POLARIS MODEL

ICCT Polaris model v1.3 documentation

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THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

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INTRODUCTION

The ICCT's Polaris model is a Python-based, global maritime emissions projection model covering all ocean transport activity from Type 1 and 2 vessels (as defined in the Fourth IMO GHG Study 2020). Tank-to-wake (TTW) and well-to-wake (WTW) emissions are reported as carbon dioxide equivalents (CO_2e) based on the 100-year or 20-year global warming potentials of carbon dioxide, methane, and nitrous oxide.

Polaris starts with the 2019 inventory of ~80,000 ships from ICCT's Systematic Assessment of Vessel Emissions (SAVE) and projects its evolution out until 2070. After considering the retirement of older vessels, Polaris models the introduction of new ships to the global fleet to meet configurable demand targets. Furthermore, it allows for the detailed investigation of the emission impacts of three key policies:

- **EEDI:** A technical efficiency standard for new ships
- **EEXI:** A technical efficiency standard for existing ships
- **CII:** An operational efficiency standard for all ships

Customizable fuel penetration and engine retrofit shares are considered when evaluating each of the three policies. These fuel penetration and engine retrofit assumptions can be used to model the emissions consequences of engine replacement/retrofit policies or fuel standards, such as a GHG fuel standard (GFS). Polaris' estimates of several operational carbon intensity metrics can also be used to determine the stringency of fuel standards needed to hit different IMO and climate targets. Polaris is highly configurable and is intended to be run with multiple policy scenarios simultaneously.

Acknowledgments

Polaris was first developed in 2022-23 by Gabe Hillman Alvarez, Xinyi Sola Zheng, Francielle Carvalho, Jakob Schmidt, Erik Pronk, Bryan Comer, and Josh Miller. Version 1.3 was developed in 2024 by Gabe Hillman Alvarez, Jonathan Benoit, and Hae Jeong Cho.

SCOPE

Following the convention outlined in the Fourth IMO GHG Study 2020, Polaris models a bottom-up emissions inventory for Type 1 and 2 vessels, who were identified and matched in both the AIS and S&P Global (formerly IHS Markit) datasets by either IMO number (Type 1) or MMSI number (Type 2). The fundamental unit of analysis in Polaris is the individual vessel. Nonetheless, many inputs are defined more coarsely, and it is generally useful to aggregate the outputs to inspect trends. The following conventions are used for grouping ships into classes and capacity bins.

Ship classes

The Polaris inventory is broken into two broad segments based on how ships measure their capacity: "Cargo", which uses deadweight tonnage (DWT, a unit of mass), and "Non-cargo", which uses gross tonnage (GT, a unit of volume). Polaris utilizes ship classes that are slightly less granular than those defined in the SAVE model. The mappings are shown below, alongside the classes defined by IMO for the purpose of EEDI regulation.

Table 1: *Ship class mapping for cargo segment.*

Polaris 'ShipClass'	SAVE 'ship_class'	IMO Regulated 'ShipTypeEEDI'
Bulk carrier	bulk carrier	Bulk carrier
Chemical tanker	chemical tanker	Tanker
Container	container	Containership
Oil tanker	oil tanker	Tanker
Gas tanker	liquified gas tanker	LNG carrier
Other cargo	refrigerated bulk	Refrigerated cargo carrier
	general cargo	General cargo ship
	other liquid tankers	N/A

Table 2: *Ship class mapping for non-cargo segment.*

Polaris 'ShipClass'	SAVE 'ship_class'	IMO Regulated 'ShipTypeEEDI'
Cruise	cruise	Cruise passenger ship having non-conventional propulsion
Ferry-pax only	ferry-pax only	Ro-ro passenger ship
Ferry-ro-pax	ferry-ropax	Ro-ro passenger ship
Ro-ro	ro-ro	Ro-ro cargo ship
Vehicle	vehicle	Ro-ro cargo ship (vehicle carrier)
Fishing	miscellaneous-fishing	N/A
Other non-cargo	miscellaneous-other	N/A
	naval ship	N/A
	offshore	N/A
	service-other	N/A
	yacht	N/A
	service-tug	N/A

Capacity bins

Ship classes are further disaggregated by capacity bins. Note that capacity bins are all defined at the SAVE 'ship_class' level.

Table 3: *Capacity bin definitions.*

SAVE ‘ship_class’	Capacity bin	Bin definition	Bin unit
bulk carrier	1	0-9999	DWT
bulk carrier	2	10000-34999	DWT

bulk carrier	3	35000-59999	DWT
bulk carrier	4	60000-99999	DWT
bulk carrier	5	100000-199999	DWT
bulk carrier	6	200000-+	DWT
chemical tanker	1	0-4999	DWT
chemical tanker	2	5000-9999	DWT
chemical tanker	3	10000-19999	DWT
chemical tanker	4	20000-39999	DWT
chemical tanker	5	40000-+	DWT
container	1	0-999	TEU
container	2	1000-1999	TEU
container	3	2000-2999	TEU
container	4	3000-4999	TEU
container	5	5000-7999	TEU
container	6	8000-11999	TEU
container	7	12000-14499	TEU
container	8	14500-19999	TEU
container	9	20000-+	TEU
general cargo	1	0-4999	DWT
general cargo	2	5000-9999	DWT
general cargo	3	10000-19999	DWT
general cargo	4	20000-+	DWT
liquefied gas tanker	1	0-49999	m^3
liquefied gas tanker	2	50000-99999	m^3
liquefied gas tanker	3	100000-199999	m^3
liquefied gas tanker	4	200000-+	m^3
oil tanker	1	0-4999	DWT
oil tanker	2	5000-9999	DWT
oil tanker	3	10000-19999	DWT
oil tanker	4	20000-59999	DWT
oil tanker	5	60000-79999	DWT
oil tanker	6	80000-119999	DWT
oil tanker	7	120000-199999	DWT
oil tanker	8	200000-+	DWT
other liquids tanker	1	0-999	DWT
other liquids tanker	2	1000-+	DWT
ferry-pax only	1	0-299	GT
ferry-pax only	2	300-999	GT
ferry-pax only	3	1000-1999	GT
ferry-pax only	4	2000-+	GT

cruise	1	0-1999	GT
cruise	2	2000-9999	GT
cruise	3	10000-59999	GT
cruise	4	60000-99999	GT
cruise	5	100000-149999	GT
cruise	6	150000-+	GT
ferry-ropax	1	0-1999	GT
ferry-ropax	2	2000-4999	GT
ferry-ropax	3	5000-9999	GT
ferry-ropax	4	10000-19999	GT
ferry-ropax	5	20000-+	GT
refrigerated bulk	1	0-1999	DWT
refrigerated bulk	2	2000-5999	DWT
refrigerated bulk	3	6000-9999	DWT
refrigerated bulk	4	10000-+	DWT
ro-ro	1	0-4999	DWT
ro-ro	2	5000-9999	DWT
ro-ro	3	10000-14999	DWT
ro-ro	4	15000-+	DWT
vehicle	1	0-29999	DWT
vehicle	2	30000-49999	DWT
vehicle	3	50000-+	DWT
yacht	1	0-+	GT
service-tug	1	0-+	GT
miscellaneous-fishing	1	0-+	GT
offshore	1	0-+	GT
service-other	1	0-+	GT
miscellaneous-other	1	0-+	GT

OVERVIEW

The Polaris model is structured as a series of calculations that advance the fleet snapshot from year X to X + 1. Each step is described in more detail in its relevant section, but an overview is provided here as an introduction. Each year, the model executes the following instructions:

1. Apply survival curves to **existing** fleet and remove retired ships (this step is skipped for the base year).
2. Evaluate EEXI compliance, apply engine power limitations, enforce limits on cruise hours, and recalculate operational speed of **existing** ships.
3. Apply operational engine/fuel switches to **existing** ships.
4. Calculate regulatory and real-world emissions of **existing** ships and note their attained CII.

5. Apply design engine/fuel switches to possible **new-build** ships and generate EEDI-compliant power and speed parameters.
6. Calculate regulatory and real-world emissions for these possible **new builds** and note their attained CII.
7. Calculate number of actual **new builds** needed to fulfill demand and add them to the fleet.

Surviving and new-build ships from the previous year become the existing fleet in the next year. See Figure 1 for a graphical visualization of this numbered list.

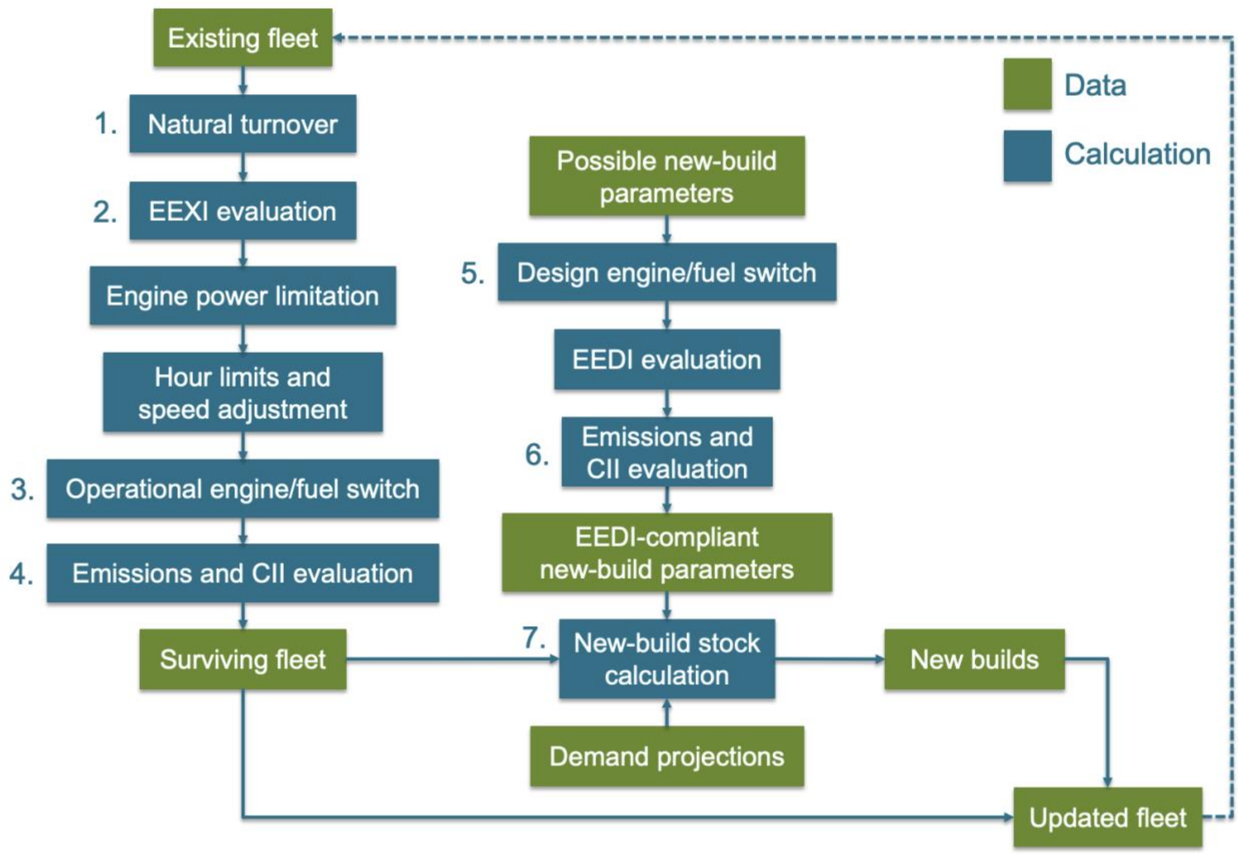

Figure 1: *Model flowchart for each analysis year.*

FLEET TURNOVER

Retirements

Polaris utilizes year-over-year survival curves and pseudorandom assignment to determine which ships retire each year. The year-over-year rates of survival are calculated from 2018 and 2019 IHS Markit data and are broken down by Polaris 'ShipClass' and age. The survival curves define the fraction of vessels surviving from one year to the next—or similarly, the likelihood that a given vessel will survive from one year to the next. To model the behavior of individual ships, the model exploits the latter interpretation, which approaches equality with the former when there are many vessels of each class and age present in the fleet.

So, each year, a pseudorandomly-generated number between 0 and 1 is assigned to each ship and compared against the year-over-year survival rate. The ship survives if the assigned number is less than or equal to the survival rate, else the ship retires and is removed from the fleet. E.g., If the survival rate for oil tankers at age 20 is 0.95, any given 20-year-old oil tanker will retire only if its assigned number is between 0.95 and 1 (occurring about 5% of the time). Note that despite appearing random, this process is exactly reproducible by running the pseudorandom number generator with the same seed.

New-build ship parameters

The parameters of individual ships from the historical fleet are generally maintained, except when modified to comply with policies for existing ships. However, no such parameters are available for vessels that enter the fleet during modeled years, called “synthetic” ships, since they don’t yet exist in the real world or have a legitimate ship ID number. The year they enter the fleet, the synthetic ships are called “new builds”.

Most parameters for these new-build ships are calculated at a more aggregate level (SAVE ‘ship_class’ and capacity bin) as the mean values of historical ships delivered after a configurable cutoff, set to 2013 by default.

The maximum engine power and corresponding maximum cruise speed are the only new-build parameters that are not just average values from recently built ships in the corresponding bins of the historical fleet. Instead, two logarithmic regressions are performed on all ships in the base year fleet:

$$\log PowerMax = A * \log Capacity + B$$

$$SpeedMax = C * \log PowerMax + D$$

and the parameters of the resulting best-fit lines are used to calculate a more accurate estimate of the maximum power and speed of vessels as a function of ship capacity (DWT for ships in the “Cargo” segment, GT for ships in the “Non-cargo” segment). If the regressions yield an insufficiently strong correlation, a constant value is used instead. The initial estimates of new-build power and speed parameters are modified as necessary to comply with EEDI regulations.

Activity

The ship activity is an estimate of how much transport work a vessel performs in a year, taking into account the fractional payload utilization (PU, defined as the share of total capacity utilized on average). The units of activity depend on how vessels define their capacity. For ships in the "Cargo" segment, activity is measured in cargo ton nautical miles (CTnm):

$$Activity_{Cargo} = DWT * PU * DistanceTraveled$$

For ships in the "Non-cargo" segment, the payload utilization is set to 1 by convention, and the activity is measured in gross ton nautical miles (GTnm):

$$Activity_{Non-cargo} = GT * 1 * DistanceTraveled$$

Demand projections

Generally, estimates for transport work demand by ship class through 2021 come directly from the UNCTAD Review of Maritime Transport (2021). Demand estimates in the model's base year are scaled to match the supply provided by the Polaris base-year fleet. Thereafter, the growth trends in demand by ship class are linearly extrapolated out to 2070, with the exception that zero growth is assumed for the following ship classes whose historical data are either incomplete or do not show clear growth trends: 'Vehicle', 'Fishing', 'Other cargo', and 'Other non-cargo'. Minor corrections are applied to ensure a reasonable junction between historical UNCTAD data and future ICCT projections.

Transport work demand estimates for oil tankers come from the SSP2_RCP2.6_L scenario in the Fourth IMO GHG Study 2020. The annual growth rates from the scenario are applied to the supply provided by the Polaris base-year fleet. As the scenario projection only extends to 2050, zero growth is assumed from 2050 through 2070.

New-build stock calculation

Once the supplied activity from existing ships and the parameters of possible-new build ships are defined, it is possible to determine the number of new-builds necessary to meet demand targets.

First, the additional activity needed is calculated as the difference between demand and existing supply. This demand is provided for each Polaris 'ShipClass' and therefore must be disaggregated by SAVE 'ship_class' and capacity bin to match the new-build group definition. To accomplish this, the model assumes that each of the subgroupings will retain its historical share of the total activity of its umbrella group (e.g., 'general cargo' bin 4 will always be assigned 75% of the additional activity needed from 'Other cargo').

Finally, the assigned activity is converted into stock by dividing by the average activity of each vessel in that 'ship_class' and bin. This mean value and the activity shares both come from a historical sample subject to the same configurable cutoff as described above (default 2013).

$$NewBuildStock_{ship\_class,Bin} = \frac{ActivityNeeded_{ShipClass} * ShareOfActivity_{ShipClass \to ship\_class,Bin}}{MeanActivityOfVessel_{ship\_class,Bin}}$$

New-build stock at the bin-level is further disaggregated by shares of main engine and primary (and potentially secondary) fuel types, rounded to the nearest integer, and then separated into individual vessels (initially identical, but may evolve differently).

EEDI

Required EEDI

Polaris applies the IMO's Energy Efficiency Design Index (EEDI), as defined in MEPC.328(76), to all possible new-build ships before estimating their activity and determining necessary stock.

New-build ships are assigned an EEDI reference line (see Table 2 under Regulation 24 in resolution 328(76), linked above), EEDI phase, and reduction factor (Regulation 24 Table 1), from which required EEDI is calculated:

$$Required\ EEDI = \left(1 - \frac{X}{100}\right) *\ EEDI\ reference\ line\ value$$

where X is the reduction factor from the reference line.

Attained EEDI

The IMO defines the full equation for attained EEDI in MEPC.364(79), but Polaris uses a simplified version, based on Equation 1 from a previous ICCT analysis (Rutherford et al., 2020):

$$Attained\ EEDI = \frac{C_f * (P_{ME} * SFC_{ME} + P_{AE} * SFC_{AE})}{Capacity\ * V_{ref}}$$

where the constituent variables are defined as follows:

- C_f : fuel carbon factor (gCO_2/g fuel)
- P_{ME} : 75% of maximum main engine power (kW)
- SFC_{ME} : specific fuel consumption of main engine (g fuel/kWh)
- P_{AE} : auxiliary engine demand in cruise phase (kW)
- SFC_{AE} : specific fuel consumption of auxiliary engine (g fuel/kWh)
- $Capacity$: DWT, except for containerships (70% of DWT) and cruise ships (GT)
- V_{ref} : reference speed associated with $\mathrm{P_{ME}}$ (knots)

We attempt to satisfy the following condition:

$$\frac{Attained\ EEDI}{Required\ EEDI} \leq 1 + Tolerance$$

In the case that attained EEDI exceeds required EEDI by more than a configurable tolerance (default 0.) representing the modeling uncertainty, we assume that shipbuilders achieve compliance by installing a smaller main engine, thereby decreasing the maximum main engine power (a.k.a. maximum continuous rating, MCR) and maximum speed. This in turn decreases P_{ME}, and, to a lesser extent, V_{ref}. For consistency with the EEXI calculations, we call this an "EEDI engine power limitation (EPL)". The critical adjustment is:

$$MCR' = MCR * (1 - EPL_{EEDI})$$

where the apostrophe denotes an updated parameter.

For the purposes of attained EEDI, the reference parameters are evaluated at 75% of maximum engine power. So, the EEDI reference speed is defined as:

$$V_{ref} = (0.75)^{1/3} * MaxSpeed$$

with the implicit assumption that main engine power scales with the cube of speed. This reference speed is recalculated if the maximum speed is altered by an EEDI EPL:

$$MaxSpeed' = MaxSpeed * (1 - EEPL_{EEDI})^{1/3}$$

$$V_{ref}' = (0.75)^{1/3} * MaxSpeed'$$

Note that, in contrast to speed, the reference engine power scales linearly with EEDI EPL:

$$P_{ME}' = 0.75 * MCR' = P_{ME} * (1 - EPL_{EEDI})$$

The EEDI EPL may be arbitrarily close to zero but is not allowed to exceed a configurable limit, set to 60% by default. New-build ships which cannot be made to comply with EEDI via this scheme are flagged for the user and built to be as close to compliance as possible. Although the EEDI EPL is generally solved for, it may also be specified explicitly by the user, enabling streamlined modeling of future changes to EEDI that encourage installing smaller engines.

EEXI

Required EEXI

The Energy Efficiency Existing Ship Index (EEXI) is defined alongside EEDI in MEPC.328(76) and uses the same EEDI reference lines, but incorporates a different set of reduction factors (Table 3 under Regulation 25). Polaris applies EEXI to all existing ships, both historical (i.e., present in the base-year fleet) and synthetic (i.e., introduced during modeled years). Required EEXI is given as:

$$Required\ EEXI = \left(1 - \frac{Y}{100}\right) * \ EEDI\ reference\ line\ value$$

where Y is the reduction factor specified for the required EEXI compared to the EEDI reference line. To date, EEXI is less stringent than the EEDI, so new ships will comply with the EEXI by virtue of complying with the EEDI.

Attained EEXI

The full equation for attained EEXI is given in MEPC.350(78), but we utilize the same simplification as for attained EEDI:

$$Attained\ EEXI = \frac{C_f * (P_{ME} * SFC_{ME} + P_{AE} * SFC_{AE})}{Capacity\ * V_{ref}}$$

where all the variables are also defined as for EEDI, except for P_{ME} and V_{ref} (details below).

We attempt to satisfy the following condition:

$$\frac{Attained\ EEXI}{Required\ EEXI} \leq 1 + Tolerance$$

In the case that attained EEXI is greater than the required EEXI by more than the configurable tolerance (default 0.), the model assumes that ship operators achieve compliance by placing an overridable limit on main engine power, called an “EEXI engine power limitation (EPL)”, which limits the engine’s maximum continuous rating (MCR) by a percentage (EPL_{EEXI}) as follows:

$$MCR_{EPL} = MCR * (1 - EPL_{EEXI})$$

Note that the ship’s maximum installed power (MCR) and speed ($MaxSpeed$) are not themselves affected by an EEXI EPL, so the $_{EPL}$ subscript is used instead of an apostrophe to denote an updated reference parameter only.

For the purposes of attained EEXI, the reference parameters are evaluated at 83% (not 75%) of the limited maximum main engine power (MCR_{EPL}). This change in evaluation point reflects the assumption that ships will operate closer to the compliance-limited maximum power than they did to the previously unrestricted maximum power.

To ensure that an EEXI EPL does not cause ships' technical efficiency to worsen, consistent with IMO guidelines, cases where 83% MCR_{EPL} would be greater than 75% MCR are not allowed. This constraint establishes a minimum EEXI EPL of about 10%. Ships that could comply with an EEXI EPL smaller than the minimum are considered compliant without needing to alter their operations. For ships requiring an EPL larger than the minimum, the updated reference parameters are given by:

$$P_{ME,EPL} = 0.83\ MCR_{EPL}$$

$$V_{ref,EPL} = (0.83)^{1/3} * MaxSpeed * (1 - EPL_{EEXI})^{1/3}$$

The EEXI EPL is also not allowed to exceed a configurable limit, set to 60% by default. Existing ships which cannot be made to comply with EEXI via this scheme are flagged for the user and retired. Although the EEXI EPL is generally solved for, it may also be specified explicitly by the user, enabling streamlined modeling of future changes to EEXI or other policies that encourage slow steaming.

Engine power limitation

Each ship class and capacity bin has a default distribution of main engine power load factors that defines the fraction of total cruise hours that ships in that class and bin spend at different engine powers. Default distributions for three major ship classes (aggregated over all capacity bins) are shown in Figure 2 as an example. An individual vessel's distribution may be affected by an EEXI EPL as follows:

1. For each load factor bin with corresponding engine power exceeding the new limited maximum (MCR_{EPL}), the share of hours is set to zero, since the ship is no longer allowed to operate at that power.
2. The sum of shares from all disallowed load factor bins is added to the bin corresponding to the greatest load factor which does not exceed the new limited maximum.

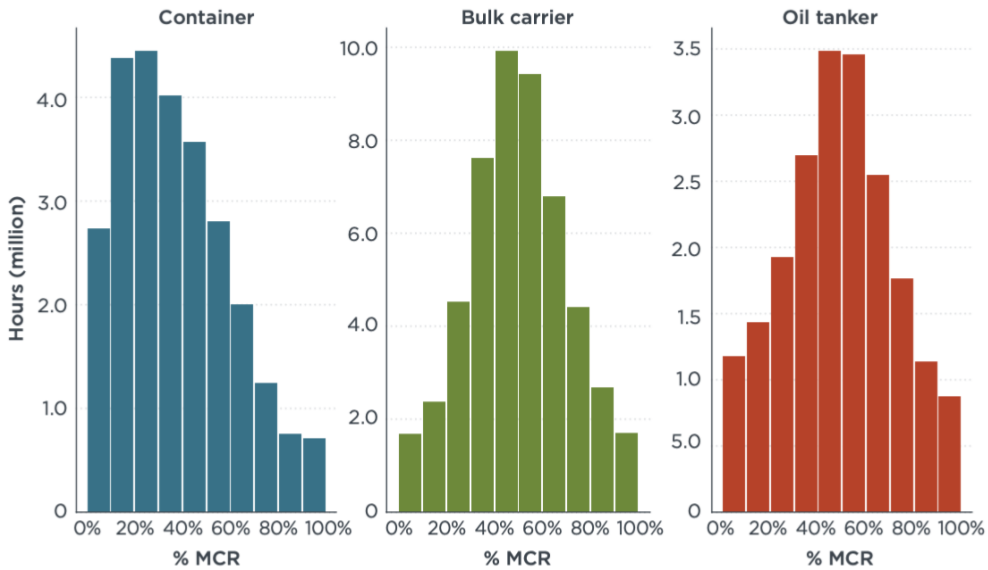

Figure 2. *Some default main engine load factor distributions (Rutherford et al., 2020).*

By default, 10 bins are used, and each is defined by its midpoint (e.g., 0.75 corresponds to the range [0.70, 0.80]), although users may provide custom bins. For example, if a ship has an EEXI EPL of 21%, then MCR_{EPL} = 79% MCR, and any hours which would normally be operated at 95% and 85% MCR are instead operated at 75% MCR.

Operational speed reduction

Once the main engine power load factor distribution is updated with an EEXI EPL, the average cruise speed is calculated as:

$$MeanCruiseSpeed = MaxSpeed * \sum_{LoadFactors} \left(LoadFactor^{1/3} * ShareOfHours_{LoadFactor}\right)$$

where the sum is over all load factors and the share refers to the share of hours operated at that load factor.

Excess hours

The total hours operated in cruise phase is calculated from the mean cruise speed as:

$$Total\ cruise\ hours = \frac{Distance\ traveled}{Mean\ cruise\ speed}$$

Since the distance traveled by a ship is not adjusted by EEXI, an EPL will therefore decrease the mean cruise speed and increase the total cruise hours. Since there are only so many extra hours a vessel can operate in a year, this cruise hours estimate is capped at the 99th percentile values by ship class from the SAVE 2019 fleet.

This limit may generate excess hours, which correspond to activity which cannot be completed by the affected ship and must instead be allocated to new ships. The calculation is done vessel-by-vessel as follows:

$$Excess\ hours = Total\ cruise\ hours - Maximum\ cruise\ hours$$

$$Distance\ traveled' = Distance\ traveled - Excess\ hours * Mean\ cruise\ speed$$

$$Activity' = Activity * \frac{Distance\ traveled'}{Distance\ traveled}$$

If there is stable or increasing demand, this reduction in activity from existing ships is automatically converted into increased activity from new-build ships in the new-build stock calculation. So, for each modeled year, the difference between total cruise hours and the cruise hours limit is exported, to give users insight into the remaining ability of ships to slow down before inducing new builds.

CII

Polaris applies IMO's Operational Carbon Intensity Indicator (CII), which quantifies the average CO_2 emissions per transport work of a ship. The CII applies to all ships 5,000 GT and above in the following ship classes: bulk carriers, gas carriers, tankers, container ships, general cargo ships, refrigerated cargo carriers, combination carriers, LNG carriers, vehicle carriers, Ro-Ro cargo vessels, Ro-Ro passenger vessels and cruise ships.

CII reference line

For each applicable ship class, the model first calculates its CII reference line, as defined in MEPC.353(78). Each reference line is given as a curve representing the median attained operational carbon intensity performance in 2019, as a function of ship capacity. The reference lines are calculated as follows:

$$CII_{Ref} = a * Capacity^{-c}$$

where Capacity is the DWT or GT of a ship, and a and c are parameters estimated by IMO through median regression fits on the 2019 data.

Required CII

Polaris then calculates the required annual operational CII as defined in MEPC.338(76). The required CII is determined based on percentage of reduction from the CII reference line:

$$Required\ annual\ operational\ CII = \left(1 - \frac{Z}{100}\right) * CII_{Ref}$$

where CII_{Ref} is the reference value as described above, and Z is the reduction factor.

The stringency of CII (i.e., reduction factor) starts at 5% in 2023 and increases gradually to 11% in 2027. Although the policy does not go into effect until 2023, Z factors of 1%, 2% and 3% were set by IMO for the years of 2020, 2021, and 2022, respectively. Z factors for years beyond 2027 will be developed as the CII is reviewed and revised. By default, Polaris holds the required CII at an 11% reduction from the reference line from 2027 onwards, but users may specify any arbitrary schedule for CII reductions.

Attained CII

As defined in MEPC.352(78), the attained annual operational CII of individual ships is calculated as the ratio of the total mass of CO_2 (M) emitted to the total transport work (W) undertaken in a given calendar year, as follows:

$$Attained\ CII = M/W$$

The mass of CO_2 emissions (M) is calculated by summing the CO_2 emissions (in grams) from all the fuel oil consumed on board a ship in a given calendar year. For each ship, the model multiplies its total fuel energy consumption with a weighted average emission factor, as detailed in the Emission section below.

Transport work (W) is defined as the product of a ship's capacity and the distance travelled in a given calendar year:

$$W = Capacity * DistanceTraveled$$

where Capacity has units of DWT or GT depending on the ship class, and the distance is in nautical miles.

CII rating

Each ship is also assigned an attained CII rating. As described in MEPC.354(78), four rating boundaries (superior, lower, upper, and inferior) are defined to sort ships into the five-grade rating system (A, B, C, D, and E).

The boundaries are set based on the distribution of attained CIIs of individual ships in 2019. Mathematically, the boundaries are determined by the required CII and a set of deviation vectors (d_1, d_2, d_3, and d_4) that indicate the direction and distance they deviate from the required value, as illustrated in Figure 3:

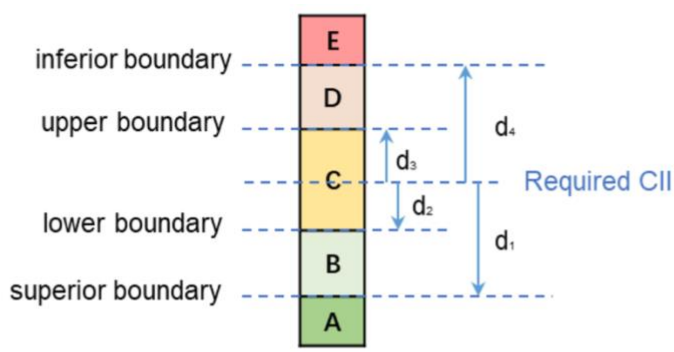

Figure 3. *CII boundaries (Resolution MEPC.354(78)).*

Based on an exponential transformation of the deviation vectors and the required CII, the four rating boundaries can be calculated as follows:

$$Superior\ boundary = \exp(d_1) * Required\ CII$$

$$Lower\ boundary = \exp(d_2) * Required\ CII$$

$$Upper\ boundary = \exp(d_3) * Required\ CII$$

$$Inferior\ boundary = \exp(d_4) * Required\ CII$$

Each ship is assigned a CII rating based on which boundaries they fall within. Note that unlike EEXI, this CII rating is not assumed to directly influence ship behavior in Polaris. CII ratings are calculated and reported to the user, and they may be used to inform engine/fuel switching choices for successive runs of the model. For example, if a particular bin of ships is skewing towards worse CII ratings in a given year, the user may choose to increase the share of ships from that bin which switch to lower-emission fuels in that year.

ENGINE AND FUEL SWITCHING

To comply with EEDI and EEXI, achieve a higher rating under CII, or achieve alignment with any other operational efficiency standard, ship operators may switch to a more efficient engine, a lower emission fuel source, or both at the same time. Polaris models such behavior based on estimated rates of engine installations/retrofits and fuel switching in each calendar year at the fleet level, rather than ship-by-ship.

Each year, the model takes in a list of possible switches for each ship class and each size bin. The “switch map” is necessary because not all engine options and fuel options are compatible with each other. For one existing engine and fuel combination, multiple replacement options may exist.

The design engine and fuel are used for EEDI and EEXI calculations, whereas the operational engine and fuel are used for CII and emissions calculations.

Design engine and fuel switching

For EEDI compliance, a ship operator may decide to purchase new-build ships with alternative engine and fuel combinations. Each year, the Turnover module calculates the number of new-build ships needed based on ship retirement and projected demand, and it initially assumes that all new builds follow the engine and fuel distributions of that ship class in the previous year.

Based on user input, the model then takes a certain share of the default new-build ships and converts them to use an alternative combination of engine and fuel. To model the use of drop-in alternative fuels, Polaris distinguishes between primary and secondary fuels, with a user-specified blend ratio between the two.

Operational engine and fuel switching

For EEXI compliance or achievement of higher CII rating, a ship operator may change the operational engine and fuels of an existing, in-service ship. For ships in the same segment (those in the same ship class and size bin and have the same design engine and fuel configuration), a pseudorandomly-generated number between 0 and 1 is assigned to each ship and compared against the share of various switch options provided by user.

For instance, the user may specify that 50% of the ships in a particular segment are not switching engines or fuels, 30% are switching to option A, and the remaining 20% are switching to option B. In this case, ships assigned values between 0 and 0.5 would not change configuration, those assigned values between 0.5 and 0.8 would switch to option A, and the rest of the ships would switch to option B. Note that despite appearing random, this process is exactly reproducible by running the pseudorandom number generator with the same seed.

ENERGY CONSUMPTION

Main engine in cruise phase

Similar to average operational speed, the total energy consumed by the main engine in cruise phase is calculated as a sum over main engine power load factor (Lf) conditions. The product of the load factor and maximum power output of the main engine gives the power output of the main engine at that load factor, and the product of total cruise hours with the share of hours spent in that load factor bin gives the number of hours operated in that load factor bin. The product of the specific fuel consumption and the fuel energy content gives an inverse engine efficiency which converts from energy out of the engine to energy into the engine. So, the full equation is written as:

$$EnergyConsumed_{Main}[MJ_{in}] = \sum_{Lf} \big(Lf * MaxPowerOutput_{Main}[kW_{out}] * ShareOfHours_{Lf} * CruiseHours\ [hr] * SpecificFuelConsumption_{Lf}[g/kWh_{out}] * FuelEnergyContent\ [MJ_{in}/g]\big)$$

where the specific fuel consumption of the main engine varies with load factor according to the relationship established in the Third IMO GHG Study 2014:

$$SpecificFuelConsumption_{Lf} = SpecificFuelConsumption_{Baseline} * (0.455 * Lf^2 - 0.71 * Lf + 1.28)$$

To enable modeling of efficiency improvements other than slow steaming, Polaris allows users to provide alternative assumptions for the baseline specific fuel consumption over time.

Auxiliary engines, boilers, and non-cruise phases

The hours spent in phases other than cruise (namely, anchor, berth, and maneuver) are defined by estimates from the SAVE 2019 fleet and assumed not to change. The main engine is assumed to only operate during cruise phase. The average energy demand on the auxiliary engines and boilers in each phase, including cruise, is also derived from the SAVE 2019 fleet and left unmodified. The efficiencies of auxiliary engines and boilers are also assumed to be constant. So, for auxiliary engines and boilers, the energy consumption is given by:

$$EnergyConsumed_{EnergyConsumer,Phase}\ [MJ_{in}] = MeanPowerDemand\ [kW_{out}] * HoursInPhase\ [hr] * SpecificFuelConsumption\ [g/kWh_{out}] * FuelEnergyContent\ [MJ_{in}/g]$$

The total energy consumed by all energy consumers in all phases is tabulated by summing up the energy consumed by main engines, auxiliary engines, and boilers in each phase.

EMISSIONS

Carbon dioxide equivalent (CO_2e) emissions are calculated from energy consumption using emission factors:

$$Emissions = Energy\ consumed * Emission\ factor$$

Weighted average emission factors

Polaris allows ships to be modeled with both a primary and secondary fuel. The emission factors are therefore an average of the values for the two fuels, weighted by the energy provided by each. E.g., if a ship derives 70% of its energy, measured in megajoules (MJ), from fuel A (emission factor = 1 g/MJ) and the other 30% from fuel B (emission factor = 0 g/MJ), the weighted average emission factor would be 0.7 g/MJ. Note that this calculation assumes that auxiliary engines and boilers use the same blend of fuels as the main engine.

Regulatory vs. estimated real-world emissions

Polaris allows a variety of scopes of emissions, generally falling into two broad categories: regulatory and real-world. Regulatory emissions are calculated using the official emission factors listed in IMO policies, which currently reflect only the tank-to-wake (TTW) scope.

Although the model uses regulatory emission factors for the EEDI, EEXI, and CII compliance calculations, it also allows the user to add well-to-tank (WTT) emission factors and to modify the default TTW emission factors to produce estimated real-world well-to-wake (WTW) emissions.

Fleetwide carbon intensity

In each modeled year, Polaris exports several operational carbon intensity metrics (e.g., gCO2e100/MJ) for each ship class and capacity bin, as well as the aggregated global fleet. These reference outputs are intended to help users determine the stringency of fuel standards needed to hit different IMO and climate targets.

SCENARIOS

Polaris comes pre-packaged with a robust set of default data to allow for quick modeling of baseline trends. Users can provide inputs defining alternate scenario pathways or updating baseline assumptions.

Scenario inputs

Polaris currently allows each of the inputs defined in Table 4 to vary between multiple scenarios in a single model run.

Table 4: *Scenario input descriptions.*

Scenario Input	Description
payload_utilization	Payload utilization projections file. Subject to the upper limits defined for that ship class and year
demand	Projection of demand for transport work (t-nm). For cargo ships, demand is based on cargo tonnes; for non-cargo ships, it is based on gross tonnes
design_fuel_switch	Specifies the design engine and fuels of new-build ships
design_fuel_blend	Specifies the blend between the alternative main and secondary fuels of new-build ships defined in the design fuel switch input
op_fuel_switch	Alters the operational engine and fuels of all existing ships

op_fuel_blend	Defines the blend between the alternative main and secondary fuels defined in the operational fuel switch input for all ships
eedi_on	Toggles on/off enforcement of EEDI requirements for new-build ships (on by default)
eexi_on	Toggles on/off enforcement of EEXI requirements for existing ships (on by default)
max_epl	Configurable upper limit on maximum engine power limitation allowed to comply with EEDI/EEXI policies (default 60%)
eedi_required	Custom modifications to required EEDI reductions from reference lines
eexi_required	Custom modifications to required EEXI reductions from EEDI reference lines
explicit_epl	Externally-specified engine power limitations to be used directly in model instead of solvers
eedi_eexi_tolerance	Tolerance for EEDI/EEXI exceedance within which we consider ships to be compliant (default 0.)
cii_required	Required CII reductions from reference lines
emission_factor	Emission factors for each fuel/engine combination
sfc	Specific fuel consumption of main, auxiliary, and boiler engines by fuel and engine
seed	Seed for random number generation, to provide reproducible results

Default inputs

The default data used to define the baseline (a.k.a. business-as-usual or BAU) scenario are described in Table 5. Sources are included for transparency and replicability. See relevant sections above to learn more about how each input is used in the model.

Table 5: *Default input descriptions and sources.*

Input	Description	Source
base_fleet	Base year fleet inventory from SAVE database	SAVE 2019 – Olmer et al. (2017) Fourth IMO GHG Study – Faber et al. (2020)
size_bin	SAVE capacity bin definitions with corresponding boiler and auxiliary power demand	Olmer et al. (2017)
survival_curves	Fleet survival curves by ship class	2018 and 2019 data from IHS Markit ShipData database (bespoke database purchased by the ICCT)
engine_shares	Engine and fuel share projections for new builds	Forward filled from SAVE 2019 - Olmer et al. (2017)
sfc	Specific Fuel Consumption of main and auxiliary engines	SSD, MSD, HSD, LNG-Otto-medium/slow, LBSI, GT, ST (Distillate, Residual, or LNG) – Faber et al. (2020) SSD or MSD running on methanol – MAN Engine's calculation tool Fuel cells (hydrogen, ammonia) – Marine Service Noord and Comer et al. (2022) ST (nuclear, coal) - World Nuclear and U.S. EIA
efs	Emission factors for different fuels and propulsion systems	Distillate and Residual – Faber et al. (2020) and GREET (2023) LNG, Bio-LNG, and E-LNG - Faber et al. (2020), GREET (2023), Comer et al. (2022), and Pavlenko et al. (2020) Biofuels - GREET (2021)

		Methanol – GREET (2022) Biomethanol and E-methanol - GREET (2021) Hydrogen and Ammonia - GREET (2021) Coal – GREET (2021) Nuclear - Center for Sustainable Systems (2021)
demand	Demand for transport work	UNCTAD (2021), Faber et al. (2020)
payload_utilization	Share of total capacity utilized on average	UNCTAD (2021) and Olmer et al. (2017)
payload_utiization_limit	Realistic upper limit for payload utilization	105% of historical maximums from 2013-2019, via UNCTAD (2021)
new_build_param	Estimated parameters for synthetic ships such as maximum engine power	Extrapolated from historical data – IHS ShipData database and Olmer et al. (2017)
power_speed	Linear regression for PowerMax and SpeedMax parameters	Olmer et al. (2017)
hours_by_phase	Annual hours spent in each phase	Olmer et al. (2017)
max_cruise_hours	Historical upper limits on operating hours	Olmer et al. (2017)
load_factor_bins	Definitions of load factor bins used in power distribution	Olmer et al. (2017)
power_dist	Distribution of operational power load factors	Olmer et al. (2017)
eedi_reference_lines	Definitions of EEDI reference lines	Resolution MEPC.328(76)
eedi_required	Required EEDI reductions from reference lines	Resolution MEPC.328(76)
eexi_required	Required EEXI reductions from EEDI reference lines	Resolution MEPC.350(78) Resolution MEPC.328(76)
cii_capacities	Capacities for use in CII calculations	Resolution MEPC.353(78)
cii_reference_lines	CII reference lines	Resolution MEPC.353(78)
cii_required	Required CII reductions from reference lines	Resolution MEPC.338(76)
cii_rating	Definitions of CII ratings	Resolution MEPC.354(78)