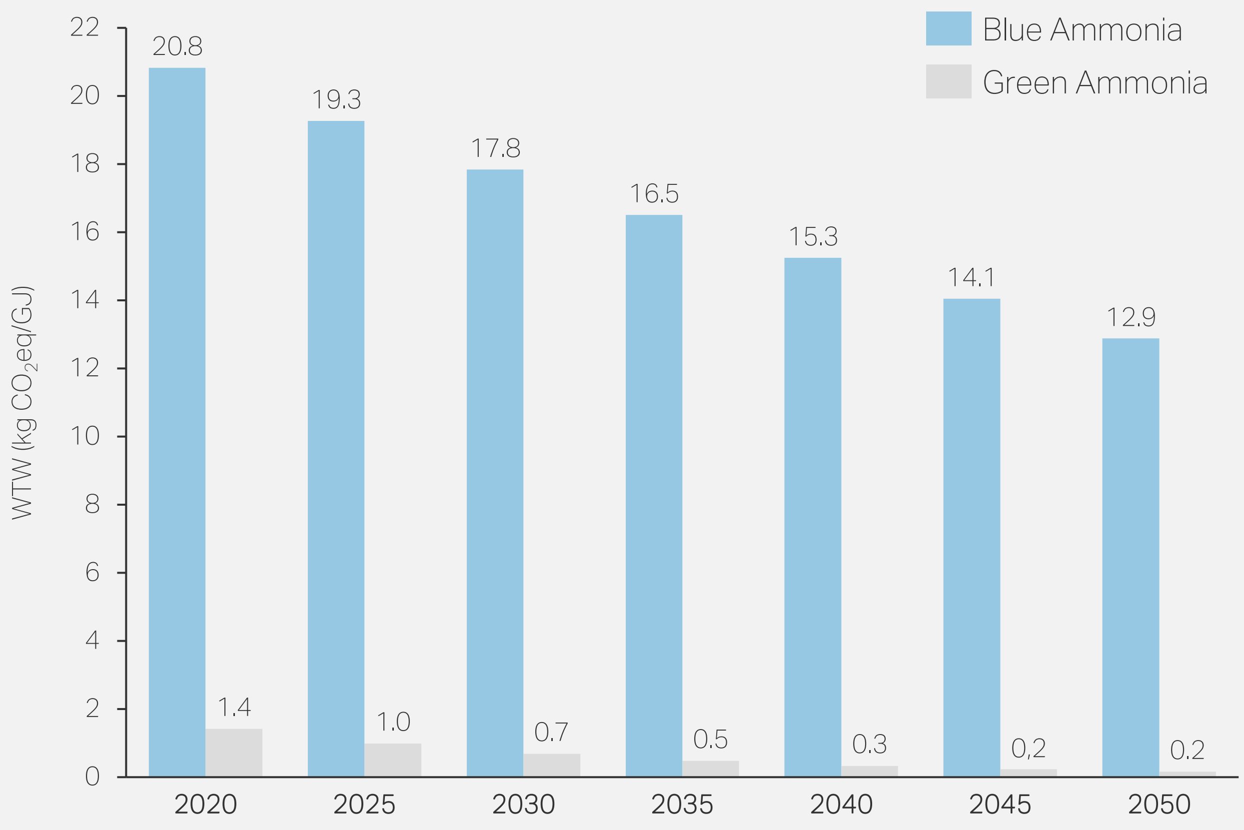
Supporting Assumptions

The NavigaTE model assumes that fuel production utilizes renewable energy sources in the case of green ammonia. For this reason, the emissions from this unit process are assumed as zero. Blue ammonia production assumes a blue hydrogen production.

Emissions from fuel logistics assume a tanker speed of 12 knots, 0,375 ton/m3/year and distance traveled of 3,734 km, a voyage duration of 7 days, and an overall capacity utilization of 40% to account for returning empty and loading/unloading operation.

- Assumed 15 days of refrigerated storage.
- TTW emissions are calculated based on the LHV and CO2 emission factors. See appendix – supplementary data.
- Blue ammonia production assumes the conversion of natural gas: hydrogen of 3,59 kg natural gas/kg of hydrogen.
- NavigaTE assumes carbon capture with a system efficiency of 89% for blue ammonia production.
- Decarbonization of blue ammonia is driven by decarbonization of fuel transport and energy efficiency improvements of the synthesis process. The same is true for green ammonia.

Ammonia WTW Emissions

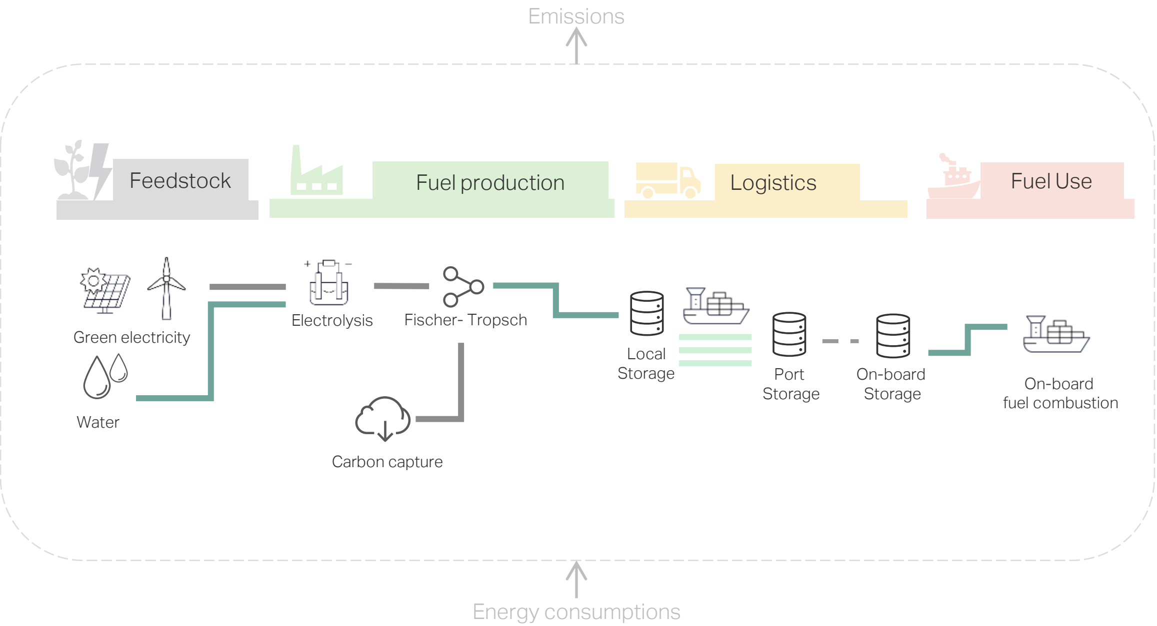


E-Diesel

E-Diesel WTW Scope

System boundary

The system boundary includes the whole supply chain from fuel production up to the delivery of e-diesel to the e-diesel fuelled vessels and on-board combustion.



E-Diesel WTW inventory

Data collection for e-diesel relies on secondary data from the literature. The average confidence level is reported as 4, which is indicative of solid analysis behind the values.

Unit Process	Sub unit process	Parameter	Value	Unit
Feedstock production	Green electricity	Energy consumption	0	MWh/ton $_{e\text{-diesel}}$
Feedstock production	Water	Energy consumption	0	MWh/ton $_{e\text{-diesel}}$
Feedstock production	Energy consumption	CO_2eq emissions	0	tonCO_2eq/ton $_{e\text{-diesel}}$
Fuel Production	Electrolysis	Energy consumption	53,4	kWh/kg $_{H2}$
Fuel Production	Fischer - Tropsch	Energy consumption	0,3	MWh/ton $_{e\text{-diesel}}$
Fuel Production	Carbon capture (DAC)	Energy consumption	3,0	MWh/ton $_{CO2}$
Fuel Production	Carbon capture (DAC and PS)	CO_2eq emissions	-3,21	tonCO_2eq/ton $_{e\text{-diesel}}$
Fuel Production	Energy consumption	CO_2eq emissions	0	tonCO_2eq/MWh
Fuel Logistics	Local storage	Energy consumption	0	kWh/kg $_{e\text{-diesel}}$
Fuel Logistics	Fuel transport	Energy consumption	0	Ton $_{fuel}$/voyage
Fuel Logistics	Port storage	Energy consumption	0	kWh/kg $_{e\text{-diesel}}$
Fuel Logistics	Onboard storage	Energy consumption	0	Ton $_{fuel}$/kg $_{e\text{-diesel}}$
Fuel Logistics	Energy consumption	CO_2eq emissions	0,020	tonCO_2eq/ton $_{e\text{-diesel}}$
Fuel use	Onboard combustion	CO_2eq emissions	80,10	kgCO_2eq/GJ

e-Diesel Assumptions

Supporting Assumptions

- The NavigaTE model assumes that fuel production utilizes renewable energy sources. For this reason, the emissions from this unit process are assumed as zero.

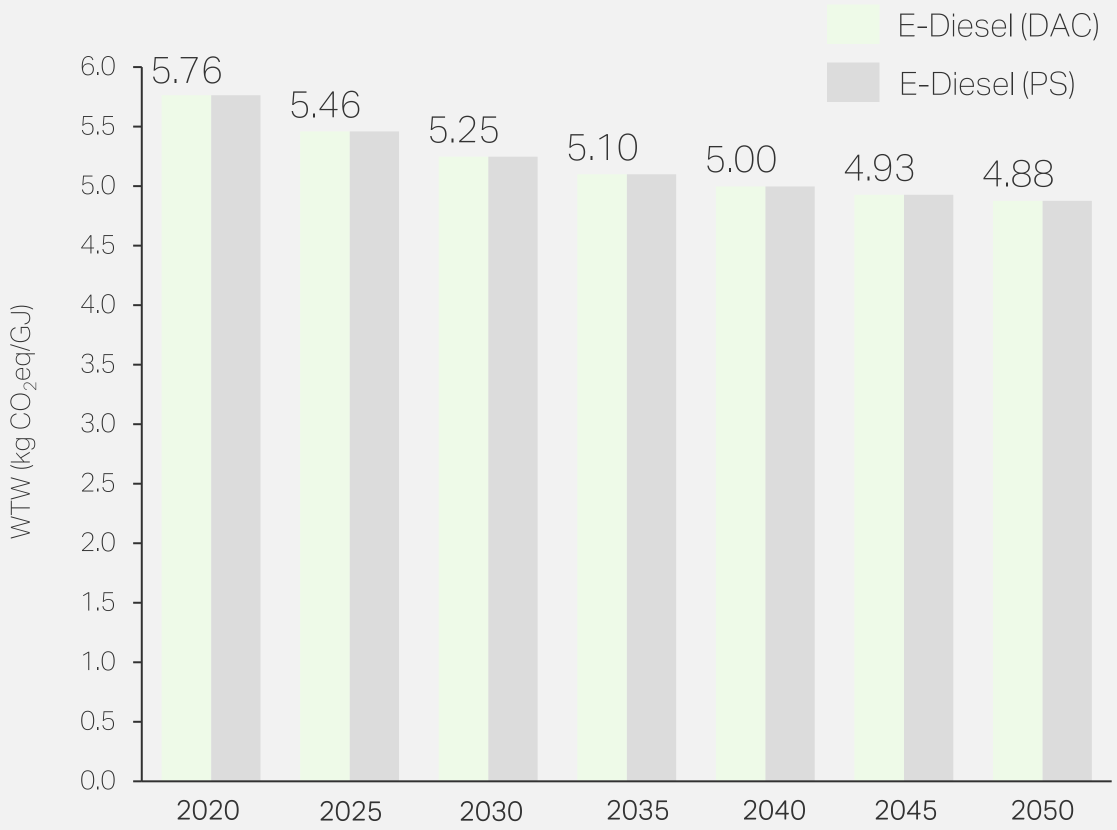
- Emissions from fuel logistics assumes a tanker speed of 12 knots, 0,375 ton/m_3/year and distance traveled of 3,734 km, a voyage duration of 7 days, and an overall capacity utilization of 40% to account for returning empty and loading/unloading operation.

- Fuel production assumes the following stoichiometry 3,48 kgCO2/kg e-diesel produced.

- TTW emission are calculated based on the LHV and CO2 emission factors. See appendix – supplementary data.

- NavigaTE assumes direct air capture (DAC) as the means of CO2 supply, creating a carbon credit of -75,1kgCO2eq/GJ in WTT. The DAC is assumed to be located close to the production facility therefore no emissions associated with CO2 transport.

E-Diesel WTW Emissions

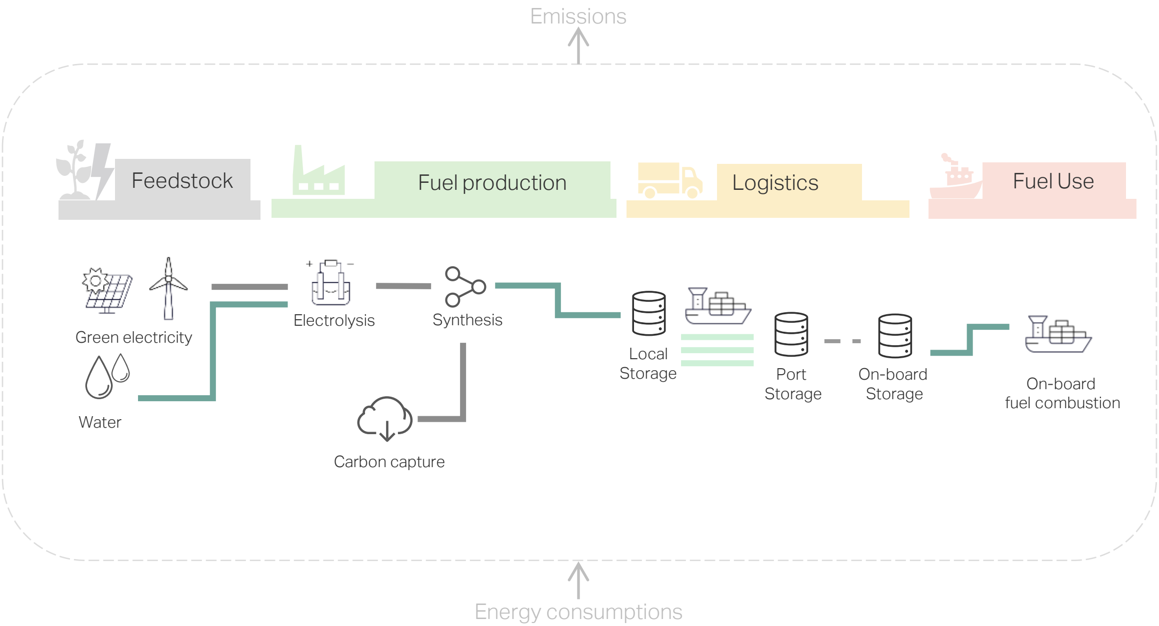


E-Methanol

e-Methanol WTW Scope

System boundary

The system boundary includes the whole supply chain from fuel production up to the delivery of e-methanol to the e-methanol fuelled vessels.



e-Methanol WTW inventory

Data collection for e-methanol relies on secondary data from literature. The average confidence level is reported as 4, which is indicative of solid analysis behind the values.

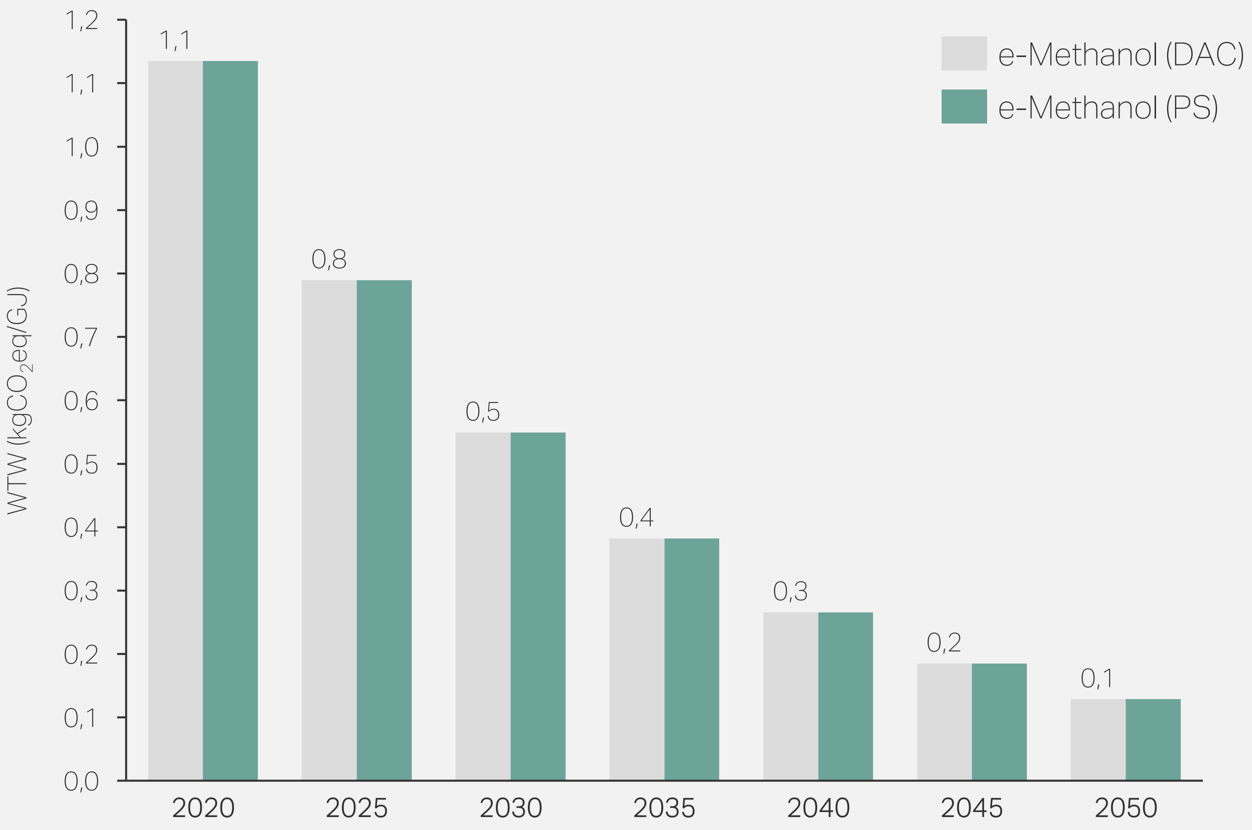
Unit Process	Sub unit process	Parameter	Value	Unit
Feedstock production	Green electricity	Energy consumption	0	MWh/ton $_{MeOH}$
Feedstock production	Water	Energy consumption	0	MWh/ton $_{MeOH}$
Feedstock production	Energy consumption	CO_2eq emissions	0	tonCO$_2$eq/ton$_{MeOH}$
Fuel Production	Electrolysis	Energy consumption	53,4	kWh/kg $_{H2}$
Fuel Production	Methanol Synthesis	Energy consumption	0	MWh/ton $_{MeOH}$
Fuel Production	Carbon capture (DAC)	Energy consumption	3,0	MWh/ton $_{CO2}$
Fuel Production	Carbon capture (DAC and PS)	CO_2eq emissions	-1,38	tonCO$_2$eq/ton $_{MeOH}$
Fuel Production	Energy consumption	CO_2eq emissions	0	tonCO$_2$eq/MWh
Fuel Logistics	Local storage	Energy consumption	0	kWh/kg $_{MeOH}$
Fuel Logistics	Fuel transport	Energy consumption	0	Ton $_{fuel}$/voyage
Fuel Logistics	Port storage	Energy consumption	0	kWh/kg $_{MeOH}$
Fuel Logistics	Onboard storage	Energy consumption	0	Ton $_{fuel}$/kg $_{MeOH}$
Fuel Logistics	Energy consumption	CO_2eq emissions	0,032	tonCO$_2$eq/ton $_{MeOH}$
Fuel use	Onboard combustion	CO_2eq emissions	69,1	kg CO$_2$eq/GJ

e-Methanol Assumptions

Supporting Assumptions

- Emissions from fuel logistics assumes a tanker speed of 12 knots, 0,375 ton/m_3/year and distance travelled of 3,734 km, a voyage duration of 7 days and an overall capacity utilization of 40% to account for returning empty and loading/unloading operation.
- Fuel production assumes the following stoichiometry 1,50 kgCO2/kg methanol produced.
- NavigaTE assumes direct air capture as the means of CO2 supply, creating a carbon credit of -69,1kgCO2eq/GJ. The DAC is assumed to be located close to the production facility therefore no emissions associated with CO2 transport.
- TTW emission are calculated based on the LHV and CO2 emission factors. See appendix – supplementary data.
- Methanol synthesis is assumed to generate no emissions based on energy consumption from renewable sources.

E-Methanol WTW Emissions

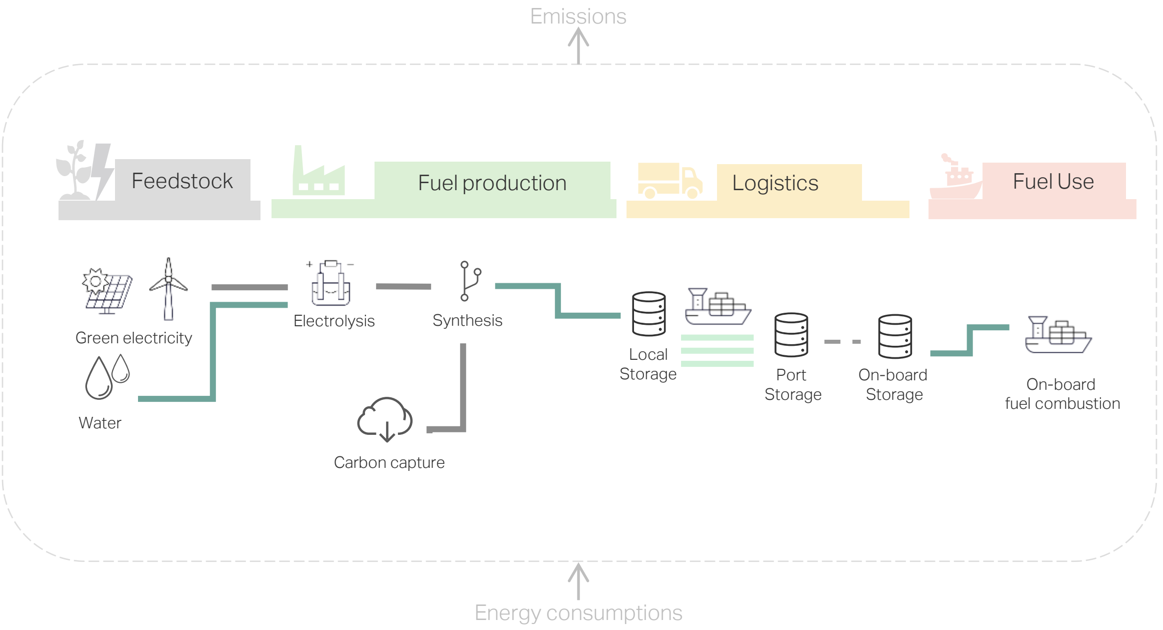


E-methane

e-Methane WTW Scope

System boundary

The system boundary includes the whole supply chain from fuel production up to the delivery of e-methane to the e-methane fuelled vessels and on-board combustion.



E-Methane WTW inventory

Data collection for e-Methane relies on secondary data from literature. The average confidence level is reported as 4, which is indicative of solid analysis behind the values.

Unit Process	Sub unit process	Parameter	Value	Unit
Feedstock production	Green electricity	Energy consumption	0	MWh/ton_{CH4}
Feedstock production	Water	Energy consumption	0	MWh/ton_{CH4}
Feedstock production	Energy consumption	CO_2eq emissions	0	$tonCO_2eq/ton_{CH4}$
Fuel Production	Electrolysis	Energy consumption	53,4	kWh/kg_{H2}
Fuel Production	Methane Synthesis	Energy consumption	0,21	MWh/ton_{CH4}
Fuel Production	Liquefaction	Energy consumption	0,5	MWh/kg_{CH4}
Fuel Production	Carbon capture (DAC)	Energy consumption	3,0	MWh/ton_{CO2}
Fuel Production	Carbon capture (DAC and PS)	CO_2eq emissions	-2,75	$tonCO_2eq/ton_{CH4}$
Fuel Production	Energy consumption	CO_2eq emissions	0	$tonCO_2eq/MWh$
Fuel Logistics	Local storage	Energy consumption	0	kWh/kg_{CH4}
Fuel Logistics	Fuel transport	Energy consumption	0	$Ton_{fuel}/voyage$
Fuel Logistics	Port storage	Energy consumption	0,7	kWh/ton_{CH4}
Fuel Logistics	Onboard storage	Energy consumption	0	Ton_{fuel}/kg_{CH4}
Fuel Logistics	Fuel transport	Fugitive emissions	2,0	$kgCO_2/GJ$
Fuel Logistics	Energy consumption	CO_2eq emissions	0,043	$tonCO_2eq/ton_{CH4}$
Fuel use	Onboard combustion	CO_2eq emissions	64	kgO2eq/GJ

e-Methane Assumptions

Supporting Assumptions

- Emissions from fuel logistics assumes a tanker speed of 12 knots, 0,375 ton/m_3/year and distance travelled of 3,734 km, a voyage duration of 7 days and an overall capacity utilization of 40% to account for returning empty and loading/unloading operation.

- A methane slip factor is included in our fuel logistics calculations, this value is assumed to be 2,0 kgCO_2/GJ.

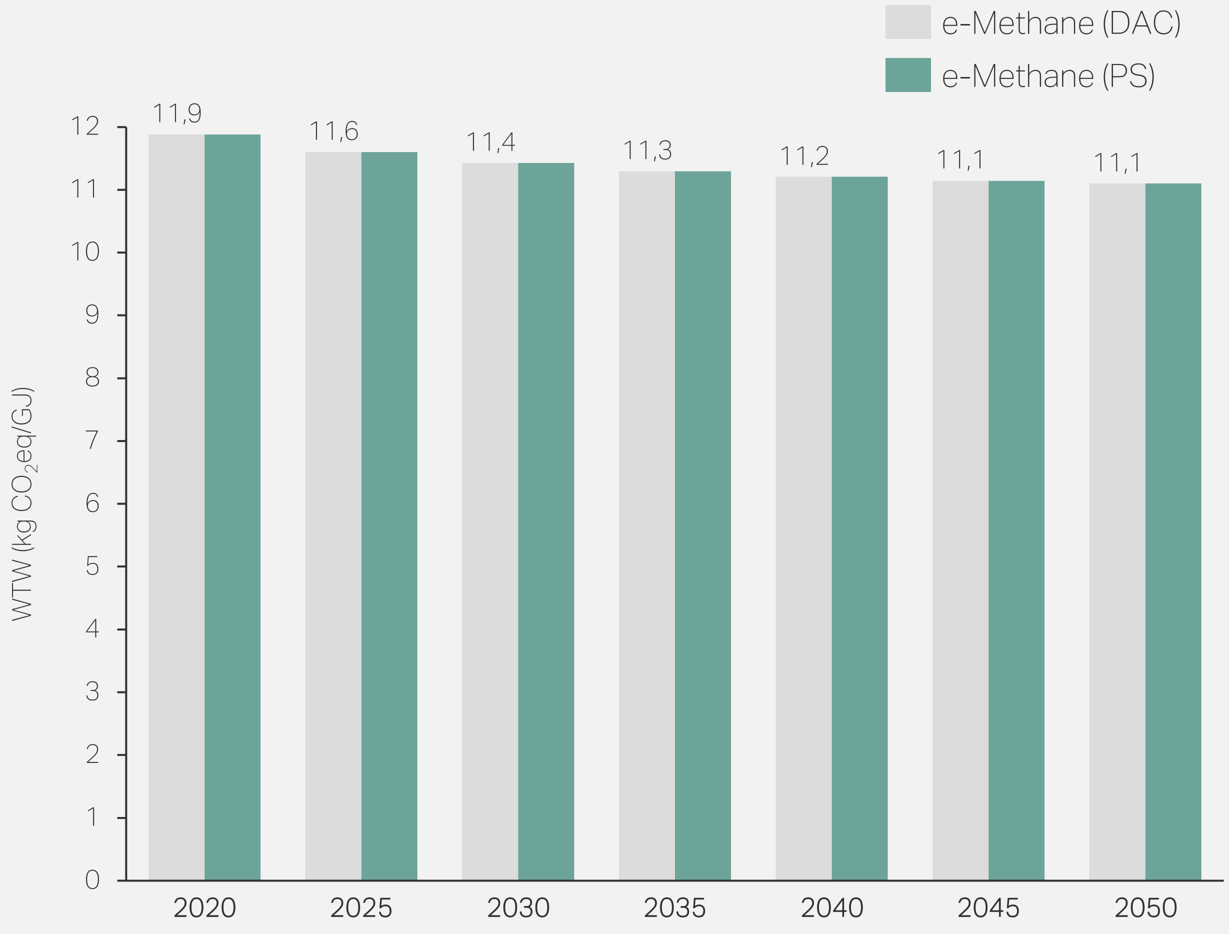
- Fuel production assumes the following stoichiometry 2,75 tonCO2/ton methane produced. Lower Heating Value is assumed 50.000,00 MJ/ton.

- Primarily, WTT emissions are based on CO_2eq emissions generated during fuel logistics. Here we have assumed a fugitive methane slip of 2kgCO_2eq/GJ.

- NavigaTE assumes direct air capture as the means of CO_2 supply, creating a carbon credit of -51 kgCO2eq/GJ. The DAC is assumed to be located close to the production facility therefore no emissions associated with CO_2 transport. The carbon credit essentially offsets 76% of the WTW emissions

- TTW emission are calculated based on the LHV and CO2 emission factors. See appendix – supplementary data and assumptions for LNG.

E-Methane WTW Emissions

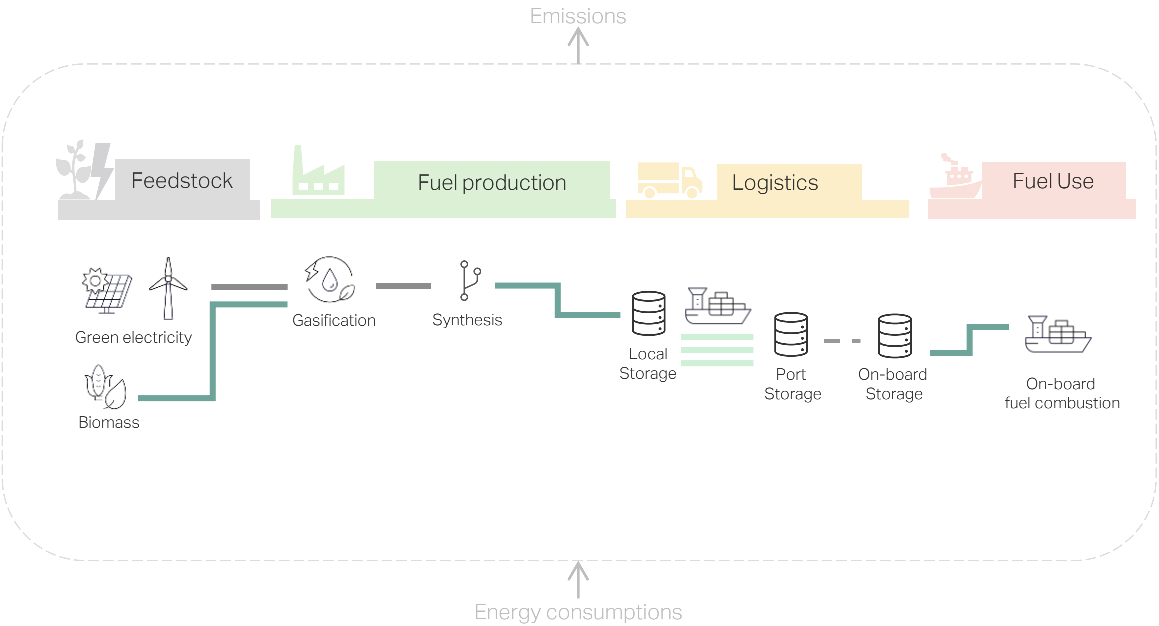


Bio-methanol

Bio-methanol WTW Scope

System boundary

The system boundary includes the whole supply chain from fuel production up to the delivery of bio-methanol to bio-methanol fuelled vessels and on-board combustion.



Bio-methanol WTW inventory

Data collection for bio-methanol relies on secondary data from literature. The average confidence level is reported as 4, which is indicative of solid analysis behind the values.

Unit Process	Sub unit process	Parameter	Value	Unit
Feedstock production	Green electricity	Energy consumption	0	MWh/ton_{CH3OH}
Feedstock production	Woody biomass	CO_2eq emissions	0,09	$tonCO_2eq/ton_{biomass}$
Feedstock production	Energy consumption	CO_2eq emissions	0	$tonCO_2eq/ton_{CH3OH}$
Fuel Production	Gasification	Energy consumption	0	MWh/ton_{CH3OH}
Fuel Production	Methanol Synthesis	Energy consumption	0,53*	MWh/ton_{CH3OH}
Fuel Production	Energy consumption	CO_2eq emissions	0	$tonCO_2eq/MWh$
Fuel Logistics	Local storage	Energy consumption	0	kWh/kg_{CH3OH}
Fuel Logistics	Fuel transport	Energy consumption	0	$Ton_{fuel}/voyage$
Fuel Logistics	Port storage	Energy consumption	0	kWh/kg_{CH3OH}
Fuel Logistics	Onboard storage	Energy consumption	0	Ton_{fuel}/kg_{CH3OH}
Fuel Logistics	Energy consumption	CO_2eq emissions	0,032	$tonCO_2eq/ton_{CH3OH}$
Fuel use	Onboard combustion	CO_2eq emissions	69,10	$kgCO_2eq/GJ$

*Combined demand for gasification and methanol synthesis.

Bio-methanol assumptions

Supporting Assumptions

- Emissions from fuel logistics assume a tanker speed of 12 knots, 0,375 ton/m3/year and distance travelled of 5,334 km, a voyage duration of 10 days, and an overall capacity utilization of 40% to account for returning empty and loading/unloading operation.

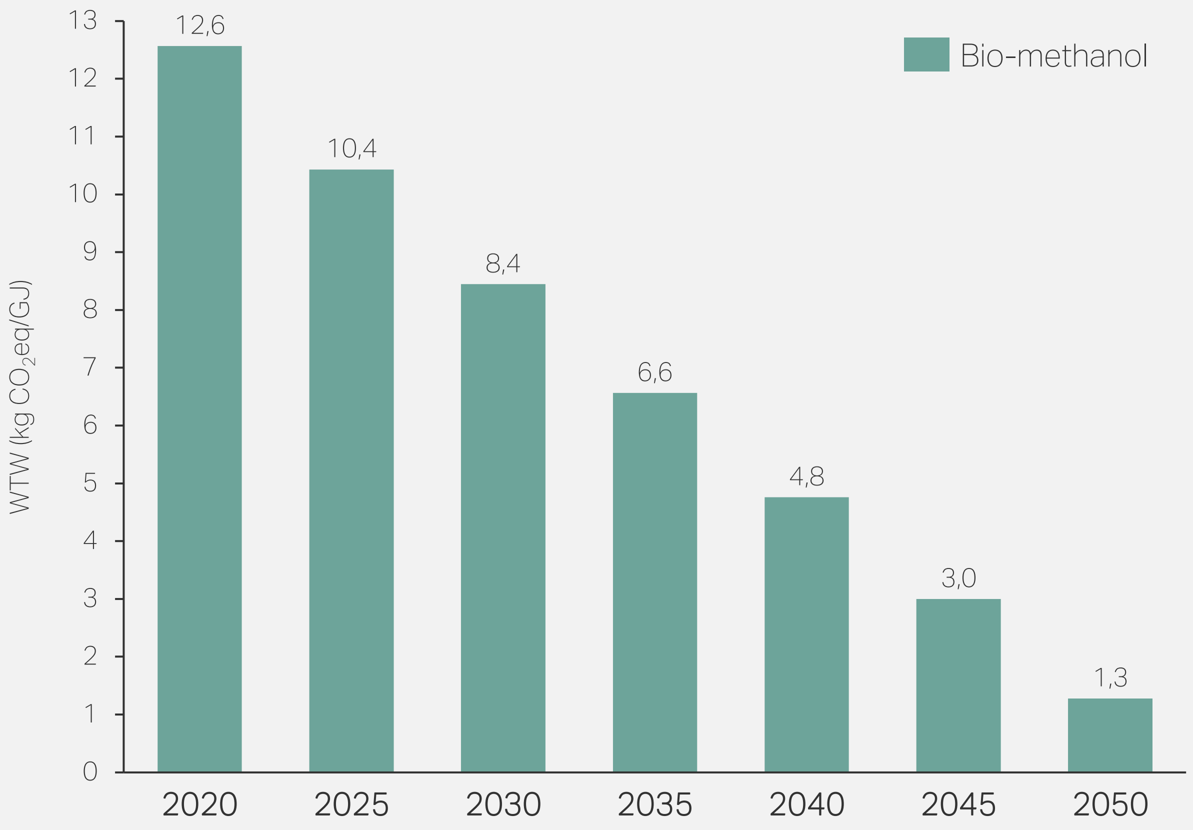
- The density of bio-methanol is 792 kg/m3.

- Fuel production assumes the conversion of 2,42 dry woody biomass (tons) per ton of bio-methanol. The same ratio is assumed for the conversion of organic wet waste to bio-methanol.

- Biogenic CO2eq captured in the growth of the biomass is assumed to be -69,1 kgCO2eq/GJ. This value non-changing up to 2050.

- TTW emission are calculated based on the LHV and CO2 emission factors. See appendix – supplementary data.

Bio-methanol WTW Emissions

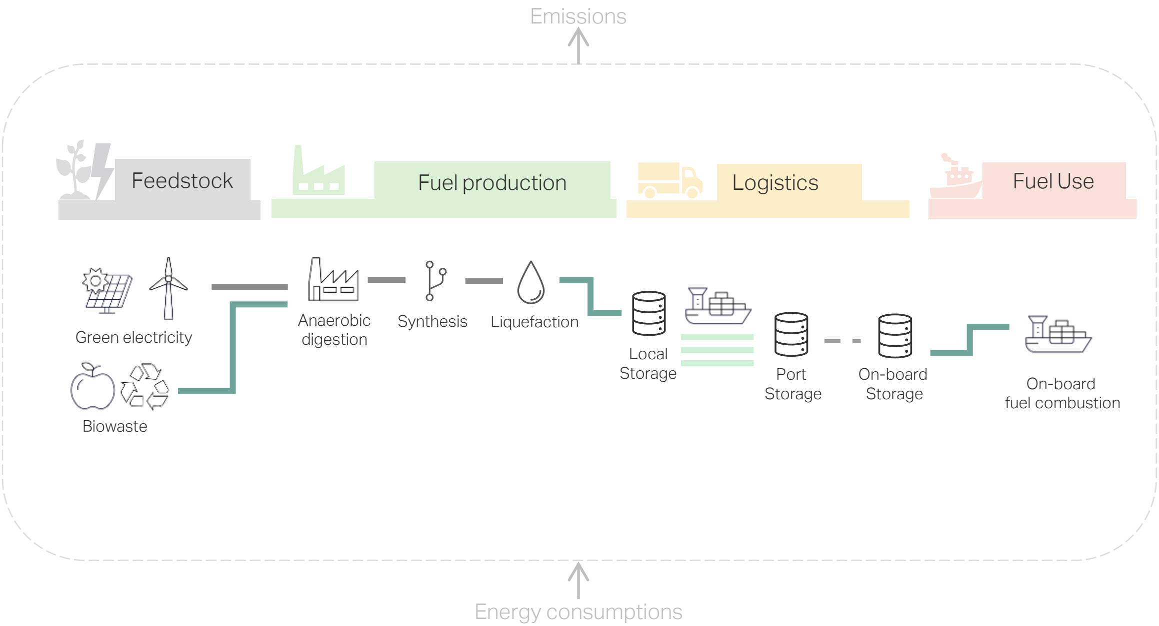


Bio-methane

Bio-Methane WTW Scope

System boundary

The system boundary includes the whole supply chain from fuel production up to the delivery of bio-methane fuelled vessels and on-board combustion.



Bio-methane WTW inventory

Data collection for bio-methane relies on secondary data from literature. The average confidence level is reported as 4, which is indicative of solid analysis behind the values.

Unit Process	Sub unit process	Parameter	Value	Unit
Feedstock production	Green electricity	Energy consumption	0	MWh/ton $_{CH4}$
Feedstock production	Organic wet waste	CO_2eq emissions	0,09	$tonCO_2/ton_{biomass}$
Feedstock production	Energy consumption	CO_2eq emissions	0	$tonCO_2eq/ton_{CH4}$
Fuel Production	Anaerobic digestion	Energy consumption	0	MWh/ton_{CH4}
Fuel Production	Methane Synthesis	Energy consumption	1,19*	MWh/ton_{CH4}
Fuel Production	Liquefaction	Energy consumption	0	MWh/ton_{CH4}
Fuel Production	Energy consumption	CO_2eq emissions	0	$tonCO_2eq/MWh$
Fuel Production	Methane Synthesis	CO_2eq emissions	0,4	$tonCO_2eq/ton_{CH4}$
Fuel Logistics	Local storage	Energy consumption	0	kWh/kg_{CH4}
Fuel Logistics	Fuel transport	Energy consumption	0	$Ton_{fuel}/voyage$
Fuel Logistics	Port storage	Energy consumption	0	kWh/kg_{CH4}
Fuel Logistics	Onboard storage	Energy consumption	0	Ton_{fuel}/kg_{CH4}
Fuel Logistics	Energy consumption	CO_2eq emissions	0,061	$tonCO_2eq/ton_{CH4}$
Fuel Logistics	Fuel transport	Fugitive emissions	2,0	gCO_2eq/MJ
Fuel use	Onboard combustion	CO_2eq emissions	64	kgCO2eq/GJ

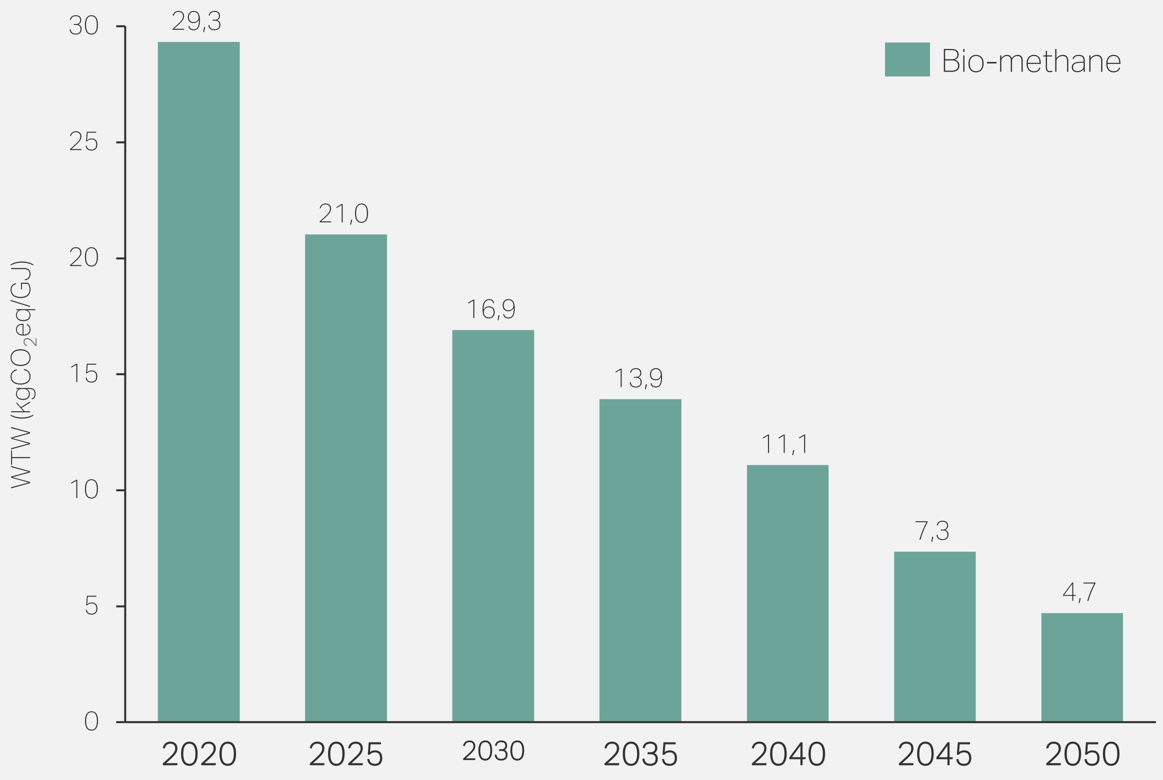
*Combined demand for gasification and methane synthesis.

Bio-methane Assumptions

Supporting Assumptions

- Emissions from fuel logistics assumes a tanker speed of 12 knots, 0,375 ton/m3/year and distance travelled of 5,334 km, a voyage duration of 10 days and an overall capacity utilization of 40% to account for returning empty and loading/unloading operation.
- The density of bio-methane is assumed to be the same as methane, 420 kg/m3 .
- A methane slip factor is included in our fuel logistics calculations, this value is assumed to be 2,0 kgCO2/GJ.
- Fuel production assumes the conversion of 4,46 organic wet waste (tons) per ton of bio-methane.
- The lower heating value is assumed the same as LNG, 50.000 MJ/ ton.
- TTW emission are calculated based on the LHV and CO2 emission factors. See appendix – supplementary data.

Bio-methane WTW Emissions

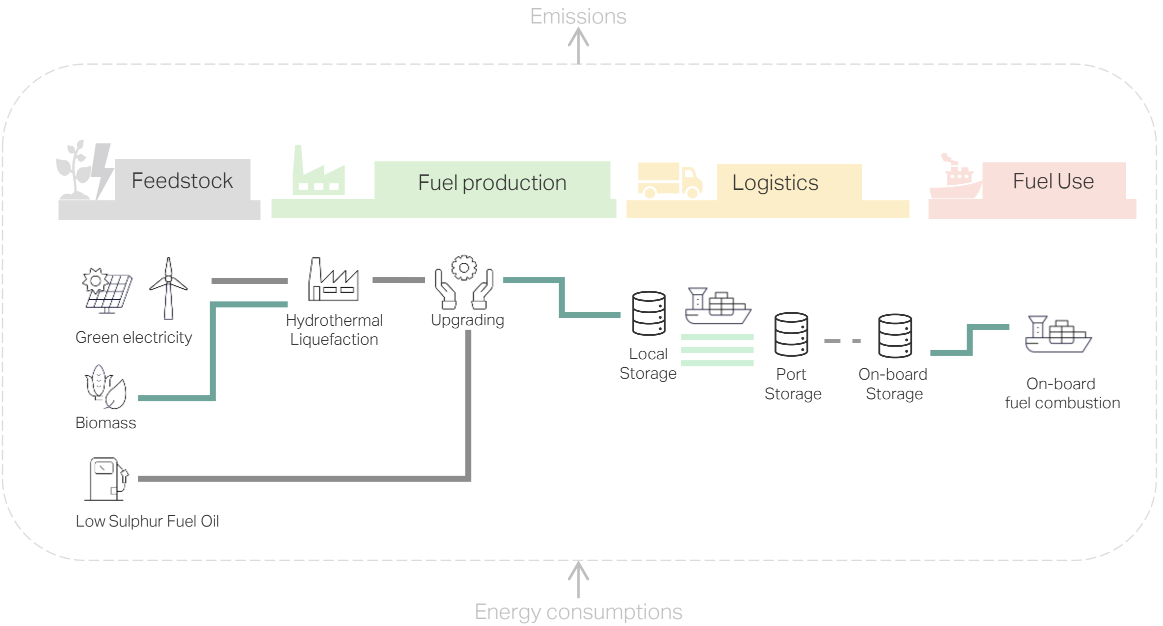


Hydrothermal Liquefaction (HTL) Oil Blend

HLT Oil Blend WTW Scope

System boundary

The system boundary includes the whole supply chain from fuel production up to the delivery of HTL to HTL fuelled vessels and on-board combustion.



HTL Oil Blend WTW inventory

Data collection for HTL relies on secondary data from literature and partner input. The average confidence level is reported as 4, which is indicative of solid analysis behind the values.

Unit Process	Sub unit process	Parameter	Value	Unit
Feedstock production	Green electricity	Energy consumption	0	MWh/ton $_{fuel}$
Feedstock production	Biomass	CO_2eq emissions	0,09	tonCO_2/ton $_{biomass}$
Feedstock production	LSFO	CO_2eq emissions	0,68	tonCO_2eq/ton $_{LSFO}$
Feedstock production	Energy consumption	CO_2eq emissions	0	tonCO_2eq/ton$_{fuel}$
Fuel Production	HTL	Energy consumption	0,8	MWh/ton$_{fuel}$
Fuel Production	Upgrading	Energy consumption	0	MWh/ton$_{fuel}$
Fuel Production	Energy consumption	CO_2eq emissions	0	tonCO_2eq/MWh
Fuel Logistics	Local storage	Energy consumption	0	kWh/kg$_{fuel}$
Fuel Logistics	Fuel transport	Energy consumption	0	Ton $_{fuel}$/voyage
Fuel Logistics	Port storage	Energy consumption	0	kWh/kg$_{fule}$
Fuel Logistics	Onboard storage	Energy consumption	0	Ton $_{fuel}$/kg$_{fuel}$
Fuel Logistics	Energy consumption	CO_2eq emissions	0,0285	tonCO_2eq/ton$_{fuel}$
Fuel use	Onboard combustion	CO_2eq emissions	67,97	kgCO_2eq/GJ

*Combined demand for gasification and methanol synthesis.

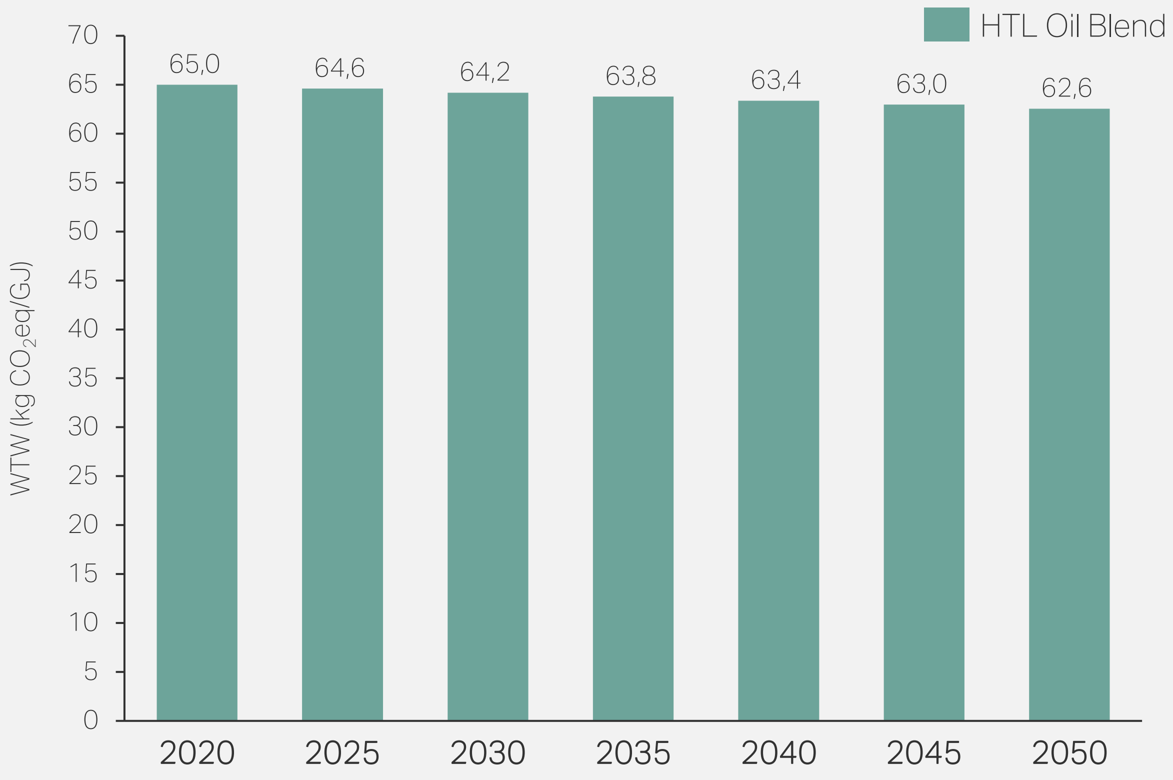
HTL Oil Blend Assumptions

Supporting Assumptions

- Emissions from fuel logistics assume a tanker speed of 12 knots, 0,375 ton/m3/year and distance traveled of 5,334 km, a voyage duration of 10 days, and an overall capacity utilization of 40% to account for returning empty and loading/unloading operation.
- NavigaTE assumes an HTL oil blend contains 60% LSFO with an LHV of 39,400 MJ/ ton and 40% HTL Oil.
- LSFO contribution is described in the petroleum fuels.
- The HTL Oil is assumed 50:50 blend of dry wood and organic wet waste feedstocks.
- TTW emissions are calculated based on the LHV and CO2 emission factors. See appendix – supplementary data.
- NavigaTE assumes the following conversion ratios

Conversion	Value	Unit
Dry wood biomass	1,44	Ton feedstock/ton fuel
Organic wet waste	1,55	Ton feedstock/ton fuel
Biogenic CO2 captured in growth	-47,1	kgCO2/GJ fuel

HTL Oil Blend WTW Emissions

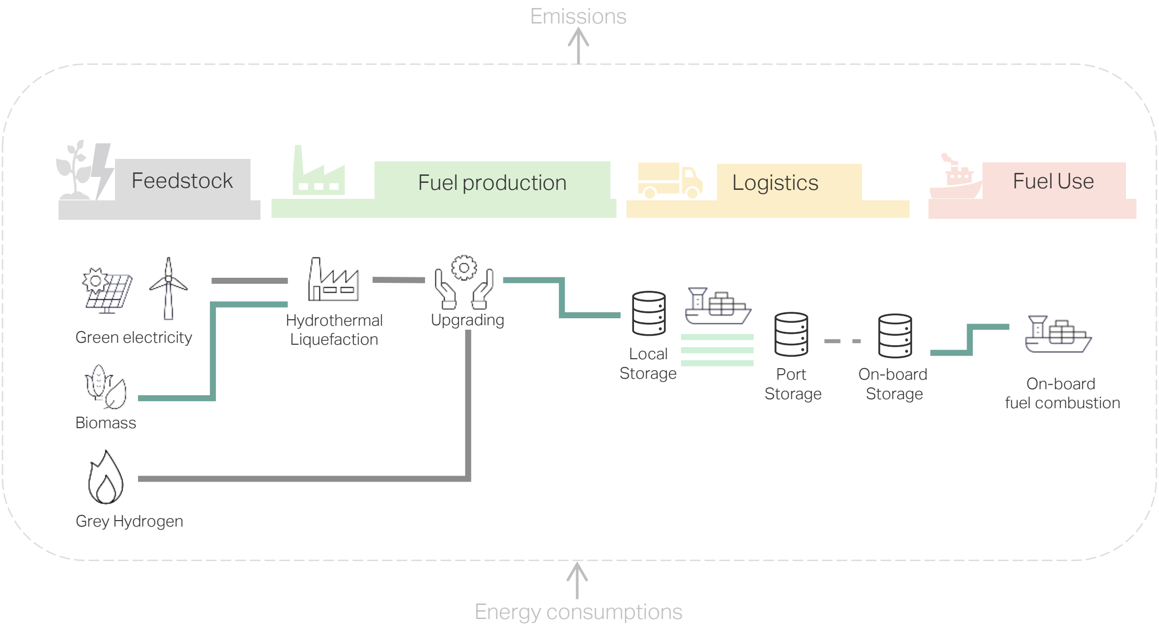


Hydrothermal Liquefaction (HTL) Oil

HLT Oil WTW Scope

System boundary

The system boundary includes the whole supply chain from fuel production up to the delivery of HTL to HTL fuelled vessels and on-board combustion.



HTL Oil WTW inventory

Data collection for bio-methanol relies on secondary data from literature. The average confidence level is reported as 4, which is indicative of solid analysis behind the values.

Unit Process	Sub unit process	Parameter	Value	Unit
Feedstock production	Green electricity	Energy consumption	0	MWh/ton_{fuel}
Feedstock production	Biomass/wet waste	CO_2eq emissions	0.09	$tonCO_2eq/ton_{BIOMASS}$
Feedstock production	Grey hydrogen	CO_2eq emissions	9.06	$tonCO_2eq/ton_{H2}$
Feedstock production	Energy consumption	CO_2eq emissions	0	$tonCO_2eq/ton_{fuel}$
Fuel Production	HTL	Energy consumption	0.8	MWh/ton_{fuel}
Fuel Production	Upgrading	Energy consumption	0	MWh/ton_{fuel}
Fuel Production	Energy consumption	CO_2eq emissions	0	$tonCO_2eq/MWh$
Fuel Logistics	Local storage	Energy consumption	0	kWh/kg_{fuel}
Fuel Logistics	Fuel transport	Energy consumption	0	$Ton_{fuel}/voyage$
Fuel Logistics	Port storage	Energy consumption	0	kWh/kg_{fule}
Fuel Logistics	Onboard storage	Energy consumption	0	Ton_{fuel}/kg_{fuel}
Fuel Logistics	Energy consumption	CO_2eq emissions	0.0285	$tonCO_2eq/ton_{fuel}$
Fuel use	Onboard combustion	CO_2eq emissions	71,59	$kgCO_2eq/GJ$

*Combined demand for gasification and methanol synthesis.

HTL Oil Assumptions

Supporting Assumptions

- Emissions from fuel logistics assumes a tanker speed of 12 knots, 0,375 ton/m3/year and distance travelled of 5,334 km, a voyage duration of 10 days and an overall capacity utilization of 40% to account for returning empty and loading/unloading operation.

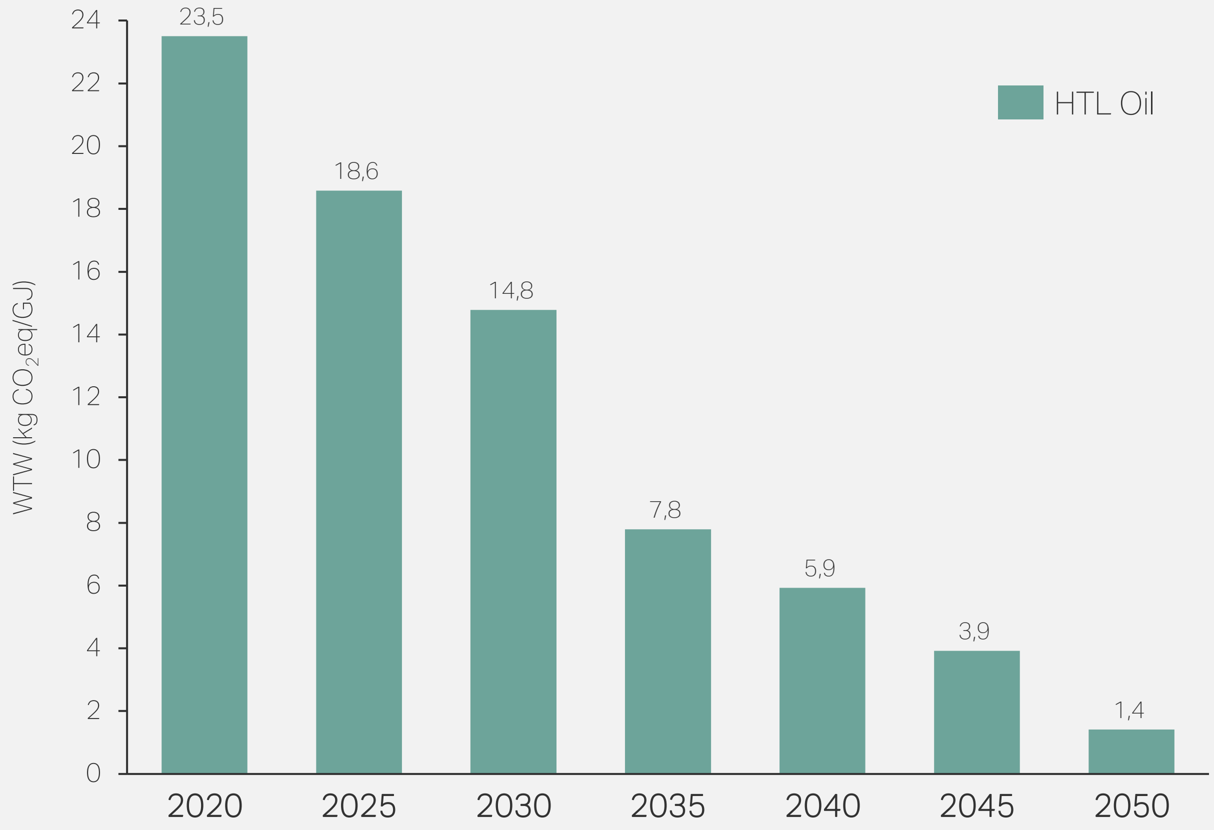
- NavigaTE assumes a HLT oil is upgraded using grey hydrogen at a conversion ratio of 0.06 ton/ton HLT Oil. It also assumes the grey hydrogen will be gradually phased out from 2025 onwards where the use of blue hydrogen will become more prevalent. Green hydrogen is assumed to be the dominant hydrogen source in HTL Oil by 2040. The model also assumes a ratio of 30:70 for dry woody biomass and organic wet waste, respectively.

- NavigaTE assumes the following conversion ratios.

- TTW emission are calculated based on the LHV and CO2 emission factors. See appendix – supplementary data.

Conversion	Value	Unit
Dry wood biomass	3.16	Ton feedstock/ton fuel
Organic wet waste	4.46	Ton feedstock/ton fuel
Biogenic CO2 captured in growth	-71,6	kgCO2/GJ fuel

HTL Oil WTW Emissions

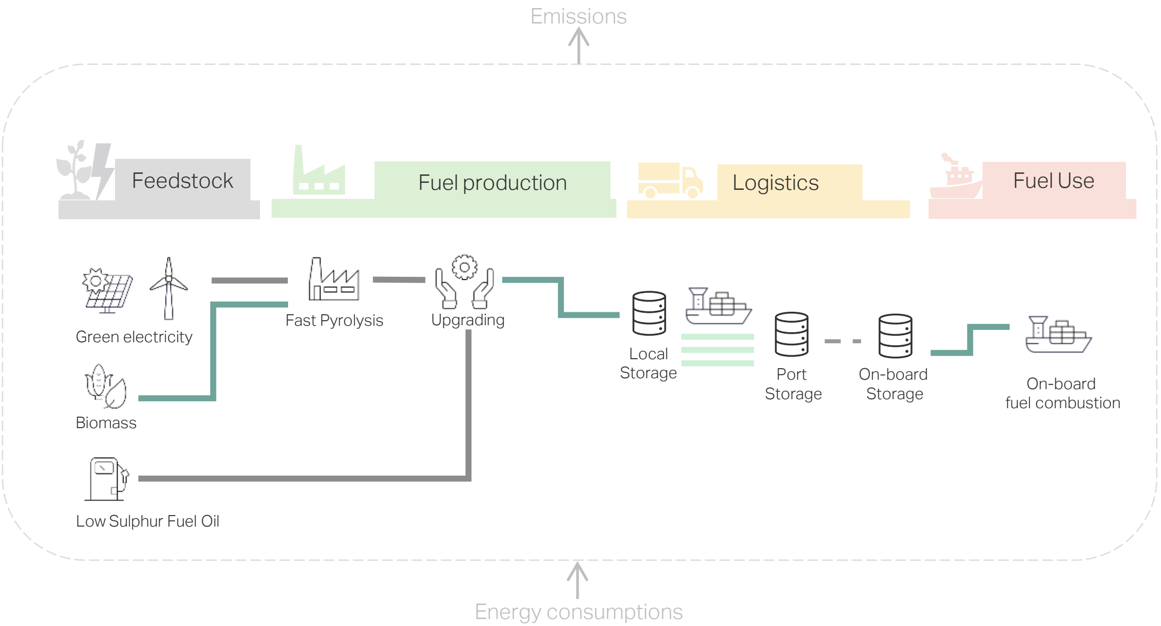


Pyrolysis Oil Blend

Pyrolysis Oil Blend WTW Scope

System boundary

The system boundary includes the whole supply chain from fuel production up to the delivery of pyrolysis oil blend to pyrolysis fuelled vessels and on-board combustion.



Impact category

The impact category for this analysis is Climate Change expressed as GWP_{100} as $kgCO_2eq/GJ$.

Pyrolysis Oil Blend WTW inventory

Data collection for pyrolysis oil blend relies on secondary data from literature and partner input. The average confidence level is reported as 4, which is indicative of solid analysis behind the values.

Unit Process	Sub unit process	Parameter	Value	Unit
Feedstock production	Green electricity	Energy consumption	0	MWh/ton_{fuel}
Feedstock production	Biomass/wet waste	CO_2eq emissions	0,09	$tonCO_2eq/ton_{BIOMASS}$
Feedstock production	LSFO	CO_2eq emissions	0,68	$tonCO_2eq/ton_{LSFO}$
Feedstock production	Energy consumption	CO_2eq emissions	0	$tonCO_2eq/ton_{fuel}$
Fuel Production	Fast Pyrolysis	Energy consumption	0	MWh/ton_{fuel}
Fuel Production	Upgrading	Energy consumption	0.05	MWh/ton_{fuel}
Fuel Production	Energy consumption	CO_2eq emissions	0	$tonCO_2eq/MWh$
Fuel Logistics	Local storage	Energy consumption	0	kWh/kg_{fuel}
Fuel Logistics	Fuel transport	Energy consumption	0	$Ton_{fuel}/voyage$
Fuel Logistics	Port storage	Energy consumption	0	kWh/kg_{fule}
Fuel Logistics	Onboard storage	Energy consumption	0	Ton_{fuel}/kg_{fuel}
Fuel Logistics	Energy consumption	CO_2eq emissions	0,0285	$tonCO_2eq/ton_{fuel}$
Fuel use	Onboard combustion	CO_2eq emissions	83,5	$kgCO_2eq/GJ$

*Combined demand for gasification and methanol synthesis.

Pyrolysis Oil Blend Assumptions

Supporting Assumptions

- Emissions from fuel logistics assumes a tanker speed of 12 knots, 0,375 ton/m3/year and distance travelled of 5,334 km, a voyage duration of 10 days and an overall capacity utilization of 40% to account for returning empty and loading/unloading operation.

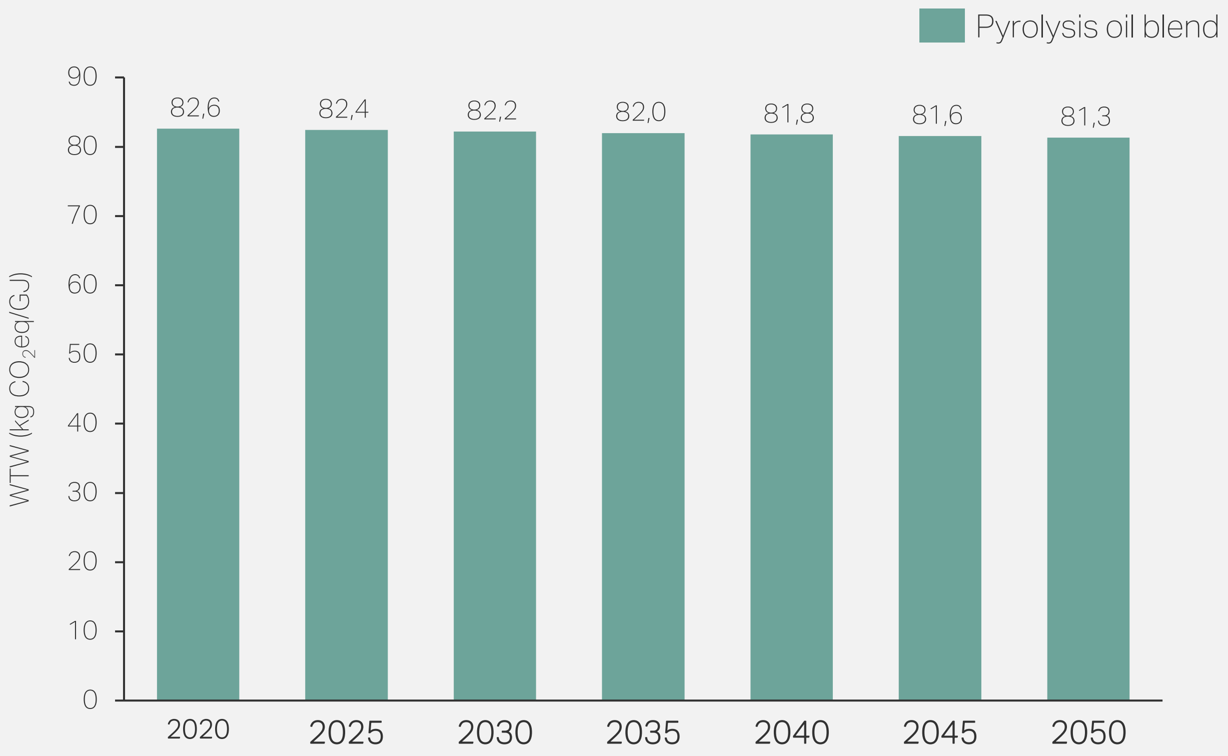
- NavigaTE assumes a pyrolysis oil blend contains 70% LSFO with a LHV of 35,260 MJ/ ton. The pyrolysis oil blend assumes woody biomass as the only feedstock material.

- NavigaTE assumes the following conversion ratios.

- TTW emission are calculated based on the LHV and CO2 emission factors. See appendix – supplementary data.

Conversion	Value	Unit
Dry wood biomass	1,89	Ton feedstock/ton fuel

Pyrolysis Oil Blend WTW Emissions

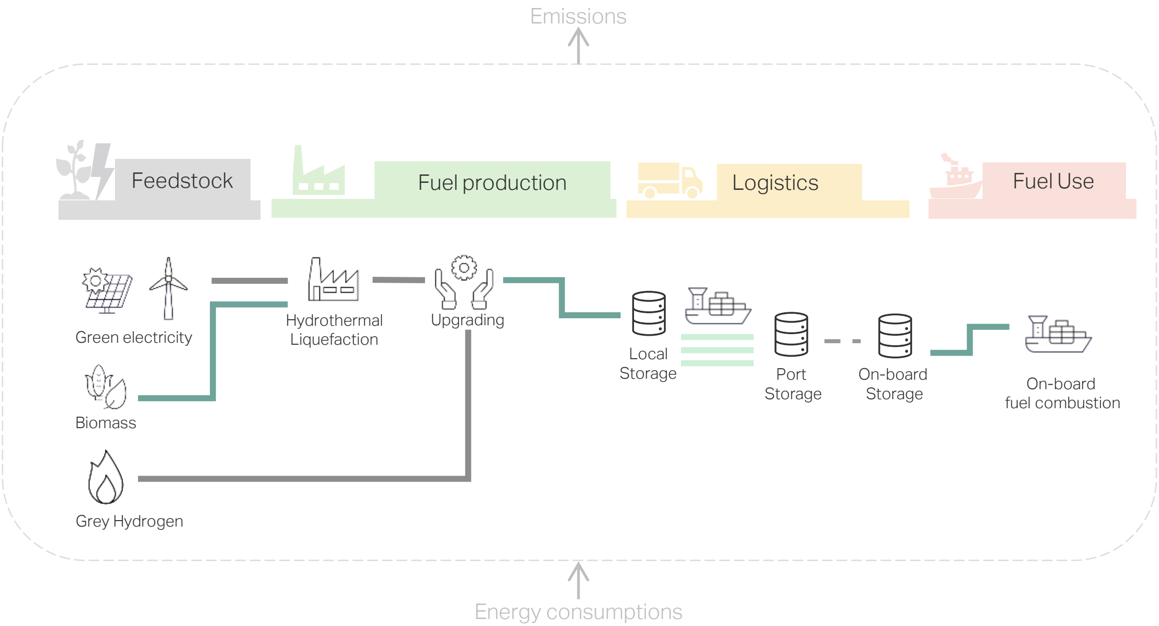


Pyrolysis Oil

Pyrolysis Oil WTW Scope

System boundary

The system boundary includes the whole supply chain from fuel production up to the delivery of pyrolysis oil to pyrolysis fuelled vessels and on-board combustion.



Pyrolysis Oil WTW inventory

Data collection for pyrolysis relies on secondary data from literature and partner input. The average confidence level is reported as 4, which is indicative of solid analysis behind the values.

Unit Process	Sub unit process	Parameter	Value	Unit
Feedstock production	Green electricity	Energy consumption	0	MWh/ton_{fuel}
Feedstock production	Biomass	CO_2eq emissions	0,09	$tonCO_2eq/ton_{BIOMASS}$
Feedstock production	Grey hydrogen	CO_2eq emissions	9,06	$tonCO_2eq/ton_{H2}$
Feedstock production	Energy consumption	CO_2eq emissions	0	$tonCO_2eq/ton_{fuel}$
Fuel Production	Fast Pyrolysis	Energy consumption	0	MWh/ton_{fuel}
Fuel Production	Upgrading	Energy consumption	0.05	MWh/ton_{fuel}
Fuel Production	Energy consumption	CO_2eq emissions	0	$tonCO_2eq/MWh$
Fuel Logistics	Local storage	Energy consumption	0	kWh/kg_{fuel}
Fuel Logistics	Fuel transport	Energy consumption	0	$Ton_{fuel}/voyage$
Fuel Logistics	Port storage	Energy consumption	0	kWh/kg_{fule}
Fuel Logistics	Onboard storage	Energy consumption	0	Ton_{fuel}/kg_{fuel}
Fuel Logistics	Energy consumption	CO_2eq emissions	0,0285	$tonCO_2eq/ton_{fuel}$
Fuel use	Onboard combustion	CO_2eq emissions	70,6	$kgCO_2eq/GJ$

*Combined demand for gasification and methanol synthesis.

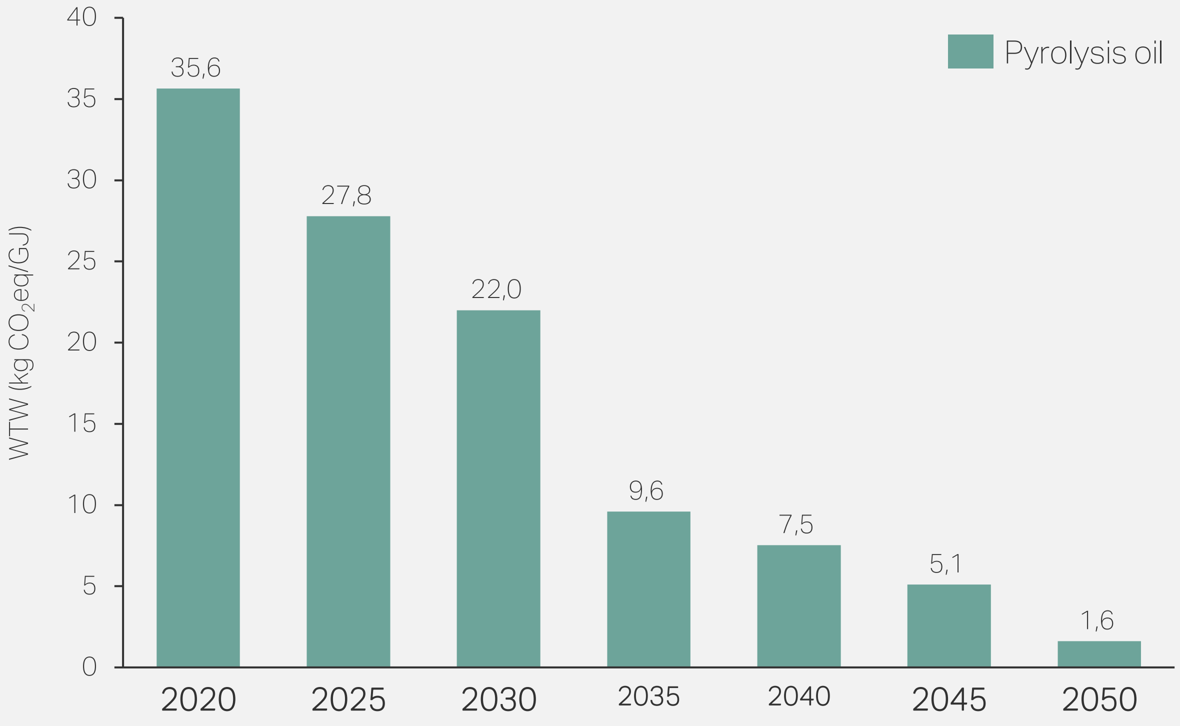
Pyrolysis Oil Assumptions

Data description

- Emissions from fuel logistics assumes a tanker speed of 12 knots, 0,375 ton/m3/year and distance travelled of 5,334 km, a voyage duration of 10 days and an overall capacity utilization of 40% to account for returning empty and loading/unloading operation.
- NavigaTE assumes a pyrolysis oil blend contains 70% LSFO with a LHV of 43,000 MJ/ ton. It also assumes the grey hydrogen will be gradually phased out from 2025 onwards where the use of blue hydrogen will become more prevalent. Green hydrogen is assumed to be the dominant hydrogen source in HTL Oil by 2040.
- NavigaTE assumes the following conversion ratios.
- TTW emission are calculated based on the LHV and CO2 emission factors. See appendix – supplementary data.

Conversion	Value	Unit
Dry wood biomass	3,94	Ton feedstock/ton fuel

Pyrolysis Oil WTW Emissions



Petroleum based fuels

Liquid Natural Gas

Data description

To conduct benchmarking activities, NavigaTE contains WTW emissions for a number of reference fuels. These include Liquid Natural Gas (LNG), Low Sulphur Fuel Oil (LSFO) and Liquified Petroleum Gas (LPG).

In order to estimate the TTW emissions (gCO_2e/MJ) at a fleet level, the percentage of main energy converters on LNG-fueled vessels was used to calculate a weighted average emission value.

2020 values are based on ships in operation and on order as of mid-2018 from ICCT's "The climate implications of using LNG as a marine fuel"

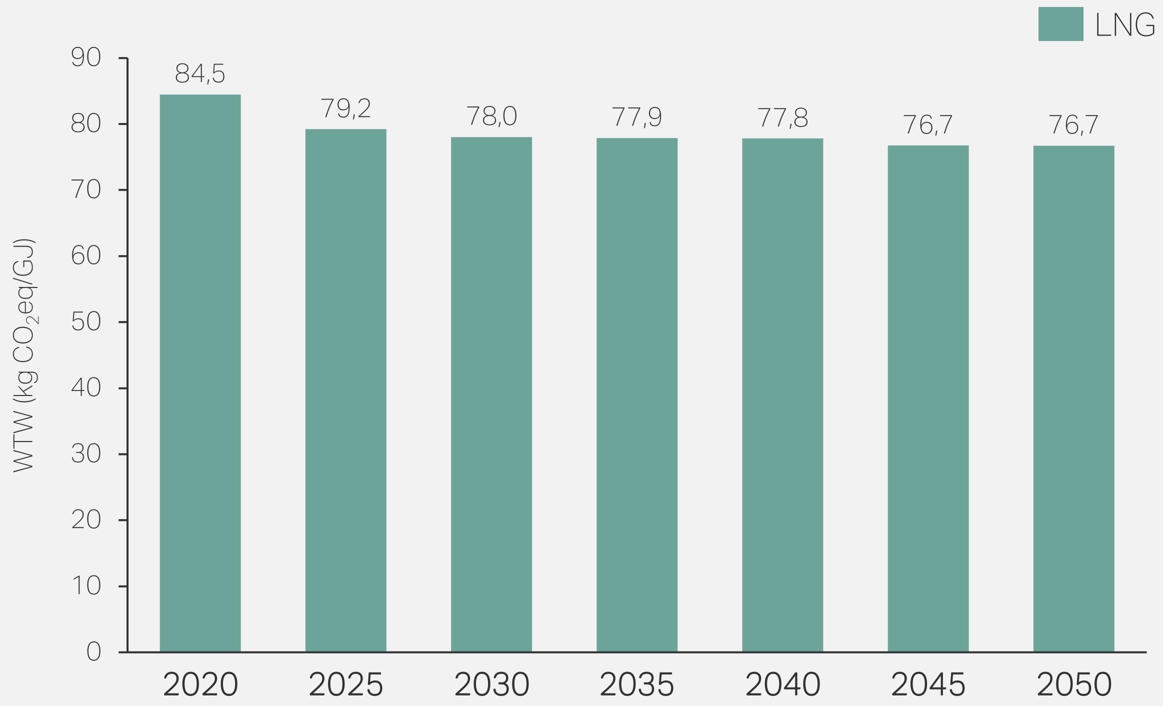
Emission values for subsequent years are scaled based on potential uptake of more efficient technologies like HPDF two-stroke engines and fuel cells. See tables in supplementary information.

Due to emission variance depending on onboard engine technology and operation, in particular the associated methane slip, a range for WTW emissions is given.

2050 emission values assume no methane slip due to improved engine and after-treatment technology or the use of fuel cells.

Parameter	Value	Unit
Fuel Production (Well-to-Tank)	20,48	kgCO2eq/GJ
Fuel use (Tank-to-Wake)	64,0	kgCO2eq/GJ

LNG WTW Emissions



Low Sulphur Fuel Oil

Data description

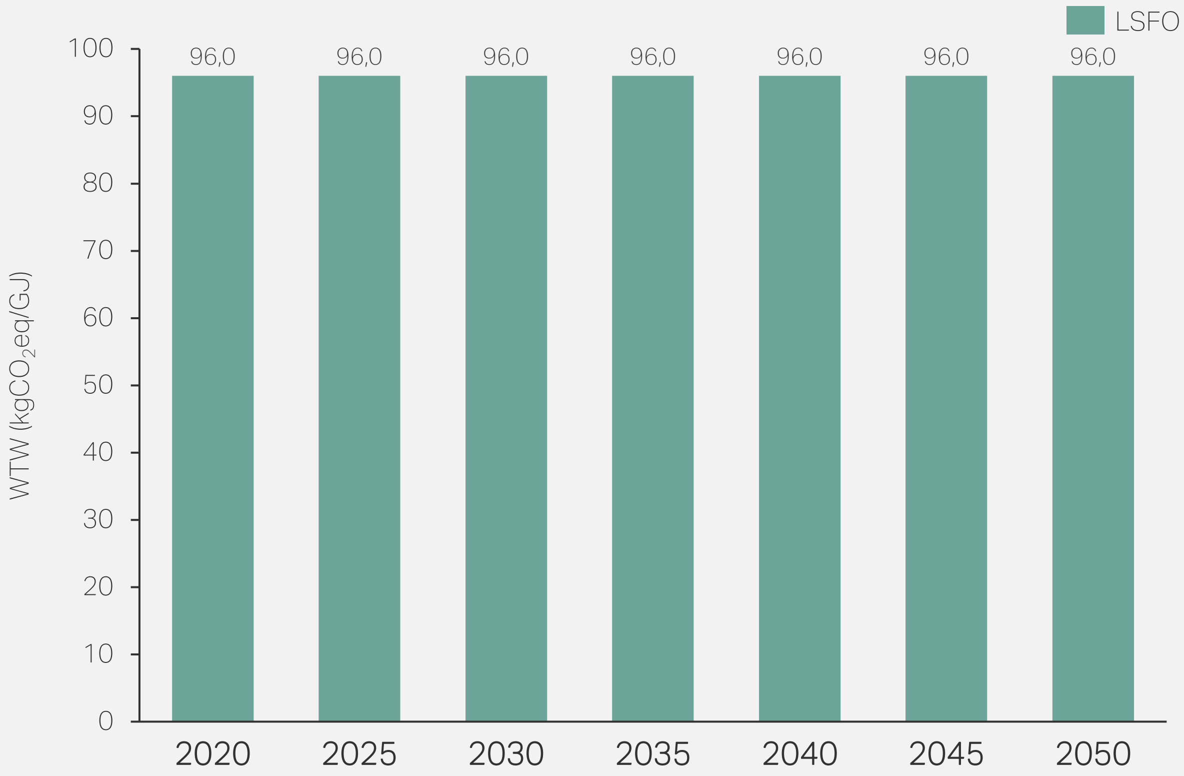
To conduct benchmarking activities, NavigaTE contains WTW emissions for a number of reference fuels. These include Liquid Natural Gas (LNG), Low Sulphur Fuel Oil (LSFO), and Liquified Petroleum Gas (LPG).

WTW data for these fuel pathways have been collected from recognized sources. Details of the assumptions for LPG are described below.

TTW emission are calculated based on the LHV and CO2 emission factors. See appendix – supplementary data.

Parameter	Value	Unit
Fuel Production (Well-to-Tank)	15,9	kgCO2eq/GJ
Fuel use (Tank-to-Wake)	80,1	kgCO2eq/GJ

LSFO WTW Emissions



Liquified Petroleum Gas

Data description

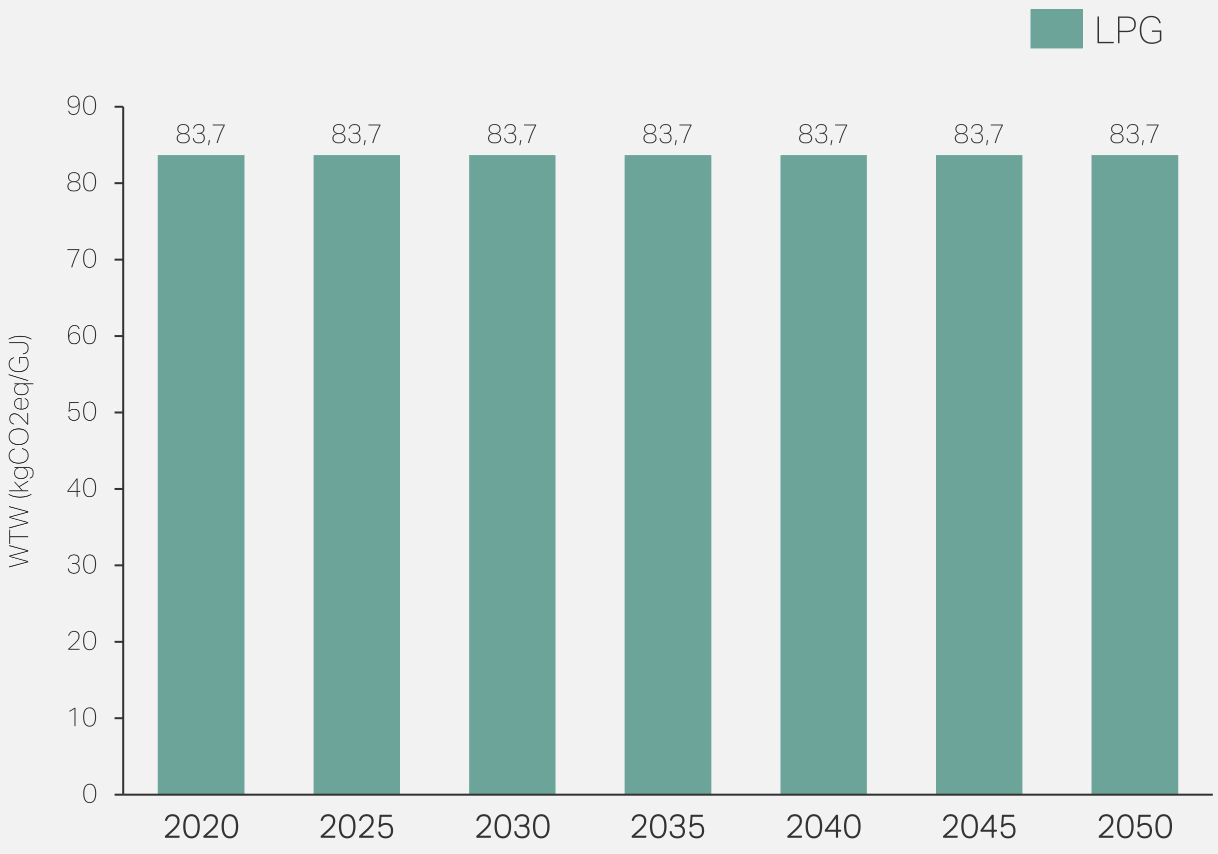
To conduct benchmarking activities, NavigaTE contains WTW emissions for a number of reference fuels. These include Liquid Natural Gas (LNG), Low Sulphur Fuel Oil (LSFO) and Liquified Petroleum Gas (LPG).

WTW data for these fuel pathways has been collected from recognised sources. Details of the assumptions for LPG are described below.

TTW emission are calculated based on the LHV and CO2 emission factors. See appendix – supplementary data.

Parameter	Value	Unit
Fuel Production (Well-to-Tank)	17,10	kgCO2eq/GJ
Fuel use (Tank-to-Wake)	66	kgCO2eq/GJ

LPG WTW Emissions



Supplementary Information

TTW Supplementary Data

Fuel	Emission Factor (tonCO2/ton of fuel)
Hydrogen	0
LSFO	3,41
LNG	3,2
NH3	0
Methanol	1,38
Methane	3,2
Diesel	3,41
Biodiesel (Pyr)	3,04
Biodiesel (HtL)	3,01
Biodiesel (Pyr blend)	1,85
Biodiesel (HtL blend)	1,58

Fuel	Lower Heating Value (MJ/ton)*
LSFO	42600
LNG	50000
LPG	46000
e-Ammonia	18800
e-Hydrogen	120000
Bio-methanol	19900
e-Methanol	19900
e-Diesel	42600
e-Methane	50000
Blue Ammonia	120000
Blue Hydrogen	120000
Biomethane	50048
Biodiesel (Pyr)	42000
Biodiesel (HtL)	43000
Biodiesel (Pyr blend)	39400
Biodiesel (HtL blend)	35260

*IMO Carbon Dioxide emission factors

TTW Supplementary Data

% of main converter type for LNG-fueled vessels

Engine Type	WTW (gCO2e/MJ)	2020	2025	2030	2035	2040
HPDF 2-stroke	58	12%	18%	27%	35%	37%
LPDF 2-stroke	67	7%	7%	5%	4%	4%
Steam/Gas Turbine	57	37%	30%	23%	16%	9%
LPDF 4-stroke	71	45%	45%	40%	35%	30%
Fuel Cell	57	0%	0%	5%	10%	20%

Engine Type	Fuel Consumption (g/kWh)	Methane Slip (g/kWh)	WTT Emissions (gCO_2e/MJ)	WTW Emissions (gCO_2e/kWh)	WTW Emissions (gCO_2e/MJ)
HPDF 2-stroke	135	0,25	19,6	506	78
LPDF 2-stroke	145	2,25	19,6	605	87
LPDF 4-stroke	165	3,5	19,6	717	91

NavigaTE Input	2020	2025	2030	2035	2040	2045	2050
TTW Emissions (gCO2e/MJ)	64	59	58	58	58	57	57

Assumption	Value
Emission Factor – LNG (gCO2/g fuel)	2,75
100-year Global Warming Potential – Methane	31
Lower calorific value (kJ/g LNG)	48
Lower calorific value (kJ/g Methane)	50

References:

International Council on Clean Transportation "The climate implications of using LNG as a marine fuel" February 2020

Sphera "2nd Life Cycle GHG Emission Study on the Use of LNG as Marine Fuel – On behalf of SEA-LNG and SGMF" 15.04.2021

ABS "Setting the course to low carbon shipping: View of the value chain"