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Development of the Well-to-Wake Life Cycle Assessment Model for Marine Fuels in R&D GREET 2025

Energy Systems & Infrastructure Analysis (ESIA)

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Development of the Well-to-Wake Life Cycle Assessment Model for Marine Fuels in R&D GREET 2025

by

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ACRONYMS AND ABBREVIATIONS

\dot{W}_i	Ship's instantaneous propulsive power demand at a given time t
\dot{W}_{ref}	Reference power
$\frac{\dot{W}_i}{\dot{W}_{ref}}$	Average ship's propulsive power demand
$Blendstock_A$	Energy consumption estimates for fuel blendstock A
$Blendstock_B$	Energy consumption estimates for fuel blendstock B
$Blendstock_i$	Fuel consumption of the fuel i
$EC_{Op.Mode}^{Aux}$	energy consumption of the auxiliary engines
$EC_{Op.Mode}^{Boiler}$	energy consumption of the steam turbine (and boilers)
$EC_{Op.Mode}^{ME}$	energy consumption of the main engine
$EC_{Op.Mode}^{Pilot Fuel}$	energy consumption of the pilot fuel
$EF_{Conversion}^{(metric,fuel)}$	emission factor for the conversion stage for a given metric and fuel type
$EF_{Feedstock}^{(metric,fuel)}$	emission factor for the feedstock stage for a particular metric and fuel type
$EF_{dual-fuel}^{(metric,fuel)}$	Emission factor for dual-fuel operation (LNG, methanol and ammonia groups)
$EM_{e,PM10-HFO}$	Energy-based PM ₁₀ emission factor (g/kWh) for HFO type of fuels
$EM_{e,PM10-MDO}$	Energy-based PM ₁₀ emission factor (g/kWh) for MDO type of fuels
$EM_{f,SOx}$	fuel-based SO _x emission factor
$Fuel_{\%i}$	fuel i in percentage (%)
$Power Output_j$	Power output (kW)
$SFC_{ME,i}$	Specific fuel consumption of the main engine using fuel i
SFC_{adj}	Adjustment factor (unitless)
$SFC_{base,pilot}$	Specific fuel consumption of the pilot oil
SFC_{base}	Base specific fuel consumption
$Trip_{Combustion}^{(Energy-based,dual-fuel)}$	total trip-level result for a specific energy-based emission-type group
$Trip_{Combustion}^{(Energy-based,single-fuel)}$	total trip-level result for a specific energy-based emission-type group associated with the combustion life-cycle stage
$Trip_{Combustion}^{(Fuel-based,dual-fuel)}$	total trip-level result for a specific fuel-based emission-type group associated with the combustion life-cycle stage
$Trip_{Combustion}^{(Fuel-based,single-fuel)}$	total trip-level result for a specific fuel-based emission-type group associated with the combustion life-cycle stage, under single-fuel engine configuration
$Trip_{Combustion}^{Energy,water}$	total trip-level result for a specific metric (water or energy group) associated with the combustion life-cycle stage
$Trip_{Conversion}^{metric}$	total trip-level result for a specific metric associated with the conversion life-cycle stage
$Trip_{Feedstock}^{metric}$	total trip-level result for a specific metric associated with the feedstock life-cycle stage
$W_{Op.Mode}^{Aux}$	power output of the auxiliary engine(s)
$W_{Op.Mode}^{Boiler}$	power output of the steam turbines (and boilers)
$W_{Op.Mode}^{ME}$	power output of the main engine

t_i	Instantaneous draught
t_{ref}	Reference draught
v_i	Instantaneous speed
v_{ref}	Reference speed
δ_w	correction factor to adjust the speed-power relationship
η_f	fouling modifier to the ship's propulsive efficiency
η_w	weather modifier to the ship's propulsive efficiency
Argonne	Argonne National Laboratory
BC	Black Carbon
BSFC	Specific Fuel Consumption
CAP	Criteria air pollutants
CH ₄	Methane
CO ₂	Carbon dioxide
DWT	Deadweight tonnage
ECA	Emissions Control Areas
EPA	Environmental Protection Agency
EtOH	Ethanol
FT-Diesel	Fischer Tropsch diesel
GHG	Greenhouse gases
GT	Gross Tonnage
GWP	Global warming potential
HFO	Heavy Fuel Oil
HHV	Higher Heating Value
HSD	High Speed Diesel
IDL	Indirect Liquefaction
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
LBSI	Lean-Burn Spark Ignition
LCA	Life-Cycle Analysis
LHV	Lower heating value
LNG	Liquefied natural gas
MCR	Maximum Continuous Rating
MDO	Marine Diesel Oil
MeOH	Methanol
MGO	Marine Gas Oil
MSD	Medium Speed Diesel
N ₂ O	Nitrogen dioxide
NH ₃	Ammonia
NO _x	Nitrogen oxides
PM ₁₀	Particulate matter with diameters measuring 10 micrometers or less
PM _{2.5}	Particulate matter with diameters measuring 2.5 micrometers or less
R&D GREET	Research and Development Greenhouse gases, Regulated Emissions, and Energy use in Technologies
RSZ	Reduced Speed Zone
SOG	Speed Over Ground

SO _x	Sulfur Oxides
SSD	Slow Speed Diesel
VLCC	Very Large Crude Carrier
VOC	Volatile organic compounds
WTH	Well-to-Hull
WTW	Well-to-Wake
<i>Additional Converters</i>	Fuel consumption of auxiliary engines or boilers
<i>Eng Rat</i>	'Main Engine Rating' of the ship
<i>Load</i>	'Load Factor (unitless)' of the main engine
<i>Op. Mode</i>	Operational Mode
<i>Pilot Fuel</i>	Pilot fuel consumption
<i>Sulfur</i>	sulfur content of the fuel (in percentage)
<i>Time</i>	Time in mode of operation
<i>m</i>	Draught ration exponent
<i>n</i>	Speed ration exponent

UNITS OF MEASURE

BTU	British Thermal Unit
g	gram(s)
gal	gallon(s)
J	Joule(s)
kg	Kilogram(s)
kJ	Kilojoule(s)
kn	Knot(s)
kWh	Kilowatt hours(s)
L	Liter(s)
lb	Pound(s)
MBTU	One thousand British Thermal Unit
MJ	megajoule
oz	Ounce

EXECUTIVE SUMMARY

The Marine analysis capabilities in the 2025 Research and Development Greenhouse gases, Regulated Emissions, and Energy use in Technologies (R&D GREET) have been updated to incorporate the latest findings from the Fourth International Maritime Organization (IMO) GHG Study.¹ To support these updates and enhance user flexibility, the former single marine module used in previous R&D GREET versions has been split into two workbook tabs: The Marine_Fuel tab, which covers the fuel-cycle, and the Marine_Trip tab, which covers the trip-cycle.

In the Marine_Fuel tab, fuel cycle results for 39 marine fuels are available—assuming a slow speed diesel engine—and can be seen in Appendix A. However, there are options for changing feedstocks for multiple fuels, ability to view results with or without pilot fuels for fuels such as methanol and ammonia, and carbon capture options. All these combinations make the number of total possible pathways over one hundred. For each pathway, life cycle emission results are divided into feedstock, conversion, and combustion categories, along with pilot fuel supply chain emissions for fuels used in dual fuel engines.

In the newly created Marine_Trip tab, users can view the life cycle emissions of using these fuels from a trip perspective. Compared to R&D GREET 2024, 16 new types of vessels are added in R&D GREET 2025. Examples of results assuming the default size for each vessel type are available in Appendix A. Additional information categories on vessels are included such as vessel size, main propulsion type, engine power rating, combustion cycle, etc. based on the Fourth IMO GHG Study.¹ Operational mode of the trip, fuel consumption, and load calculation were updated based on the report. The fuel consumption calculation also incorporates low-load adjustment, speed–power correction, weather correction, and fouling correction factors. Furthermore, fuel consumption in boilers or steam turbines is also added for the first time, besides fuel use in main propulsion engines and auxiliary engines.

This effort makes the R&D GREET Marine capabilities more robust than before. Users will be able to estimate fuel consumption more accurately for more diverse choices of vessel categories, vessel sizes, and energy converters.

1 Introduction

The marine sector is very important to the US economy. It also has global implications as 90% of all goods are moved by ships.² Studying the diverse aspects of the marine sector in a similar system boundary is difficult because of its variety of vessel characteristics such as vessel types, energy converter choices. The fuel choices are also diverse which further complicates a harmonized comparison.

Marine fuel/energy pathways have been developed in the R&D Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (R&D GREET®) model to increase our understanding of current and future energy sources and propulsion systems.³ Argonne's R&D GREET model has been developed and maintained through ongoing support from the U.S. Department of Energy offices and other sponsors for over 30 years. The R&D GREET model is updated annually by Argonne National Laboratory.

The goal of the R&D GREET Marine tabs is to allow the users to view default and customized (i.e., user-defined) life cycle results for marine energy systems. While the Marine_Fuel tab shows harmonized comparison between fuel options, Marine_Trip tab allows the user to calculate trip-based emissions. The separate tab creation was required to put additional vessel- and trip-related factors that can influence the fuel consumption and, therefore, life cycle assessment on a trip-basis. The primary goal of the updates made in R&D GREET 2025 is to incorporate the latest information from IMO 4th GHG Study for increased vessel choices, selection of diverse engine and capacity choices, more accurate consumption of fuel quantity, estimation of GHGs (CO₂, CH₄, N₂O, VOC, and CO) and other criteria air pollutant emissions (SO_x, NO_x, PM_{2.5}, PM₁₀).

The functional unit for Marine_Fuel tab is on an energy basis, suitable for comparing fuels for use in internal combustion engines when the fuels do not affect engine efficiency significantly. Users can select between several energy units such as grams per MJ, kJ, J, MMBTU, BTU, and kWh. The functional unit for Marine_Trip is based on per trip or per million tonne-kilometers. The tonne-kilometers and trip total functional units are suitable for comparing emissions from fuel use between different vessels in the same category.

The system boundary, in both tabs, covers all stages of the supply chain of marine fuel production pathways, including feedstock production, feedstock transportation, fuel production, fuel transportation and distribution, and fuel combustion (Figure 1). This is consistent with the ISO 14040 standards and the methodology adopted in the studies that were incorporated in both tabs.⁴⁻⁹ Results are presented by life cycle stages. For example, for biooils, results are divided into feedstock, conversion, and combustion stages.⁵ For waste feedstocks such as manure or corn stover, upstream impacts are attributed to the primary product, and therefore, waste feedstock impacts are tracked from the point they are collected for use. In cases where there are coproducts, impacts are allocated based on the R&D GREET default coproduct management method (i.e., system expansion/displacement or allocation by mass or energy).

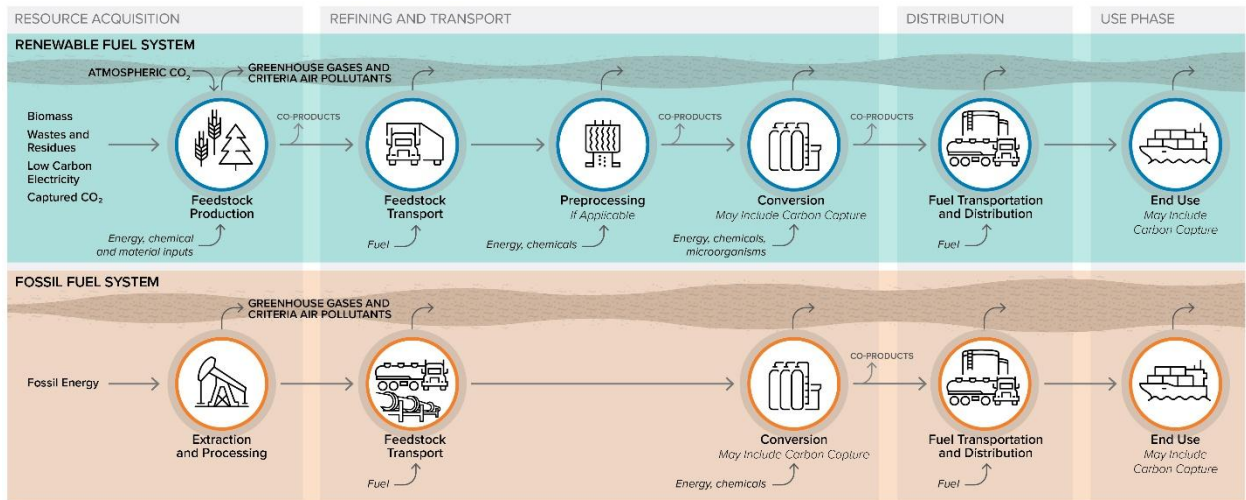


Figure 1. System boundary of marine fuels presented in the marine tabs.

The environmental metrics covered in both Marine_Fuel and Marine_Trip tabs are harmonized with the rest of the R&D GREET model.³ The LCA results can be generated for GHG emissions including CO₂, CH₄, and N₂O; criteria pollutant emissions including sulfur oxides (SO_x), nitrogen oxides (NO_x), particulate matter (PM_{2.5}, PM₁₀), carbon monoxide (CO), and volatile organic compounds (VOC); energy use by type including petroleum, natural gas, and coal; and water consumption. For total GHG emissions, results are presented in grams of CO₂ equivalent (gCO₂e) based on the global warming potential (GWP) characterization factors from the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report for a 100-year time horizon.¹⁰ Biogenic carbon is considered carbon neutral in the results presented and therefore not included in CO₂ results and assigned a GWP of zero in GHG totals.

1.1 Fuels included in the Marine_Fuel Tab

The pathways added to date reflect outcomes of projects sponsored by the U.S. Department of Energy’s Bioenergy Technologies Office, and the U.S. Department of Transportation’s Maritime Administration.⁴⁻⁹ They include a host of pathways ranging from conventional fossil fuel pathways as well as new biofuel pathways developed specifically for marine applications, such as biooils and partially upgraded biocrudes from pyrolysis and hydrothermal liquefaction and Fischer-Tropsch fuels from biomass and fossil feedstocks (Table 1). The pathways also include those leveraging other work on renewable diesel and natural gas. The R&D GREET marine energy pathways are being further developed through ongoing studies related to methanol and ammonia—both conventional and renewable—for marine vessels. The fuels covered in both Marine_Fuel and Marine_Trip are as follows –

1. Ammonia
2. Biocrude
3. Biodiesel
4. Biooil
5. Ethanol
6. FT-Diesel
7. Heavy Fuel Oil
8. Liquefied Natural Gas
9. Marine Diesel Oil
10. Marine Gas Oil
11. Methanol

12. Pyrolysis Oil
13. Renewable Diesel
14. Straight Vegetable Oil

Fuel- and trip-based results presented in the Marine_Fuel tab are connected to the other upstream or supply-chain emission related factors that are presented in other tabs. Understanding the connection to those tabs is important to explore the full potential of marine fuel capabilities in R&D GREET. For example, there are several pathways for which multiple feedstock options are available. But to view those feedstock options, users need to visit those other tabs. A list of such connections is presented in Table 1.

Table 1. Pathways in R&D GREET 2025 and their dependency.

Fuel groups	Precedent tab
HFO, MDO, MGO	Petroleum
FT-Diesel	MeOH_FTD
LNG	NG
Renewable Diesel, Biodiesel, Straight Vegetable Oil	Biooil
Ethanol	EtOH
Methanol	MeOH_FTD
e-FT fuel	E_fuel
Ammonia	Ag_Inputs
Pyrolysis oil, Biocrude, Marine Biooil	Pyrolysis_IDL

The results generated in the R&D GREET Marine tabs reflect the full life cycle of fuel production and use based on an LCA framework developed in previous work by Argonne researchers.⁴⁻⁹

1.2 Vessels included in the Marine_Trip tab

The vessels included in the Marine_Trip tab are the ones presented in the IMO 4th GHG Study –

15. Bulk carrier
16. Container
17. Oil tanker
18. Chemical tanker
19. General cargo
20. Liquefied gas tanker
21. Other liquids tankers
22. Ferry-pax only
23. Cruise
24. Ferry-RoPax
25. Refrigerated bulk
26. Ro-Ro (Roll On, Roll Off)
27. Vehicle carrier
28. Yacht
29. Service - tug
30. Miscellaneous - fishing
31. Offshore
32. Service - other
33. Miscellaneous – other

Capacities for these vessels, wherever available, are included. For example, for bulk carriers, six different capacities (in DWT or dead weight tonnage) are included; starting from 0-9999 DWT to 200000+ DWT, keeping 35000-59999 DWT as the default capacity. For each vessel, information on multiple energy converters—main engine, auxiliary engine, and boiler—is included. More options, such as fuels available for or compatible with certain vessels and energy converters, are discussed in Section 2 of this report.

2 Expansions in the Marine Model of R&D GREET1 2025

As with other transportation modes in the R&D GREET model, the former Marine_WTH provided outputs for four key metrics (i) energy consumption, (ii) greenhouse GHG emissions, (iii) water consumption, and (iv) criteria air pollutants (CAPs). Within this scope, the tab provides results for (i) trip-specific vessel operations and (ii) the overall fuel-cycle performance by marine fuel. These results are now split into two tabs—Marine_Trip and Marine_Fuel—described below.

2.1 Marine_Fuel tab

2.1.1 Scenario Selection

This subsection contains five drop-down lists, as shown in Figure 2. The first drop-down list allows the user to select the main engine type, choosing from Slow Speed Diesel (SSD), Medium Speed Diesel (MSD), Steam Turbine (ST), and Gas Turbine (GT), as presented in Figure 3.

The second drop-down list pertains to the auxiliary engine type, with options between MSD and high speed diesel (HSD). The third drop-down, indicates whether pilot oil will be considered in the calculations. If ‘Fuel only’ is selected, well to wake (WTW) results are based solely on the main fuel. If ‘With pilot oil’ is selected, the pilot oil use will be included in the results when methanol and ammonia fuel types are selected.

The fourth drop-down list specifies whether carbon dioxide (CO₂) is captured during the production of ammonia (NH₃) from natural gas. Finally, the fifth drop-down list pertains to the feedstock source for liquefied natural gas (LNG) production, as shown in Figure 4.

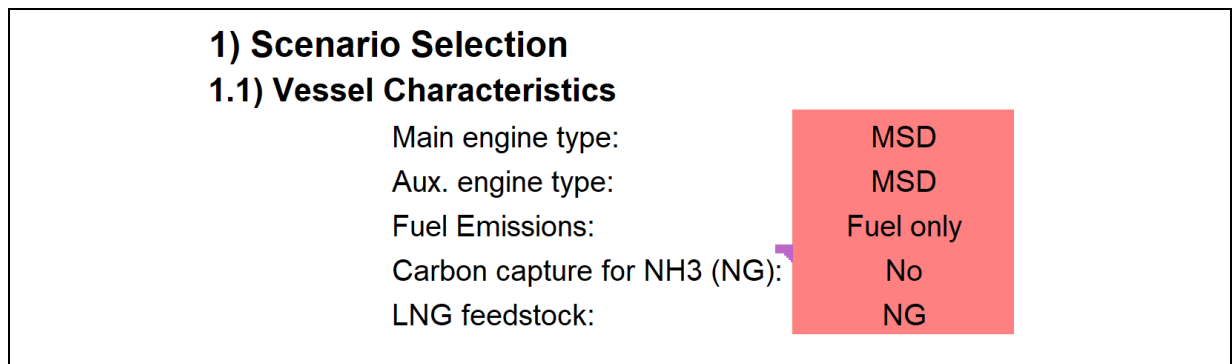


Figure 2. Scenario selection section showing engine type and fuel production characteristics in the Marine_Fuel tab (R&D GREET 2025).

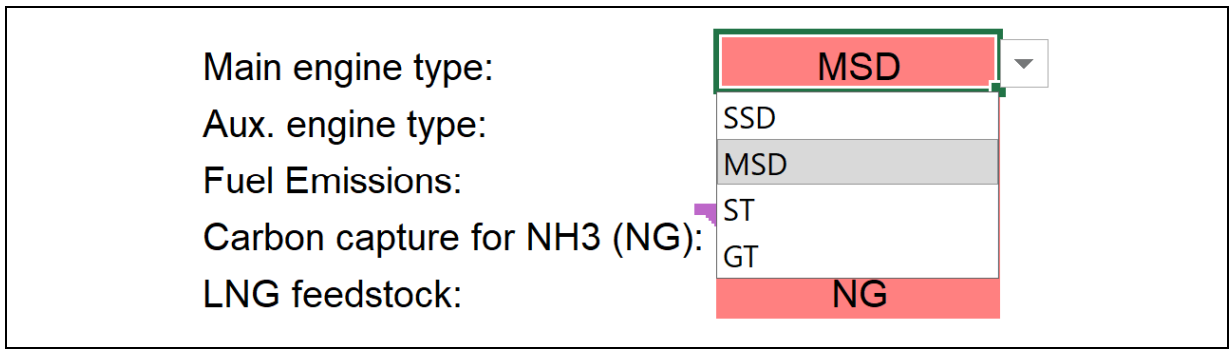


Figure 3. Main engine type selection in the Marine_Fuel tab (R&D GREET 2025), showing options for SSD (Slow Speed Diesel), MSD (Medium Speed Diesel), ST (Steam Turbine), and GT (Gas Turbine).

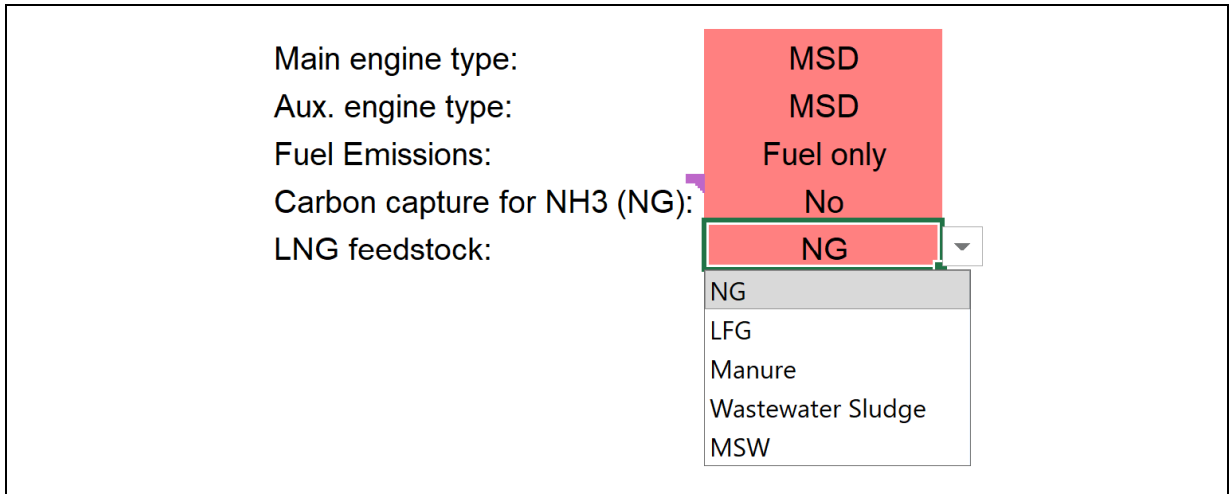


Figure 4. LNG feedstock source drop-down list for selecting among natural gas (NG), landfill gas (LFG), municipal solid waste (MSW), manure, and wastewater sludge in the Marine_Fuel tab (R&D GREET 2025).

2.1.2 Summary Results

This section presents the summary results for the well-to-wake (WTW) analysis, disaggregated into feedstock, conversion, combustions and overall WTW results, as shown in Figure 5. The feedstock stage includes emission associated with producing the feedstock used to generate the selected fuel. The conversion stage represents the process of converting the feedstock into fuel. The combustion stage accounts for the emissions released when the fuel is combusted, considering the vessel characteristics previously specified (Figure 2). Finally, the WTW results represent the sum of these stages. Users may adjust several dropdown lists, such as the ‘Selected fuel type’, ‘Engine type’, ‘Energy unit’, ‘Emission Unit’, and ‘Energy Functional Unit’.

The ‘Selected fuel type’ allows the user to choose from the 39 available fuels in the Marine_Fuel tab, as shown in Figure 6. The selected fuel is assigned to either the main engine or the auxiliary engine, depending on whether 1 or 2 is selected in the ‘Engine Type’ drop-down list.

Users can also view the results in different energy, emission, and functional energy units. Available energy units include BTU, MBTU, J, kJ, MJ; emission units include g, mg, kg, lb, oz; and functional energy units include BTU, MBTU, J, kJ, MJ. The results displayed in the table are based on the units selected (2nd column).

2) Summary Results

2.1.) Selected Fuels: Energy Consumption, Water Consumption, and Emissions

Selected fuel type: MGO (0.1% sulfur)
 Engine type: 1
 1--Main engine, 2--Aux engine
 Energy Unit: Btu
 Emission Unit: g
 Energy Functional Unit: MJ

	Units	Feedstock	Conversion	Combustion	Well-to-Wake
Total energy	Btu/MJ	58	76	948	1,082
Fossil fuels	Btu/MJ	54	75	948	1,076
Coal	Btu/MJ	4.91	1.32	0.00	6.23
Natural gas	Btu/MJ	39	42	0.00	81
Petroleum	Btu/MJ	9.80	32	948	989
Water consumption	gal/MJ	0.02	0.00	0.00	0.02
VOC	g/MJ	0.00	0.00	0.09	0.10
CO	g/MJ	0.01	0.00	0.08	0.09
NOx	g/MJ	0.01	0.01	2.04	2.06
PM10	g/MJ	0.00	0.00	0.03	0.03
PM2.5	g/MJ	0.00	0.00	0.03	0.03
SOx	g/MJ	0.00	0.00	0.05	0.05
BC	g/MJ	0.00	0.00	0.00	0.00
OC	g/MJ	0.00	0.00	0.01	0.01
CH4	g/MJ	0.09	0.01	0.00	0.10
N2O	g/MJ	0.00	0.00	0.00	0.00
CO2	g/MJ	4.70	5.09	74	83
CO2 (w/ C in VOC & CO)	g/MJ	4.72	5.10	74	84
GHGs	g CO2e/MJ	7.29	5.40	75	88
VOC: Urban	g/MJ	0.00	0.00	0.00	0.00
CO: Urban	g/MJ	0.00	0.00	0.00	0.00
NOx: Urban	g/MJ	0.00	0.00	0.00	0.00
PM10: Urban	g/MJ	0.00	0.00	0.00	0.00
PM2.5: Urban	g/MJ	0.00	0.00	0.00	0.00
SOx: Urban	g/MJ	0.00	0.00	0.00	0.00
BC: Urban	g/MJ	0.00	0.00	0.00	0.00
OC: Urban	g/MJ	0.00	0.00	0.00	0.00
Biogenic CO2 credit	g/MJ	0.00			

Figure 5. Summary results table showing the WTW analysis, disaggregated into feedstock, conversion, combustions and overall WTW results in the Marine_Fuel tab (R&D GREET 2025).

2) Summary Results
2.1.) Selected Fuels: Energy Consumption, Water Consumption, and Emissions

Selected fuel type: **MGO (0.1% sulfur)**

Engine type: **Combustion** / Well-to-Wake

Energy Unit:

Total energy	MGO (0.1% sulfur)			948	1,082
Fossil fuels	FT-Diesel (NG)			948	1,076
Coal	Liquefied Natural Gas (LNG)			0.00	6.23
Natural gas	FT-Diesel (Biomass&Coal)	Btu/MJ	39	42	0.00
Petroleum		Btu/MJ	9.80	32	948
Water consumption		gal/MJ	0.02	0.00	0.00

Figure 6. Fuel options available in the Marine_Fuel tab (R&D GREET 2025).

2.1.3 Input Parameters

2.1.3.1 Fuel Properties

This subsection compiles information on the fuel properties of the 39 available fuels in the Marine_Fuel tab (R&D GREET 2025). The listed properties include lower heating value (LHV, in MJ/kg), higher heating value (HHV, in MJ/kg), density (kg/L), carbon ratio (% by weight), sulfur ratio (% by weight), and the carbon credit (% by weight) a particular fuel can credit in combustion stage depending on the feedstock used.

2.1.3.2 Engine Type and Energy Consumption

This subsection presents the energy consumption (Btu/kWh of operation) of the main engine and auxiliary engine, based on the LHV and the fuel consumption for each engine converter and fuel group type. Figure 7 shows the assumed fuel consumption for each engine type and fuel. These values were updated using data from the Fourth IMO GHG Study report and are further described in section Fuel Consumption within the Marine_Trip tab, also displayed in Table B7 in Appendix B.

5) Supporting information
5.1.) Fuel Consumption (g/kWh)

Main engine		MGO/MDO	RM/HFO	NG / MeOH / Diesel energy Ammonia consumption
	SSD	165.0	175.0	6,692
	MSD	175.0	185.0	7,098
	ST	320.0	340.0	12,979
	GT	300.0	305.0	12,168
	LNG			148.0
	Methanol			332.6
	Ammonia			350.0
Aux engine		MGO/MDO	RM/HFO	Diesel energy consumption
	HSD	185.0	195.0	7,503
	MSD	185.0	195.0	7,503
	LNG			156.0

Figure 7. Fuel consumption values for the main engine and auxiliary engine per fuel type group (Table 5.1 of the Marine_Fuel tab, R&D GREET 2025).

2.1.3.3 Emission Factors

This subsection presents the emission factors for each fuel type, which are used in the combustion section to calculate emissions by dividing the emission factor (g/kWh) by the corresponding energy consumption (Btu/kWh). Figure 8 shows the assumed emission factors for each engine type, fuel type group, and emitter. These values were updated using data from the Fourth IMO GHG Study report and are further described in section Emission Factors within the Marine_Trip tab, and are also shown in Table B8 and Table B9 in Appendix B.

5.2) Emission Factors (g/kWh)										
Tier		Main engine					Aux. engine			
		SSD	MSD	ST	GT	LNG	MSD	HSD	LNG	
VOC (HC)		0.632	0.527	0.105	0.105	0.5	0.421	0.421	0.5	
CO		0.54	0.54	0.2	0.1	1.3	0.54	0.54	1.3	
NOx	HFO	0	18.1	14	2.1	6.1	1.3	11.2	11.2	1.3
		1	17	13	2.1	6.1	1.3	11.2	11.2	1.3
		2	14.4	10.5	2.1	6.1	1.3	11.2	8.2	1.3
	MGO/MDO	3	3.4	2.6	2.1	6.1	1.3	2.0	2.6	1.3
		0	18.1	14	2.1	6.1	1.3	11.2	11.2	1.3
		1	17	13	2.1	6.1	1.3	9.8	11.2	1.3
	2	14.4	10.5	2.1	6.1	1.3	7.7	10.5	1.3	
	3	3.4	2.6	2.1	6.1	1.3	2	2.6	1.3	
	PM10	HFO (2.7% sulfur)	1.42	1.42	0.03	0.03		1.42	1.42	
HFO (0.5% sulfur)		0.81	0.78	0.03	0.03		0.75	0.75		
HFO (0.1% sulfur)		0.70	0.66	0.03	0.03		0.63	0.63		
MDO (1.92% sulfur)		0.67	0.69	0.03	0.03		0.72	0.72		
MDO (0.5% sulfur)		0.30	0.30	0.03	0.03		0.31	0.31		
MDO (0.1% sulfur)		0.19	0.19	0.03	0.03		0.19	0.19		
MGO (1.0% sulfur)		0.42	0.43	0.03	0.03		0.44	0.44		
MGO (0.5% sulfur)		0.29	0.30	0.03	0.03		0.30	0.30		
MGO (0.1% sulfur)		0.20	0.19	0.03	0.03		0.19	0.19		
						0.020			0.02	
CH4		0.01	0.01	0.002	0.002	5.5	0.01	0.01	5.5	
N2O		0.03	0.03	0.04	0.040	0.02	0.04	0.04	0.02	

Figure 8. Emission factors values for the main engine and auxiliary engine per fuel type group (Table 5.2 of the Marine_Fuel tab, R&D GREET 2025).

2.1.4 Fuel-specific Results by Life-cycle Stages: Energy Consumption, Water Consumption, and Emissions

This section presents the life-cycle results for each of the 39 fuels, disaggregated by stage: feedstock, conversion, combustion, pilot fuel, and overall WTW. The units displayed in this table depend on the units previously set in the Summary Results section. Users can compare emissions across different fuels in these tables. In the pilot fuel stage, only methanol and ammonia display value. All stages are aggregates in the WTW section.

2.2 Marine_Trip tab

The main updates incorporated into the marine model tabs are summarized in Table 2. These updates are primarily based on the Fourth IMO GHG study report,¹ and detailed descriptions are provided below.

Table 2. Summary of the new additions to the marine module R&D GREET 2025 tab – specific to trip results.

Category	R&D GREET 2024 Rev1	R&D GREET 2025
	Marine_WTH	Marine_Trip
Vessel types	3	19
Vessel sizes	-	1-9
Engine types	SSD, MSD, ST, GT	SSD 2-Stroke, MSD 4-Stroke, HSD 4-Stroke, Gas Turbines, Auxiliary Engine(s), and Steam Turbines (and Boilers)
2-stroke vs 4-stroke	-	SSD 2-Stroke, MSD 4-Stroke, HSD 4-Stroke
Combustion cycles	-	Diesel, Otto, Brayton
Single vs. dual-fuel	Methanol, Ammonia	Methanol, Ammonia, LNG
Pilot fuel only under load factor	-	25% engine load
Operation mode	EPA terminology (Cruise, RSZ, Hotelling)	IMO terminology (Sea Normal Cruising, Slow Transit, Maneuvering, Anchored, At Berth)
Emission Control Area (ECA)	Reduced Speed Zone	ECA
Emission factors	EPA & Unknown	IMO 4 th GHG Study

Note: EPA: Environmental Protection Agency; GHG: Greenhouse Gas; GT: Gas Turbine; HSD: High Speed Diesel; IMO: International Maritime Organization; LNG: Liquefied Natural Gas; MSD: Medium Speed Diesel; R&D GREET: Research & Development Greenhouse Gases, Regulated Emissions, and Energy use in Technologies; SSD: Slow Speed Diesel; ST: Steam Turbine.

2.2.1 Scenario Selection

When the Marine_Trip tab is opened, the first step is *Scenario Selection*, where users define the vessel and trip characteristics for their analysis. The *Scenario Selection* section is divided into two subsections: (i) *Vessel Type, Engine Type, Emission Regulation* and (ii) *Trip Characteristics*, described below. These two subsections are the only areas that require user input. All remaining sections consist of supporting tables that provide the necessary reference data and intermediate calculations for the tab’s key results: (i) energy consumption, (ii) GHG emission, (iii) water consumption, and (iv) criteria air pollutants (CAPs).

2.2.1.1 Vessel Type, Engine Type, Emission Regulation

This subsection contains eight drop-down lists (Figure 9). The user first selects the vessel type, followed by the vessel size (Figure 10). Originally, users could choose from only three vessel types—bulk carrier, container-large and tanker VLCC—but the list has now been expanded to 19 options. Besides those three vessel types, users can select chemical tanker, ferry-pax only, cruise, general cargo, liquified gas tanker, ferry-RoPax, refrigerated bulk, Ro-Ro, vehicle carrier, other liquid tankers, yacht, service – tug, miscellaneous – fishing, offshore, service – other, and miscellaneous – other. For each vessel type, different size categories are available according to their grouping characteristics (Figure 11). Table 3 presents the available vessel size options for each vessel type, based on Fourth IMO GHG study.¹

Marine Module

1) Scenario Selection:

1.1) Vessel Type, Engine Type, Emission Regulation

Vessel Characteristics	Vessel type:	Bulk
	Vessel size:	35000-59999 DWT (Default)
	IMO NOx regulation Tier:	2
Select and change all main propulsion type:		SSD 2-Stroke
	Combustion cycle:	Diesel
	Single vs. dual-fuel engine:	Single-fuel
Pilot fuel only in dual fuel engine when load factor is below:		Not Applicable
	Regional characteristics:	Pre-defined

Figure 9. Vessel Characteristics subsection from the Marine_Trip tab (R&D GREET 2025).

Vessel Characteristics	Vessel type:	Bulk
	Vessel size:	Bulk
	IMO NOx regulation Tier:	Container
Select and change all main propulsion type:		Oil tanker
	Combustion cycle:	Chemical tanker
	Single vs. dual-fuel engine:	General cargo
Pilot fuel only in dual fuel engine when load factor is below:		Liquefied gas tanker
	Regional characteristics:	Other liquids tankers
		Ferry-pax only
		Cruise
		Ferry-RoPax
		Refrigerated bulk
		Ro-Ro

Figure 10. Dropdown list for vessel type from the Marine_Trip tab (R&D GREET 2025).

Vessel Characteristics	Vessel type:	Bulk
	Vessel size:	35000-59999 DWT (Default)
	IMO NOx regulation Tier:	0-9999 DWT
Select and change all main propulsion type:		10000-34999 DWT
	Combustion cycle:	35000-59999 DWT (Default)
	Single vs. dual-fuel engine:	60000-99999 DWT
Pilot fuel only in dual fuel engine when load factor is below:		100000-199999 DWT
	Regional characteristics:	200000+ DWT
		Pre-defined

Figure 11. Dropdown list for vessel size from the Marine_Trip tab (R&D GREET 2025).

The third selection pertains to the NO_x regulation Tier level (Figure 12). The default setting estimates results based on Tier level 2, but the user can modify this to Tier 0, 1, 2 and 3. The fourth drop-down list corresponds to the main propulsion type (Figure 13), which is dependent on the vessel type, as shown on Table 4. The available main engine options are:

- Slow Speed Diesel (SSD 2-Stroke)
- Medium Speed Diesel (MSD 4-Stroke)
- High-Speed Diesel (HSD 4-Stroke)
- Gas Turbines

Not all vessel types operate under all engine configurations. Table 4 lists the available options for each vessel type.

Vessel Characteristics	Vessel type:	Bulk
	Vessel size:	35000-59999 DWT (Default)
	IMO NOx regulation Tier:	2
Select and change all main propulsion type:		0
	Combustion cycle:	1
	Single vs. dual-fuel engine:	2
		3
Pilot fuel only in dual fuel engine when load factor is below:		25%
	Regional characteristics:	User-defined

Figure 12. Dropdown list for IMO NO_x regulation Tier type from the Marine_Trip tab (R&D GREET 2025).

Vessel Characteristics	Vessel type:	Container
	Vessel size:	35000-59999 DWT (Default)
	IMO NOx regulation Tier:	2
Select and change all main propulsion type:		SSD 2-Stroke
	Combustion cycle:	SSD 2-Stroke
	Single vs. dual-fuel engine:	MSD 4-Stroke
		Gas Turbines
Pilot fuel only in dual fuel engine when load factor is below:		25%
	Regional characteristics:	User-defined

Figure 13. Dropdown list for main propulsion type from the Marine_Trip tab (R&D GREET 2025).

Table 3. Vessel sizes per vessel type options (Table 6.5 of Marine_Fuel tab from R&D GREET 2025).

Vessel type	Engine type
Bulk	0-9999 DWT, 10000-34999 DWT, 35000-59999 DWT (Default), 60000-99999 DWT, 100000-199999 DWT, 200000+ DWT
Container	0-999 TEU, 1000-1999 TEU, 2000-2999 TEU, 3000-4999 TEU (Default), 5000-7999 TEU, 8000-11999 TEU, 12000-14499 TEU, 14500-19999 TEU, 20000+ TEU
Oil tanker	0-4999 DWT, 5000-9999 DWT, 10000-19999 DWT, 20000-59999 DWT, 60000-79999 DWT, 80000-119999 DWT (Default), 120000-199999 DWT, 200000+ DWT
Chemical tanker	0-4999 DWT, 5000-9999 DWT, 10000-19999 DWT (Default), 20000-39999 DWT, 40000+ DWT
General cargo	0-4999 DWT, 5000-9999 DWT, 10000-19999 DWT (Default), 20000+ DWT
Liquefied gas tanker	0-49999 CBM, 50000-99999 CBM, 100000-199999 CBM (Default), 200000 CBM
Other liquids tankers	0-999 DWT, 1000+ DWT (Default)
Ferry-pax only	0-299 GT, 300-999 GT, 1000-1999 GT (Default), 2000+ GT
Cruise	0-1999 GT, 2000-9999 GT, 10000-59999 GT, 60000-99999 GT (Default), 100000-149999 GT, 150000+ GT
Ferry-RoPax	0-1999 GT, 2000-4999 GT, 5000-9999 GT (Default), 10000-19999 GT, 20000+ GT
Refrigerated bulk	0-1999 DWT, 2000-5999 DWT, 6000-9999 DWT (Default), 10000+ DWT
Ro-Ro	0-4999 DWT, 5000-9999 DWT, 10000-14999 DWT (Default), 15000+ DWT
Vehicle carrier	0-29999 GT, 30000-49999 GT (Default), 50000+ GT
Yacht	0+ GT
Service - tug	0+ GT
Miscellaneous fishing	- 0+ GT
Offshore	0+ GT
Service - other	0+ GT

Table 4. Main engine type selection per vessel type (Table 6.4 of Marine_Fuel tab from R&D GREET 2025).

Vessel type	Engine type
Bulk	SSD 2-Stroke, MSD 4-Stroke
Container	SSD 2-Stroke, MSD 4-Stroke, Gas Turbines
Oil tanker	SSD 2-Stroke, MSD 4-Stroke, Gas Turbines
Chemical tanker	SSD 2-Stroke, MSD 4-Stroke
General cargo	SSD 2-Stroke, MSD 4-Stroke, HSD 4-Stroke
Liquefied gas tanker	SSD 2-Stroke, MSD 4-Stroke, Gas Turbines
Other liquids tankers	SSD 2-Stroke, MSD 4-Stroke
Ferry-pax only	MSD 4-Stroke, HSD 4-Stroke, Gas Turbines
Cruise	MSD 4-Stroke, Gas Turbines
Ferry-RoPax	MSD 4-Stroke, HSD 4-Stroke, Gas Turbines
Refrigerated bulk	SSD 2-Stroke, MSD 4-Stroke
Ro-Ro	SSD 2-Stroke, MSD 4-Stroke, HSD 4-Stroke
Vehicle carrier	SSD 2-Stroke, MSD 4-Stroke, HSD 4-Stroke
Yacht	MSD 4-Stroke, HSD 4-Stroke, Gas Turbines
Service - tug	MSD 4-Stroke, HSD 4-Stroke
Miscellaneous - fishing	MSD 4-Stroke, HSD 4-Stroke
Offshore	MSD 4-Stroke, HSD 4-Stroke
Service - other	MSD 4-Stroke, HSD 4-Stroke
Miscellaneous - other	MSD 4-Stroke, HSD 4-Stroke

The fifth drop-down list allows the users to select the combustion cycle (Figure 14), which depends on the main engine type. Table 5 presents the available options for each engine type.

Table 5. Combustion cycle options per engine type (Table 6.8 of Marine_Trip tab from R&D GREET 2025).

Main propulsion engine type	Combustion cycle
SSD 2-Stroke	Diesel, Otto
MSD 4-Stroke	Diesel, Otto, LBSI
HSD 4-Stroke	Diesel
Gas Turbines	Brayton

The screenshot shows a form titled 'Vessel Characteristics' with several fields. The 'Combustion cycle' field has a dropdown menu open, displaying 'Diesel' as the selected option. Other visible options in the dropdown are 'Otto' and 'User-defined'. The background of the form is red.

Figure 14. Dropdown list for combustion cycle options from the Marine_Trip tab (R&D GREET 2025).

The sixth drop-down list displays the available options for the main engine combustion (Figure 15), which can operate in either single-fuel or dual-fuel mode. The dual-fuels configuration is typically required for LNG-, methanol-, and ammonia-fueled ships due to the high autoignition temperature of these fuels. This requirement does not apply to engines operating under Lean-Burn Spark Ignition (LBSI) mode, as ignition is achieved through a spark rather than compression.

Table 6 presents the engine configuration options per engine and combustion type.

Table 6. Engine configuration options in terms of single vs. dual-fuel configuration (Table 6.9 of Marine_Trip tab from R&D GREET 2025).

Main propulsion engine type	Combustion cycle	Engine configuration
SSD 2-Stroke	Diesel	Single-fuel, Dual-fuel
MSD 4-Stroke	Diesel	Single-fuel, Dual-fuel
HSD 4-Stroke	Diesel	Single-fuel
Gas Turbines	Brayton	Single-fuel, Dual-fuel
SSD 2-Stroke	Otto	Dual-fuel
MSD 4-Stroke	Otto	Dual-fuel
MSD 4-Stroke	LBSI	Single-fuel

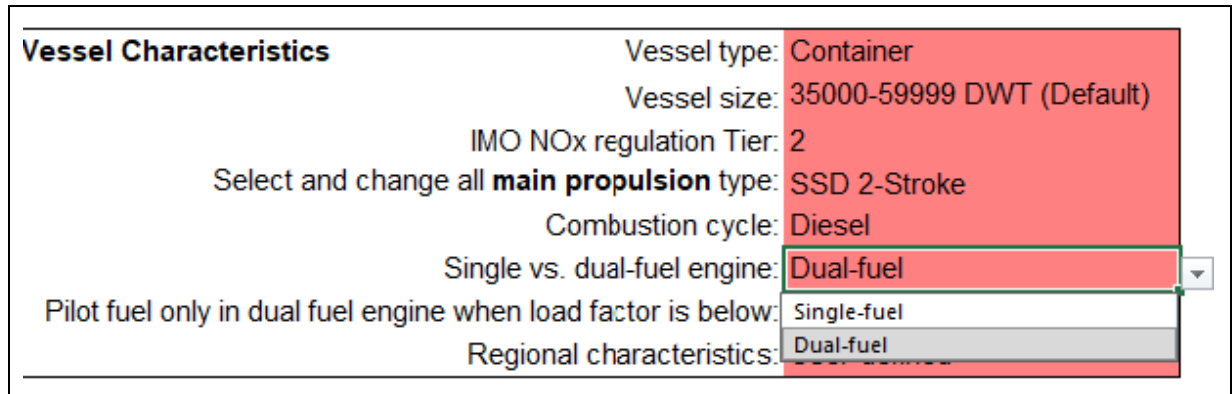


Figure 15. Dropdown list for engine configuration, single vs. dual-fuel, from the Marine_Trip tab (R&D GREET 2025).

The seventh drop-down list defines the load threshold used by ship operators to determine when the primary engine should switch to pilot oil fuel. This fuel-switching practice aims to prevent an increase in methane slip—which is more likely to occur during low load operations—and to improve combustion quality. The default threshold is set at 25% load factor, but users may adjust this value within a range of 5% to 50% (Figure 16).

The eighth and final drop-down list specifies how regional characteristics are considered—either using pre-defined GREET values or user-defined (Figure 17). The relevant parameters include distance, speed, time in mode, main engine rating, load factors, auxiliary (aux.) power out, and boiler(s) power output, which are described in more detailed below.

Vessel Characteristics	Vessel type:	Container
	Vessel size:	35000-59999 DWT (Default)
	IMO NOx regulation Tier:	2
	Select and change all main propulsion type:	SSD 2-Stroke
	Combustion cycle:	Diesel
	Single vs. dual-fuel engine:	Dual-fuel
	Pilot fuel only in dual fuel engine when load factor is below:	25%
	Regional characteristics:	Not Applicable
		5%
		10%
		15%
		20%
		25%
		30%
		35%
		40%
		45%
		50%

Figure 16. Dropdown list for pilot fuel only in dual fuel engine when load factor is below the threshold from the Marine_Trip tab (R&D GREET 2025).

Vessel Characteristics	Vessel type:	Container
	Vessel size:	35000-59999 DWT (Default)
	IMO NOx regulation Tier:	2
	Select and change all main propulsion type:	SSD 2-Stroke
	Combustion cycle:	Diesel
	Single vs. dual-fuel engine:	Dual-fuel
	Pilot fuel only in dual fuel engine when load factor is below:	25%
	Regional characteristics:	User-defined
		Pre-defined
		User-defined

Figure 17. Dropdown list for regional characteristics—whether pre-defined or user-defined—type from the Marine_Trip tab (R&D GREET 2025).

2.2.2 Trip Characteristics

2.2.2.1 Section: “Fuel Selection per Operational Mode”

After defining the vessel characteristics as described in the Vessel Type, Engine Type, Emission Regulation section, users can proceed to the fuel configuration selection section (Figure 18). The available fuel options may vary depending on the vessel’s characteristics. This means that users must first complete the selections shown in Figure 9 before modifying the options in Figure 18.

The first set of selections pertains to ‘Fuel Blendstock A – Main Engine’ (Figure 19), where users specify the fuel used by the main engine under each operational mode. The ‘Anchored’ and ‘At berth’ modes are shaded in dark gray as the main engine is inactive during these stages. The second set of selection related to the ‘Fuel Blendstock B – Main Engine’ (Figure 20), where users may choose an alternative fuel if the vessel operates on a blended-fuel configuration. Similar to the first set, users can define different fuel

combinations for each operational mode, except for ‘Anchored’ and ‘At berth’, for the same reasons noted above.

The third set of selections allows users to specify the volume percentage of the ‘Fuel Blendstock B – Main Engine’ (Figure 21). For example, if a vessel operates with 10% biodiesel, the user would select the base fuel under Blendstock A, biodiesel under Blendstock B, and enter 10% in the field ‘Share of Fuel Blendstock B (%)’. It is worth noting that an equivalent result can be obtained if the user specifies biodiesel first (under Blendstock A) and the base fuel second (under Blendstock), setting the share of Blendstock B to 90%—assuming a 10% biodiesel operation. Fuel options are determined by the configuration set in Section 1.1. Scenario Selection and are listed in Appendix B Table B2. The ‘Fuel Blendstock B – Main Engine’ will display ‘Not Applicable’ when a dual-system configuration has been previously selected.

1.2) Trip Characteristics					
Operational Mode:	Fuel Selection per Operational Mode:				
	Fuel Blendstock A - Main Engine	Fuel Blendstock B - Main Engine	Share of Fuel Blendstock B (%)	Pilot Fuel for Main Engine	Fuel for Aux. Engine(s) and Boilers (or Steam Turbines)
Sea (Normal Cruising)	HFO (0.1% sulfur)	Not Applicable	0%	No pilot fuel	MDO (0.1% sulfur)
Slow Transit	HFO (0.1% sulfur)	Not Applicable	0%		
Maneuvering	HFO (0.1% sulfur)	Not Applicable	0%		
Anchored					
At berth					
ECA	HFO (0.1% sulfur)	Not Applicable	0%		
Payload (wet ton)	49,487				
million tonne-km	46				

Figure 18. Fuel selection per operational mode section of the trip characteristics (Table 1.2 of Marine_Trip tab from R&D GREET 2025).

1.2) Trip Characteristics					
Operational Mode:	Fuel Selection per Operational Mode:				
	Fuel Blendstock A - Main Engine	Fuel Blendstock B - Main Engine	Share of Fuel Blendstock B (%)	Pilot Fuel for Main Engine	Fuel for Aux. Engine(s) and Boilers
Sea (Normal Cruising)	MGO (0.1 % sulfur)	Not Applicable	0%	No pilot fuel	MGO (0.1 % sulfur)
Slow Transit	MGO (0.1 % sulfur)	Not Applicable	0%		
Maneuvering	HFO (2.7% sulfur)		0%		
Anchored	HFO (0.5% sulfur)				
At berth	HFO (0.1% sulfur)				
ECA	MDO (1.92% sulfur)		0%		
Payload (wet ton)	MDO (0.5% sulfur)				
million tonne-km	MDO (0.1% sulfur)				
	MGO (1.0% sulfur)				
	MGO (0.5 % sulfur)				
	MGO (0.1 % sulfur)				
	FT-Diesel (NG)				
	FT-Diesel (Biomass&Coal)				
	Renewable diesel (Yellow grease&HFO)				

Figure 19. Drop-down for ‘Fuel Blendstock A – Main Engine’ under ‘Slow Transit’ (Table 1.2 of Marine_Trip tab from R&D GREET 2025).

1.2) Trip Characteristics					
Operational Mode:	Fuel Selection per Operational Mode:				
	Fuel Blendstock A - Main Engine	Fuel Blendstock B - Main Engine	Share of Fuel Blendstock B (%)	Pilot Fuel for Main Engine	Fuel for Aux. Engine(s) and Boilers
Sea (Normal Cruising)	MDO (0.1% sulfur)	Biodiesel	6	Pilot fuel	MGO (0.1 % sulfur)
Slow Transit	MDO (0.1% sulfur)	MGO (1.0% sulfur)			
Maneuvering	MDO (0.1% sulfur)	MGO (0.5 % sulfur)			
Anchored		MGO (0.1 % sulfur)			
At berth		FT-Diesel (NG)			
ECA	MDO (0.1% sulfur)	FT-Diesel (Biomass&Coal)			
		Renewable diesel (Yellow grease&HFO)			
Payload (wet ton)	57,541	FT-Diesel (Biomass&NG)			
million tonne-km	69	Straight Vegetable Oil (SVO)			
		Pyrolysis oil (Woody biomass)			
		FT-Diesel (Biomass)			
		Renewable diesel (Yellow grease)			
		Biodiesel			

Figure 20. Drop-down for ‘Fuel Blendstock B – Main Engine’ under ‘Sea (Normal Cruising)’ (Table 1.2 of Marine_Trip tab from R&D GREET 2025).

1.2) Trip Characteristics					
Operational Mode:	Fuel Selection per Operational Mode:				
	Fuel Blendstock A - Main Engine	Fuel Blendstock B - Main Engine	Share of Fuel Blendstock B (%)	Pilot Fuel for Main Engine	Fuel for Aux. Engine(s) and Boilers
Sea (Normal Cruising)	MDO (0.1% sulfur)	Biodiesel	10%	Pilot fuel	MGO (0.1 % sulfur)
Slow Transit	MDO (0.1% sulfur)	Biodiesel	10%		
Maneuvering	MDO (0.1% sulfur)	Not Applicable	5%		
Anchored			10%		
At berth			15%		
ECA	MDO (0.1% sulfur)	Not Applicable	20%		
			25%		
Payload (wet ton)	57,541		30%		
million tonne-km	69		35%		
			40%		
			45%		
			50%		
			55%		
			60%		

Figure 21. Drop-down for ‘Share of Fuel Blendstock B (%)’ under ‘Slow Transit’ (Table 1.2 of Marine_Trip tab from R&D GREET 2025).

The fourth selection pertains to the pilot oil fuel, ‘*Pilot Fuel for Main Engine*’ (Figure 22), which becomes available when dual-fuel group is selected in Section 1.1 (Figure 9). Finally, the fifth and last selection in this section is ‘*Fuel for Aux. Engine(s) and Boilers (or Steam Turbines)*’ (Figure 23). The default fuel is MGO (0.1% sulfur), and the available options are listed in Appendix B, Table B4.

1.2) Trip Characteristics					
Operational Mode:	Fuel Selection per Operational Mode:				
	Fuel Blendstock A - Main Engine	Fuel Blendstock B - Main Engine	Share of Fuel Blendstock B (%)	Pilot Fuel for Main Engine	Fuel for Aux. Engine(s) and Boilers
Sea (Normal Cruising)	Liquefied Natural Gas (LNG)	Not Applicable	0%	MDO (0.1% sulfur)	MGO (0.1 % sulfur)
Slow Transit	Liquefied Natural Gas (LNG)	Not Applicable	0%		
Maneuvering	Liquefied Natural Gas (LNG)	Not Applicable	0%		
Anchored					
At berth					
ECA	Liquefied Natural Gas (LNG)	Not Applicable	0%		
Payload (wet ton)	57,541			MDO (1.92% sulfur)	
million tonne-km	69			MDO (0.5% sulfur)	
				<ul style="list-style-type: none"> MDO (0.1% sulfur) MGO (1.0% sulfur) MGO (0.5 % sulfur) MGO (0.1 % sulfur) FT-Diesel (NG) FT-Diesel (Biomass&Coal) Renewable diesel (Yellow grease&HFO) FT-Diesel (Biomass&NG) Straight Vegetable Oil (SVO) Pyrolysis oil (Woody biomass) 	

Figure 22. Drop-down for ‘Pilot Fuel Blendstock B (%)’ (Table 1.2 of Marine_Trip tab from R&D GREET 2025).

1.2) Trip Characteristics					
Operational Mode:	Fuel Selection per Operational Mode:				
	Fuel Blendstock A - Main Engine	Fuel Blendstock B - Main Engine	Share of Fuel Blendstock B (%)	Pilot Fuel for Main Engine	Fuel for Aux. Engine(s) and Boilers
Sea (Normal Cruising)	MGO (0.1 % sulfur)	Not Applicable	0%	No pilot fuel	MGO (0.1 % sulfur)
Slow Transit	MGO (0.1 % sulfur)	Not Applicable	0%		
Maneuvering	MGO (0.1 % sulfur)	Not Applicable	0%		
Anchored					
At berth					
ECA	MGO (0.1 % sulfur)	Not Applicable	0%		
Payload (wet ton)	57,541			MGO (0.1 % sulfur)	
million tonne-km	69			<ul style="list-style-type: none"> Liquefied Natural Gas (LNG) FT-Diesel (NG) FT-Diesel (Biomass&Coal) Renewable diesel (Yellow grease&HFO) FT-Diesel (Biomass&NG) Straight Vegetable Oil (SVO) Pyrolysis oil (Woody biomass) FT-Diesel (Biomass) Renewable diesel (Yellow grease) Biodiesel Marine biocrude, HTL-partially upgraded (Sludge) 	

Figure 23. Drop-down for ‘Fuel for Aux. Engine(s) and Boilers’ (Table 1.2 of Marine_Trip tab from R&D GREET 2025).

Lastly, the payload (wet ton) value is determined either from a default value (Table B5 in Appendix B) or from a user-defined input, as described in the next subsection. The ‘million tonne-km’ value is calculated based on the payload and travel distance (also described in the next subsection), as it represents a unit of transport work. Both the payload and million tonne-km values do not require any user input changes in this section.

This section concludes the user input selections required when “Pre-defined” is chosen under regional characteristics in Section 1.1. The following subsection provides the steps necessary to complete the analysis.

2.2.2.2 Section: “Selected: Pre-defined or User-defined”

Figure 24 and Figure 25 present similar sections under different assumptions: user-defined and pre-defined, respectively. These represent the assumptions applied in the model and are not editable. The ‘Distance’ value shown in Figure 24 and Figure 25 represents the distance—in nautical miles (nm)—that a particular vessel travels in each operational mode (Sea, Slow Transit, Maneuvering, Anchored, At berth, ECA). Similarly, the ‘Speed’ (in knots) and ‘Time in Mode’ (in hours) indicate the average speed and duration of operation for each mode. The ‘Main Engine Rating’ refers to the power the engine is specified to deliver, and ‘Aux Power Output’ and ‘Boiler Power Output’ represent the average power demand from the auxiliary engines and boilers, respectively. Table B5 in Appendix B provides the default values for distance, speed and time in mode used in the pre-defined configuration. Table B6 in Appendix B lists the default values for the main engine rating, auxiliary power output, and boiler power output.

Selected: User-defined						
Distance (nm)	Speed (knots)	Time in Mode (hours)	Main Engine Rating (kW)	Load Factors (unitless)	Aux. Power Output (kW)	Boiler(s) Power Output (kW)
500	18	28	37457	0.83	8278	300
10	10	1	37457	0.83	8278	300
5	4	1	37457	0.83	8278	600
0	0	6		0	8278	600
0	0	6		0	8278	7000
200	10	20	37457	0.10	8278	0

Figure 24. Operational information when ‘User-defined’ is selected under regional characteristics drop-list (in Scenario Selection). The information presented is the user input added in Figure 26 (part of Table 1.2 of the Marine_Trip tab, R&D GREET1 2025).

Selected: Pre-defined						
Distance (nm)	Speed (knots)	Time in Mode (hours)	Main Engine Rating (kW)	Load Factors (unitless)	Aux. Power Output (kW)	Boiler(s) Power Output (kW)
500	18	28	8177	0.64	260	0
10	10	1	8177	0.43	260	0
5	4	1	8177	0.03	680	120
0	0	6		0	250	130
0	0	6		0	150	130
200	10	20	8177	0.43	260	0

Figure 25. Operational information when ‘Pre-defined’ is selected under regional characteristics drop-list (in Scenario Selection). The information will show the default information from the Marine_Trip tab, Table B5 (part of Table 1.2 of the Marine_Trip tab, R&D GREET1 2025).

The ‘Load Factor (unitless)’ column represents the average load factor under which the vessel operated in each mode. Unless otherwise specified by the user—as described hereafter—the pre-defined load factors were estimated using following the methodology of the Fourth IMO GHG Study report.¹ Load factors are calculated for each vessel type and vessel size using the Admiralty formula, Equation 1:

$$W_i = \frac{\delta_w * W_{ref} * \left(\frac{t_i}{t_{ref}}\right)^m * \left(\frac{v_i}{v_{ref}}\right)^n}{\eta_w * \eta_f} \quad 1$$

where W_i is the ship’s instantaneous propulsive power demand at a given time and W_{ref} is the reference power. The t_{ref} and v_{ref} are the reference draught and speed, respectively. t_i and v_i are the instantaneous draughts and speeds, respectively. In the 4th IMO report, the draught ratio exponent, m , is assumed to be 0.66 while the speed ratio exponent, n , is assumed to be 3. They represent the relationship between draught and power and speed and power, respectively. The η_w represent the weather modifier to the ship’s propulsive efficiency, and η_f represents the fouling modifier. Finally, δ_w is a correction factor applied to certain ship types and sizes to adjust the speed-power relationship.

As in IMO report, it was assumed that on average, the ships operate at maximum speed, i.e., at the ship maximum continuous rating (MCR), resulting in $\delta_w = 1$. However, for larger container vessels above 14,500 TEU and cruise ships, this factor was assumed $\delta_w = 0.75$ and $\delta_w = 0.7$, respectively. Due to lack of draught data availability, we assumed t_i equals to t_{ref} and Equation 2 was used to estimate the average load factor, $\frac{W_i}{W_{ref}}$, for each ship type and size range, as well as per operational mode, *Op. Mode*, as follows:

- For Slow Transit and Emission Control Area (ECA), the Speed Over Ground (SOG), $v_i^{Slow Transit}$ and v_i^{ECA} , equals $v_i^{Sea (Normal Cruising)}$ if ≤ 10 knots (kn); otherwise, it is set at 10 kn.
- For Maneuvering, the SOG, $v_i^{Maneuvering}$, was set at 4 kn.

$$\frac{W_i}{W_{ref}} = \frac{\delta_w * \left(\frac{v_i^{Op. Mode}}{v_{ref}}\right)^n}{\eta_w * \eta_f} \quad 2$$

The reference and instantaneous speed, the weather correction and fouling factors, as well as the estimated load factors by vessel type, size and operational mode, are provided in Appendix B, Table B1.

Figure 26 presents the subsequence section where the user assumptions are required when ‘User-defined’ is selected under Scenario Selection. The yellow-highlighted cells indicate the field that require user inputs. These entries are automatically transferred to the section shown in Figure 24.

User-defined							
Distance (nm)	Speed (knots)	Time in Mode (hours)	Main Engine Rating (kW)	Load Factor (unitless) User-	Aux. Power Output (kW)	Boiler Power Output (kW)	Urban Emission Share (%)
500	18	28	37457	0.8	8278	300	0.0%
10	10	1	37457	0.8	8278	300	0.0%
5	4	1	37457	0.8	8278	600	0.0%
0	0	6		0.0	8278	600	0.0%
0	0	6		0.0	8278	7000	0.0%
200	10	20	37457	0.1	8278		0.0%
49,487							
59							

Figure 26. Section for the user inputs for the case where Regional Characteristics is set on ‘User-defined’ (part of Table 1.2 of the Marine_Trip tab, R&D GREET1 2025).

2.2.2.3 Fuel Consumption

The fuel consumption by main propulsion (Figure 27) for each operational mode is expressed in metric tons (MT) and calculated using Equation 3:

$$Blendstock_i = Fuel_{\%i} * Eng\ Rat * SFC_{ME,i} * SFC_{adj} * Time * Load \quad 3$$

where $Blendstock_i$ is the fuel consumption of the fuel i (in MT), which is either fuel blendstock A or B. $Fuel_{\%i}$ is the share of the respective fuel in percentage (%). $Eng\ Rat$ is the ‘Main Engine Rating’ of the ship (kW). $SFC_{ME,i}$ is the specific fuel consumption of the main engine using fuel i , calculated by Equation 4 (g/kWh). SFC_{adj} is the adjustment factor (unitless) assumed for when using different fuels beyond the IMO baseline fuels: HFO, MDO, and methanol. The factor is estimated based on the respective baseline fuel lower heating value (LHV) divided by the chosen fuel LHV. For example, for ‘Renewable Diesel (Yellow grease&HFO)’, the baseline fuel would be MDO. Since renewable diesel has higher LHV than conventional fuel, when the estimated adjustment factor, 0.93, is multiplied by the $SFC_{ME,i}$ it enables a more accurate assumption of the fuel being consumed (g/kWh) during engine operation. Adjustment factors can be seen in Appendix B (Table B3). $Time$ is the ‘Time in Mode’ (in hours) and $Load$ is the ‘Load Factor (unitless)’ of the main engine. Conversion from grams to MT is also necessary for the result.

Equation 4 estimates the $SFC_{ME,i}$ based on SFC_{base} and the respective load factor per operational mode. SFC_{base} is the base specific fuel consumption based on the vessel engine characteristics. Base values were based on the IMO report^{1, p. 70-71} with some additions: SFC pilot fuel under methanol operation and additional configurations for LNG (MSD 4-Stroke Otto and Diesel).

Under SSD 2-Stroke Diesel operating with methanol, the SFC of the pilot fuel was assumed to be the same as SSD 2-Stroke Diesel operating with LNG, i.e. 6 g/kWh. Then, the SFC of the main engine was assumed to achieve the same brake thermal efficiency (BTE) as the SSD 2-Stroke Diesel-LNG (i.e., 52.6%).

Under MSD 4-Stroke Diesel operating with methanol, the SFC of the pilot fuel was calculated based on the ratio of SFCs between SSD 2-Stroke Diesel and MSD 4-Stroke Diesel, scaled proportionally to SSD

2-Stroke Diesel LNG value. The main engine SFC was estimated based on the ratio of the LHV between methanol and LNG, and proportionally to the MSD 4-Stroke Diesel-LNG value.

For MSD 4-Stroke Otto operating with LNG, the SFC of the pilot fuel was calculated from the ratio of SFCs between SSD 2-Stroke Diesel and MSD 4-Stroke Diesel. The main engine SFC was set to achieve a BTE 47.5%, corresponding to its original BTE without pilot fuel.

Finally, for MSD 4-Stroke Diesel operating with LNG, the SFC of the pilot fuel was again calculated based on the ratio of SFCs between SSD 2-Stroke Diesel and MSD 4-Stroke Diesel, scaled proportionally to the SSD 2-Stroke Diesel-LNG value. The main engine SFC was estimated using the same ratio of SFCs between SSD 2-Stroke Diesel and MSD 4-Stroke Diesel. The resulting values are provided in Appendix B (Table B7).

$$SFC_{ME,i} = SFC_{base} * (0.455 * Load^2 - 0.71 * Load + 1.28) \quad 4$$

When a dual-fuel configuration is selected, under Slow Transit, Maneuvering, and ECA operational modes, the values for Fuel Blendstock A and B become zero if the respective load factor is equal or less than the load factor threshold defined in the Scenario Selection section. When this occurs, the pilot fuel becomes the primary fuel for main engine operation, resulting in an increase in fuel consumption under the Pilot Fuel column. The pilot fuel consumption is calculated using Equation 5.

$$Pilot\ Fuel = Eng\ Rat * SFC_{base,pilot} * SFC_{adj} * Time * Load \quad 5$$

where *Pilot Fuel* is the pilot fuel consumption (in MT), *Eng Rat* is the ‘Main Engine Rating’ of the ship (kW), *SFC_{base,pilot}* is the specific fuel consumption of the pilot oil (in g/kWh, Table B7). *SFC_{adj}* is the adjustment factor (unitless) assumed—as described before—for when using different pilot fuels beyond the IMO baseline fuels for pilot oil: MDO (see Table B7 in Appendix B).

The fuel consumption (MT) estimate for *Additional Converters*—such as auxiliary engines and boiler or steam turbines—is presented in Equation 6.

$$Additional\ Converters = Power\ Output_j * SFC_{base} * SFC_{adj} * Time \quad 6$$

where *j* refers to the converter type, either ‘Auxiliary Engine’ or ‘Boiler or Steam Turbines’. *Power Output_j* refers to the respective power output (kW) used by each converter, dependent on vessel type, vessel size and operational mode. *SFC_{base}* is the specific fuel consumption (g/kWh) of the type of converter (see Table B7 in Appendix B). *Time* is the time in mode of operation (hours). Conversion from grams to MT is also necessary for the result.

Fuel Consumption by Main Propulsion (MT)			Fuel Consumption by Auxiliary Engine (MT)	Fuel Consumption by Boiler or Steam Turbines (MT)
Fuel Blendstock A	Fuel Blendstock B	Pilot fuel		
54.0	0	0.00	6.9	0.0
0.7	0	0.00	0.2	0.0
0.1	0	0.00	0.6	0.2
			1.4	0.9
			1.2	0.9
13.5	0	0.00	5.0	0.0

Figure 27. Fuel consumption section of the main propulsion, auxiliary and boilers or steam turbines. Expressed in metric tonne (MT) (part of Table 1.2 of the Marine_Trip tab, R&D GREET1 2025).

2.2.2.4 Energy Consumption

The energy consumption is expressed in megajoules (MJ) (Figure 28). The ‘Energy Consumption by Main Propulsion’ section is divided into three parts: ‘Fuel Blendstock A’, ‘Fuel Blendstock B’, and ‘Pilot Fuel’. The energy consumption estimates for fuel $Blendstock_A$ and fuel $Blendstock_B$ are defined by Equations 7 and 8, respectively.

$$Blendstock_A = Fuel_{\%,A} * Eng\ Rat * SFC_{ME,A} * SFC_{adj} * Time * Load * LHV_A * Volume_{correction,A} \quad 7$$

$$Blendstock_B = Fuel_{\%,B} * Eng\ Rat * SFC_{ME,B} * SFC_{adj} * Time * Load * LHV_B * Volume_{correction,B} \quad 8$$

where $Fuel_{\%i}$ is the share of the respective fuel in percentage (%). $Eng\ Rat$ is the ‘Main Engine Rating’ of the ship (kW). $SFC_{ME,A(or\ B)}$ is the specific fuel consumption of the main engine using fuel A or B calculated by Equation 4 (g/kWh). SFC_{adj} is the adjustment factor (unitless) assumed for when using different fuels beyond the IMO baseline fuels: HFO, MDO, and methanol. $Time$ is the ‘Time in Mode’ (in hours) and $Load$ is the ‘Load Factor (unitless)’ of the main engine. $LHV_{A(or\ B)}$ is the lower heating value of fuel A or B . $Volume_{correction,A}$ is the calculation step to convert mass-based to volume-based result, expressed by Equations 9 and 10. Volume-based is commonly adopted by industry, e.g., 10% biodiesel (volume-based).

$$Volume_{correction,A} = \frac{Fuel_{\%,A} * \rho_A}{(Fuel_{\%,A} * \rho_A) + (Fuel_{\%,B} * \rho_B)} \quad 9$$

$$Volume_{correction,B} = \frac{Fuel_{\%,B} * \rho_B}{(Fuel_{\%,A} * \rho_A) + (Fuel_{\%,B} * \rho_B)} \quad 10$$

The same load factor threshold criterion applies when operating under a dual-fuel configuration and during the Slow Transit, Maneuvering, and ECA operational modes. The values for Fuel Blendstock A and Fuel Blendstock B become zero if the respective load factor is equal to or less than the load factor threshold defined in the Scenario Selection section. In this case, the pilot fuel serves as the main engine fuel.

Equation 11 and 12 present the calculations used to estimate the energy consumption of the pilot fuel and of the additional converters, auxiliaries, and boilers, respectively.

$$Pilot\ Fuel = Eng\ Rat * SFC_{base,pilot} * SFC_{adj} * Time * Load * LHV \quad 11$$

$$Additional\ Converters = Power\ Output_j * SFC_{base} * SFC_{adj} * Time * LHV \quad 12$$

Energy Consumption by Main Propulsion (MJ)			Energy Consumption by Auxiliary Engine (MJ)	Energy Consumption by Boiler or Steam Turbines (MJ)
Fuel Blendstock A	Fuel Blendstock B	Pilot fuel		
2,309,240	0	0	294,798	0
28,913	0	0	10,616	0
2,433	0	0	23,697	7,050
			61,422	37,775
			50,047	37,775
578.259	0	0	212.322	0

Figure 28. Energy consumption section of the main propulsion, auxiliary and boilers or steam turbines. Expressed in metric tonne (MT) (part of Table 1.2 of the Marine_Trip tab, R&D GREET1 2025).

2.2.3 Summary Results

2.2.3.1 Selected Fuels: Energy Consumption, Water Consumption, and Emissions

From this point forward, no user input is required. Users may adjust a few dropdowns list, as described below. Figure 29 presents the results for the four key metrics: (i) energy consumption, (ii) GHG emissions, (iii) water consumption, and (iv) criteria air pollutants (CAPs)—each expressed per unit of energy and based on the selected fuel type. The summary results are organized by feedstock, conversion, combustion, and final well-to-wake (WTW) stages. Users can also view the results in different energy and emission units, as well as energy functional units.

2) Summary Results					
2.1.) Selected Fuels: Energy Consumption, Water Consumption, and Emissions					
Selected fuel type	MDO (0.1% sulfur)				
Energy Unit:	Btu	Emission Unit:		g	
		Energy Functional Unit		MJ	
	Units	Feedstock	Conversion	Combustion	WTW
Total energy	MJ/Trip	714,642	1,211,912	11,676,379	13,602,933
Fossil fuels	MJ/Trip	691,245	1,198,953	11,676,379	13,566,577
Coal	MJ/Trip	25,715	14,907	0.00	40,622
Natural gas	MJ/Trip	613,688	979,950	6,796,971	8,390,609
Petroleum	MJ/Trip	51,842	204,096	4,879,408	5,135,346
Water consumption	gal/Trip	106,224	20,373	0.00	126,597
VOC	kg/Trip	105	23	650	778
CO	kg/Trip	257	74	1,401	1,732
NOx	kg/Trip	305	105	21,279	21,688
PM10	kg/Trip	4.82	6.65	117	128
PM2.5	kg/Trip	4.41	6.02	99	109
SOx	kg/Trip	9.86	15	97	122
BC	kg/Trip	0.87	0.55	2.38	3.80
OC	kg/Trip	1.74	2.50	16	20
CH4	kg/Trip	1,303	944	219	2,466
N2O	kg/Trip	1.18	0.72	53	55
CO2	kg/Trip	47,213	68,725	759,967	875,905
CO2 (w/ C in VOC & C	kg/Trip	47,943	68,913	764,195	881,051
GHGs	kg CO2e/Trip	87,090	97,252	785,277	969,619
VOC: Urban	kg/Trip	4.34	14	0.00	19
CO: Urban	kg/Trip	5.65	15	0.00	21
NOx: Urban	kg/Trip	7.51	8.03	0.00	16
PM10: Urban	kg/Trip	0.22	2.02	0.00	2.24
PM2.5: Urban	kg/Trip	0.19	2.10	0.00	2.29
SOx: Urban	kg/Trip	1.22	2.95	0.00	4.17
BC: Urban	kg/Trip	0.02	0.35	0.00	0.37
OC: Urban	kg/Trip	0.06	0.21	0.00	0.27
Biogenic CO2 credit	kg CO2e/Trip	0.00			

Figure 29. Energy consumption, water consumption and emissions of the stages: feedstock, conversion, and combustion, as well as the sum in WTW (Table 2.1 of the Marine_Trip tab, R&D GREET1 2025).

2.2.3.2 Selected Trips: Energy Consumption, Water Consumption, and Emissions

Figure 30 presents the results for the four key metrics: (i) energy consumption, (ii) GHG emissions, (iii) water consumption, and (iv) criteria air pollutants (CAPs), per trip (or per million tonne-km). The summary results are organized by operational mode—Sea (Normal Cruising), Slow Transit, Maneuvering, Anchored, At berth, and ECA—as well as the total trip. Users can also view the results in different energy and emission units, as well as functional units.

2.2) Selected Trips: Energy Consumption, Water Consumption, and Emissions								
Energy Unit: MJ		Emission Unit: kg						
Functional Unit: 1		1--Per Trip, 2--Per million tonne-km						
Units	Selected fu	Sea (Normal	Slow Transit	g	Anchored	At berth	ECA	Trip
MJ/Trip		9,143,780	326,564	413,856	487,029	1,065,764	2,165,941	13,602,933
MJ/Trip		9,125,240	325,901	412,999	484,500	1,060,231	2,157,705	13,566,577
MJ/Trip		20,823	744	962	2,803	6,133	9,157	40,622
MJ/Trip		6,895,849	246,280	308,306	39,236	85,860	815,079	8,390,609
MJ/Trip		2,208,568	78,877	103,731	442,462	968,238	1,333,469	5,135,346
gal/Trip		64,335	2,298	2,975	8,851	19,368	28,771	126,597
kg/Trip		555	20	25	24	31	124	778
kg/Trip		1,321	47	59	33	46	226	1,732
kg/Trip		15,924	569	712	572	662	3,250	21,688
kg/Trip		61	2.19	2.31	11	17	34	128
kg/Trip		57	2.02	2.58	9.63	7.16	32	109
kg/Trip		101	3.62	4.78	1.89	4.31	6.29	122
kg/Trip		2.73	0.10	0.12	0.08	0.31	0.45	3.80
kg/Trip		10	0.37	0.48	1.50	2.50	5.08	20
kg/Trip		1,884	67	85	41	90	299	2,466
kg/Trip		37	1.32	1.58	2.04	4.01	9.08	55
kg/Trip		560,742	20,026	25,465	37,177	81,354	151,141	875,905
kg/Trip		564,546	20,162	25,535	37,303	81,524	151,880	881,051
kg CO2e/Trip		630,829	22,530	28,513	39,089	85,293	163,266	969,619
kg/Trip		12	0.42	0.53	0.81	1.78	3.25	19
kg/Trip		15	0.53	0.57	0.58	1.26	2.98	21
kg/Trip		8.83	0.32	0.40	0.89	1.95	3.14	16
kg/Trip		1.11	0.04	0.05	0.16	0.36	0.52	2.24
kg/Trip		1.25	0.04	0.06	0.14	0.31	0.49	2.29
kg/Trip		1.80	0.06	0.08	0.36	0.79	1.08	4.17
kg/Trip		0.24	0.01	0.01	0.02	0.03	0.06	0.37
kg/Trip		0.12	0.00	0.01	0.02	0.05	0.07	0.27
Biogenic kg CO2e/Trip		0.00	0.00	0.00	0.00	0.00	0.00	0.00

Figure 30. Energy consumption, water consumption and emissions of the stages: Sea (Normal Cruising), Slow Transit, Maneuvering, Anchored, At berth, ECA, as well as the sum of the Trip (Table 2.2 of the Marine_Trip tab, R&D GREET1 2025).

2.2.4 Input Parameters

2.2.4.1 Emission Factors

This section describes the emission factors by fuel type. Figure 31 presents a portion of the complete table. R&D GREET1 2025 version expands the results to include emission factors for ‘Steam Turbines (and Boilers)’ and updates existing factors following the guidelines provided by the Fourth IMO GHG Study report.¹

Emission calculations are categorized into two groups: fuel-based and energy-based.^{1, p. 72} Energy-based emissions depend on the power output of the engine or boiler and use energy-based emission factors, expressed in grams of pollutant per kilowatt-hour (g/kWh). Examples of energy-based pollutants include NO_x, CH₄, CO, N₂O, PM_{2.5}, PM₁₀, and VOC.

Fuel-based emissions, on the other hand, depend on the pollutant content of the fuel and engine type, and use fuel-based emission factors, expressed in grams of pollutant per grams of fuel (g pollutant/g fuel). Examples of fuel-based pollutants include CO₂, SO_x, and BC. For LNG engines, steam turbines, and gas turbines, BC is characterized using energy-based factors (g/kWh), as indicated in the ‘units’ column of Figure 31.

All emission factors—based on the Fourth IMO GHG Study report—are provided in Table B8 in Appendix B. The emission factors for VOC, CO, NO_x, BC, CH₄, and N₂O are taken directly from Table B8. For PM₁₀, since it also depends on the specific fuel consumption, the value is determined using the calculations shown in Equations 13 and 14:^{1, p. 75}

$$EM_{e,PM10-HFO} = 1.35 + SFC * 7 * 0.02247 * (sulfur - 0.0246) \quad 13$$

where $EM_{e,PM10-HFO}$ is the energy-based PM₁₀ emission factor (g/kWh) for HFO type of fuels, SFC is the specific fuel consumption and $sulfur$ in the sulfur content of the fuel in percentage.

$$EM_{e,PM10-MDO} = 0.23 + SFC * 7 * 0.02247 * (sulfur - 0.0024) \quad 14$$

where $EM_{e,PM10-MDO}$ is the energy-based PM₁₀ emission factor (g/kWh) for MDO type of fuels. Table B3 (Appendix B) shows which fuel category each of the 39 fuels fall into (HFO or MDO). Methanol, ethanol and ammonia are grouped under the methanol fuel category. As previously mentioned, this categorization is used to adjust the SFC calculation. For methanol and ethanol, the same from the IMO report—that their PM₁₀ emission factor are 10% of the HFO value—was applied. Ammonia is assigned to zero PM₁₀ emission. For Gas Turbines and LNG, PM₁₀ emission factors are explicitly provided in Table B9 in Appendix B.

For SO_x emission factor is estimated based on the sulfur content of each fuel, minus the fraction of sulfur converted to particulate matter, as defined in Equation 15:

$$EM_{f,SOx} = 2 * (1 - 2.247\%) * Sulfur \quad 15$$

where $EM_{f,SOx}$ is the fuel-based SO_x emission factor (g/g fuel), 2.247% represents the fraction of sulfur converted to particulate matter, and $Sulfur$ denotes the sulfur content of the fuel (in percentage).

For BC, as previously mentioned, some emission factors are fuel-based, while others are energy-based. Additionally, BC emissions depend on the engine load factor and the engine configuration (2-Stroke or 4-Stroke). Therefore, BC emission factors from Table B8 vary according to Equations 16 to 19: ^{1, p. 77}

$$EM_{f,BC,2-Stroke,HFO} = 1.5 * 10^{-4} * (Load^{-0.359}) \quad 16$$

$$EM_{f,BC,2-Stroke,MDO} = 3.11 * 10^{-5} * (Load^{-0.397}) \quad 17$$

$$EM_{f,BC,4-Stroke,HFO} = 2.5 * 10^{-4} * (Load^{-0.968}) \quad 18$$

$$EM_{f,BC,4-Stroke,MDO} = 1.201 * 10^{-4} * (Load^{-1.124}) \quad 19$$

where $EM_{f,BC}$ is the fuel-based BC emission factor for either a 2-Stroke or 4-Stroke engine and for HFO or MDO fuel type group. For methanol, the assumption is that its BC emission factor equals 10% of the HFO value.

An important observation from Table B8 (emission factors) is that the MSD 4-Stroke Diesel configuration operating on LNG—not included in the Fourth IMO GHG Study report—was added to the Marine_Trip tab. Its emission factors were assumed to be proportional to those of the SSD 2-Stroke Diesel operated on LNG, using the ratio between the SSD 2-Stroke Diesel and MSD 4-Stroke Diesel emission factors as the scaling basis.

3) Input Parameters		3.1) Emission Factors					
Selected IMO NOx regulation tier for each fuel type:		2	2	2	2	2	2
Main Engine	Units	HFO (2.7% sulfur)	HFO (0.5% sulfur)	HFO (0.1% sulfur)	MDO (1.92% sulfur)	MDO (0.5% sulfur)	MDO (0.1% sulfur)
VOC	g/kWh operation	0.63	0.63	0.63	0.63	0.63	0.63
CO	g/kWh operation	0.54	0.54	0.54	0.04	0.04	0.04
NOx	g/kWh operation	14.40	14.40	14.40	14.40	14.40	14.40
PM10	g/kWh operation	1.42	0.81	0.70	0.67	0.30	0.19
PM2.5	g/kWh operation	1.30	0.75	0.64	0.61	0.27	0.18
SOx	g/g of fuel	0.05	0.01	0.00	0.04	0.01	0.00
BC	g/g of fuel & g/kWh (LNG, GT, ST)	0.00	0.00	0.00	0.00	0.00	0.00
OC	g/kWh operation	0.20	0.11	0.10	0.09	0.04	0.03
CH4	g/kWh operation	0.01	0.01	0.01	0.01	0.01	0.01
N2O	g/kWh operation	0.03	0.03	0.03	0.03	0.03	0.03
CO2	g/g of fuel	3.18	3.18	3.18	3.18	3.18	3.18
Aux Engine							
VOC	g/kWh operation	0.42	0.42	0.42	0.42	0.42	0.42
CO	g/kWh operation	0.54	0.54	0.54	0.54	0.54	0.54
NOx	g/kWh operation	11.20	11.20	11.20	11.20	11.20	11.20
PM10	g/kWh operation	1.42	0.75	0.63	0.72	0.31	0.19
PM2.5	g/kWh operation	1.31	0.69	0.58	0.66	0.28	0.17
SOx	g/g of fuel	0.05	0.01	0.00	0.04	0.01	0.00
BC	g/g of fuel & g/kWh (LNG, GT, ST)	0.00	0.00	0.00	0.00	0.00	0.00
OC	g/kWh operation	0.20	0.10	0.09	0.10	0.04	0.03
CH4	g/kWh operation	0.01	0.01	0.01	0.01	0.01	0.01
N2O	g/kWh operation	0.04	0.04	0.04	0.04	0.04	0.04
CO2	g/g of fuel	3.18	3.18	3.18	3.18	3.18	3.18
Steam Turbines (and Boilers)							
VOC	g/kWh operation	0.11	0.11	0.11	0.11	0.11	0.11
CO	g/kWh operation	0.20	0.20	0.20	0.20	0.20	0.20
NOx	g/kWh operation	2.10	2.10	2.10	2.10	2.10	2.10
PM10	g/kWh operation	1.48	0.30	0.09	1.08	0.36	0.16
PM2.5	g/kWh operation	1.36	0.28	0.08	0.99	0.33	0.15
SOx	g/g of fuel	0.05	0.01	0.00	0.04	0.01	0.00
BC	g/g of fuel & g/kWh (LNG, GT, ST)	0.01	0.01	0.01	0.00	0.00	0.00
OC	g/kWh operation	0.20	0.04	0.01	0.15	0.05	0.02
CH4	g/kWh operation	0.00	0.00	0.00	0.00	0.00	0.00
N2O	g/kWh operation	0.04	0.04	0.04	0.05	0.05	0.05
CO2	g/g of fuel	3.18	3.18	3.18	3.18	3.18	3.18

Figure 31. A section of the emission factors for the main engine, auxiliary engine and steam turbines (and boilers) (Table 3.1 of the Marine_Trip tab, R&D GREET1 2025).

2.2.5 Trip-specific Results: Energy Consumption, Water Consumption, and Emissions

2.2.5.1 Trip-specific Results by Life-cycle Stages

This subsection presents trip-specific results by life-cycle stage. Figure 32 displays the energy-type group consumption (total, fossil fuels, coal, natural gas, and petroleum), water consumption, and emission-type group values (VOC, CO, NO_x, PM₁₀, PM_{2.5}, SO_x, BC, OC, CH₄, N₂O, CO₂, and CO₂ (w/ C in VOC & CO)) for the feedstock stage. These results are expressed on a per-trip basis and are disaggregated by operational mode. The last column presents the total (summed) result, calculated using Equation 20:

$$Trip_{Feedstock}^{metric} = \sum_{Op. Mode} (EC_{Op.Mode}^{ME} + EC_{Op.Mode}^{Pilot Fuel} + EC_{Op.Mode}^{Aux} + EC_{Op.Mode}^{Boiler}) * EF_{Feedstock}^{(metric, fuel)} \quad 20$$

where $Trip_{Feedstock}^{metric}$ is the total trip-level result for a specific metric—whether from the energy-type group, water consumption, or the emission-type group—associated with the feedstock life-cycle stage. *Op.Mode* refers to the operational modes: Sea (Normal Cruising), Slow Transit, Maneuvering, Anchored, At berth, and ECA. $EC_{Op.Mode}^{ME}$, $EC_{Op.Mode}^{Pilot Fuel}$, $EC_{Op.Mode}^{Aux}$ and $EC_{Op.Mode}^{Boiler}$ represent the energy consumption of the main engine, pilot fuel, auxiliary engines, and steam turbine (and boilers), respectively. These trip-specific energy consumptions are calculated in the tab's Table 1.2 for each operational mode, as described in Energy Consumption. Finally, $EF_{Feedstock}^{(metric, fuel)}$ denotes the emission factor for the feedstock stage for a particular metric and fuel type. These factors are provided in the Marine_Fuel tab, described in the next section.

It is worth noting that during 'Anchored' and 'At berth' stages, the main engine and pilot fuel—if applicable—are not in operation. Consequently, Equation 20 is reduced to account only for the energy consumption of auxiliary engines and boilers calculations. The units displayed in the 'Units' column can be adjusted using the 'Energy Unit' and 'Functional Unit' dropdown lists located in the summary results section (Figure 30).

	Units	Feedstock							Trip
		Sea (Normal Cruising)	Slow Transit	Maneuvering	Anchored	At berth	ECA		
Total energy	MJ/Trip	478,098	17,075	21,646	26,060	57,028	114,735	714,642	
Fossil fuels	MJ/Trip	467,956	16,713	21,170	24,061	52,652	108,692	691,245	
Coal	MJ/Trip	11,155	398	523	2,196	4,805	6,638	25,715	
Natural gas	MJ/Trip	434,099	15,504	19,582	17,483	38,258	88,762	613,688	
Petroleum	MJ/Trip	22,703	811	1,064	4,382	9,589	13,293	51,842	
Water consumption	gal/Trip	53,670	1,916.79	2,482.92	7,491.36	16,393.33	24,269.93	106,224.31	
VOC	kg/Trip	81	2.90	3.64	1.53	3.34	12.24	104.79	
CO	kg/Trip	202	7.20	9.04	3.14	6.88	28.82	256.77	
NOx	kg/Trip	235	8.41	10.56	4.58	10.02	35.90	304.89	
PM10	kg/Trip	3	0.11	0.14	0.21	0.46	0.84	4.82	
PM2.5	kg/Trip	3	0.10	0.13	0.18	0.38	0.74	4.41	
SOx	kg/Trip	4	0.15	0.20	0.85	1.86	2.57	9.86	
BC	kg/Trip	1	0.02	0.03	0.03	0.07	0.14	0.87	
OC	kg/Trip	1	0.04	0.05	0.06	0.14	0.28	1.74	
CH4	kg/Trip	925	33.05	41.73	36.33	79.50	186.87	1,302.85	
N2O	kg/Trip	1	0.03	0.04	0.03	0.07	0.17	1.18	
CO2	kg/Trip	30,294	1,081.94	1,375.52	1,990.24	4,355.23	8,115.60	47,213	
CO2 (w/ C in VOC & CO)	kg/Trip	30,864	1,102	1,401	2,000	4,376	8,199	47,943	
GHGs	kg CO2e/Trip	58,668	2,095	2,655	3,092	6,766	13,814	87,090	
VOC: Urban	kg/Trip	2	0.09	0.11	0.27	0.58	0.91	4	
CO: Urban	kg/Trip	4	0	0	0	0	1	6	
NOx: Urban	kg/Trip	5	0	0	0	0	1	8	
PM10: Urban	kg/Trip	0	0	0	0	0	0	0	
PM2.5: Urban	kg/Trip	0	0	0	0	0	0	0	
SOx: Urban	kg/Trip	1	0	0	0	0	0	1	
BC: Urban	kg/Trip	0	0	0	0	0	0	0	
OC: Urban	kg/Trip	0	0	0	0	0	0	0	
Biogenic CO2 credit during fuel combustion	kg CO2e/Trip	0	0	0	0	0	0	0	

Figure 32. Energy Consumption, Water Consumption, and Emissions results per operational mode and per trip in the feedstock stage (Table 4.1 of the Marine_Trip tab, R&D GREET1 2025).

Figure 33 shows energy consumption (total, fossil fuels, coal, natural gas, and petroleum), water consumption, and emissions for conversion and combustion stages. The conversion calculation, shown in Equation 21, follows similar approach to that used for the feedstock stage:

$$Trip_{Conversion}^{metric} = \sum_{Op. Mode} (EC_{Op. Mode}^{ME} + EC_{Op. Mode}^{Pilot Fuel} + EC_{Op. Mode}^{Aux} + EC_{Op. Mode}^{Boiler}) * EF_{Conversion}^{(metric, fuel)} \quad 21$$

where $Trip_{Conversion}^{metric}$ represents is the total trip-level result for a specific metric—whether from the energy-type group, water consumption, or the emission-type group—associated with the conversion life-cycle stage. *Op. Mode* refers to the operational modes: Sea (Normal Cruising), Slow Transit, Maneuvering, Anchored, At berth, and ECA. $EC_{Op. Mode}^{ME}$, $EC_{Op. Mode}^{Pilot Fuel}$, $EC_{Op. Mode}^{Aux}$ and $EC_{Op. Mode}^{Boiler}$ represent the energy consumption of the main engine, pilot fuel, auxiliary engines, and steam turbine (and boilers), respectively, in MJ. $EF_{Conversion}^{(metric, fuel)}$ denotes the emission factor for the conversion stage for a given metric and fuel type (g of emitter / MJ of fuel). As with the feedstock stage, the equation is reduced to include only the auxiliary engines and boiler during the ‘Anchored’ and ‘At Berth’ modes.

Combustion calculations differ from those of the previous stages. As previously noted, emission calculations can be either fuel-based or energy-based. This means that the combustion-stage calculations vary depending on the type of metric considered, except for energy consumption and water consumption, which follows a similar pattern, as shown in Equation 22.

$$Trip_{Combustion}^{(Energy, water)} = \sum_{Op. Mode} (EC_{Op. Mode}^{ME} + EC_{Op. Mode}^{Pilot Fuel} + EC_{Op. Mode}^{Aux} + EC_{Op. Mode}^{Boiler}) * EF_{Combustion}^{(metric, fuel)} \quad 22$$

where $Trip_{Combustion}^{Energy, water}$ is the total trip-level result for a specific metric—whether from the energy-type group, or water consumption—associated with the combustion life-cycle stage.

For single-fuel vessel operation, the trip-level values for energy-based metrics are calculated using Equation 23, while for fuel-based emissions are determined using Equation 26.

$$Trip_{Combustion}^{(Energy-based, single-fuel)} = \sum_{Op. Mode} (W_{Op. Mode}^{ME} + W_{Op. Mode}^{Aux} + W_{Op. Mode}^{Boiler}) * EF_{energy-based}^{(metric, fuel)} \quad 23$$

where $Trip_{Combustion}^{(Energy-based, single-fuel)}$ represents the total trip-level result for a specific energy-based emission-type group—whether from VOC, NO_x, CH₄, CO, N₂O, PM_{2.5}, and PM₁₀—associated with the combustion life-cycle stage. $W_{Op. Mode}^{ME}$, $W_{Op. Mode}^{Aux}$, and $W_{Op. Mode}^{Boiler}$ is the power output of the main engine, auxiliary engines, and steam turbines (and boilers), respectively, calculated using Equations 24 and 25.

$$W_{Op. Mode}^{ME} = Eng\ Rat_{Op. Mode} * Load_{Op. Mode} * Time_{Op. Mode} \quad 24$$

where $Eng\ Rat_{Op. Mode}$ is the main engine rating (kW), $Load_{Op. Mode}$ is the load factor (unitless), and $Time_{Op. Mode}$ is the time in mode (hours). These parameters are obtained from Table 1.2 of the tab for each operational mode, as described in section Energy Consumption.

$$W_{Op. Mode}^{(Aux, Boiler)} = Power\ Output_{Op. Mode} * Time_{Op. Mode} \quad 25$$

where $Power\ Output_{Op. Mode}$ is the auxiliary engine or steam turbine (and boilers) power rating (kW) in a given operational mode.

$$Trip_{Combustion}^{(Fuel-based, single-fuel)} = \sum_{Op. Mode} (FC_{Op. Mode}^{ME} + FC_{Op. Mode}^{Aux} + FC_{Op. Mode}^{Boiler}) * EF_{fuel-based}^{(metric, fuel)} \quad 26$$

where $Trip_{Combustion}^{(Fuel-based, single-fuel)}$ is the total trip-level result for a specific fuel-based emission-type group—whether from SO_x, BC, and CO₂—associated with the combustion life-cycle stage, under single-fuel engine configuration (excludes vessels running on LNG, methanol and ammonia).

Under dual-fuel vessel operation, calculation differs a bit. Another set of emission factors, $EF_{dual-fuel}^{(metric, fuel)}$, are used when vessel operates on LNG, methanol and ammonia. The corresponding values are provided in Table B10 of Appendix B. Equation 27 and 28 present the updated calculations involved:

$$Trip_{Combustion}^{(Energy-based, dual-fuel)} = \sum_{Op. Mode} (EC_{Op. Mode}^{ME} + EC_{Op. Mode}^{Pilot\ Fuel}) * EF_{dual-fuel}^{(metric, fuel)} + (W_{Op. Mode}^{Aux} + W_{Op. Mode}^{Boiler}) * EF_{energy-based}^{(metric, fuel)} \quad 27$$

where $Trip_{Combustion}^{(Energy-based, dual-fuel)}$ represents the total trip-level result for a specific energy-based emission-type group—whether from VOC, NO_x, CH₄, CO, N₂O, PM_{2.5}, and PM₁₀—associated with the combustion life-cycle stage, under dual-fuel engine configuration.

$$\begin{aligned}
 & Trip_{Combustion}^{(Fuel-based,dual-fuel)} \\
 &= \sum_{Op. Mode} (EC_{Op. Mode}^{ME} + EC_{Op. Mode}^{Pilot Fuel}) * EF_{dual-fuel}^{(metric,fuel)} + (FC_{Op. Mode}^{Aux} + FC_{Op. Mode}^{Boiler}) \\
 & * EF_{fuel-based}^{(metric,fuel)}
 \end{aligned}$$

where $Trip_{Combustion}^{(Fuel-based,dual-fuel)}$ represents the total trip-level result for a specific fuel-based emission-type group— whether from SO_x, BC, and CO₂—associated with the combustion life-cycle stage, under dual-fuel engine configuration.

Conversion							Fuel Combustion						
Sea (Normal Cruising)	Slow Transit	Maneuvering	Anchored	At berth	ECA	Trip	Sea (Normal Cruising)	Slow Transit	Maneuvering	Anchored	At berth	ECA	Trip
844,836	30,173	38,147	37,109	81,206	180,440	1,211,912	7,820,846	279,316	354,064	423,859	927,530	1,870,766	11,676,379
836,438	29,873	37,765	36,580	80,049	178,247	1,198,953	7,820,846	279,316	354,064	423,859	927,530	1,870,766	11,676,379
9,668	345	439	607	1,328	2,520	14,907	0	0	0	0	0	0	0
722,819	25,815	32,521	21,753	47,601	129,441	979,950	5,738,931	204,962	256,202	0	0	596,876	6,796,971
103,951	3,713	4,806	14,221	31,119	46,287	204,096	2,081,915	74,354	97,861	423,859	927,530	1,273,890	4,879,408
10,665	380.89	491.89	1,359.55	2,975.10	4,500.74	20,373.03	0	0.00	0.00	0.00	0.00	0.00	0.00
14	0.50	0.64	1.12	2.45	4.24	22.89	460	16	21	21	25	107	650.28
53	1.90	2.40	1.99	4.35	10.49	74.32	1,066	38	48	28	35	186	1,400.90
72	2.56	3.24	3.46	7.57	16.08	104.55	15,617	558	698	564	644	3,198	21,278.86
4	0.15	0.19	0.32	0.70	1.22	6.65	54	2	2	10	16	32	117.00
4	0.13	0.17	0.28	0.61	1.08	6.02	50	2	2	9	6	30	98.99
8	0.28	0.37	1.03	2.26	3.40	15.26	89	3	4	0	0	0	96.99
0	0.01	0.01	0.03	0.07	0.12	0.55	2	0	0	0	0	0	2.38
2	0.06	0.08	0.06	0.14	0.35	2.50	7	0	0	1	2	4	16.15
776	27.72	34.70	4.41	9.64	91.71	944.34	183	7	8	1	1	20	219.04
0	0.01	0.02	0.04	0.09	0.15	0.72	36	1	2	2	4	9	53.31
46,837	1,672.76	2,117.95	2,327.28	5,092.79	10,676.94	68,725	483,610	17,272	21,971	32,859	71,906	132,348	759,967
46,964	1,677	2,124	2,334	5,107	10,707	68,913	486,718	17,383	22,110	32,969	72,040	132,975	764,195
70,206	2,507	3,163	2,476	5,419	13,480	97,252	501,955	17,927	22,795	33,520	73,108	135,972	785,277
9	0.33	0.42	0.55	1.20	2.34	14	0	0	0	0	0	0	0
11	0	0	0	1	2	15	0	0	0	0	0	0	0
4	0	0	1	1	2	8	0	0	0	0	0	0	0
1	0	0	0	0	0	2	0	0	0	0	0	0	0
1	0	0	0	0	0	2	0	0	0	0	0	0	0
1	0	0	0	1	1	3	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 33. Energy Consumption, Water Consumption, and Emissions results per operational mode and per trip in the conversion and combustion stage (Table 4.1 of the Marine_Trip tab, R&D GREET1 2025).

3 Appendix A: Examples of WTW results available in the Marine_Fuel and the Marine_Trip tabs



Figure A1. Greenhouse gas (GHG) emission of fuel pathways available in the Marine_Fuel tab;³ when used in a slow-speed diesel main engine.

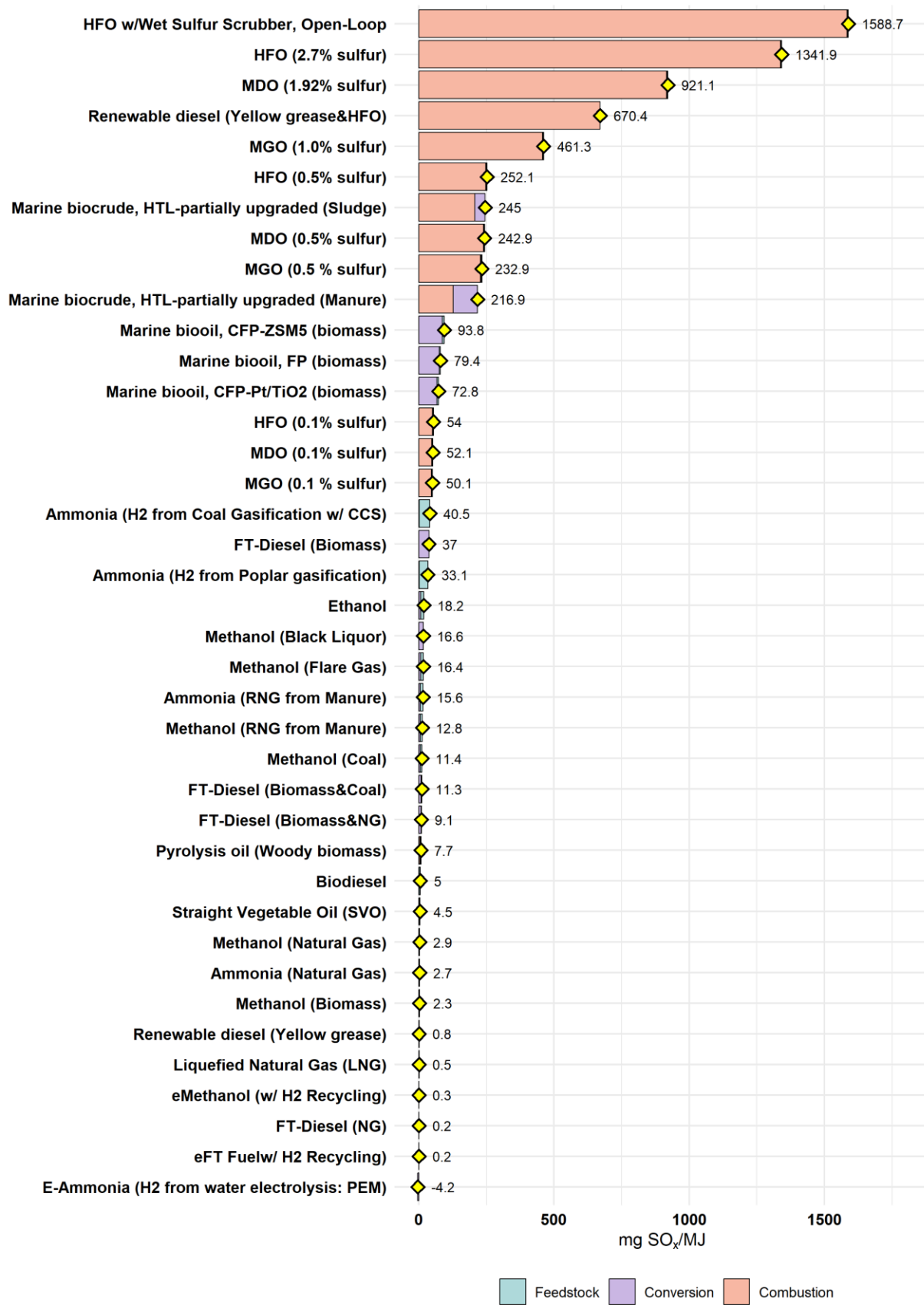


Figure A2. Sulfur Oxide (SO_x) emission of fuel pathways available in the Marine_Fuel tab;³ when used in a slow-speed diesel main engine.

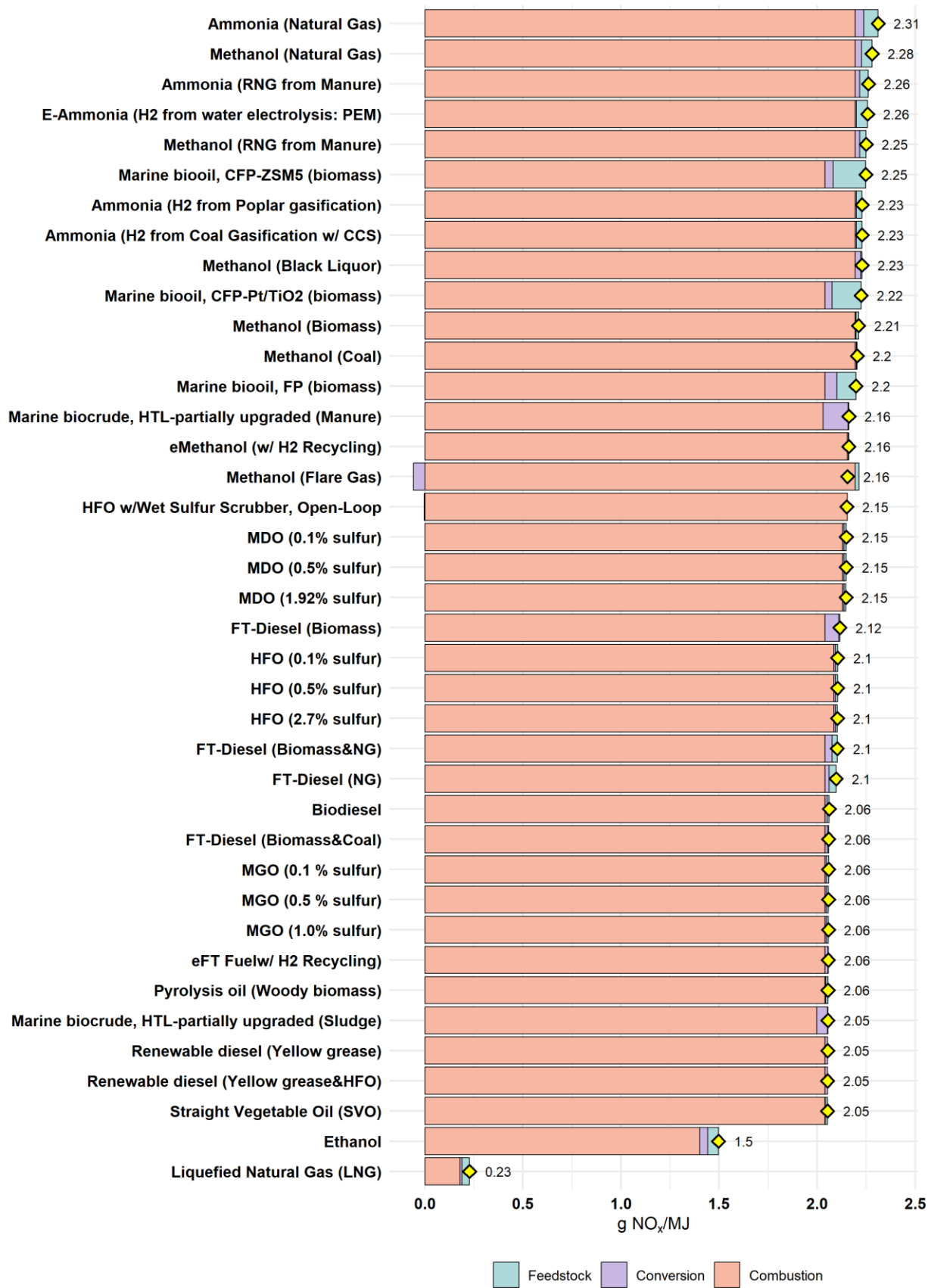


Figure A3. Nitrogen oxides (NO_x) emission of fuel pathways available in the Marine_Fuel tab;³ when used in a slow-speed diesel main engine.

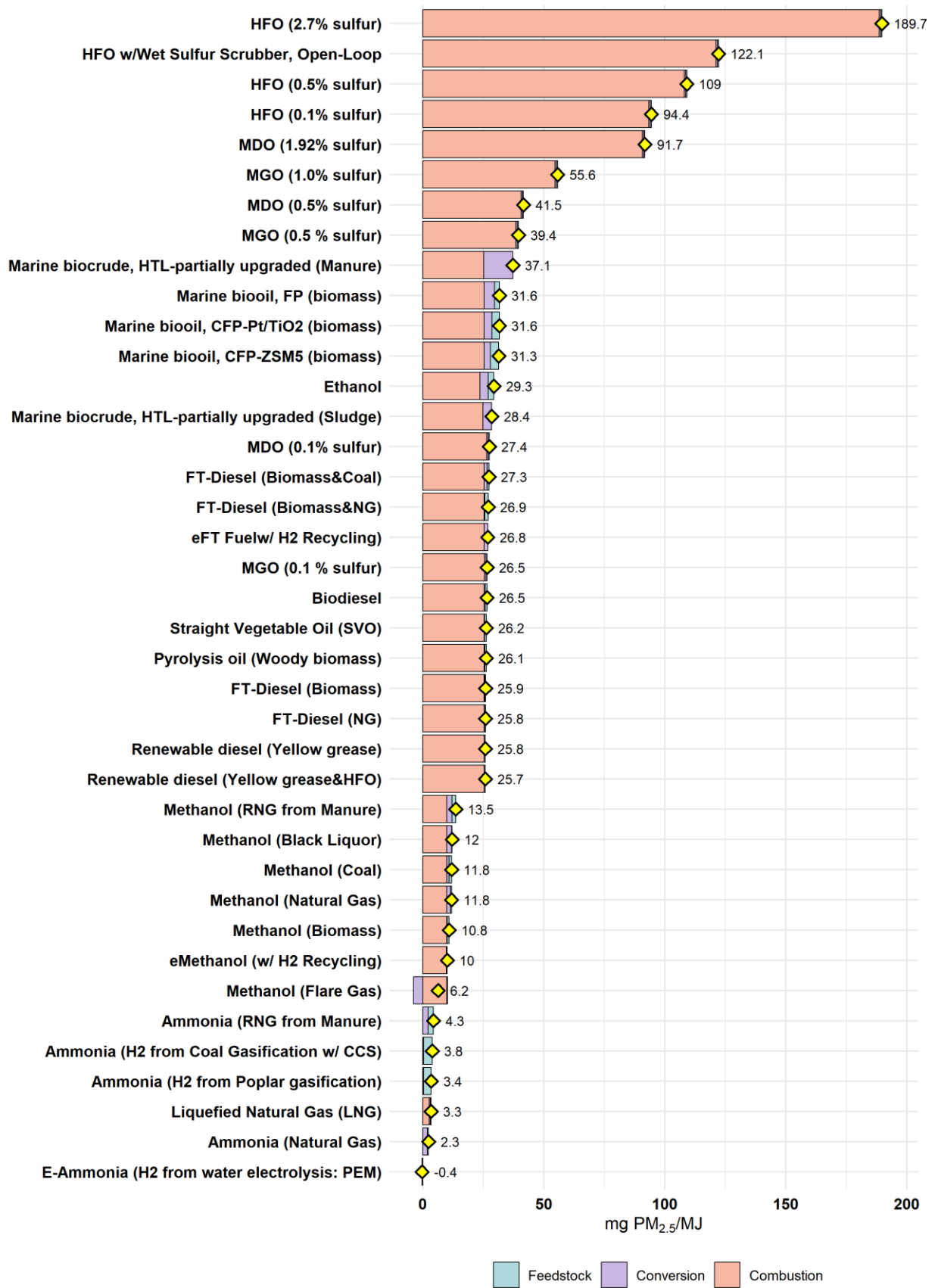


Figure A4. Particulate matter (PM_{2.5}) emission of fuel pathways available in the Marine_Fuel tab;³ when used in a slow-speed diesel main engine.

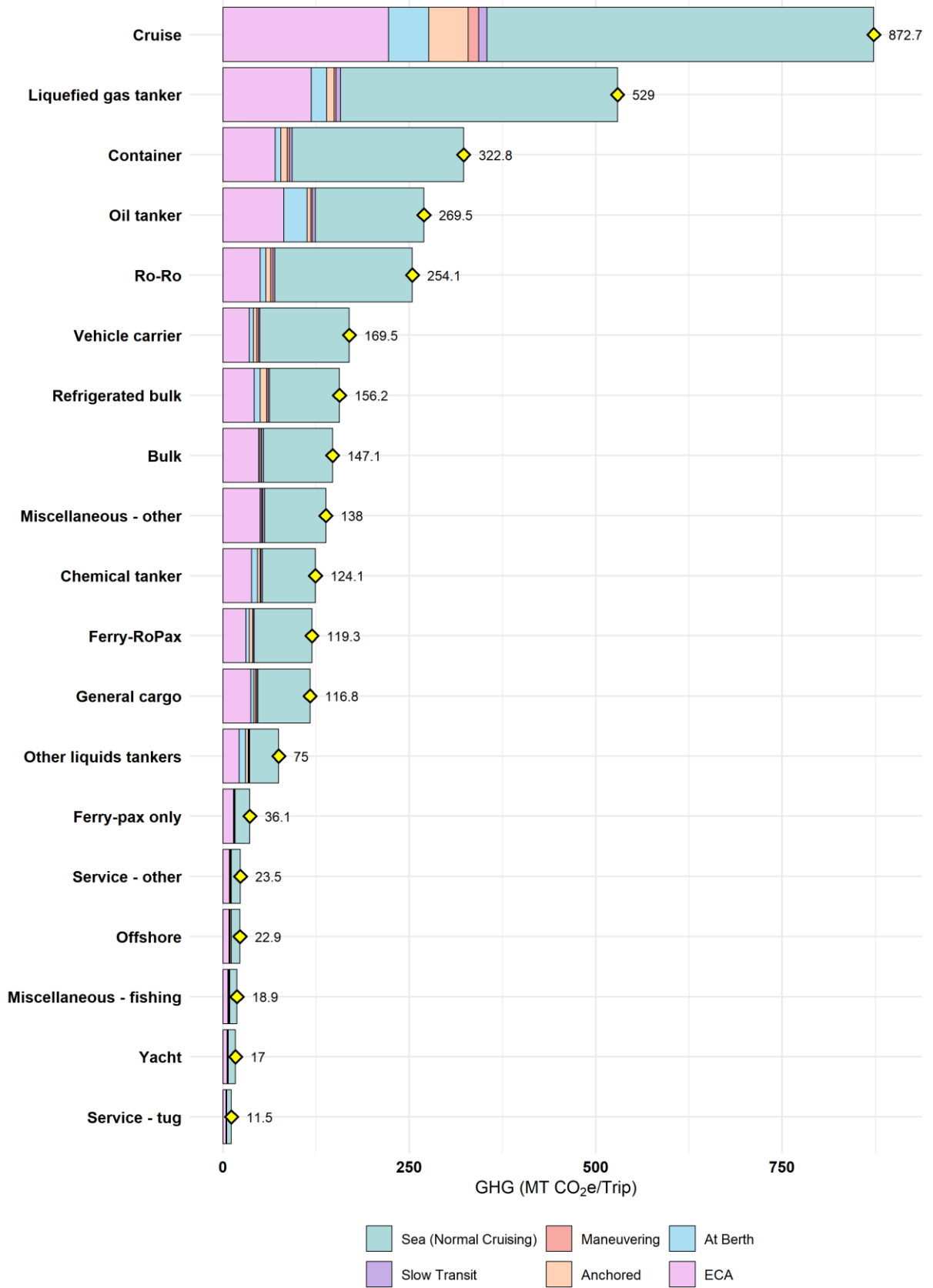


Figure A5. Sulfur Oxide (SO_x) emission of trips made by different vessels using MGO (0.1% sulfur) on the main engine, auxiliary engines and boilers, available in the Marine_Trip tab;³ assuming the default pre-defined trips distance, speed and time in mode. Further efforts to have different default characteristics per vessel type are expected to be implemented in the next GREET version.

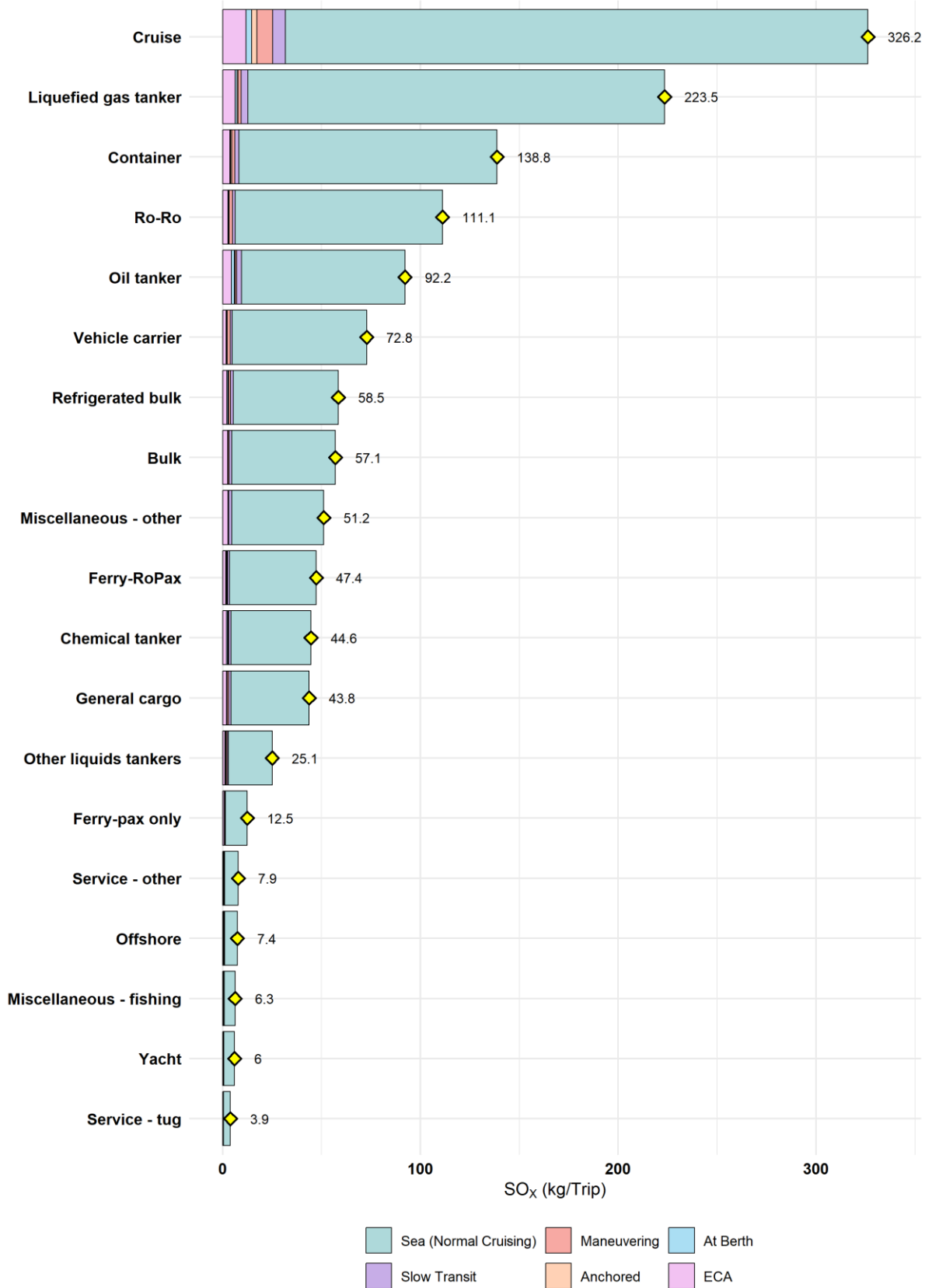


Figure A6. Sulfur Oxide (SO_x) emission of trips made by different vessels using MGO (0.1% sulfur) on the main engine, auxiliary engines and boilers, available in the Marine_Trip tab;³ assuming the default pre-defined trips distance, speed and time in mode. Further efforts to have different default characteristics per vessel type are expected to be implemented in the next GREET version.

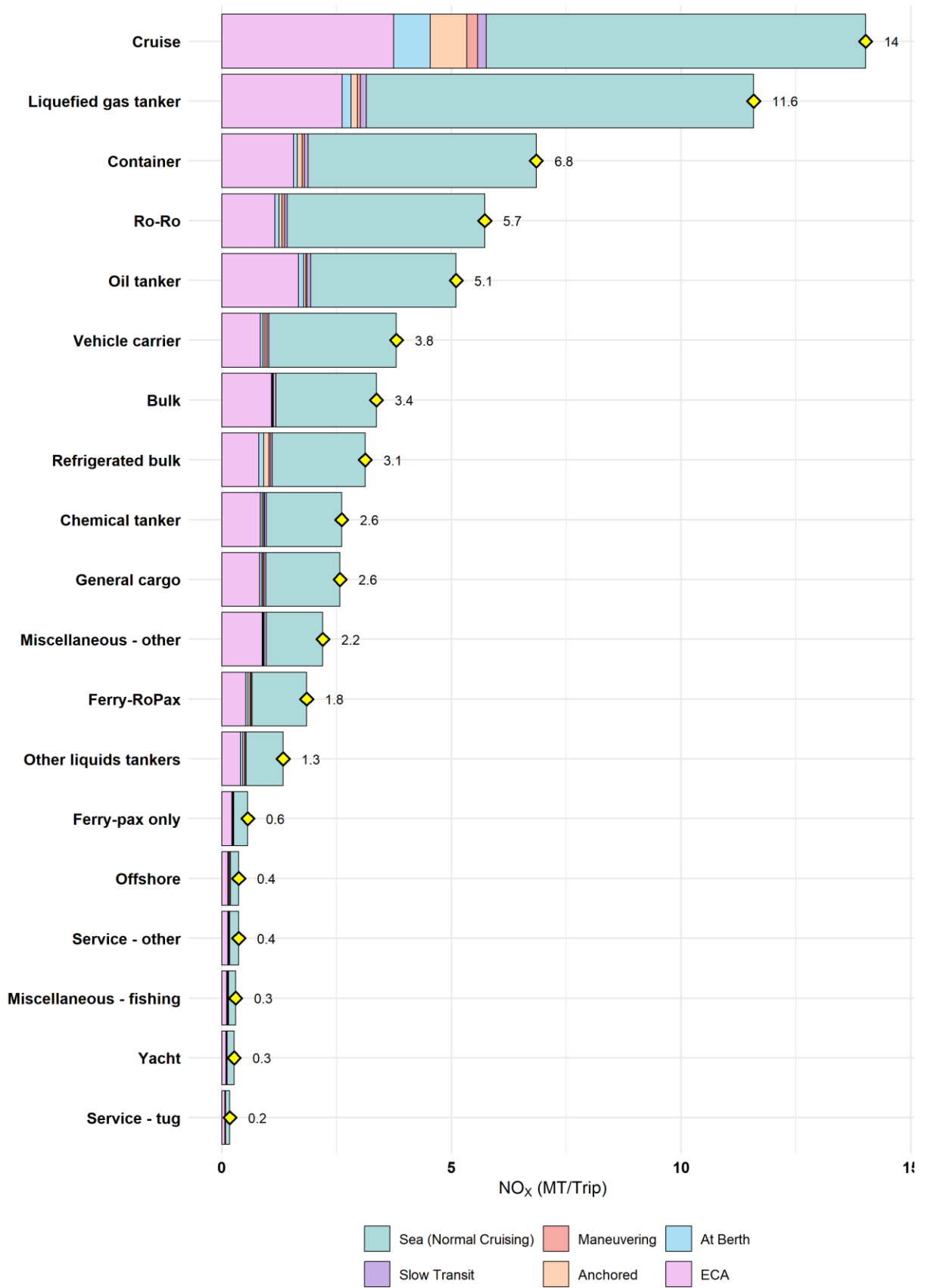


Figure A7. Nitrogen oxides (NO_x) of trips made by different vessels using MGO (0.1% sulfur) on the main engine, auxiliary engines and boilers, available in the Marine_Trip tab;³ assuming the default pre-defined trips distance, speed and time in mode. Further efforts to have different default characteristics per vessel type are expected to be implemented in the next GREET version.

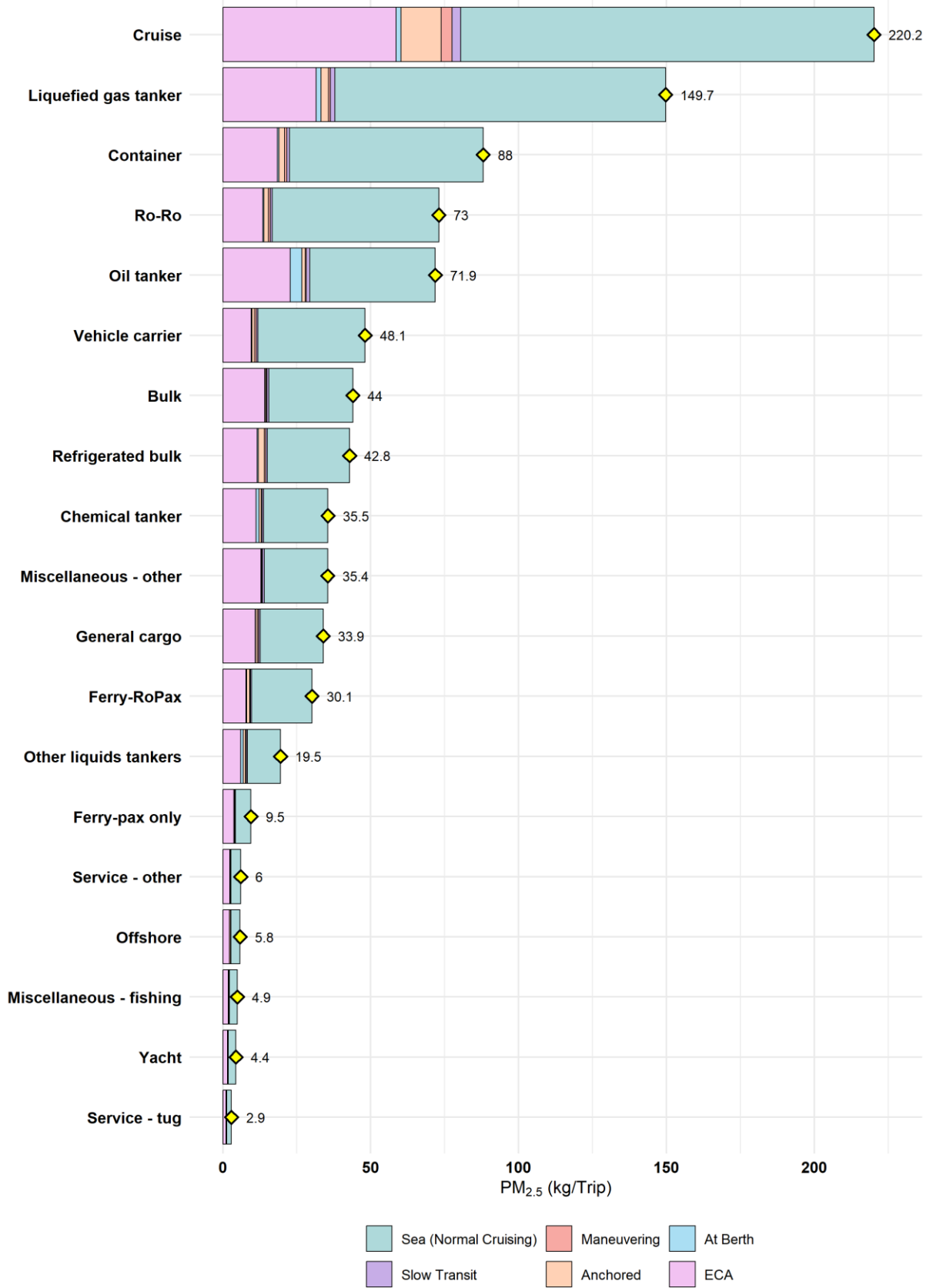


Figure A8. Particulate matter (PM_{2.5}) emission of trips made by different vessels using MGO (0.1% sulfur) on the main engine, auxiliary engines and boilers, available in the Marine_Trip tab,³ assuming the default pre-defined trips distance, speed and time in mode. Further efforts to have different default characteristics per vessel type are expected to be implemented in the next GREET version.

4 Appendix B: Supporting Information

Table B1. Parameters used for load factor estimation per vessel type and size for different operation modes using Equation 2 and its results.

Vessel Type		Avg. design speed (v_{ref})	Avg. SOG at Maneuvering (assumed)	Avg. SOG at Slow Speed (assumed)	Avg. SOG at Sea (v_i)	Speed-power correction factor (δ_w)	Weather Correction Factor (η_w)	Fouling correction factor (η_f)	Estimated Load (Maneuvering)	Estimated Load (Slow Speed and ECA)	Estimated Load Sea (Normal Cruising)
	Unit ->	(kn)	(kn)	(kn)	(kn)	unitless	unitless	unitless	unitless	unitless	unitless
Bulk	0-9999 DWT	11.8	4	9.3	9.3	1	0.909	0.917	0.05	0.59	0.59
Bulk	10000-34999 DWT	13.8	4	10	11	1	0.867	0.917	0.03	0.48	0.64
Bulk	35000-59999 DWT (Default)	14.3	4	10	11.4	1	0.867	0.917	0.03	0.43	0.64
Bulk	60000-99999 DWT	14.4	4	10	11.4	1	0.867	0.917	0.03	0.42	0.62
Bulk	100000-199999 DWT	14.5	4	10	11.2	1	0.867	0.917	0.03	0.41	0.58
Bulk	200000+ DWT	14.6	4	10	11.8	1	0.867	0.917	0.03	0.40	0.66
Container	0-999 TEU	16.00	4	10	11.8	1	0.909	0.917	0.02	0.29	0.48
Container	1000-1999 TEU	19	4	10	13.4	1	0.867	0.917	0.01	0.18	0.44
Container	2000-2999 TEU	21.1	4	10	14.2	1	0.867	0.917	0.01	0.13	0.38
Container	3000-4999 TEU (Default)	23.1	4	10	14.7	1	0.867	0.917	0.01	0.10	0.32
Container	5000-7999 TEU	24.6	4	10	15.7	1	0.867	0.917	0.01	0.08	0.33
Container	8000-11999 TEU	23.9	4	10	16.3	1	0.867	0.917	0.01	0.09	0.40
Container	12000-14499 TEU	23.8	4	10	16.3	1	0.867	0.917	0.01	0.09	0.40
Container	14500-19999 TEU	20.2	4	10	16.5	0.75	0.867	0.917	0.01	0.15	0.69
Container	20000+ TEU	20.3	4	10	16.3	0.75	0.867	0.917	0.01	0.15	0.65
Oil Tanker	0-4999 DWT	11.4	4	8.7	8.7	1	0.909	0.917	0.05	0.53	0.53
Oil Tanker	5000-9999 DWT	12.1	4	9.1	9.1	1	0.909	0.917	0.04	0.51	0.51
Oil Tanker	10000-19999 DWT	12.9	4	9.8	9.8	1	0.867	0.917	0.04	0.55	0.55
Oil Tanker	20000-59999 DWT	14.6	4	10	11.2	1	0.867	0.917	0.03	0.40	0.57
Oil Tanker	60000-79999 DWT	14.8	4	10	11.6	1	0.867	0.917	0.02	0.39	0.61
Oil Tanker	80000-119999 DWT (Default)	14.8	4	10	11.2	1	0.867	0.917	0.02	0.39	0.55
Oil Tanker	120000-199999 DWT	15.1	4	10	11.4	1	0.867	0.917	0.02	0.37	0.54
Oil Tanker	200000+ DWT	15.5	4	10	11.9	1	0.867	0.917	0.02	0.34	0.57
Chemical tanker	0-4999 DWT	12.2	4	9.6	9.6	1	0.909	0.917	0.042	0.585	0.585
Chemical tanker	5000-9999 DWT	12.9	4	10	10.3	1	0.909	0.917	0.036	0.559	0.611
Chemical tanker	10000-19999 DWT (Default)	13.8	4	10	11.4	1	0.867	0.917	0.031	0.479	0.709
Chemical tanker	20000-39999 DWT	14.7	4	10	12.1	1	0.867	0.917	0.025	0.396	0.701
Chemical tanker	40000+ DWT	14.6	4	10	11.9	1	0.867	0.917	0.026	0.404	0.681
General cargo	0-4999 DWT	11.1	4	8.8	8.8	1	0.909	0.917	0.056	0.598	0.598

General cargo	5000-9999 DWT	12.7	4	9.8	9.8	1	0.909	0.917	0.037	0.551	0.551
General cargo	10000-19999 DWT (Default)	14	4	10	11.4	1	0.867	0.917	0.029	0.458	0.679
General cargo	20000+ DWT	15	4	10	11.9	1	0.867	0.917	0.024	0.373	0.628
Liquefied gas tanker	0-49999 CBM	14.2	4	10	11.7	1	0.867	0.917	0.028	0.439	0.704
Liquefied gas tanker	50000-99999 CBM	16.4	4	10	14.1	1	0.867	0.917	0.018	0.285	0.799
Liquefied gas tanker	100000-199999 CBM (Default)	19	4	10	14.9	1	0.867	0.917	0.012	0.183	0.607
Liquefied gas tanker	200000 CBM	19.2	4	10	16	1	0.867	0.917	0.011	0.178	0.728
Other liquids tankers	0-999 DWT	9.6	4	7.5	7.5	1	0.867	0.917	0.091	0.600	0.600
Other liquids tankers	1000+ DWT (Default)	13.6	4	10	11.6	1	0.867	0.917	0.032	0.500	0.780
Ferry-pax only	0-299 GT	19.3	4	10	14.1	1	0.909	0.917	0.011	0.167	0.468
Ferry-pax only	300-999 GT	26.2	4	10	14.7	1	0.909	0.917	0.004	0.067	0.212
Ferry-pax only	1000-1999 GT (Default)	14.5	4	9.3	9.3	1	0.909	0.917	0.025	0.317	0.317
Ferry-pax only	2000+ GT	16.2	4	10	12.4	1	0.909	0.917	0.018	0.282	0.538
Cruise	0-1999 GT	12.7	4	8.1	8.1	0.7	0.909	0.917	0.037	0.311	0.311
Cruise	2000-9999 GT	13.8	4	9.2	9.2	0.7	0.867	0.917	0.031	0.373	0.373
Cruise	10000-59999 GT	19	4	10	13.4	0.7	0.867	0.917	0.012	0.183	0.441
Cruise	60000-99999 GT (Default)	21.8	4	10	15.3	0.7	0.867	0.917	0.008	0.121	0.435
Cruise	100000-149999 GT	21.3	4	10	16	0.7	0.867	0.917	0.008	0.130	0.533
Cruise	150000+ GT	22	4	10	16.4	0.7	0.867	0.917	0.008	0.118	0.521
Ferry-RoPax	0-1999 GT	13	4	9	9	1	0.909	0.917	0.035	0.398	0.398
Ferry-RoPax	2000-4999 GT	17.4	4	10	11.4	1	0.909	0.917	0.015	0.228	0.337
Ferry-RoPax	5000-9999 GT (Default)	21.6	4	10	13.2	1	0.909	0.917	0.008	0.119	0.274
Ferry-RoPax	10000-19999 GT	20.3	4	10	15.1	1	0.909	0.917	0.009	0.143	0.494
Ferry-RoPax	20000+ GT	22.6	4	10	16.5	1	0.909	0.917	0.007	0.104	0.467
Refrigerated bulk	0-1999 DWT	12.1	4	9.1	9.1	1	0.867	0.917	0.045	0.535	0.535
Refrigerated bulk	2000-5999 DWT	14.7	4	10	11.1	1	0.867	0.917	0.025	0.396	0.542
Refrigerated bulk	6000-9999 DWT (Default)	17.4	4	10	13.6	1	0.867	0.917	0.015	0.239	0.601
Refrigerated bulk	10000+ DWT	20.2	4	10	16.3	1	0.867	0.917	0.010	0.153	0.661
Ro-Ro	0-4999 DWT	11.2	4	8.1	8.1	1	0.909	0.917	0.055	0.454	0.454
Ro-Ro	5000-9999 DWT	17.6	4	10	14.2	1	0.867	0.917	0.015	0.231	0.661
Ro-Ro	10000-14999 DWT (Default)	19.6	4	10	15.5	1	0.867	0.917	0.011	0.167	0.622
Ro-Ro	15000+ DWT	19.1	4	10	15.2	1	0.867	0.917	0.012	0.181	0.634
Vehicle	0-29999 GT	17.3	4	10	13.6	1	0.867	0.917	0.016	0.243	0.611
Vehicle	30000-49999 GT (Default)	19.4	4	10	14.7	1	0.867	0.917	0.011	0.172	0.547

Vehicle	50000+ GT	19.9	4	10	15.5	1	0.867	0.917	0.010	0.160	0.594
Yacht	0+ GT	16.7	4	10	10.7	1	0.867	0.917	0.017	0.270	0.331
Service - tug	0+ GT	11.9	4	6.6	6.6	1	0.909	0.917	0.046	0.205	0.205
Miscellaneous fishing	- 0+ GT	11.7	4	7.5	7.5	1	0.909	0.917	0.048	0.316	0.316
Offshore	0+ GT	13.9	4	8.5	8.5	1	0.909	0.917	0.029	0.274	0.274
Service - other	0+ GT	13.6	4	8.1	8.1	1	0.909	0.917	0.031	0.253	0.253
Miscellaneous other	- 0+ GT	18.2	4	10	10.7	1	0.909	0.917	0.013	0.199	0.244
Note: CBM: Cubic Meter; DWT: Deadweight Tonnage; ECA: Emission Control Area; GT: Gross Tonnes; kn: knots; TEU: Twenty-foot Equivalent Units; SOG: Speed Over Ground;											

Table B2. Fuel list per engine type and cycle type (Table 6.10 of the Marine Trip tab, R&D GREET1 2025).

Configuration	Engine type	Combustion cycle	Available fuels
Single-fuel	SSD 2-Stroke	Diesel	HFO (2.7% sulfur), HFO (0.5% sulfur), HFO (0.1% sulfur), MDO (1.92% sulfur), MDO (0.5% sulfur), MDO (0.1% sulfur), MGO (1.0% sulfur), MGO (0.5 % sulfur), MGO (0.1 % sulfur), FT-Diesel (NG), FT-Diesel (Biomass&Coal), Renewable diesel (Yellow grease&HFO), FT-Diesel (Biomass&NG), Straight Vegetable Oil (SVO), Pyrolysis oil (Woody biomass), FT-Diesel (Biomass), Renewable diesel (Yellow grease), Biodiesel, HFO (2.7% S), Wet Sulfur Scrubber (Open-Loop), Marine biocrude, HTL-partially upgraded (Sludge), Marine biocrude, HTL-partially upgraded (Manure), Marine biooil, FP (biomass), Marine biooil, CFP-ZSM5 (biomass), Marine biooil, CFP-Pt/TiO2 (biomass)
Dual-fuel	SSD 2-Stroke	Diesel	Liquefied Natural Gas (LNG), Methanol (Natural Gas), Methanol (Flare Gas), Methanol (Renewable Natural Gas), Methanol (Biomass), Methanol (Coal), Methanol (Black Liquor), eMethanol (w/ H2 Recycling), eFT Fuelw/ H2 Recycling, Ammonia (Natural Gas), Ammonia from RNG, Ammonia (H2 from Coal Gasification w/ CCS), Ammonia (H2 from Poplar gasification), E-Ammonia (H2 from water electrolysis: PEM), Ethanol
Single-fuel	MSD 4-Stroke	Diesel	HFO (2.7% sulfur), HFO (0.5% sulfur), HFO (0.1% sulfur), MDO (1.92% sulfur), MDO (0.5% sulfur), MDO (0.1% sulfur), MGO (1.0% sulfur), MGO (0.5 % sulfur), MGO (0.1 % sulfur), FT-Diesel (NG), FT-Diesel (Biomass&Coal), Renewable diesel (Yellow grease&HFO), FT-Diesel (Biomass&NG), Straight Vegetable Oil (SVO), Pyrolysis oil (Woody biomass), FT-Diesel (Biomass), Renewable diesel (Yellow grease), Biodiesel, HFO (2.7% S), Wet Sulfur Scrubber (Open-Loop), Marine biocrude, HTL-partially upgraded (Sludge), Marine biocrude, HTL-partially upgraded (Manure), Marine biooil, FP (biomass), Marine biooil, CFP-ZSM5 (biomass), Marine biooil, CFP-Pt/TiO2 (biomass)
Dual-fuel	MSD 4-Stroke	Diesel	Liquefied Natural Gas (LNG), Methanol (Natural Gas), Methanol (Flare Gas), Methanol (Renewable Natural Gas), Methanol (Biomass), Methanol (Coal), Methanol (Black Liquor), eMethanol (w/ H2 Recycling), eFT Fuelw/ H2 Recycling, Ammonia (Natural Gas), Ammonia from RNG, Ammonia (H2 from Coal Gasification w/ CCS), Ammonia (H2 from Poplar gasification), E-Ammonia (H2 from water electrolysis: PEM), Ethanol
Single-fuel	HSD 4-Stroke	Diesel	MDO (1.92% sulfur), MDO (0.5% sulfur), MDO (0.1% sulfur), MGO (1.0% sulfur), MGO (0.5 % sulfur), MGO (0.1 % sulfur), FT-Diesel (NG), FT-Diesel (Biomass&Coal), Renewable diesel (Yellow grease&HFO), FT-Diesel (Biomass&NG), Straight Vegetable Oil (SVO), Pyrolysis oil (Woody biomass), FT-Diesel (Biomass), Renewable diesel (Yellow grease), Biodiesel
Single-fuel	Gas Turbines	Brayton	FT-Diesel (NG), FT-Diesel (Biomass&Coal), Renewable diesel (Yellow grease&HFO), FT-Diesel (Biomass&NG), Straight Vegetable Oil (SVO), Pyrolysis oil (Woody biomass), FT-Diesel (Biomass), Renewable diesel (Yellow grease), Biodiesel, HFO (2.7% S), Wet Sulfur Scrubber (Open-Loop), Marine biocrude, HTL-partially upgraded (Sludge), Marine biocrude, HTL-partially upgraded (Manure), Marine biooil, FP (biomass), Marine biooil, CFP-ZSM5 (biomass), Marine biooil, CFP-Pt/TiO2 (biomass)
Dual-fuel	Gas Turbines	Brayton	Liquefied Natural Gas (LNG)
Dual-fuel	SSD 2-Stroke	Otto	Liquefied Natural Gas (LNG)
Dual-fuel	MSD 4-Stroke	Otto	Liquefied Natural Gas (LNG)
Single-fuel	MSD 4-Stroke	LBSI	Liquefied Natural Gas (LNG)

Table B3. Support table: index number for each fuel, fuel category group, and conversion ratio for adjusting the specific fuel consumption, SFC (Table 6.7 of the Marine Trip tab, R&D GREET1 2025).

Fuel Type	Index	Fuel Category	SFC factor adjustment
HFO (2.7% sulfur)	1	HFO	1
HFO (0.5% sulfur)	2	HFO	1
HFO (0.1% sulfur)	3	HFO	1
MDO (1.92% sulfur)	4	MDO	1
MDO (0.5% sulfur)	5	MDO	1
MDO (0.1% sulfur)	6	MDO	1
MGO (1.0% sulfur)	7	MDO	0.96
MGO (0.5 % sulfur)	8	MDO	0.96
MGO (0.1 % sulfur)	9	MDO	0.96
FT-Diesel (NG)	10	MDO	0.95
Liquefied Natural Gas (LNG)	11	LNG	1.00
FT-Diesel (Biomass&Coal)	12	MDO	0.95
Renewable diesel (Yellow grease&HFO)	13	MDO	0.93
FT-Diesel (Biomass&NG)	14	MDO	0.95
Straight Vegetable Oil (SVO)	15	MDO	1.10
Pyrolysis oil (Woody biomass)	16	MDO	2.73
FT-Diesel (Biomass)	17	MDO	0.95
Renewable diesel (Yellow grease)	18	MDO	0.93
Biodiesel	19	MDO	1.08
Ethanol	20	MeOH	1.52
Methanol (Natural Gas)	21	MeOH	1.00
Methanol (Flare Gas)	22	MeOH	1.00
Methanol (Renewable Natural Gas)	23	MeOH	1.00
Methanol (Biomass)	24	MeOH	1.00
Methanol (Coal)	25	MeOH	1.00
Methanol (Black Liquor)	26	MeOH	1.00
eMethanol (w/ H2 Recycling)	27	MeOH	0.98
eFT Fuelw/ H2 Recycling)	28	MDO	0.93
Ammonia (Natural Gas)	29	MeOH	1.05
Ammonia from RNG	30	MeOH	1.05
Ammonia (H2 from Coal Gasification w/ CCS)	31	MeOH	1.05
Ammonia (H2 from Poplar gasification)	32	MeOH	1.05
E-Ammonia (H2 from water electrolysis: PEM)	33	MeOH	1.05
HFO (2.7% S), Wet Sulfur Scrubber (Open-Loop)	34	HFO	1.04
Marine biocrude, HTL-partially upgraded (Sludge)	35	MDO	0.952
Marine biocrude, HTL-partially upgraded (Manure)	36	MDO	0.968
Marine biooil, FP (biomass)	37	MDO	2.461
Marine biooil, CFP-ZSM5 (biomass)	38	MDO	1.298
Marine biooil, CFP-Pt/TiO2 (biomass)	39	MDO	1.267

Table B4. Fuel type options for auxiliary engine(s) and boilers (or steam turbines), Pilot Fuel, and Blendstock B. Share percentage options for Fuel Blendstock B (%) (Table 6.11 of Marine_Trip tab from R&D GREET1 2025).

Operational group	Configuration	Fuel options
Aux. engine(s) and boilers (or steam turbines)		HFO (2.7% sulfur), HFO (0.5% sulfur), HFO (0.1% sulfur), HFO w/Wet Sulfur Scrubber, Open-Loop, MDO (1.92% sulfur), MDO (0.5% sulfur), MDO (0.1% sulfur), MGO (1.0% sulfur), MGO (0.5 % sulfur), MGO (0.1 % sulfur), Liquefied Natural Gas (LNG), FT-Diesel (NG), FT-Diesel (Biomass&Coal), Renewable diesel (Yellow grease&HFO), FT-Diesel (Biomass&NG), Straight Vegetable Oil (SVO), Pyrolysis oil (Woody biomass), FT-Diesel (Biomass), Renewable diesel (Yellow grease), Biodiesel, Marine biocrude, HTL-partially upgraded (Sludge), Marine biocrude, HTL-partially upgraded (Manure), Marine biooil, FP (biomass), Marine biooil, CFP-ZSM5 (biomass), Marine biooil, CFP-Pt/TiO2 (biomass), Not Applicable
Pilot Fuel	Single-fuel	No pilot fuel
Pilot Fuel	Dual-Fuel	MDO (1.92% sulfur), MDO (0.5% sulfur), MDO (0.1% sulfur), MGO (1.0% sulfur), MGO (0.5 % sulfur), MGO (0.1 % sulfur), FT-Diesel (NG), FT-Diesel (Biomass&Coal), Renewable diesel (Yellow grease&HFO), FT-Diesel (Biomass&NG), Straight Vegetable Oil (SVO), Pyrolysis oil (Woody biomass), FT-Diesel (Biomass), Renewable diesel (Yellow grease), Biodiesel, Marine biocrude, HTL-partially upgraded (Sludge), Marine biocrude, HTL-partially upgraded (Manure), Marine biooil, FP (biomass), Marine biooil, CFP-ZSM5 (biomass), Marine biooil, CFP-Pt/TiO2 (biomass)
Blendstock B options	Not Applicable	Not Applicable
Blendstock B options	Fuel_BlendstockB	HFO (2.7% sulfur), HFO (0.5% sulfur), HFO (0.1% sulfur), HFO w/Wet Sulfur Scrubber, Open-Loop, MDO (1.92% sulfur), MDO (0.5% sulfur), MDO (0.1% sulfur), MGO (1.0% sulfur), MGO (0.5 % sulfur), MGO (0.1 % sulfur), FT-Diesel (NG), FT-Diesel (Biomass&Coal), Renewable diesel (Yellow grease&HFO), FT-Diesel (Biomass&NG), Straight Vegetable Oil (SVO), Pyrolysis oil (Woody biomass), FT-Diesel (Biomass), Renewable diesel (Yellow grease), Biodiesel, Marine biocrude, HTL-partially upgraded (Sludge), Marine biocrude, HTL-partially upgraded (Manure), Marine biooil, FP (biomass), Marine biooil, CFP-ZSM5 (biomass), Marine biooil, CFP-Pt/TiO2 (biomass), Not Applicable
Share of Fuel Blendstock B (%)	Not Applicable	0
Share of Fuel Blendstock B (%)	Fuel_BlendstockB	0.05, 0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4, 0.45, 0.5, 0.55, 0.6, 0.65, 0.7, 0.75, 0.8, 0.85, 0.9, 0.95

Table B5. Default pre-defined trips distance, speed and time in mode (Table 5.1 of Marine_Trip tab from R&D GREET 2025).

Operational Mode	Distance (nm)	Speed (knots)	Time in Mode (hours)
Sea (Normal Cruising)	500	18	28
Slow Transit	10	10	1
Maneuvering	5	4	1
Anchored	0	0	6
At berth	0	0	6
ECA	200	10	20
Payload (wet ton)	60,076		
million tonne-km	46		

Table B6. Average deadweight tonne (DWT) and power rating from the main propulsion, and power output from the auxiliary engine(s) and boilers (or steam turbines) per vessel type and size (Table 6.6 of Marine Trip tab from R&D GREET 2025).

Vessel Type	Unit ->	Average deadweight tonne	Power Rating (main engine)	Auxiliary Engine(s) Power Output				Boilers (or Steam Turbines) Power Output			
				At berth	Anchored	Maneuvering	Sea (Normal Cruising)	At berth	Anchored	Maneuvering	Sea (Normal Cruising)
		DWT	kW	kW	kW	kW	kW	kW	kW	kW	kW
Bulk	0-9999 DWT	4,271	1,796	110	180	500	190	70	70	60	0
Bulk	10000-34999 DWT	27,303	5,941	110	180	500	190	70	70	60	0
Bulk	35000-59999 DWT (Default)	49,487	8,177	150	250	680	260	130	130	120	0
Bulk	60000-99999 DWT	76,147	9,748	240	400	1100	410	260	260	240	0
Bulk	100000-199999 DWT	169,868	16,741	240	400	1100	410	260	260	240	0
Bulk	200000+ DWT	251,667	30,094	240	400	1100	410	260	260	240	0
Container	0-999 TEU	8,438	5,077	370	450	790	410	250	250	240	0
Container	1000-1999 TEU	19,051	12,083	820	910	1750	900	340	340	310	0
Container	2000-2999 TEU	34,894	20,083	610	910	1900	920	460	450	430	0
Container	3000-4999 TEU (Default)	52,372	34,559	1100	1350	2500	1400	480	480	430	0
Container	5000-7999 TEU	74,661	52,566	1100	1400	2800	1450	590	580	550	0
Container	8000-11999 TEU	110,782	57,901	1150	1600	2900	1800	620	620	540	0
Container	12000-14499 TEU	149,023	61,231	1300	1800	3250	2050	630	630	630	0
Container	14500-19999 TEU	179,871	60,202	1400	1950	3600	2300	630	630	630	0
Container	20000+ TEU	195,615	20,210	1400	1950	3600	2300	700	700	700	0
Oil Tanker	0-4999 DWT	3,158	966	250	250	375	250	500	100	100	0
Oil Tanker	5000-9999 DWT	6,789	2,761	375	375	560	375	750	150	150	0
Oil Tanker	10000-19999 DWT	14,733	4,417	690	500	580	490	1250	250	250	0
Oil Tanker	20000-59999 DWT	43,750	8,975	720	520	600	510	2700	270	270	270
Oil Tanker	60000-79999 DWT	72,826	11,837	620	490	770	560	3250	360	360	280
Oil Tanker	80000-119999 DWT (Default)	109,262	13,319	800	640	910	690	4000	400	400	280
Oil Tanker	120000-199999 DWT	155,878	17,446	2500	770	1300	860	6500	500	500	300
Oil Tanker	200000+ DWT	307,866	27,159	2500	770	1300	860	7000	600	600	300
Chemical tanker	0-4999 DWT	4,080	987	110	170	190	200	670	160	130	0
Chemical tanker	5000-9999 DWT	7,276	3,109	330	490	560	580	670	160	130	0
Chemical tanker	10000-19999 DWT (Default)	15,324	5,101	330	490	560	580	1000	240	200	0

Chemical tanker	20000-3999 DWT	32,492	8,107	790	550	900	660	1350	320	270	0
Chemical tanker	40000+ DWT	48,796	8,929	790	550	900	660	1350	320	270	0
General cargo	0-4999 DWT	2,104	1,454	90	50	180	60	0	0	0	0
General cargo	5000-9999 DWT	6,985	3,150	240	130	490	180	110	110	100	0
General cargo	10000-19999 DWT (Default)	13,423	5,280	720	370	1450	520	150	150	130	0
General cargo	20000+ DWT	36,980	9,189	720	370	1450	520	150	150	130	0
Liquefied gas tanker	0-49999 CBM	8,603	2,236	240	240	360	240	1000	200	200	100
Liquefied gas tanker	50000-99999 CBM	52,974	12,832	1700	1700	2600	1700	1000	200	200	100
Liquefied gas tanker	100000-199999 CBM (Default)	83,661	30,996	2500	2000	2300	2650	1500	300	300	150
Liquefied gas tanker	200000 CBM	121,977	36,735	6750	7200	7200	6750	3000	600	600	300
Other liquids tankers	0-999 DWT	3,450	687	500	500	750	500	1000	200	200	100
Other liquids tankers	1000+ DWT (Default)	10,813	2,034	500	500	750	500	1000	200	200	100
Ferry-pax only	0-299 GT	4,034	1,152	190	190	190	190	0	0	0	0
Ferry-pax only	300-999 GT	102	3,182	190	190	190	190	0	0	0	0
Ferry-pax only	1000-1999 GT (Default)	354	2,623	190	190	190	190	0	0	0	0
Ferry-pax only	2000+ GT	1,730	6,539	520	520	520	520	0	0	0	0
Cruise	0-1999 GT	3,115	911	450	450	580	480	1100	950	980	0
Cruise	2000-9999 GT	867	3,232	450	450	580	450	1100	950	980	0
Cruise	10000-59999 GT	4,018	19,378	3500	3500	5500	3500	1100	950	980	0
Cruise	60000-99999 GT (Default)	8,249	51,518	11500	11500	14900	11500	1100	950	980	0
Cruise	100000-149999 GT	10,935	67,456	11500	11500	149000	11500	1100	950	980	0
Cruise	150000+ GT	13,499	73,442	11500	11500	14900	11500	1100	950	980	0
Ferry-RoPax	0-1999 GT	2,720	1,383	105	105	105	105	260	250	270	0
Ferry-RoPax	2000-4999 GT	832	5,668	330	330	330	330	260	250	170	0
Ferry-RoPax	5000-9999 GT (Default)	1,891	12,024	670	670	670	670	260	250	170	0
Ferry-RoPax	10000-19999 GT	3,952	15,780	1100	1100	1100	1100	390	380	260	0
Ferry-RoPax	20000+ GT	6,364	28,255	1950	1950	1950	1950	390	380	260	0
Refrigerated bulk	0-1999 DWT	2,420	793	530	570	560	570	270	270	270	0
Refrigerated bulk	2000-5999 DWT	3,986	3,223	1100	1200	1150	1200	270	270	270	0

Refrigerated bulk	6000-9999 DWT (Default)	7,476	6,206	1500	1650	1600	1650	270	270	270	0
Refrigerated bulk	10000+ DWT	12,612	11,505	2850	3100	3000	3100	270	270	270	0
Ro-Ro	0-4999 DWT	1,406	1,618	750	430	1300	430	260	250	170	0
Ro-Ro	5000-9999 DWT	6,955	9,909	1100	680	2100	680	260	250	170	0
Ro-Ro	10000-14999 DWT (Default)										
Ro-Ro	15000+ DWT										
Vehicle	0-29999 GT										
Vehicle	30000-49999 GT (Default)										
Vehicle	50000+ GT										
Yacht	0+ GT										
Service - tug	0+ GT										
Miscellaneous - fishing	0+ GT										
Offshore	0+ GT										
Service - other	0+ GT										
Miscellaneous - other	0+ GT										
Note: CBM: Cubic Meter; DWT: Deadweight Tonnage; ECA: Emission Control Area; GT: Gross Tonnes; kn: knots; TEU: Twenty-foot Equivalent Units; SOG: Speed Over Ground;											

Table B7. Specific fuel consumption (SFC) and brake thermal efficiency per engine category, propulsion type, combustion cycle, and fuel type (Table 6.1 of Marine Trip tab from R&D GREET 2025).

Engine Category	Main Propulsion Type	Combustion Cycle	Fuel-Group	SFC	2001+ Pilot Fuel	Brake thermal efficiency
			unit->	g/kWh	g/kWh	%
Main Propulsion	SSD 2-Stroke	Diesel	HFO	175.00	0	52.1%
	SSD 2-Stroke	Diesel	MDO	165.00	0	53.2%
	SSD 2-Stroke	Diesel	MeOH	332.60	6.00	52.85%
	MSD 4-Stroke	Diesel	HFO	185.00	0	49.3%
	MSD 4-Stroke	Diesel	MDO	175.00	0	50.2%
	MSD 4-Stroke	Diesel	MeOH	352.75	6.36	49.8%
	HSD 4-Stroke	Diesel	HFO	195.00	0	46.8%
	HSD 4-Stroke	Diesel	MDO	185.00	0	47.5%
	MSD 4-Stroke	Otto	LNG	155.00	0.85	47.5%
	MSD 4-Stroke	Diesel	LNG	143.18	6.36	49.8%
	SSD 2-Stroke	Otto	LNG	148.00	0.80	49.8%
	SSD 2-Stroke	Diesel	LNG	135.00	6	52.9%
	MSD 4-Stroke	LBSI	LNG	156.00	0	47.5%
	Gas Turbines	Brayton	HFO	305.00	0	29.9%
	Gas Turbines	Brayton	MDO	300.00	0	29.3%
	Gas Turbines	Brayton	LNG	203.00	0	36.5%
Boilers	Steam Turbines (and Boilers)		HFO	340.00	0	26.8%
	Steam Turbines (and Boilers)		MDO	320.00	0	27.4%
	Steam Turbines (and Boilers)		LNG	285.00	0	26.0%
Auxiliary	Aux. Engine(s)		HFO	195.00	0	46.8%
	Aux. Engine(s)		MDO	185.00	0	47.5%
	Aux. Engine(s)		LNG	156.00	0	47.5%

Table B8. Emission factors per engine category, propulsion type, combustion cycle, and fuel type (Table 6.1 of Marine Trip tab from R&D GREET 2025).

Engine Category	Main Propulsion Type	Combustion Cycle	Fuel-Group	VOC	CO	Tier 0	Tier 1	Tier 2	Tier 3	BC	CH ₄	N ₂ O	CO ₂
						unit->	g/kWh	g/kWh	g/kWh				
Main Propulsion	SSD 2-Stroke	Diesel	HFO	0.632	0.54	18.1	17	14.4	3.4	0.0002	0.010	0.031	3.114
	SSD 2-Stroke	Diesel	MDO	0.632	0.044	18.1	17	14.4	3.4	0.00003	0.010	0.030	3.206
	SSD 2-Stroke	Diesel	MeOH	0.063	0.054	18.1	17	14.4	3.4	0.0000	0.001	0.003	1.375
	MSD 4-Stroke	Diesel	HFO	0.527	0.54	14	13	10.5	2.6	0.0003	0.010	0.034	3.114
	MSD 4-Stroke	Diesel	MDO	0.527	0.046	14	13	10.5	2.6	0.0001	0.010	0.030	3.206
	MSD 4-Stroke	Diesel	MeOH	0.053	0.054	14	13	10.5	2.6	0.0003	0.001	0.003	1.375
	HSD 4-Stroke	Diesel	HFO	0.527	0.54	10	9.8	7.7	2	0.0003	0.010	0.030	3.114
	HSD 4-Stroke	Diesel	MDO	0.527	0.54	10	9.8	7.7	2	0.0001	0.010	0.034	3.206
	MSD 4-Stroke	Otto	LNG	0.5	1.3	1.3	1.3	1.3	1.3	0.0030	5.500	0.020	2.750
	MSD 4-Stroke	Diesel	LNG	0.33	1.09	14	13	10.5	2.6	0.0020	0.200	0.030	2.750
	SSD 2-Stroke	Otto	LNG	0.5	1.3	1.3	1.3	1.3	1.3	0.0030	2.500	0.020	2.750
	SSD 2-Stroke	Diesel	LNG	0.4	1.04	18.1	17	14.4	3.4	0.0020	0.200	0.030	2.750
	MSD 4-Stroke	LBSI	LNG	0.5	1.3	1.3	1.3	1.3	1.3	0.0030	4.100	0.020	2.750
	Gas Turbines	Brayton	HFO	0.105	0.1	6.1	6.1	6.1	6.1	0.0800	0.002	0.040	3.114
	Gas Turbines	Brayton	MDO	0.105	0.1	6.1	6.1	6.1	6.1	0.0600	0.002	0.049	3.206
Gas Turbines	Brayton	LNG	0.105	0.2	1.3	1.3	1.3	1.3	0.0030	0.060	0.020	2.750	
Boilers	Steam Turbines (and Boilers)		HFO	0.105	0.2	2.1	2.1	2.1	2.1	0.0050	0.002	0.040	3.114
	Steam Turbines (and Boilers)		MDO	0.105	0.2	2.1	2.1	2.1	2.1	0.0040	0.002	0.049	3.206
	Steam Turbines (and Boilers)		LNG	0.105	0.2	1.3	1.3	1.3	1.3	0.0030	0.040	0.020	2.750
Auxiliary	Aux. Engine(s)		HFO	0.421	0.54	11.2	11.2	11.2	11.2	0.0002	0.010	0.040	3.114
	Aux. Engine(s)		MDO	0.421	0.54	11.2	11.2	11.2	11.2	0.00003	0.010	0.036	3.206
	Aux. Engine(s)		LNG	0.5	1.3	1.3	1.3	1.3	1.3	0.0030	5.500	0.020	2.750

Note: Purple section: g/g of fuel, Other: g/kWh.

Table B9. Particulate Matter (PM₁₀) for LNG as fuel and for auxiliary engines (Table 6.2 of Marine_Trip tab from R&D GREET 2025).

Engine Category	Main Propulsion Type	Combustion Cycle	Fuel-Group	PM ₁₀
			unit->	g/kWh
Main Propulsion	MSD 4-Stroke	Otto	LNG	0.020
	MSD 4-Stroke	Diesel	LNG	0.010
	SSD 2-Stroke	Otto	LNG	0.020
	SSD 2-Stroke	Diesel	LNG	0.010
	MSD 4-Stroke	LBSI	LNG	0.020
	Gas Turbines	Brayton	HFO	0.030
	Gas Turbines	Brayton	MDO	0.030
Boilers	Gas Turbines	Brayton	LNG	0.030
	Steam Turbines (and Boilers)		LNG	0.030
Auxiliary	Aux. Engine(s)		HFO	
	Aux. Engine(s)		MDO	
	Aux. Engine(s)		LNG	0.020

Table B10. Emission estimates for LNG, Methanol and Ammonia combustion (g/MJ) along with pilot fuel (MGO 0.1% S) (Table 5.4 of Marine_Trip tab from R&D GREET 2025).

	Liquefied Natural Gas (LNG)	Methanol (Natural Gas)	Methanol (Flare Gas)	Methanol (Renewable Natural Gas)	Methanol (Biomass)	Methanol (Coal)	Methanol (Black Liquor)	eMethanol (w/ H2 Recycling)	Ammonia (Natural Gas)	Ammonia from RNG	Ammonia (H2 from Coal Gasification w/ CCS)	Ammonia (H2 from Poplar gasification)	E-Ammonia (H2 from water electrolysis : PEM)
Shaft Emissions													
VOC	0.061	0.010	0.010	0.010	0.010	0.010	0.010	0.009	0.000	0.000	0.000	0.000	0.000
CO	0.158	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.045	0.045	0.045	0.045	0.045
NOx	2.184	2.035	2.035	2.035	2.035	2.035	2.035	2.035	2.034	2.034	2.034	2.034	2.034
PM10	0.002	0.011	0.011	0.011	0.011	0.011	0.011	0.010	0.000	0.000	0.000	0.000	0.000
PM2.5	1.40E-03	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.000	0.000	0.000	0.000	0.000
SOx	0.00	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.045	0.045	0.045	0.045	0.045
BC	3.03E-04	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
OC	2.09E-04	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.000	0.000	0.000	0.000	0.000
CH4	3.03E-02	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
N2O	4.55E-03	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CO2	56.91	69.419	69.419	69.419	69.419	69.419	69.419	69.419	0.000	0.000	0.000	0.000	0.000
CO2 (w/ C in VOC & CO)	57.35	69.52	69.52	69.52	69.52	69.52	69.52	69.52	0.07	0.07	0.07	0.07	0.07
GHGs	59.50	69.6491	69.6491	69.6491	69.6491	69.6491	69.6491	69.6463	0.2070	0.2070	0.2070	0.2070	0.2070

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