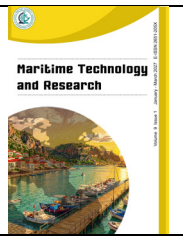
Maritime Technology and Research
https://so04.tci-thaijo.org/index.php/MTR



Research Article

An Energy Efficiency Existing Ship Index (EEXI) calculation and compliance screening tool: Development, verification, and benchmark comparison

Aditya Rinaldi*, Larsen Barasa, Natanael Suranta and Titis Ari Wibowo

Maritime Institute, Sekolah Tinggi Ilmu Pelayaran Jakarta, Jakarta Utara 14150, Jakarta, Indonesia

Corresponding author's e-mail address: aditya.rinaldi@stipjakarta.ac.id

Article information
Received: June 22, 2026
Revision: August 31, 2026
Accepted: October 1, 2026

Keywords
Compliance screening tool;
Energy Efficiency Existing Ship Index;
Maritime decarbonization;
MARPOL Annex VI;
Ship energy efficiency;
Verification and validation

Abstract

The Energy Efficiency Existing Ship Index (EEXI), mandatory under MARPOL Annex VI since January 2023, requires existing ships to demonstrate a design-efficiency level that a large share of the conventionally configured fleet cannot meet without intervention. The tools available to evaluate and plan for compliance, however, are limited: certification grade calculators are proprietary and opaque, while academic treatments tend to embed the computation within one-off scenario studies rather than provide a reusable, openly described instrument. This paper presents the development and preliminary verification of an open, single-file, offline capable web based tool for EEXI calculation and compliance screening. The tool implements the attained-EEXI method of IMO Resolution MEPC.333(76) for the twelve applicable ship types, computes the required EEXI and a quantitative compliance verdict, models the engine and shaft power-limitation (EPL/ShaPoLi) regime, and estimates, for non-compliant vessels, the limiting rating that would bring the attained index to the required value. This was developed under the V-Model methodology, which embeds verification and validation as a structural counterpart of each design stage. Software verification and external validation are reported separately. For verification, two independently written implementations of the governing equations agreed to machine precision ($\varepsilon \leq 10^{-12}$ %) across a thirteen-vessel matrix of hypothetical test cases spanning ship types, sizes, regulatory boundaries, and the power-limitation regime, and the inverse solver converged to the intended root; this establishes internal consistency of the encoding, not regulatory correctness. For external evidence, the outputs are compared with a published worked example (≈0.2 % deviation) and found to be consistent with an established commercial calculator and with the peer-reviewed literature. Validation against certified EEXI Technical Files has not yet been performed and is reserved for a planned fleet-level study. The tool offers a transparent, auditable decision-support instrument of particular value to smaller operators and developing maritime economies, and a transferable template for verifying regulatory calculation software.

List of Acronyms

CII = Carbon Intensity Indicator;
C_F = Carbon conversion factor (g CO_2 per g fuel);
CO_2 = Carbon dioxide;
DSR = Design Science Research;

DWT = Deadweight tonnage (t);
EEDI = Energy Efficiency Design Index;
EEXI = Energy Efficiency Existing Ship Index;
EPL = Engine Power Limitation;
FR = Functional Requirement;
GHG = Greenhouse Gas;
GT = Gross Tonnage;
HFO = Heavy Fuel Oil;
IMO = International Maritime Organization;
kn = Knot (1 nautical mile per hour);
kW = Kilowatt;
LNG = Liquefied Natural Gas;
MARPOL = International Convention for the Prevention of Pollution from Ships;
MCR = Maximum Continuous Rating (kW);
MEPC = Marine Environment Protection Committee;
NFR = Non-Functional Requirement;
P_{AE} = Auxiliary engine power (kW);
P_{ME} = Main engine design power (kW);
SDLC = Software Development Life Cycle;
SFC = Specific Fuel Consumption ($g \cdot kWh^{-1}$);
ShaPoLi = Shaft Power Limitation;
V&V = Verification and Validation;
V_{ref} = Reference speed (kn).

1. Introduction

Maritime transport accounts for about 80 % of world trade by volume, but represents about three percent of global anthropogenic CO_2 emissions; a share which is difficult to reduce, because shipping is inherently international and therefore difficult to regulate through national policy alone (IMO, 2020; Kaya et al., 2026). The world's leading regulator in this area is the International Maritime Organisation (IMO). The IMO's regulatory ambition was substantially increased when it replaced its Initial Strategy from 2018 (which targeted a 50 % reduction in GHG emissions by 2050) with the IMO Strategy on the Reduction of GHG Emissions from Ships of 2023 that aims at net-zero emissions by or around 2050 and sets out indicative checkpoints of 20 % (aiming for 30 %) by 2030 and 70 % (aiming for 80 %) by 2040, both against a baseline of 2008 (IMO, 2023). With this new approach, ship energy efficiency is no longer a sought-after feature in design. It is a mandatory, time-bound compliance obligation.

The regulatory instruments that translate these ambitions into practice are found in Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL). The Energy Efficiency Design Index (EEDI) has been progressively tightening the design-efficiency requirements for newbuild vessels since 2013. To apply comparable discipline to the existing fleet, the 2021 revision of MARPOL Annex VI introduced two short-term measures that became mandatory on 1 January 2023: the Energy Efficiency Existing Ship Index (EEXI), a technical measure, and the Carbon Intensity Indicator (CII), an operational measure (Bayraktar & Yuksel, 2023; IMO, 2021a). Together they require in-service ships both to demonstrate an adequate design-efficiency level and to improve their operational carbon intensity continuously.

The EEXI is a design-based metric expressing a ship's theoretical CO_2 output per unit of transport work, in grams of CO_2 per tonne-nautical mile, and applies to virtually all cargo and passenger ships of 400 gross tonnage and above engaged in international trade. Each vessel must compute an attained EEXI, following the calculation method in IMO Resolution MEPC.333(76), and demonstrate that this value does not exceed a required EEXI obtained by applying a ship-type- and

size-dependent reduction factor to the corresponding EEDI reference line (IMO, 2021b). The EEXI obtained is in principle certified only once in the lifetime of a ship (unless the energy efficiency characteristics are changed), unlike the operational CII which is re-evaluated on an annual basis. Conceptually, the calculation is a single exercise, but is far from trivial: it depends on a large number of interacting parameters (main- and auxiliary-engine power, certified specific fuel consumption, carbon factors, reference speed, capacity, and a family of ship-type-specific correction factors), and the value itself to be calculated varies discontinuously across size bands (Czermański et al., 2022).

Thus, active compliance measures are necessary, as the attained EEXI is higher than the required one for a significant part of the existing fleet. The scale of the shortfall is now well documented. Kalajdžić et al. (2022) analyzed bulk carriers against the EEXI reference lines and showed that compliance for a large part of that segment can be achieved only through substantial power reduction, with the required limitation varying systematically with deadweight. Extending the same framework to tankers, Vasilev et al. (2025) reported that conventionally fueled vessels sit close to, and frequently beyond, the required limits. The most recent evidence is stronger still: in a study of 162 container ships built between 2000 and 2020, Vasilev et al. (2026) found that only about 12 % of the sample met the required EEXI in its as-built configuration, so that the remainder would require a significant speed reduction to comply. Among the options that can be implemented, the overridable engine power limitation (EPL) and shaft power limitation (ShaPoLi) are the most commonly used, because they are relatively simple, cheap, and require minimal physical intervention. The IMO has provided specific guidance for these systems and for the power reserve associated with them (IMO, 2021c). These measures reduce the power of the main engine used for the index calculation, and thus the achieved EEXI, at the expense of a corresponding reduction in service speed. Studies of in-service tankers show that slow steaming alone is often insufficient to meet regulatory limits, and that explicit EPL, at rates that can exceed thirty percent of installed power, may be necessary to achieve compliance, while also improving CII ratings (Ersoy et al., 2025). Beyond power limitation, deeper decarbonization pathways such as energy-saving devices, hull and propeller optimization, and the use of alternative fuels (LNG, methanol, and potential zero-carbon fuels) provide larger reductions but at significantly higher capital costs, and their cost-effectiveness varies greatly by ship type and size (Tu et al., 2024). Tanker assessments under the EEDI, EEXI, and CII schemes demonstrate that conventional-fuel ships are approaching or exceeding the required limitations, underlining the need for systematic, vessel-specific compliance analysis (Vasilev et al., 2025).

Those pressures are felt unevenly across the industry. Owners of older ships and operators in developing maritime economies face severe difficulties: retrofitting is costly, payback periods are long, and there is a real risk that non-compliant assets become commercially stranded (Chuah et al., 2023). Vakili et al. (2023) document how the operational consequences of EEXI-driven speed reduction propagate through the supply chains of small island developing states and least-developed countries, lengthening voyage times and raising freight costs for economies that depend heavily on maritime imports. For such operators, the ability to rapidly and transparently screen a fleet (estimate the attained and required EEXI of each ship, identify non-compliant vessels, and quantify the power limitation required to restore compliance) is a prerequisite for sound investment and fleet-renewal decisions.

Against this background, the state of the available computational tools is the gap this study addresses, with three distinct components. First, the calculation engines that are provided by the classification societies and commercial vendors tend to be proprietary, license-based, and opaque in their internal logic and therefore restrict independent scrutiny and hamper their use for exploratory planning. Second, the recent academic literature computes the EEXI as a bespoke step inside a specific scenario study rather than as a reusable instrument: Kalajdžić et al. (2022) and Vasilev et al. (2025, 2026) construct fleet-level assessments around their own calculations, Ersoy et al. (2025) and Soltani Motlagh et al. (2025) embed the index inside machine-learning performance models, and

Alshareef and Alghanmi (2024) treat it as a constraint inside a reinforcement-learning optimizer. In each case the computational core is described in the text but is not released as an artifact that a practitioner can run. Third, and consequently, none of these studies reports an explicit verification argument for the calculation itself: the correctness of the encoding is assumed rather than demonstrated, so a reader cannot separate an error in the index computation from an error in the scenario built on top of it. This leaves a practical gap between the regulatory requirement and the means available to the operators who must satisfy it.

In this paper, this gap is addressed by presenting the design, implementation, and preliminary verification of an open, web-based tool for EEXI calculation and compliance screening. The tool implements the attained-EEXI method of MEPC.333(76) for the twelve EEXI applicable ship types, calculates the required EEXI and a quantitative compliance verdict, models the EPL/ShaPoLi regime and, in the case of a non-compliant vessel, estimates the limiting power rating that would bring the attained index to the required value. It is delivered as a single, self-contained, offline-capable file to maximize portability and transparency, and is built for auditability by exposing every intermediate quantity and correction factor. The study's detailed aims are: (i) formalizing the EEXI computational model and the related compliance and power-limitation logic in a deterministic software artifact; (ii) developing that artifact under a rigorous software-engineering methodology (the Verification and Validation V-Model) that embeds testing as a structural counterpart of each design stage; and (iii) verifying the implementation against the governing equations by independent re-implementation, and comparing its output with an independently published worked example. The present study is described as development and preliminary verification. External validation against certified EEXI Technical Files is outside the scope of this paper and is the explicit objective of a planned second phase.

2. Material and methods

2.1 Research design

This study follows a design science research (DSR) perspective: a software tool as the main artifact and the V-Model (Verification and Validation model) as the software development life cycle (SDLC). The selection of the V-Model, as opposed to linear (Waterfall) or evolutionary (Prototyping, Agile) alternatives, is motivated by one sole reason: the scientific contribution of this paper is to demonstrate that the artifact accurately reproduces a standardized, deterministic regulatory equation. The V-Model embeds verification and validation (V&V) as structural counterparts of every development stage, rather than as a terminal activity, which directly supports an evidence-based claim of correctness and makes the development process reproducible and auditable, both expectations of a high-quality engineering submission.

The applicable requirements are based on a comprehensive and well-established set of regulations: IMO Resolution MEPC.333(76), regarding the calculation method for the EEXI (IMO, 2021b), MARPOL Annex VI, Regulations 23 and 25, regarding the implementation and mandatory EEXI (IMO, 2021a), the 2018 EEDI Calculation Guidelines MEPC.308(73), for inherited parameters (IMO, 2018), the 2013 Reference Line Guidelines MEPC.231(65) (IMO, 2013), and MEPC.335(76) for the shaft power/engine power limitation regime (ShaPoLi/EPL) (IMO, 2021c). Since these documents fully detail the calculations, the identification of requirements is based on these documents rather than stakeholder surveys, and the acceptance criteria are exact compliance with the specifications.

The end-to-end research workflow comprises six stages: (i) requirements analysis; (ii) system architecture design; (iii) component (module) design; (iv) implementation; (v) verification and validation; and (vi) deployment and reporting. Stages (i) - (iv) form the descending (left) arm of the V; their paired testing activities form the ascending (right) arm. The mapping is summarized in **Figure 1**.

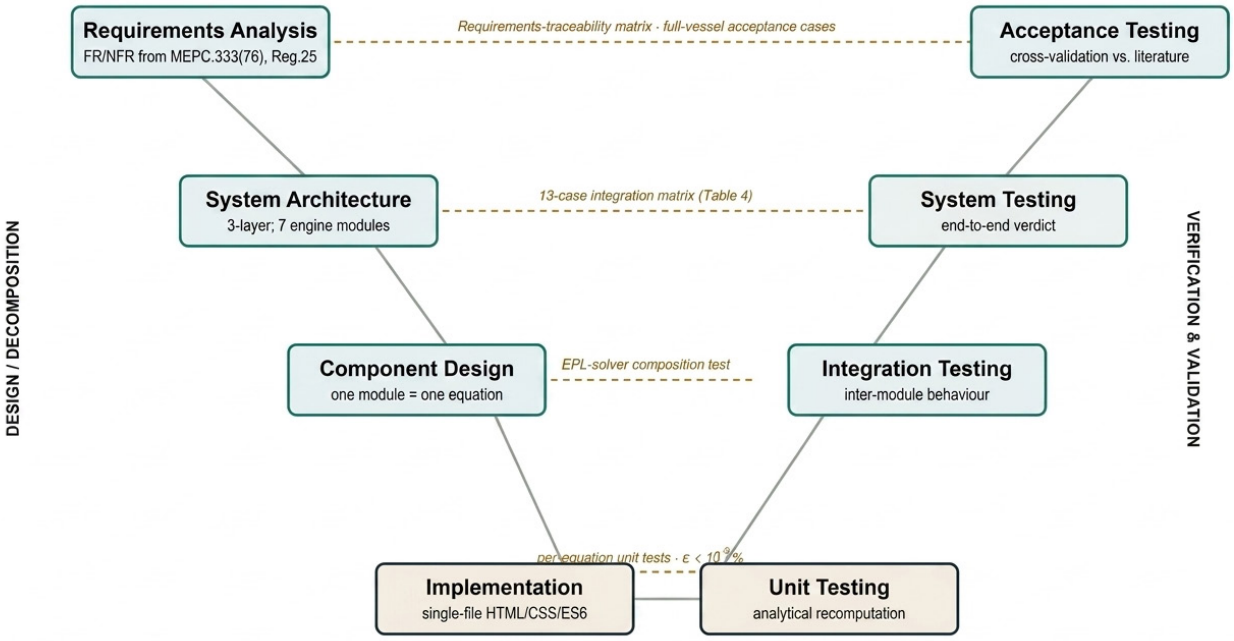


Figure 1 V-Model adapted to EEXI tool development.

2.2. Computational model

The simplified attained EEXI formulation of MEPC.333(76) applicable to conventionally propelled ships is defined in Eq. (1):

$$EEXI = \frac{A+B-C}{f_i \cdot f_C \cdot f_l \cdot Capacity \cdot f_w \cdot V_{ref} \cdot f_m} \quad (1)$$

where:

$$A = \left(\prod_{j=1}^{n} f_j\right)\left(\sum_{i=1}^{nME} P_{ME(i)} \cdot C_{F,ME(i)} \cdot SFC_{ME(i)}\right) + \left(P_{AE} \cdot C_{F,AE} \cdot SFC_{AE}\right) \quad (1a)$$

$$B = \left[\left(\prod_{j=1}^{n} f_j \cdot \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} \cdot P_{AEeff(i)}\right) \cdot C_{F,AE} \cdot SFC_{AE}\right] \quad (1b)$$

$$C = \sum_{i=1}^{neff} f_{eff(i)} \cdot P_{eff(i)} \cdot C_{F,ME} \cdot SFC_{ME} \quad (1c)$$

The numerator represents the CO_2 mass flow rate ($g \cdot h^{-1}$) from the main engine and auxiliary engines, while the denominator represents the transport work per unit time, resulting in the unit g $CO_2 \cdot t^{-1} \cdot nm^{-1}$. The symbols are defined in **Table 1** so that the notation, the units, and the subscripting are stated once and used consistently in the text, the equations, the figures, and the tables.

2.2.1 Main engine power

For each main engine i, the design power is taken at 75 % of the maximum continuous rating (MCR). When an overridable ShaPoLi/EPL system compliant with MEPC.335(76) is installed, P_{ME} is the lower of 83 % of the limited rating and 75 % of the original rating, as in Eq. (2):

$$P_{ME} = 0.75 \cdot MCR \quad (2a)$$

$$P_{ME} = min(0.83 \cdot MCR_{lim},\ 0.75 \cdot MCR) \quad (2b)$$

Table 1 Symbols used in Eq. (1) to Eq. (14).

Symbol	Definition	Unit
$P_{ME(i)}$	Design power of main engine i	kW
P_{AE}	Total auxiliary-engine power	kW
$P_{PTI(i)}$	Power of shaft motor i	kW
$P_{eff(i)}$	Output power of innovative energy-efficiency technology i	kW
$C_{F,ME}$; $C_{F,AE}$	Carbon conversion factor, main / auxiliary engine fuel	g CO_2 per g fuel
SFC_{ME}; SFC_{AE}	Certified specific fuel consumption, main / auxiliary engine	$g \cdot kWh^{-1}$
$f_{eff(i)}$	Availability factor of innovative technology i	–
f_i	Capacity factor for ice-class ships	–
f_j	Correction factor for ship-specific design elements	–
f_C	Cubic capacity correction factor (vehicle carriers, Eq. 11)	–
f_l	Factor for general cargo ships equipped with cranes	–
f_w	Weather correction factor (set to 1.0 for EEXI)	–
f_m	Ice-class deadweight difference factor	–
Capacity	Ship capacity (see Eq. 4a - 4c)	t or GT
V_{ref}	Reference speed at the relevant shaft power	kn
MCR	Maximum continuous rating of main engine(s)	kW
MCR_{lim}	Declared limited rating under EPL/ShaPoLi system	kW
Y	Reduction factor of MARPOL Annex VI Reg. 25 (**Table 3**)	%

2.2.2 Auxiliary engine power

Following MEPC.308(73), P_{AE} is estimated from the total installed propulsion power, Eq. (3a - 3b); for passenger ship types where this estimate is unrepresentative, the approximations of MEPC.333(76) are provided, Eq. (3c - 3d):

$$P_{AE} = 0.025 \cdot \sum MCR_{ME} + 250 \quad (3a)$$

$$P_{AE} = 0.05 \cdot \sum MCR_{ME} \quad (3b)$$

$$P_{AE,app} = 0.1193 \cdot GT + 1{,}814.4 \quad (3c)$$

$$P_{AE,app} = 0.866 \cdot GT^{0.732} \quad (3d)$$

2.2.3 Capacity

The capacity basis is not a single expression: it depends on the ship type. The EEDI/EEXI framework defines three bases (IMO, 2018, 2021b), given in Eq. (4a - 4c) and mapped to ship type in **Table 2**:

$$Capacity = DWT \quad (4a)$$

$$Capacity = 0.70 \cdot DWT \quad (4b)$$

$$Capacity = GT \quad (4c)$$

Table 2 Capacity basis by ship type.

Ship type	Capacity basis	Equation
Bulk carrier	DWT	(4a)
Gas carrier	DWT	(4a)
Tanker	DWT	(4a)
Containership	70 % of DWT	(4b)
General cargo ship	DWT	(4a)
Refrigerated cargo carrier	DWT	(4a)
Combination carrier	DWT	(4a)
LNG carrier	DWT	(4a)
Ro-ro cargo ship (vehicle carrier)	DWT	(4a)
Ro-ro cargo ship	DWT	(4a)
Ro-ro passenger ship	DWT	(4a)
Cruise passenger ship (non-conventional propulsion)	GT	(4c)

2.2.4 Reference line and required EEXI

The required EEXI is the product of the EEDI reference-line value and the size-dependent reduction factor of MARPOL Annex VI Reg. 25, Eqs. (5) - (6):

$$Refline = a \cdot b^{-c} \quad (5)$$

$$EEXI_{required} = \left(1 - \frac{Y}{100}\right) \cdot Refline \quad (6)$$

where (a, c) are the type-specific coefficients of **Table 4**, b is the deadweight (capped at 279,000 t for bulk carriers) or GT for cruise ships, and Y is the reduction factor of **Table 3**. Within transition size bands the reduction factor is linearly interpolated, the lower value applying to the smaller ship, Eq. (7):

$$Y(b) = Y_{Low} + \left(Y_{High} - Y_{Low}\right) \cdot \frac{b - b_{Low}}{b_{High} - b_{Low}} \quad (7)$$

Compliance is the inequality of Eq. (8):

$$EEXI_{attained} \leq EEXI_{required} \quad (8)$$

Table 3 Reduction factor Y of MARPOL Annex VI Regulation 25, as implemented in the tool.

Ship type	Size (DWT unless stated)	Y (%)
Bulk carrier	≥ 200,000	15
	20,000 - 199,999	20
	10,000 - 19,999	0 - 20 (interp.)
Gas carrier	≥ 15,000	30
	10,000 - 14,999	20
	2,000 - 9,999	0 - 20 (interp.)
Tanker	≥ 200,000	15
	20,000 - 199,999	20
	4,000 - 19,999	0 - 20 (interp.)
Containership	≥ 200,000	50
	120,000 - 199,999	45
	80,000 - 119,999	35
	40,000 - 79,999	30
	15,000 - 39,999	20
	10,000 - 14,999	0 - 20 (interp.)
General cargo ship	≥ 15,000	30
	3,000 - 14,999	0 - 30 (interp.)
Refrigerated cargo carrier	≥ 5,000	15
	3,000 - 4,999	0 - 15 (interp.)
Combination carrier	≥ 20,000	20
	4,000 - 19,999	0 - 20 (interp.)
LNG carrier	≥ 10,000	30
Ro-ro cargo ship (vehicle carrier)	≥ 10,000	15
Ro-ro cargo ship	≥ 2,000	5
	1,000 - 1,999	0 - 5 (interp.)
Ro-ro passenger ship	≥ 1,000	5
	250 - 999	0 - 5 (interp.)
Cruise passenger ship (non-conv.)	≥ 85,000 GT	30
	25,000 - 84,999 GT	0 - 30 (interp.)

2.2.5 Type specific correction factors

For ro-ro cargo and ro-ro passenger ships the speed correction factor of MEPC.333(76) is applied, Eqs. (9) - (10), capped at unity; for vehicle carriers with DWT/GT < 0.35 the cubic-capacity correction is applied, Eq. (11):

$$f_{j,roro} = \frac{1}{F_{nL}{}^{\alpha} \cdot \left(\frac{Lpp}{B_S}\right)^{\beta} \cdot \left(\frac{B_S}{d_S}\right)^{\gamma} \cdot \left(\frac{Lpp}{\nabla^{1/3}}\right)^{\delta}} \quad (9)$$

where the Froude number F_{nL} is defined as:

$$F_{nL} = \frac{0.5144 \cdot V_{ref,F}}{\sqrt{L_{pp} \cdot g}} \quad (10)$$

$$f_{c,VEHICLE} = \left[\frac{\frac{DWT}{GT}}{0.35}\right]^{-0.8} \quad (11)$$

Table 4 EEDI reference line coefficients (a, c) used to compute the required EEXI (IMO, 2013, 2018).

Ship type	a	b	c
Bulk carrier	961.79	DWT (≤ 279,000)	0.477
Gas carrier	1,120.00	DWT	0.456
Tanker	1,218.80	DWT	0.488
Containership	174.22	DWT	0.201
General cargo ship	107.48	DWT	0.216
Refrigerated cargo carrier	227.01	DWT	0.244
Combination carrier	1,219.00	DWT	0.488
LNG carrier	2,253.70	DWT	0.474
Ro-ro cargo (vehicle carrier)	1,812.63	DWT	0.471
Ro-ro cargo ship	1,405.15	DWT	0.498
Ro-ro passenger ship	752.16	DWT	0.381
Cruise passenger (non-conv.)	170.84	GT	0.214

2.2.6 EPL estimation (inverse problem)

When Eq. (8) is violated, the tool estimates the limited rating at which the attained index would equal the required index. The result is a preliminary planning estimate, not an approved limitation. The estimate is obtained by solving Eq. (12) for the main-engine power P and converting the result to a declared rating through Eq. (13):

$$EEXI_{attained}(P) = \frac{f_j \cdot P \cdot C_{F,ME} \cdot SFC_{ME} + P_{AE} \cdot C_{F,AE} \cdot SFC_{AE}}{K \cdot V_{ref,0} \cdot \left(\frac{P}{P_{ME,0}}\right)^{\frac{1}{3}}} \quad (12)$$

$$MCR_{lim} = \frac{P_{ME}}{0.83} \quad (13)$$

Two properties of Eq. (12) require comment. First, K collects the constant part of the denominator of Eq. (1), that is, $f_i \cdot f_C \cdot f_l \cdot \text{Capacity} \cdot f_w \cdot f_m$. Because the numerator is linear in P

while the denominator varies with $P^{1/3}$, the attained index is a strictly increasing function of P, so the equation has a single root in $(0, P_{ME,0}]$ whenever the vessel is non-compliant at full power. The tool locates it by bisection, and the solver is therefore guaranteed to return the minimum power reduction that satisfies Eq. (8), not an arbitrary one.

Second, the exponent 1/3 in Eq. (12) is the admiralty-type approximation $P \propto V^3$, which follows from assuming that resistance varies with the square of speed and that propulsive efficiency is constant over the speed range considered. It is used here because the tool is designed to run from the particulars that an operator has at hand, and a ship-specific speed-power curve is normally not among them. The approximation is acceptable for a screening estimate over the moderate speed reductions typical of EEXI compliance, but it is not exact for any individual hull: the true relationship depends on the resistance curve, the propeller characteristics, the hull and propeller condition, and the loading condition, and it deviates most at large speed reductions and for hull forms operating near a hump in the resistance curve. For a certification calculation, V_{ref} at the limited power must be taken from the approved speed-power curve derived from sea trial or model-test data (IMO, 2021b, 2021c), and the tool accepts such a value as a direct input. Consequently, any limitation proposed by the tool requires ship-specific engineering assessment and approval by the classification society or the flag state before it can be implemented.

Table 5 Functional and non-functional requirements with regulatory traceability.

ID	Requirement	Source
FR-1	Compute attained EEXI for the twelve EEXI-applicable ship types	MEPC.333(76); Eq. (1)
FR-2	Select the correct capacity basis automatically (DWT / 0.70·DWT / GT)	MEPC.308(73); Eqs. (4a - 4c)
FR-3	Compute the required EEXI from reference line and reduction factor	Reg. 25; Eqs. (5) - (7)
FR-4	Model the ShaPoLi/EPL regime for P_{ME}	MEPC.335(76); Eq. (2)
FR-5	Estimate P_{AE} (automatic / manual / passenger-ship approximation)	MEPC.308(73); MEPC.333(76)
FR-6	Compute type-specific correction factors $f_{j,roro}$ and $f_{c,VEHICLE}$	MEPC.333(76)
FR-7	Render a compliance verdict and quantitative margin	Reg. 23/25; Eq. (8)
FR-8	Estimate a limiting rating (MCR_{lim}) when non-compliant	Verification record
FR-9	Export/print an auditable calculation report	Verification record
NFR-1	Portability: single self-contained file, offline-capable, browser-agnostic	Field deployability
NFR-2	Numerical precision: IEEE-754 double precision; deterministic output	Scientific reliability
NFR-3	Transparency: display all factors and intermediate quantities	Auditability
NFR-4	Usability: real-time recomputation and context-sensitive inputs	Practitioner adoption
NFR-5	Maintainability: modular, data-driven coefficient tables	Regulatory updates

2.3 V-model

2.3.1 Phase 1: Requirements analysis

Requirements were elicited by structured analysis of the regulatory corpus and classified into functional (FR) and non-functional (NFR) requirements (**Table 5**). Each FR is traceable to a specific clause, establishing a requirements-traceability matrix that the acceptance test on the ascending arm later exercises end-to-end.

2.3.2 Phase 2: System architecture design

A three-layer architecture was specified (**Figure 2**): a presentation layer (input forms with conditional fields and a results panel), a computation engine decomposed into seven cohesive modules (P_{ME}, P_{AE}, capacity, reference-line, reduction-factor, correction-factor, and EPL-solver), and a data layer holding the regulatory coefficient tables (**Tables 3** and **4**) as immutable look-up structures. The engine is stateless and side-effect free: identical inputs always produce identical outputs (NFR-2), a property leveraged by the testing strategy. Regulatory coefficients are separated from procedural logic (NFR-5) to allow for future amendments by editing data, not algorithms.

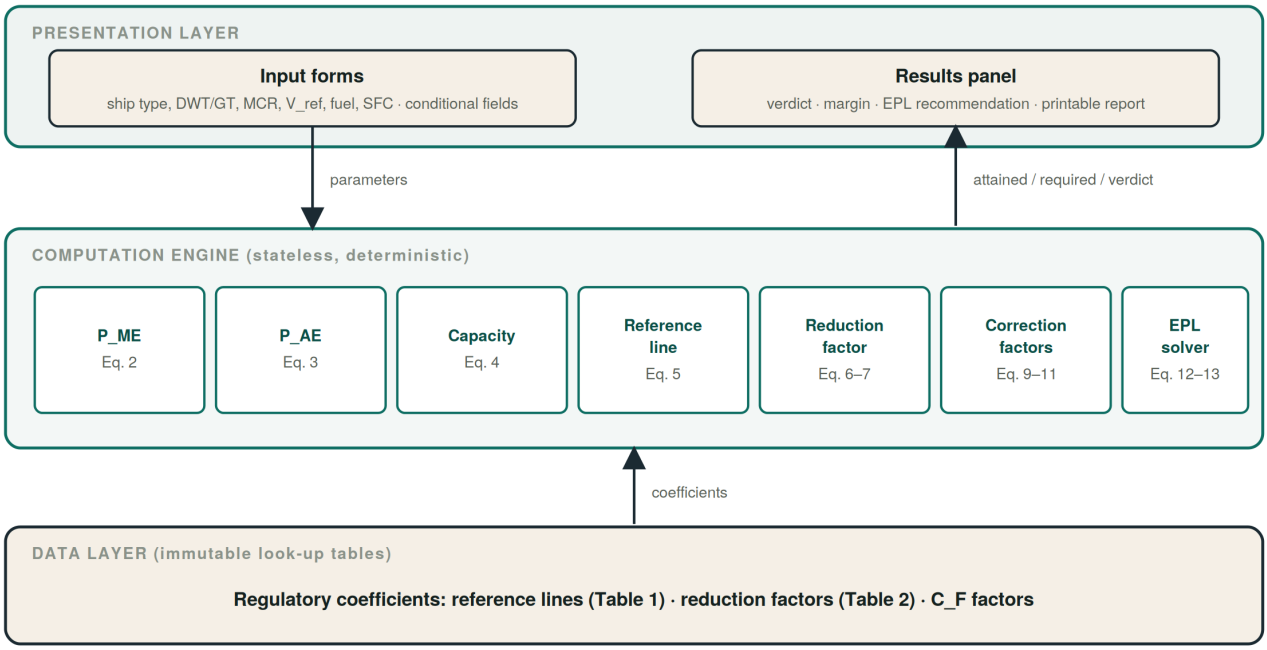


Figure 2 System architecture and data flow.

2.3.3 Phase 3 - 4: Component design and implementation

The engine modules were defined as pure functions with a clear input/output contract and a single governing equation (Eqs. (1) - (13)). This one-to-one mapping between modules and equations makes it easier to write unit tests for each equation. The integration design determines module dependencies, especially the EPL-solver that assembles the attained-EEXI and required-EEXI modules in a bisection root-finder (Eq. (12)).

The tool was implemented as a single HTML5 document with embedded CSS3 and vanilla ECMAScript (ES6); no server, build step, framework, or external runtime is required, satisfying NFR-1 and enabling offline use aboard ships and at shore offices. Computation is performed entirely client-side in double-precision floating point, satisfying NFR-2. The technology choice deliberately minimizes dependencies to maximize reproducibility and longevity of the artifact.

2.3.4 V-model ascending arm: Verification and benchmark protocol

Because the attained EEXI is a closed-form deterministic function rather than a statistical or empirically fitted model, the relevant meaning of "accuracy" in this study is fidelity to the standardized equation, not goodness of fit to observations. Two distinct questions must therefore be kept apart. Software verification asks whether the equations have been encoded correctly; it is answered entirely inside the software and can be settled to machine precision. External validation asks whether the tool reproduces the value that a competent authority would certify for a real ship; it can only be answered against externally authored results, and definitively only against certified Technical Files. The protocol below is explicit about which layer supplies which kind of evidence, and Layer 3 has not yet been executed.

Layer 1: Verification (unit and integration). Tool output is compared against an independent re-implementation of Eqs. (1) - (13) (the analytical recomputation) over a purpose-designed test matrix of thirteen vessels spanning all major ship types and size classes, deliberately including the reduction-factor breakpoints, the boundary cases (the 279,000 t bulk-carrier cap; the DWT/GT = 0.35 vehicle-carrier threshold), and EPL on/off states. The evaluation metric is the relative error of Eq. (14). This layer establishes that two independent encodings of the same specification agree. It does not, by itself, establish that the specification has been interpreted correctly, and this paper does not claim that it does.

$$\varepsilon = \frac{|x_{tool} - x_{ref}|}{x_{ref}} \times 100\% \quad (14)$$

Layer 2: Benchmark comparison against a published worked example. This is not a resampling procedure but a comparison against a single externally authored result. The tool was exercised on a documented worked example from the literature (a 40,000 DWT bulk carrier, single 10,000 kW main engine, capacity 60,000 t, V_{ref} 14 kn, SFC 190 g·kWh^{-1}, reported attained EEXI 1.70 g·t^{-1}·nm^{-1}; Czermański et al., 2022). The source computes a simplified index, and two assumptions had to be matched to reproduce it: the carbon conversion factor was set to unity instead of the HFO value of 3.114, and the auxiliary-engine term of Eq. (1a) was suppressed. Under these two matched assumptions, and with no other change, the tool reproduces 1.696 g·t^{-1}·nm^{-1} ($\varepsilon \approx 0.24$ %, attributable to rounding in the source). Applying the complete Eq. (1) to the same vessel yields 5.681 g·t^{-1}·nm^{-1}, and the discrepancy is fully explained by those omissions.

Layer 3: External validation (not yet performed). The strongest ground truth is the IMO official EEXI calculation spreadsheet and, above all, the certified EEXI Technical Files of in-service vessels. This layer is the entry point of the planned second phase and has not been executed for the present paper. Until it is, the evidence reported here supports a claim of correct implementation and of consistency with published results, but not a claim of certified accuracy.

3. Results

3.1 Developed tool: Capabilities, architecture, and workflow

The tool implements the attained-EEXI method of MEPC.333(76) (IMO, 2021b) and the required-EEXI logic of MARPOL Annex VI Regulation 25. This was built as a single HTML file with embedded CSS and client-side JavaScript. It needs no server, no build step, and no network. The same file runs in any modern browser, in a shore office or aboard ship, which satisfies NFR-1.

The tool covers all twelve EEXI-applicable ship types and chooses the capacity basis from the ship type according to Eqs. (4a) - (4c) and **Table 2** (FR-1, FR-2). When the user declares an EPL or ShaPoLi system, main-engine power becomes the lower of 0.83·MCR_{lim} and 0.75·MCR (FR-4) (IMO, 2021c); without power limitation it is 0.75·MCR. Auxiliary power has three options: estimated from installed propulsion power, entered by hand, or taken from the passenger-ship approximations

of MEPC.333(76) (FR-5). If the user provides the corresponding geometry, the tool calculates the type-specific correction factors $f_{j,roro}$ and $f_{c,VEHICLE}$ (FR-6). It returns, per vessel, the attained EEXI, the EEDI reference line, the applicable reduction factor, the required EEXI, a compliance verdict, and the quantitative margin (FR-3, FR-7). If the verdict is negative, the tool solves the inverse problem and reports an estimated limiting rating, the corresponding power reduction, and the resulting reference speed (FR-8). Each intermediate quantity is adjacent to the final indices (NFR-3), so each result can be traced back to its governing equation.

The implementation follows the three-layer architecture. The interface is divided into ship particulars, main engine and power, auxiliary engine, fuel and consumption, reference speed, and correction factors. The results panel updates whenever any field changes (NFR-4). Some input fields are displayed only if they are relevant: the limited-rating field only if power limitation is enabled; the ro-ro geometry fields only for ro-ro ship types. The computation engine has seven stateless modules and recomputes the whole result set on any change. The regulatory coefficients are maintained as immutable look-up structures in a separate data layer, so that future regulatory amendments require editing data, not code (NFR-5). The populated calculation can then be exported for documentation (FR-9) via a printable report function.

One consequence of the input design matters for the interpretation of the results below. V_{ref} is an independent user input, not a quantity derived from the declared rating. This is deliberate and follows MEPC.333(76): where an EPL or ShaPoLi is fitted, the reference speed to be used in the index is the speed at the limited power taken from the approved speed-power curve. The tool therefore does not overwrite a user-supplied V_{ref} when a limited rating is declared. The cube-root relation of Eq. (12) is used only inside the inverse solver, where no certified curve is available, and the speed it returns is labelled in the interface as an estimate.

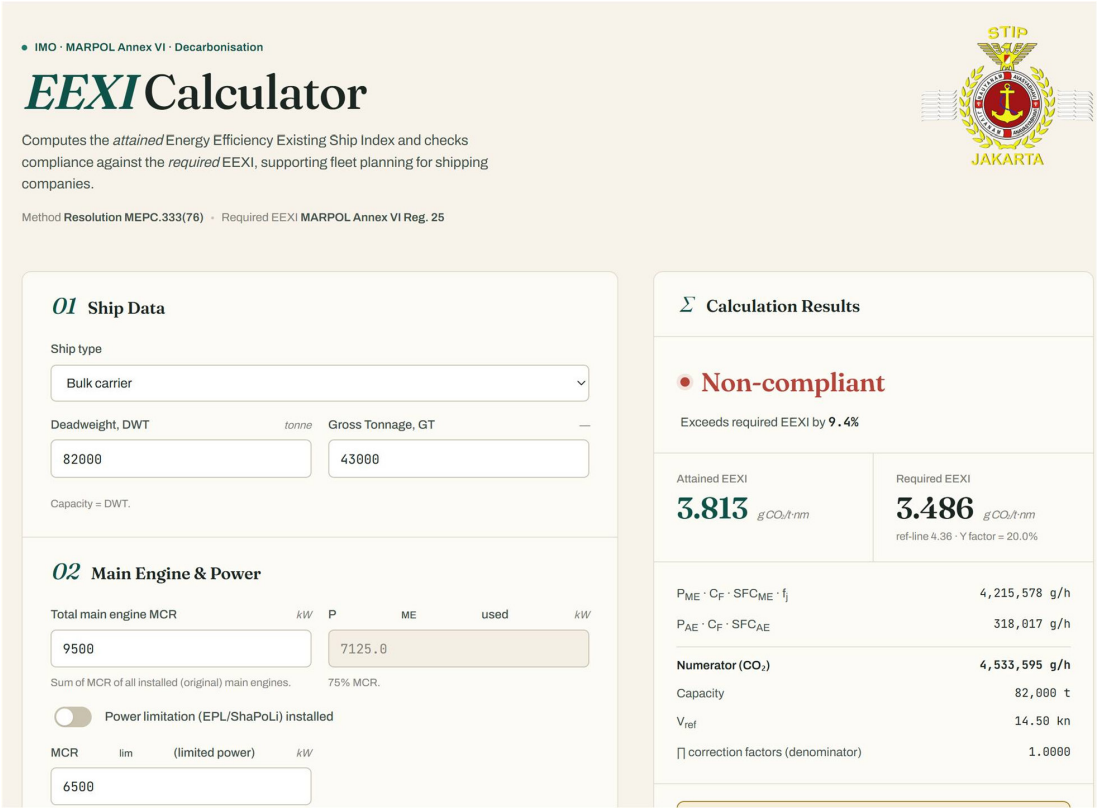


Figure 3 The developed EEXI tool in operation. The input panel sits on the left, the live results panel on the right. The screen shows the Kamsarmax case: compliance verdict, calculation breakdown, and engine-power-limitation recommendation. The interface is in Indonesian for the target operators; the technical symbols follow IMO nomenclature.

3.2 Illustrative application: Kamsarmax bulk carrier

The tool is applied to a representative Kamsarmax bulk carrier of 82,000 t deadweight (43,000 GT), with one 9,500 kW main engine, a reference speed of 14.5 knots, heavy fuel oil, and the default specific fuel consumptions. **Table 6** lists the inputs and outputs. **Figure 3** shows the tool computing them in real time.

Table 6 Illustrative application of tool to a Kamsarmax bulk carrier.

Quantity	Symbol	Value
Deadweight	DWT	82,000 t
Gross tonnage	GT	43,000
Installed main-engine rating	∑MCR	9,500 kW
Reference speed	V_{ref}	14.5 kn
Fuel / carbon factor	C_F	HFO, 3.114
Specific fuel consumption (ME / AE)	SFC	190 / 215 g·kWh^{-1}
Main-engine design power	P_{ME}	7,125 kW
Auxiliary design power	P_{AE}	475 kW
Capacity basis	–	DWT (82,000 t)
Attained EEXI	–	3.813 g CO_2·t^{-1}·nm^{-1}
Reference-line value	–	4.357
Reduction factor	Y	20 %
Required EEXI	–	3.486 g CO_2·t^{-1}·nm^{-1}
Compliance margin	–	+9.4 % (non-compliant)
Estimated limited rating	MCR_{lim}	7,375 kW (−22.4 %)
Resulting design power / estimated speed	P_{ME} / V_{ref}	6,122 kW / ≈ 13.78 kn

Equations (2) and (3) give the design powers. The installed rating sits below 10,000 kW, so auxiliary power comes out at 475 kW; main-engine design power is 7,125 kW. With deadweight as the capacity basis, the attained EEXI is 3.813 g CO_2·t^{-1}·nm^{-1}. The EEDI reference line for an 82,000 t bulk carrier is 4.357. The 20 % reduction factor of Regulation 25 yields a required EEXI of 3.486. The ship exceeds its limit by 9.4 % and the tool reports it as non-compliant. For this case the inverse solver estimates a limiting rating of about 7,375 kW, a reduction of 22.4 %. That lowers the design main-engine power to 6,122 kW and the estimated reference speed to about 13.78 knots, which brings the attained EEXI down to the required value.

3.3 Verification and benchmark comparison

The attained EEXI is a fully standardized, deterministic closed-form function (IMO, 2021b), not a statistical or empirically fitted model. Section 2.3.4 defined the protocol; the results are reported here.

The thirteen cases used for verification are hypothetical test vessels, not real ships and not literature examples. They were constructed for this study to exercise the specification systematically: each major EEXI-applicable ship type is represented, sizes are chosen to fall on both sides of the

reduction-factor breakpoints of **Table 3**, and the set includes the two boundary conditions written into the regulation (the 279,000 t reference-line cap for bulk carriers and the DWT/GT = 0.35 vehicle-carrier threshold) as well as both states of the power-limitation regime. Because they are synthetic, they cannot support any claim about the real fleet; their only function is to drive the two implementations through every branch of the code. The complete input set is given in **Table 7** so that any reader can reproduce the outputs of **Table 8** independently.

Table 7 Complete input data for the thirteen hypothetical verification cases. All cases use heavy fuel oil (C_F = 3.114) and the correction factors $f_i = f_C = f_l = f_j = f_w = f_m = 1.000$.

#	Vessel (type, size)	DWT (t)	GT	∑MCR (kW)	SFC ME/AE	V_{ref} (kn)	MCR_{lim} (kW)
1	Handysize bulk	30,000	22,000	6,000	190 / 215	13.5	–
2	Kamsarmax bulk	82,000	43,000	9,500	190 / 215	14.5	–
3	Capesize bulk	180,000	95,000	17,000	185 / 215	14.8	–
4	Aframax tanker	115,000	62,000	13,500	185 / 215	14.8	–
5	VLCC tanker	300,000	160,000	28,000	185 / 215	15.5	–
6	Feeder containership	25,000	18,000	9,000	180 / 215	18.0	–
7	Panamax containership	60,000	50,000	36,000	175 / 215	22.0	–
8	MR gas carrier	22,000	18,000	8,500	190 / 215	15.5	–
9	LNG carrier	85,000	115,000	28,000	175 / 215	19.5	–
10	Refrigerated cargo	9,000	8,500	9,500	190 / 215	18.5	–
11	General cargo	12,000	9,000	5,500	190 / 215	14.0	–
12	Ro-ro cargo	12,000	28,000	12,000	190 / 215	18.0	–
13	VLCC tanker + EPL	300,000	160,000	28,000	185 / 215	13.75	17,647

The tool's computation engine was checked against a second implementation of Eqs. (1) - (13) written independently. The two implementations differ in their organization (one mirrors the deployed JavaScript engine, the other is a re-implementation with a different internal structure), so that any transcription error, mis-entered constant, or mis-ordered operation in either would show up as a divergence. In each case the relative error follows Eq. (14).

The results are shown in **Table 8**. The two implementations agreed to the full displayed precision ($\varepsilon_{max} \leq 10^{-12}$ %) for all thirteen vessels for the attained and the required index. This is the expected result for a properly implemented deterministic closed-form method: in the absence of a stochastic component, a faithful encoding reproduces the analytical value, and any non-trivial deviation would have localized a defect through the requirements-traceability matrix. It is emphasized that this agreement demonstrates internal consistency between two encodings written by the same team from the same reading of the regulation. It would not detect a shared misinterpretation of the specification, and it is reported here as verification evidence only.

Table 8 Verification matrix: attained and required EEXI computed by the tool across the thirteen hypothetical vessels of **Table 7**, with the relative error against the independent reimplementation. The last four columns give the minimum power limitation estimated by the solver of Eq. (12) for each non-compliant case.

#	Vessel (type, size)	Attained	Required	Verdict	ε (%)	MCR_{lim} (kW)	ΔMCR (%)	P_{ME} (kW)	V_{ref} est. (kn)	EEXI attained after EPL
1	Handysize bulk, 30,000 DWT	7.070	5.631	EPL needed	0	3,667	−38.9	3,044	11.85	5.630
2	Kamsarmax bulk, 82,000 DWT	3.813	3.486	EPL needed	0	7,375	−22.4	6,121	13.78	3.485
3	Capesize bulk, 180,000 DWT	2.927	2.396	EPL needed	0	10,992	−35.3	9,123	13.24	2.395
4	Aframax tanker, 115,000 DWT	3.658	3.307	EPL needed	0	10,303	−23.7	8,551	13.99	3.307
5	VLCC tanker, 300,000 DWT	2.738	2.200	EPL needed	0	17,647	−37.0	14,647	13.75	2.200
6	Feeder containership, 25,000 DWT	12.968	18.205	Compliant	0	–	–	–	–	n/a
7	Panamax containership, 60,000 DWT	16.757	13.359	EPL needed	0	22,396	−37.8	18,589	19.43	13.359
8	MR gas carrier, 22,000 DWT	11.896	8.207	EPL needed	0	4,008	−52.8	3,327	12.48	8.206
9	LNG carrier, 85,000 DWT	7.288	7.269	EPL needed	0	25,191	−10.0	20,909	19.47	7.269
10	Refrigerated cargo, 9,000 DWT	27.229	20.923	EPL needed	0	5,449	−42.6	4,523	15.90	20.923
11	General cargo, 12,000 DWT	15.623	10.953	EPL needed	0	2,671	−51.4	2,217	11.38	10.951
12	Ro-ro cargo, 12,000 DWT	26.357	12.417	EPL needed	0	2,675	−77.7	2,220	11.29	12.415
13	VLCC tanker + EPL (MCR_{lim} 17,647 kW)	2.200	2.200	Compliant	0	–	–	14,647	13.75	2.200

Table 8 reports the minimum limitation required by each non-compliant case, not only for the VLCC. For every vessel whose baseline configuration violates Eq. (8), the solver of Eq. (12) was run to the point where the attained index equals the required index, and the resulting declared rating, power reduction, and estimated reference speed are tabulated. This makes the spread of the compliance burden visible: it ranges from a nominal 10.0 % reduction in declared rating for the LNG carrier, which starts marginally non-compliant, to 77.7 % for the ro-ro cargo ship, whose reference line is the most demanding relative to its installed power. The general-cargo, ro-ro, and refrigerated-cargo cases require reductions that would not be operationally viable, which is consistent with the finding of Vasilev et al. (2026) that a large majority of an existing segment cannot reach the required index by speed reduction alone. The attained EEXI was recomputed at the estimated limited rating, so that the effect of the limitation on the index is visible directly rather than by inference.

The closed-loop result is reported for every case in the final column of **Table 8**. For each non-compliant vessel, the estimated limited rating was fed back through the forward calculation of Eq. (1), with the reference speed taken at that power from Eq. (12), and the attained index recomputed. In all eleven cases the recomputed index reproduces the required index to three decimal places and, in every case, it lies at or just below the compliance boundary of Eq. (8). The residual difference is at most 2×10^{-3} %, and this arises only because the declared rating is reported as a whole number of kilowatts. Case 6 carries no entry because the feeder containership is compliant at full power and no limitation is applied to it.

Two points follow from this check. First, it closes the verification loop end-to-end: the inverse solver of Section 2.2.6 and the forward calculation of Section 2.2 are mutually consistent across the whole matrix, not only for the single VLCC case reported previously. Second, the declared ratings in Table 8 are rounded down to the nearest whole kilowatt. Rounding down is the physically correct convention here, because the attained index increases monotonically with power, so a rating rounded up would sit marginally above the solver root and would leave the vessel fractionally non-compliant.

Cases 5 and 13 are the same VLCC without and with engine power limitation. Case 13 is specified at the rating the solver of Eq. (12) returns, 17,647 kW, with the matching estimated reference speed of 13.75 kn. The forward calculation then reproduces the required index of 2.200 exactly. This is the closed-loop check on the solver: the rating the inverse routine proposes, fed back through the forward path, lands precisely on the compliance boundary of Eq. (8), confirming that the bisection converges to the intended root. The same check was applied to the Kamsarmax case, where feeding 7,375 kW back into the forward calculation reproduces the required EEXI of 3.486 to the displayed precision.

The benchmark comparison of Layer 2 was then performed. The tool was applied to a publicly available worked example: a 40,000 t deadweight bulk carrier with a single 10,000 kW main engine, a capacity of 60,000 t, reference speed of 14 knots, and specific fuel consumption of 190 g·kWh^{-1}. The source reports an attained EEXI of 1.70 g $CO_2 \cdot t^{-1} \cdot nm^{-1}$ (Czermański et al., 2022). Using the two matched assumptions stated in Section 2.3.4, the tool gives 1.696 g $CO_2 \cdot t^{-1} \cdot nm^{-1}$, about 0.2 % from the published figure, which is explainable by rounding in the source. Applying the complete Eq. (1) to the same vessel, with the heavy-fuel-oil carbon factor and the estimated auxiliary power, yields 5.681 g $CO_2 \cdot t^{-1} \cdot nm^{-1}$; the two omitted terms account for the full difference.

Second, the tool's behavior was compared with the established commercial DNV EEXI calculator, which uses the same conventions implemented: heavy fuel oil as the default fuel, fixing of the reference-line variable at 279,000 t for very large bulk carriers, the cubic-capacity correction for ro-ro vehicle carriers, and reporting an indicative power reduction with recalculation at the proposed power and speed when a vessel is non-compliant (DNV, 2023).

The regulatory schedule's discontinuities were exercised directly. The linear interpolation of the reduction factor within transition bands (Eq. 7) shows up in the general-cargo case at 12,000 t, where the tool returns 22.5 %, between the 0 and 30 % band limits. The containership cases verify

the ship-type-dependent capacity basis of Eq. (4b). The reference-line cap engages for bulk carriers above 279,000 t. Cases below the lowest applicable size threshold are reported with the attained value only, since no required value applies. In every case the engine returned a finite, well-defined result consistent with the specification.

4. Discussion

4.1 Interpretation of the verification evidence

The central outcome of this study is not an empirical result about any particular ship but a working, transparent, and verified computational artifact, and the first question the evidence settles is a narrow one. The agreement reported in Section 3.3 shows that the tool reproduces the standardized MEPC.333(76) methodology to the displayed precision. For a deterministic regulatory calculation, this is the appropriate correctness criterion at the implementation level, and it is the criterion that the existing literature leaves untested: Kalajdžić et al. (2022), Vasilev et al. (2025, 2026) and Ersoy et al. (2025) all compute the index as an input to a larger analysis without reporting an independent check on the computation itself. Within that artifact, the thirteen-vessel matrix offers an illustrative picture of the compliance landscape rather than a statistical one: under baseline conventional configurations, every representative tanker and bulk carrier examined, together with most other cargo types, exceeds its required EEXI and is flagged as requiring intervention, whereas the feeder containership, benefiting from a comparatively lenient reference line, is compliant. This pattern matches the independent conclusions of Bayraktar and Yüksel (2023) and Vasilev et al. (2025), who found that conventionally fueled tankers and bulk carriers generally cannot meet the required EEXI without power limitation. It is also consistent in direction with the container-ship evidence of Vasilev et al. (2026), although the present paper's synthetic feeder case is compliant, while their fleet study finds only about 12 % of real container ships compliant, a difference that illustrates precisely why a synthetic matrix cannot substitute for a fleet survey. The matrix should be read as a demonstration of capability and behavior rather than as a fleet-representative survey; the latter is the explicit purpose of the planned second phase.

4.2 Practical implications for shipping companies

For an operator, the practical value of the tool is that it collapses the path from vessel particulars to a compliance decision into a single, transparent step. The simultaneous display of the attained and required indices, the compliance margin, and (where needed) the estimated limiting rating gives a fleet manager the information needed to triage a fleet, identify the vessels at risk, and estimate the severity of each shortfall before committing to costly engineering studies. This capability matters most for the operators least well served by the existing tool ecosystem: smaller companies and operators in developing maritime economies, for whom proprietary software and consultancy are expensive and for whom the risk of older vessels becoming commercially stranded is acute (Chuah et al., 2023). The spread of limitation requirements now reported in **Table 8** sharpens this point: an operator can see immediately that a marginally non-compliant LNG carrier needs a nominal adjustment whereas a ro-ro cargo ship of the same generation may need a reduction that removes its commercial viability, and those two situations call for entirely different capital decisions. The tool also makes the central trade-off of power limitation explicit. Because it reports the reduced reference speed alongside the recommended rating, it allows an operator to weigh the regulatory benefit of an EPL or ShaPoLi installation against its operational cost in speed and schedule, an effect that the literature identifies as material and that can propagate through the supply chain (Jimenez et al., 2022; Vakili et al., 2023).

Two boundaries on that use should be stated plainly. The tool is a preliminary screening and planning instrument. It does not replace an approved EEXI Technical File, and it does not replace verification by a Recognized Organization or the flag state; any limitation it proposes is an estimate

that requires ship-specific engineering assessment and formal approval before implementation. Correspondingly, the numerical outputs of this paper support conclusions about the software, not about the certified efficiency of any real vessel.

4.3 Positioning EEXI within the wider maritime decarbonization framework

The EEXI is one of several overlapping instruments rather than a standalone test. The operational Carbon Intensity Indicator runs in parallel, subjecting each ship to an annual A-to-E rating that can trigger corrective action plans for poor performers (IMO, 2021a). In European waters, shipping entered the EU Emissions Trading System in 2024 at 40 percent of verified emissions, rising to 70 percent in 2025 and 100 percent in 2026 for vessels above 5,000 GT. Regulation (EU) 2023/1805, known as FuelEU Maritime, took effect in January 2025 and imposes a progressively tightening well-to-wake greenhouse-gas-intensity limit on the energy used onboard. Together these instruments change the practical question from whether a ship complies with EEXI to how the design-side and operational-side measures interact across the asset's remaining life.

Within that wider picture, the design-based EEXI keeps a specific and unreplaced role. It fixes the baseline against which operational improvements are measured. A vessel that addresses non-compliance through engine power limitation reduces both the attained EEXI and the absolute fuel burn, which in turn improves the CII rating and lowers the verified emissions exposed to the EU ETS. Conversely, options that look attractive on a CII or EU ETS basis alone, such as slow steaming, voyage optimization, or biofuel blending, do nothing to the attained EEXI and leave the ship in permanent technical non-compliance if the design-side gap is not closed. Recent assessments of conventional tankers across the three IMO frameworks reached the same conclusion: design and operation must be evaluated together, since improving one does not absolve the other (Vasilev et al., 2025). For owners weighing alternative fuels or hybrid propulsion against power limitation, the EEXI calculation is the entry point of every subsequent cost-effectiveness comparison (Tu et al., 2024; Yüksel et al., 2026).

4.4 Complementarity with data-driven approaches

Recent literature increasingly couples physics-based ship efficiency calculations with machine learning. Soltani Motlagh et al. (2025) showed that integrating empirical operating data with the standard propulsion model improves the accuracy of ship-specific efficiency predictions. Ersoy et al. (2025) applied a rule-based machine-learning technique to predict engine power limitation effects on tanker fuel consumption. Alshareef and Alghanmi (2024) applied deep reinforcement learning to the joint EEXI-CII compliance problem and obtained voyage-level recommendations that satisfy the design-side limit while improving the operational rating. Kaya et al. (2026) reviewed the broader technology landscape and concluded that data-driven and physics-based models increasingly need to feed each other rather than compete.

The deterministic engine described here complements that work rather than duplicates it. The EEXI is, by regulation, a closed-form calculation on certified parameters; it is not a quantity to be learned from data. Where machine-learning models add value is in the operational layer above it: in predicting the actual fuel and emissions that result from a given EPL or speed envelope, in selecting voyage plans that minimize CII degradation, and above all in replacing the cube-root speed-power approximation of Eq. (12) with a ship-specific relation inferred from sea-trial or in-service data, which is the single largest source of uncertainty in the limitation estimates of **Table 8**. The present tool is seen as the foundation layer of that stack rather than as a competitor to it.

4.5 Limitations

Several limitations qualify these conclusions and define the boundaries of the present version. First, the implemented model is the simplified conventional-propulsion form of the EEXI equation;

it does not yet account for shaft-generator power allocation, power-take-in/take-off arrangements, or the innovative-technology terms, and it supports diesel-electric, steam-turbine, and hybrid plants only through the approximations admitted for LNG carriers and cruise ships. This boundary is intrinsic to the standardized formula, which is itself recognized as not transferring directly to such propulsion architectures (Yüksel et al., 2026). Second, the power-limitation estimate relies on the cube-root speed-power relation of Eq. (12) rather than an approved speed-power curve, so it is indicative for planning and not a substitute for the curve-based calculation required in certification. Third, the thirteen verification cases are synthetic, so they establish the behavior of the software and nothing about the composition of any real fleet. Fourth, the external evidence reported here is a benchmark comparison against a single published worked example (Czermański et al., 2022) together with a consistency check against a commercial calculator (DNV, 2023) and the peer-reviewed literature; validation against certified EEXI Technical Files has not been performed. Fifth, the required-EEXI computation depends on the reference-line and reduction-factor values current at the time of writing; these are subject to periodic regulatory review under MARPOL Annex VI and to the broader evolution of the IMO strategy (IMO, 2023), and although the tool's data-driven design isolates these values for straightforward updating, it does require ongoing maintenance.

4.6 Directions for future work

These limitations define a clear research agenda. The immediate next step is the second phase of this work: a fleet-level case study applying the tool to a real fleet and validating its outputs against certified attained values, thereby supplying the external validation of Layer 3. It is worth stating what that phase will and will not require of the software, because this has bearing on the durability of the architecture presented in **Figure 2**. The computation engine and the data layer need no structural revision: the governing equations are unchanged, and the regulatory coefficients are already isolated as immutable look-up tables, so a fleet study exercises the same engine one vessel at a time. Two changes are confined to the presentation layer and to a thin layer around the engine. The first is batch input and output, since the current interface accepts one vessel at a time and a fleet study needs tabular ingestion and export. The second is a per-vessel error-reporting facility that stores the certified attained value alongside the computed one and reports the relative error of Eq. (14) against it. Neither touches the seven computation modules. The one change that would reach into the engine is the replacement of the cube-root relation in the EPL solver with an ingested speed-power curve, which would add an input contract to the solver module while leaving the other six modules intact. This is a consequence of the separation of concerns enforced by the V-Model, under which each layer addresses one aspect of the problem and does not depend on the internals of another and was an explicit design objective rather than a fortunate accident. Beyond that, the computational model can be extended to incorporate the shaft-generator, power-take-in/take-off, and innovative-technology terms and full support for non-conventional propulsion. A natural broadening is the integration of an operational Carbon Intensity Indicator module and of a cost dimension (drawing on marginal-abatement-cost analyses such as Tu et al. (2024) and the hybrid-propulsion assessments of Yüksel et al. (2026)) so that the tool could rank compliance options by cost-effectiveness rather than merely flag the need for one.

5. Conclusions

The three objectives were met. First, the EEXI computational model, its compliance test, and an inverse power-limitation solver were formalized as a deterministic software artifact: an open, single-file, offline-capable tool implementing the attained EEXI method of MEPC.333(76) for the twelve applicable ship types, computing the required EEXI and a quantitative verdict, modelling the engine and shaft power limitation regime, and estimating, for a non-compliant vessel, the minimum limiting rating at which the attained index reaches the required value. Second, it was developed under

the V-Model, which embedded verification as a structural counterpart of each design stage. Third, the implementation was verified: two independent implementations agreed to machine precision across thirteen hypothetical test cases, and the solver converged to the compliance boundary. Externally, the tool reproduced a published worked example to about 0.2 % and proved consistent with a commercial calculator and the peer-reviewed literature. The estimated limitations were themselves verified by recomputing the attained index at each proposed rating, which reproduced the required index in every non-compliant case.

The contribution is twofold. The artifact is an open EEXI screening tool that, unlike proprietary alternatives, exposes every intermediate quantity, carries an explicit verification argument, and converts a non-compliance verdict into a quantified limitation estimate. The methodological contribution is a transferable template for verifying regulatory calculation software, in which correctness means fidelity to a standardized deterministic equation corroborated by independent computation. The present version is a screening instrument, not a certification engine: it uses the simplified conventional-propulsion form of the index, a cube-root speed-power approximation, and has not been validated against certified Technical Files. That validation defines the next phase.

Acknowledgement

Thanks are given to Sekolah Tinggi Ilmu Pelayaran Jakarta for providing full support to the research team to develop this EEXI calculation system.

CRediT contribution statement

Aditya Rinaldi: Conceptualization; Methodology; Software; Validation; Formal Analysis; Investigation; Data Curation; Writing – Original Draft; Writing – Review & Editing; Visualization; Project Administration. **Larsen Barasa:** Conceptualization; Methodology; Validation; Writing – Review & Editing; Supervision. **Natanael Suranta:** Methodology; Investigation; Resources; Writing – Review & Editing. **Titis Ari Wibowo:** Validation; Data Curation; Visualization; Writing – Review & Editing.

Declaration of generative AI in scientific writing

The authors used an artificial intelligence (AI)-based tool to assist in validating the calculator system they developed; the AI application used was Genspark AI. AI-based assistance was also used for language editing and for improving the clarity of the manuscript text. All regulatory parameters, equations, numerical results, and references were verified by the authors against the primary sources. With or without AI applications, the authors are fully accountable for every process of the work and manuscript writing. All final edits, interpretations, and conclusions are the sole responsibility of the authors. The authors academically and ethically confirmed that the stated AI statements are true, and the authors are ultimately responsible and accountable for the contents of the published work, including the correctness of the references in the reference list.

Data availability

The software artifact (the EEXI calculation and compliance-screening tool, a single-file HTML/JavaScript implementation), the independent re-implementation used for verification, and the scripts that generated the verification matrix are openly available in the Zenodo repository at https://doi.org/10.5281/zenodo.20550636. The verification dataset (inputs and computed outputs for all thirteen test vessels, and inputs and outputs for the illustrative Kamsarmax case) is presented in full in **Tables 6 - 8** of this article. The regulatory parameters used by the tool, the EEDI reference-line coefficients (**Table 4**) and the size-dependent reduction factors (**Table 3**), are reproduced from

publicly available International Maritime Organization (IMO) resolutions cited in the manuscript (IMO, 2013, 2018, 2021a, 2021b, 2021c).

References

Alshareef, M. H., & Alghanmi, A. F. (2024). Optimizing maritime energy efficiency: A machine learning approach using deep reinforcement learning for EEXI and CII compliance. *Sustainability, 16*(23), 10534. https://doi.org/10.3390/su162310534

Bayraktar, M., & Yuksel, O. (2023). A scenario-based assessment of the energy efficiency existing ship index (EEXI) and carbon intensity indicator (CII) regulations. *Ocean Engineering, 278*, 114295. https://doi.org/10.1016/j.oceaneng.2023.114295

Chuah, L. F., Mokhtar, K., Mhd Ruslan, S. M., Bakar, A. A., Abdullah, M. A., Osman, N. H., Bokhari, A., Mubashir, M., & Show, P. L. (2023). Implementation of the energy efficiency existing ship index and carbon intensity indicator on domestic ship for marine environmental protection. *Environmental Research, 222*, 115348. https://doi.org/10.1016/j.envres.2023.115348

Czermański, E., Oniszczuk-Jastrząbek, A., Spangenberg, E. F., Kozłowski, Ł., Adamowicz, M., Jankiewicz, J., & Cirella, G. T. (2022). Implementation of the energy efficiency existing ship index: An important but costly step towards ocean protection. *Marine Policy, 145*, 105259. https://doi.org/10.1016/j.marpol.2022.105259

DNV. (2023). *EEXI calculator.* DNV Maritime. Retrieved from https://www.dnv.com/maritime/insights/topics/eexi/calculation.html

Ersoy, A. E., Çelebi, U. B., Yuksel, O., & Bayraktar, M. (2025). Predictive analysis of engine power limitations for fuel reduction in a tanker ship using a rule-based machine learning technique. *Journal of Cleaner Production, 507*, 145535. https://doi.org/10.1016/j.jclepro.2025.145535

IMO. (2013). *Resolution MEPC.231(65): 2013 Guidelines for calculation of reference lines for use with the EEDI*. International Maritime Organization. Retrieved from https://www.imo.org

IMO. (2018). *Resolution MEPC.308(73): 2018 Guidelines on the method of calculation of the attained EEDI for new ships, as amended*. International Maritime Organization. Retrieved from https://www.imo.org

IMO. (2020). *Fourth IMO GHG Study 2020*. International Maritime Organization. Retrieved from https://www.imo.org

IMO. (2021a). *Resolution MEPC.328(76): 2021 Revised MARPOL Annex VI*. International Maritime Organization. Retrieved from https://www.imo.org

IMO. (2021b). *Resolution MEPC.333(76): 2021 Guidelines on the method of calculation of the attained Energy Efficiency Existing Ship Index (EEXI)*. International Maritime Organization. Retrieved from https://www.imo.org

IMO. (2021c). *Resolution MEPC.335(76): 2021 Guidelines on the shaft/engine power limitation system to comply with the EEXI requirements and use of a power reserve*. International Maritime Organization. Retrieved from https://www.imo.org

IMO. (2023). *Resolution MEPC.377(80): 2023 IMO Strategy on reduction of GHG emissions from ships*. International Maritime Organization. Retrieved from https://www.imo.org

Jimenez, V. J., Kim, H., & Munim, Z. H. (2022). A review of ship energy efficiency research and directions towards emission reduction in the maritime industry. *Journal of Cleaner Production, 366*, 132888. https://doi.org/10.1016/j.jclepro.2022.132888

Kalajdžić, M., Vasilev, M., & Momčilović, N. (2022). Power reduction considerations for bulk carriers with respect to novel energy efficiency regulations. *Brodogradnja, 73*(2), 79-92. https://doi.org/10.21278/brod73205

Kaya, C., Guo, H., Bolat, F., Yang, Z., Mutlu, Y. T., Zhou, D., Zincir, B., Demirel, H., & Başhan, V. (2026). Ship energy efficiency and maritime decarbonization: A comprehensive review

of technologies, regulations and emerging solutions. *Journal of Engineering for the Maritime Environment, 240*(2), 215-243. https://doi.org/10.1177/14750902261425082

Regulation (EU) 2023/1805 of the European Parliament and of the Council of 13 September 2023 on the use of renewable and low-carbon fuels in maritime transport (FuelEU Maritime). (2023). *Official Journal of the European Union, L 234/48*. Retrieved from http://data.europa.eu/eli/reg/2023/1805/oj

Soltani Motlagh, H. R., Issa-Zadeh, S. B., Zoolfakar, M. R., & Garay-Rondero, C. L. (2025). Enhancing ship propulsion efficiency predictions with integrated physics and machine learning. *Journal of Marine Science and Engineering, 13*(8), 1487. https://doi.org/10.3390/jmse13081487

Tu, H., Liu, Z., & Zhang, Y. (2024). Study on cost-effective performance of alternative fuels and energy efficiency measures for shipping decarbonization. *Journal of Marine Science and Engineering, 12*(5), 743. https://doi.org/10.3390/jmse12050743

Vakili, S., Ballini, F., Schönborn, A., Christodoulou, A., Dalaklis, D., & Ölçer, A. I. (2023). Assessing the macroeconomic and social impacts of slow steaming in shipping: A literature review on small island developing states and least developed countries. *Journal of Shipping and Trade, 8*(1), 2. https://doi.org/10.1186/s41072-023-00131-2

Vasilev, M., Kalajdžić, M., & Momčilović, N. (2025). On energy efficiency of tankers: EEDI, EEXI and CII. *Ocean Engineering, 317*, 120028. https://doi.org/10.1016/j.oceaneng.2024.120028

Vasilev, M., Kalajdžić, M., Momčilović, N., & Miltenović, F. (2026). On energy efficiency of the container ship fleet: EEDI, EEXI and CII. *Ocean Engineering, 356*, 125429. https://doi.org/10.1016/j.oceaneng.2026.125429

Yüksel, O., Pamik, M., & Bayraktar, M. (2026). The assessment of alternative fuel and engine power limitation utilisation in hybrid marine propulsion systems regarding energy efficiency metrics. *Journal of Marine Engineering & Technology, 25*(2), 117-131. https://doi.org/10.1080/20464177.2025.2479319