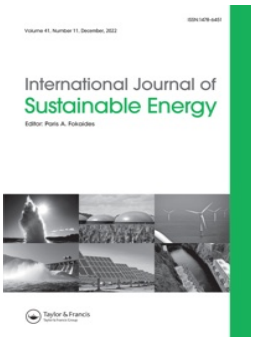

International Journal of Sustainable Energy

ISSN: 1478-6451 (Print) 1478-646X (Online) Journal homepage: www.tandfonline.com/journals/gsol20

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To cite this article: Viktoriia Koilo-Gabillaud & Jan Emblemsvåg (2026) Estimating the direct impact of nuclear propulsion on the global shipping fleet, International Journal of Sustainable Energy, 45:1, 2681303, DOI: 10.1080/14786451.2026.2681303

To link to this article: https://doi.org/10.1080/14786451.2026.2681303

Published online: 02 Jun 2026.

INTERNATIONAL JOURNAL OF SUSTAINABLE ENERGY
2026, VOL. 45, NO. 1, 2681303
https://doi.org/10.1080/14786451.2026.2681303

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Estimating the direct impact of nuclear propulsion on the global shipping fleet

Viktoriia Koilo-Gabillaud[a] and Jan Emblemsvåg[a]

[a]Department of Ocean Operations and Civil Engineering, Faculty of Engineering, Norwegian University of Science and Technology (NTNU), Ålesund, Norway

ABSTRACT

Decarbonising deep-sea shipping is difficult because vessels operate over long distances with high energy demand and limited refuelling opportunities. Most transition scenarios emphasise alternative fuels and efficiency measures, while nuclear propulsion offers a structurally different pathway by shifting propulsion energy from voyage-dependent expenditure to capital-dominated expenditure. This study examines operational implications of this shift using 2023 IMO Data Collection System dataset, covering 17,420 vessels, or about 30% of the global fleet. We compare observed operational speeds with design speeds and model a counterfactual nuclear propulsion scenario in which economic incentive for slow steaming disappears. Results show that the average observed speed is 11.49 knots, far below the design speed of 17.35 knots. Holding transport demand constant, a return to design speed would reduce required fleet capacity by approximately 31%. These findings suggest that nuclear propulsion could enable both operational CO_2 elimination and major productivity gains, representing a regime shift in fleet deployment.

ARTICLE HISTORY
Received 5 May 2026
Accepted 26 May 2026

KEYWORDS
Design speed; nuclear-powered ships; fuel consumption; speed deviation; decarbonisation pathways

1. Introduction

In an effort to curb and reduce climate gas emissions from shipping, the International Maritime Organization (IMO) has established a goal through the Initial Strategy to reduce CO_2 emissions per transport work, as an average across the international maritime transport industry, by at least 40% by 2030, and towards 70% by 2050, compared to 2008 (IMO 2018). One of the short-term operational measures for reducing CO_2 emissions from ships at sea is sailing at reduced speed, i.e. 'slow steaming' (Degiuli et al. 2021).

The reason is that fuel consumption, and therefore emissions, in shipping is strongly influenced by two interacting parameters: vessel size (deadweight class) and operating speed. Larger ships benefit from economies of scale, consuming more fuel in absolute terms but less fuel per transported unit. However, fuel consumption rises exponentially with speed due to hydrodynamic resistance, meaning that any increase in operational speed, whether for commercial scheduling or energy-related optimisation, results in a disproportionately higher fuel demand (Stopford 2009).

The IMO fuel consumption dataset (2024) shows a clear stratification of fuel use (IMO 2024). For example, for the containerships, the 40,000+ DWT classes are dominated by Heavy Fuel Oil (HFO), and Marine Diesel Oil (MDO)/Marine Gas Oil (MGO) consumption, while LNG and methanol uptake remain concentrated in the newest vessels above 120,000 DWT. This indicates that decarbonisation pathways are currently size-selective, favouring the largest and newest fleet segments. It should be noted that construction statistics for ships using green alternative fuels do not distinguish between being capable of using certain green alternative fuels and their actual usage. Using actual fuel consumption data sets is therefore critical.

Currently, slow steaming is used to reduce fuel cost and CO_2 emissions, reinforcing the industry's cost–emission trade-off. However, if fossil fuels are replaced by nuclear propulsion, this relationship fundamentally changes: (1) fuel becomes a Capital Expenditure (CAPEX) decision rather than a variable

CONTACT Viktoriia Koilo-Gabillaud viktoriia.koilo-gabillaud@ntnu.no

Voyage Expenditure (VOYEX), (2) fuel consumption will be far less related to speed decisions, and (3) emissions cease to be a constraint in speed optimisation as nuclear reactors have no emissions during operations. As a result, the economic penalty of operating at design speed largely disappears. Higher speeds would again be commercially rational, especially in time-sensitive shipping segments such as container logistics, where schedule reliability is a value driver.

Given these assumptions, the argument further leads to the fact that with the same haul distance, but higher speed at a similar net margin, transportation costs per tonne-mile fall due to increased fleet productivity. The direct effect is that fewer ships are required to transport the same global trade volume, while key indirect effects arise, such as port congestion decreases, and the competitive positioning of nuclear-powered ships improves. The result is a gradual transition from fossil ships to nuclear-powered ships, fundamentally altering both the fuel structure and operational profile of the global shipping fleet.

The aim of this study is to analyse the direct impact related to fuel consumption profile, operational speed patterns, and carbon intensity of the global fleet using the IMO 2023 Data Collection System (DCS) dataset (IMO 2024), with a specific focus on the relationship between vessel size and design speed. By comparing current slow-steaming practices with the effect of returning to the original design speeds, the study seeks to (i) assess the current practices of the global fleet, (ii) evaluate the implications of returning to design speed for fuel use, emissions, and fleet size, and (iii) discussing the wider impacts to shipping (without performing numerical analyses).

The study is motivated by the fact that 'slow steaming' has become the norm today whereby ships operate at much lower speed than design speed to conserve fuel (Degiuli, Martić, and Farkas 2019). For example, modern containerships were designed to operate at 22–25 knots, yet more than half of the global fleet sails at slow-steaming speeds (18–20 knots) or extra-slow-steaming levels (15–18 knots). Understanding this gap between *designed speed* and *operational speed* is essential for future decarbonisation pathways, because the elimination of marginal fuel cost—as in the case of nuclear propulsion—fundamentally changes the economics of ship speed, fleet size requirements, and tonne-mile efficiency.

This study contributes to the literature by integrating empirically observed slow-steaming behaviour at fleet scale with a counterfactual propulsion regime characterised by zero marginal fuel cost. While prior studies examine nuclear propulsion feasibility or slow steaming under fossil fuel conditions, few quantify how a return to design speeds would directly affect fleet productivity and capacity requirements using real-world DCS data. By modelling this structural shift, the paper isolates the fleet-level consequences of altered fuel economics rather than forecasting adoption dynamics.

The paper first provides some more basic background information about the topic that is needed to appreciate the content of the paper. Then, in Section 3 a brief literature review is provides before the methodology and data is discussed in Section 4. Results are found in Section 5, after which a discussion is provided. Conclusions are presented in Section 7.

2. Background

There are two issues that are useful to discuss before entering into the literature. First, what drives fuel consumption in ships, and second, the implications of introducing nuclear propulsion.

2.1. The drivers of fuel consumption of ships

Fuel consumption in shipping is primarily a function of vessel size, hull lines and cruising speed, with an exponential relationship emerging above approximately 14 knots for cargo ships. For example, a containership of around 8 000 TEU consumes approximately 225 tonnes of bunker fuel per day at 24 knots, whereas at 21 knots the consumption drops to roughly 150 tonnes per day—a reduction of 33% (Rodrigue 2024). While lower speeds significantly reduce fuel consumption and therefore emissions, lower speed also increases voyage duration and ultimately drives the need for the deployment of more vessels to maintain weekly port call frequency and ultimately trade volume. Thus, the cost burden shifts from fuel to fleet capacity, or from direct costs to indirect costs.

The widespread adoption of slow steaming began during the 2008–2009 financial crisis, when freight demand collapsed while an oversupply of newly delivered tonnage entered the market. The practice has since remained, reinforced by high fossil fuel prices to cut costs and, more recently, to cut emissions under the environmental regulation under MARPOL Annex VI. Thus, slow-steaming was originally a cost-reduction strategy rather than a climate-driven measure. The shift to slower speeds required technical engine de-rating, adjusting fuel injection timing and turbocharger configuration to allow engines designed for 22–25 knots to operate efficiently at 70–80% power levels (CE Delft 2012).

2.2. Implication for nuclear propulsion scenarios

Nuclear propulsion technologies will alter the business model of shipping in many ways, which we have tried to illustrate in the model in Figure A1 in Appendix. First, with fuel being purchased for at least 5 years, fuel essentially becomes CAPEX and no longer VOYEX. Also, there are no emissions to factor into speed decisions. The implication of this is that it no longer makes sense to slow-steam to conserve fuel. Therefore, a return to the design speed for nuclear-powered ships is the only sensible choice.

Second, as a consequence of the first, a return to the design speed will reduce the number of ships required to perform the same job for the world economy *ceteris paribus*. With fewer ships performing the same job, the productivity of the fleet will rise because the transport will be carried out using fewer kilometres of travel, thus driving the functional unit (tonnkm) upward. Also, fewer ships will give indirect effects such as less port congestion, improving the productivity further.

Subsequently, with higher fleet productivity, the overhead costs per functional unit will fall, improving the competitiveness. The competitiveness will also improve by the sheer increase in speed, particularly in ship segments where time to delivery is an element, such as in container shipping. Thus, nuclear-powered ships will not only generate more revenue, but they will also have lower overhead costs per functional unit.

This leaves us with two key questions to discuss: How will the CAPEX of nuclear-powered ships become, and how will the Operational Expenditures (OPEX) develop? The CAPEX will most likely rise, but the OPEX will remain at the current levels, while at the same time, more revenues will be generated. Hence, the net margin for the shipowner stays the same as before. This is obviously a simplification, but current studies are hard to come by to a level of detail that is useful. However, Emblemsvåg (2021) made an initial estimate indicating that a Molten Salt Reactor (MSR) would outcompete HFO without any subsidies on an AfraMax tanker. If this holds to be true, the analysis performed here is very conservative because the result of that AfraMax tanker study indicates that the net margin will improve, at least as long as there are fossil ships keeping the freight rates at current levels.

Given these assumptions, the argument further leads to the fact that with the same haul distance, but higher speed at a similar net margin, the transportation costs will fall, benefiting the world economy. The result is a gradual transition from fossil ships to nuclear-power ships, fundamentally altering the fleet characteristics.

Thus, introduction of nuclear propulsion does not simply replace one fuel type with another—it reverses the operational logic that has dominated shipping since 2009 and triggers a structural shift in fleet size, speed regimes, and cost allocation. Subsequent indirect effects are also expected, such as less port congestions, benefits for the world economy and more. These indirect effects are not analysed in this paper.

3. Literature review

The research question in this paper sits at the intersection of four strands of literature:

(i) the economics of ship speed and slow steaming,
(ii) empirical work on fuel consumption and carbon intensity at the fleet level,
(iii) shipping decarbonisation pathways and alternative fuels,
(iv) nuclear propulsion for merchant shipping and its system-level implications.

This section briefly reviews each strand and identifies the gap that motivates the present study. Furthermore, it is useful to address the issues of nuclear safety, security, safeguards and liability (3SL) since they are fundamental to the acceptance of nuclear propulsion as a viable technology.

3.1. Economics of ship speed and slow steaming

Classical maritime economics frames vessel speed as a profit-optimising decision that balances freight rates, fuel prices and technical characteristics. Stopford's speed model shows that the optimal steaming speed is found where the marginal cost of transporting one additional tonne-mile equals the marginal revenue, with speed depending on the freight rate, bunker price, ship fuel coefficient and voyage distance (Stopford 2009). This theoretical relationship underpins later analytical models of optimal speed in liner shipping.

Building on such foundations, Wu (2020) develops an explicit optimisation framework for container services, demonstrating that slow steaming can be profit-maximising when fuel prices are high, even after accounting for the cost of deploying more vessels to maintain weekly frequency. Similar conclusions appear in earlier work on bunker adjustment factors and fuel surcharges, where slow steaming is shown to fundamentally reshape the relation between bunker costs and surcharges passed on to shippers (Notteboom and Cariou 2013).

A growing body of work revisits the speed–fuel relationship from a more critical, technical perspective. Psaraftis and Lagouvardou (2023) review speed–power and speed–fuel formulations and warn that some widely used models rest on oversimplified or inconsistent assumptions about resistance curves and engine performance, potentially biasing policy analysis. Nevertheless, there is broad agreement that, above a threshold (around 14 knots for many container vessels), fuel consumption per day grows roughly with the cube of speed, which makes slow steaming an attractive strategy under high bunker price or stringent climate policy conditions (Borén, Grifoll, and Castells-Sanabra 2023).

From a service-quality perspective, studies by Lee, Lee, and Zhang (2015) and others show that slow steaming reduces fuel use but increases transit times and delivery-time uncertainty, with implications for schedule reliability and supply chain design. This literature typically assumes fossil propulsion and treats fuel as a variable voyage cost that strongly disciplines speed decisions—a key assumption that is questioned in nuclear propulsion scenarios.

3.2. Operational and environmental impacts of slow steaming

A second literature stream quantifies how slow steaming affects emissions and operational performance at the level of individual vessels, routes and fleets. Using technical or AIS-based models, several studies show that speed reductions deliver substantial CO_2 and pollutant reductions per voyage, often in the range of 20–40% for typical containership services, depending on the baseline speed and engine loading (Borén, Grifoll, and Castells-Sanabra 2023; Degiuli, Martić, and Grlj 2024; Zincir, Zincir, and Arslanoglu 2025). These gains, however, may be partially offset by the need to deploy more ships on a loop and by longer transit times, raising questions about system-wide efficiency.

Recent work is increasingly grounded in the IMO DCS. The IMO's 2023 DCS summary report provides anonymised fleet-wide statistics on fuel use, distance travelled, hours under way and derived carbon intensity indicators such as Annual Efficiency Ratio) (AER) and Capacity Gross Ton Distance (ccgDIST) by ship type and size class (IMO 2024).

These data reveal strong stratification in fuel consumption and carbon intensity across size segments, and confirm that containerships, bulk carriers and tankers dominate total fuel use (IMO 2024). Studies that combine DCS-style data with technical models show that many vessels operate substantially below their design speeds, with slow-steaming and extra-slow-steaming regimes now embedded in 'normal' operations (Borén, Grifoll, and Castells-Sanabra 2023; Psaraftis and Lagouvardou 2023).

However, the majority of this work treats slow steaming as an operational measure within the fossil-fuel paradigm, focusing on marginal changes in speed for given fleets. Few studies ask what happens if the underlying cost structure of fuel is transformed, e.g. if the marginal fuel cost per voyage becomes negligible, as in nuclear propulsion scenarios.

3.3. Shipping decarbonisation pathways and alternative fuels

A large and rapidly growing literature assesses pathways to decarbonise international shipping in line with IMO and Paris-aligned targets. Global scenario studies by IRENA and others typically emphasise scalable production of renewable e-fuels (ammonia, methanol, hydrogen), efficiency measures and market-based policies such as carbon pricing and fuel standards (IRENA 2021). These studies generally treat nuclear as a marginal or niche option, if it is mentioned at all, mainly due to perceived regulatory, safety and public acceptance barriers.

More recent assessments acknowledge nuclear as a potentially significant option, especially for deep-sea segments where the energy demands of e-fuels would be extremely high. Bhattacharyya, El-Emam, and Khalid (2023) argue that nuclear-assisted shipping could materially alter the economics of decarbonisation by providing a high-energy-density, zero-carbon source of propulsion that reduces reliance on large-scale e-fuel supply chains. Expert-elicitation work suggests that even with strong uptake of low-carbon fuels and efficiency measures, there is persistent uncertainty around the pace and cost of decarbonisation, particularly for large, long-haul vessels such as container ships (Laskar, Dowlatabadi, and Giang 2025; Li and Hu 2024).

Within this broader decarbonisation debate, speed policies and slow steaming are often framed as transitional or complementary measures—useful for early emissions reductions but not sufficient to achieve full decarbonisation, especially when they reduce fleet productivity and increase capital requirements (Bhattacharyya, El-Emam, and Khalid 2023; Degiuli, Martić, and Grlj 2024). This sets the stage for exploring propulsion options that fundamentally change the cost and emissions structure of speed, rather than continuing to trade emissions for capacity.

3.4. Nuclear propulsion in merchant shipping

The literature on nuclear propulsion for merchant shipping has historically been small but is now expanding quickly. Early work focused on technical feasibility, basic reactor concepts and historical experiences with the NS Savannah, Otto Hahn, Mutsu and Sevmorput. Carlton, Smart, and Jenkins (2011) discuss risk and regulatory aspects, highlighting public acceptance, liability regimes and international conventions as principal barriers despite favourable technical characteristics.

More recent contributions develop structured frameworks to assess the sustainability and viability of nuclear propulsion. Schøyen and Steger-Jensen (2017) propose a multi-dimensional sustainability framework that combines transport efficiency, CO_2 performance, safety and geopolitical considerations, and identify specific trades and flag states where nuclear propulsion could be most relevant. Kunze (2022) assesses the role of Generation IV reactors in shipping decarbonisation and concludes that advanced reactor concepts could be competitive for medium and large vessels under certain policy and cost assumptions. Holbert (2025) provides a comprehensive review of maritime nuclear reactor systems, including naval, icebreaker and emerging small modular reactor (SMR) designs, and outlines key technological and regulatory challenges for commercial deployment.

Policy-oriented reports by DNV (2024); EMSA (2024) and industry coalitions similarly conclude that nuclear could play a significant role in deep-sea decarbonisation but stress the need for updated safety codes, liability frameworks, financing models and port-state arrangements. Recent overview papers and white papers argue that SMR-based solutions could be cost-competitive with fossil fuels on some routes and highlight the potential for nuclear to offer essentially zero marginal fuel cost and 24/7 carbon-free energy at sea (Duong et al. 2025).

At the more detailed techno-economic level, Emblemsvåg (2021) estimates that a thorium-based MSR could outcompete HFO propulsion on an Aframax tanker without subsidies, suggesting that nuclear propulsion may improve, not just maintain, shipowners' net margins under certain conditions. The work has then subsequently been expanded into two projects, Nuclear Propulsion in Merchant Ships (NuProShip) I and II. While the economic analyses are still ongoing, the plan is to deploy the first commercial nuclear-powered ships in the first half of the 2030s (Emblemsvåg et al. 2024). The project team highlights that there are no fundamental showstoppers of any kind.

However, most of these studies are either conceptual, focused on particular ship types, or do not explicitly link nuclear propulsion to fleet-wide speed regimes and capacity requirements.

3.5. Fleet productivity, capacity and macro-system effects

A separate stream of work examines how speed decisions and fuel costs propagate into fleet capacity, productivity and freight markets. Classic maritime economics shows that lower speeds require more vessels to maintain a given service frequency, thereby raising capital requirements and changing the supply–demand balance in freight markets. Studies of slow steaming in liner shipping empirically confirm these effects: the introduction of slow steaming increased the number of ships deployed per loop and contributed to the absorption of post-crisis overcapacity in the container sector.

Kalimeris (2017) and related work extend the analysis to supply chains, showing that slow steaming reduces shipping emissions but can increase total logistics costs through longer transit times, higher inventory carrying costs and more complex network design. Yet even in these system-oriented studies, the propulsion technology is taken as given; the primary variables are speed, route choice and fleet size, all within a fossil-fuel framework in which fuel remains a major variable cost component.

From a risk and decision-analytic perspective, Emblemsvåg (2003) advocates the use of Monte Carlo simulation and life-cycle costing to capture uncertainty in future costs and performance of complex industrial systems, including shipping investments. This approach is directly relevant when comparing fossil and nuclear propulsion, where uncertainty in capital costs, regulation and fuel prices is substantial.

3.6. Identified research gap

In summary, existing literature provides a rich understanding of:

- How speed and fuel costs interact under fossil propulsion (optimal speed, slow steaming),
- How slow steaming affects emissions, service quality and capacity requirements,
- Decarbonisation pathways dominated by e-fuels and efficiency measures, and
- The technical and policy feasibility of nuclear propulsion as a decarbonisation option.

However, several gaps remain. First, while there is growing work on nuclear propulsion, most studies focus on feasibility, safety and high-level decarbonisation potential. They rarely quantify how nuclear propulsion would change operational speed patterns and fleet size requirements for specific segments, such as container shipping, where design speeds (22–25 knots) and current operating speeds (15–20 knots) diverge substantially (Duong et al. 2025; Holbert 2025).

Second, the literature has only begun to exploit the granularity of the IMO DCS for scenario analysis. The 2023 IMO DCS report provides detailed, disaggregated data on fuel use, distance travelled and carbon intensity across ship types and size classes, but most analyses remain descriptive or focused on current fossil-fuel operations rather than counterfactual propulsion regimes (IMO 2024).

Third, there is a lack of studies that integrate (1) empirically observed slow-steaming behaviour at fleet scale, (2) the economics of zero-marginal-cost nuclear fuel, and finally (3) explicit modelling of how a return to design speeds would affect fleet productivity, required number of vessels and long-term emissions. No studies include the indirect effects.

This study addresses the gaps related to direct effects by using the 2023 IMO DCS dataset to characterise the current fuel consumption and speed profile of the global merchant fleet, quantifying the ‘speed gap’ between design and operational speeds, and modelling a nuclear propulsion scenario in which the economic incentive for slow steaming disappears. Building on earlier techno-economic work on nuclear propulsion and Monte Carlo–based uncertainty analysis, the paper estimates how much of today's fossil-fuelled merchant fleet would become redundant if ships systematically returned to their design speeds under nuclear propulsion, and discusses the implications for decarbonisation, capacity management and long-term climate impacts.

Next, we will address the 3SL issues to argue that the paper is built on a viable technological solution.

3.7. Safety, security, safeguards and liability of nuclear-powered commercial ships

The acceptance of nuclear power for commercial ships is critical for the study at hand. Although it does not impact the study *per se*, it is relevant to appreciate the importance of the study. This study, therefore, builds on previous work performed under the auspices of the NuProShip I and II projects, where one of us is the project leader. From those projects, two critical insights are obtained. First, the choice of reactor technologies built on passive safety, low pressure and high proliferation resistance effectively addresses the safety, security and safeguards (Emblemsvåg et al. 2025).

Second, there seems to be no financial stoppers to liability insurance as long as the political risks of nuclear power. The reason is that maritime risk insurers are reluctant to take on insurance objects where there might be a long tail of unresolved cases (Emblemsvåg 2026), which arise from the highly unpredictable outcome of court cases involving radiation risks, as demonstrated by nine cases in South Korea (Han 2024) or 50 cases in the US (Jose 2027). If the political risk can be solved, for example, via government indemnification, then there are no financial showstoppers. More work on liability insurance is work in progress to be published in early 2027 (Emblemsvåg et al. 2020).

Therefore, the work presented in this paper implicitly assumes that there are successful resolutions of the 3SL issues, which the work so far in the NuProShip projects indicates to be true.

4. Methodology

The analysis assumes constant global transport demand and freight-rate conditions (partial-equilibrium framework) to isolate the mechanical fleet-productivity effect of speed changes. Dynamic market adjustments, investment cycles, and phased adoption are beyond the scope of this study. Thus, the research question leads to a high-level analysis where being approximately right is the key. Yet, great care is taken both concerning the selection of data sources and the selection of data to ensure relevance, discussed in Section 4.1, as well as in the analytical procedure discussed in Section 4.2.

4.1. Data source and selection

Of the approximately 100,000 commercial vessels worldwide (UNCTAD 2025), 28,620 reported fuel and activity data to the IMO DCS for 2023. From these, 17,420 vessels were retained after excluding ships lacking reliable distance-travelled data or identifiable design-speed information. Although the final sample represents roughly 30% of the global fleet numerically, it includes the dominant ship types (containerships, tankers, bulk carriers) responsible for the majority of tonne-mile activity and CO_2 emissions. The dataset is therefore considered representative for structural fleet-level analysis. Only ships under EEDI classification are selected (IMO 2024).

The analysis is further stratified by deadweight segments (DWT <10k, 10–15k, 40–80k, 80–120k, 120–200k, >200k), enabling comparison across vessel sizes. The analysis is structured around four groups of variables derived from the IMO DCS 2023 (IMO 2024) dataset, described in Table 1.

4.2. Analytical procedure

The study follows a five-stage analytical structure:

1. Descriptive analysis of fuel consumption by DWT class and fuel type, identifying scale effects.
2. Speed gap estimation: designed speed (from ship class specifications) vs. observed operational speed (distance/hours under way).
3. Fleet-level tonne-km productivity estimation under (a) current slow-steaming baseline and (b) nuclear propulsion scenario with return to design speed.
4. Scenario modelling:
   - Baseline 2023 fossil fleet (slow steaming, marginal fuel cost).
   - Counterfactual nuclear fleet (zero marginal fuel cost, CAPEX-based fuel, design-speed operation).
5. Uncertainty- and tracing analysis using Monte-Carlo simulations.

Table 1. Input variables for the analysis.

Variable group	Input variables used
Operational intensity	Distance sailed (nm), hours under way, average operating speed (nm/h)
Ship characteristics	Deadweight, number of vessels, gross tonnage
Derived metrics	Fuel per tonne-mile, fuel per hour, speed deviation from design speed

The uncertainty analysis implies modelling the uncertainty as closely as represented by the data set, running the Monte Carlo simulations using Oracle Crystal Ball software, which works like a macro in MS Excel, to estimate the impact on the forecast (output) variables with the aim of understanding how uncertainty impacts the results. The tracing analysis involves using bounded and symmetric triangular distributions at all chosen input variables to trace their impact on the results independently of whether they are uncertain or not. The purpose is to establish what input variables drive the output variables (Emblemsvåg 2003).

The details of the Monte Carlo simulations are explicated in great detail by Emblemsvåg (2003). Essentially, there are two approaches in two stages. The first stage concerns modelling the impact of input variables on the output variables, and the first and most intuitive approach is to analyse the actual impact of the uncertainty on the output variables. This allows us to understand how the uncertainty propagates throughout the entire model. The second approach is to model the input variables using bounded and symmetric distributions with the same relative uncertainty, for example, ±10%. Then, we can measure the actual impact the input variables have on the output variables as governed by the model logic and not the uncertainty. Hence, the combination of the two approaches allows us to measure both the importance of an input variable on the output variables as well as the impact the uncertainty in the input variables has on the output variables.

The second stage concerns the identification of critical success factors through a process referred to as tracing. This is achieved by performing an Analysis of Variance (ANOVA) of the entire data set after the simulation is complete. This represents the exact approach to rank and track the importance of input variables on how they influence uncertainty, as well as the model logic.

A final issue to mention, concerning the Monte Carlo simulations, is that the sampling of the solution space can be done in many different ways, and in our approach, we use Latin Hypercube Sampling to minimise random errors. This, and much more, is explicated by Kalimeris (2017), to which the interested reader is referred.

It should be mentioned that the IMO DCS does not report design speed. Design-speed values were therefore assigned based on ship-type-specific technical specifications reported in classification society data and published ship series documentation. For each ship category, a representative design-speed range was identified (see Table 3), and midpoint values were applied for aggregate modelling. Uncertainty in design speed was incorporated into the Monte Carlo analysis using bounded triangular distributions reflecting observed specification ranges.

5. Results

This section presents the empirical results derived from the 2023 IMO DCS dataset and the nuclear propulsion scenario analysis. Results are organised into four sub-sections: (i) baseline operational characteristics, (ii) the speed gap between observed and design speeds, (iii) fleet-capacity effects under a return to design speed, and (iv) emissions outcomes and CO_2 avoidance potential.

5.1. Baseline fleet operational characteristics

The analytical dataset contains 17,420 ships, extracted from the 28,620 vessels that reported to the IMO DCS in 2023. The remaining vessels were excluded because designed speed values could not be reliably established (for the category of 'other ships'), and, particularly for bulk carriers of 10,000 DWT and above—because distance-travelled information was missing, making them unsuitable for the speed-gap and productivity analysis. Across ship types, the distribution of operational intensity is highly uneven:

- Containerships and tankers dominate total activity, together accounting for over 60% of total CO_2.
- Ro-ro cargo and vehicle carriers show high CO_2 per nautical mile due to large hull forms and high auxiliary loads.
- General cargo, reefers, and smaller segments show much lower speeds and utilisation.

In Table 2, we find the descriptive statistics at the aggregate ship level, i.e. not broken down into all the subcategories as defined by their deadweight (dw) tonnage.

Table 2. Descriptive statistics for the ship types at the aggregate level. Source: IMO (2024).

Ship categories at the aggregate level	Number of ships	Distance travelled [nm]	Hours under way [hrs]	CO_2 emissions [tonne]	CO_2 emission per vessel [tonne/vessel]	Hours at sea per vessel [hrs/vessel]	Days at sea per vessel [days/vessel]	Transport utilisation	Observed speed [nm/h]
Bulk carrier	69	2,456,353	263,746	342,277	4,961	3,822	159	57%	10.69
Combination carrier	25	1,481,644	132,273	455,908	18,236	5,291	220	61%	11.20
Containership	5,075	371,674,202	28,556,471	183,738,939	36,205	5,627	234	65%	13.02
Cruise passenger ship	267	20,173,489	1,451,796	19,426,595	72,759	5,437	227	63%	13.90
Gas carrier	811	56,203,481	4,205,676	17,979,426	22,169	5,186	216	60%	13.36
General cargo ship	2,280	97,762,404	9,638,750	22,622,726	9,922	4,228	176	49%	10.14
LNG carrier	649	58,470,869	4,231,625	43,901,419	67,645	6,520	272	75%	13.82
Refrigerated cargo carrier	209	11,662,471	869,498	3,225,555	15,433	4,160	173	48%	13.41
Ro-ro cargo ship (vehicle carrier)	677	62,136,924	4,286,958	19,751,188	29,175	6,332	264	73%	14.49
Ro-ro passenger ship	349	22,861,965	1,458,030	11,187,031	32,055	4,178	174	48%	15.68
Tanker	6,594	339,553,054	31,104,968	133,408,026	20,232	4,717	197	55%	10.92
Total/weighted average	**17,420**	**1,072,783,246**	**88,252,410**	**468,318,360**	**26,884**	**4,984**	**208**	**58%**	**11.49**

Legend:

- Number of ships—the number of ships that have reported emission data to the IMO.
- Distance travelled [nm]—the aggregate distance travelled by the vessels in that category, measured in nautical miles [nm].
- Hours under way [hrs]—the hours of actual ship movement between ports for the vessels in that category.
- CO_2 emissions [tonne]—the aggregate emissions of carbon dioxide (CO_2) of the ships in the respective ship categories.
- CO_2 emissions per vessel[tonne/vessel]—the average CO_2 emissions per vessel in that category.
- Hours at sea per vessel [hrs/vessel]—the average number of hours at sea for the vessels in the respective category.
- Days at sea per vessel [days/vessel]—the average number of days at sea for the vessels in the respective category.
- Transport utilisation—the actual share of hours in a year the vessel is at sea.
- Observed speed [nm/h]—the average, actual, observed speed at sea for the vessels in that category.

For the purpose of the presented work, the actual observed speed is very interesting because it is far lower than the design speed, i.e. the speed the ship is designed for operating in. The low actual observed speed is combined with the low utilisation rate of only 58% on average. Thus, with higher speed, fewer ships and improved utilisation, the impact on shipping should be immense if nuclear propulsion succeeds. This is discussed later.

5.2. The speed gap: observed vs. design speed

Across all 17,420 ships, the average observed operational speed is 11.49 knots, compared to an average design speed of 17.35 knots. This confirms a global structural slow-steaming regime. The speed gap varies strongly by segment:

- Containerships: observed 13.0 kn vs. design 20 kn → 35% speed deficit.
- Tankers: observed ~11.0 kn vs. design 15.5 kn → 29% speed deficit.
- Bulk carriers: observed ~10.7 kn vs. design 14.0 kn → 24% speed deficit.
- Passenger and cruise ships: ~13–14 kn vs. 22.5 kn → 40% speed deficit.
- Ro-ro and vehicle carriers: ~14–15 kn vs. 19 kn 22%–25% speed deficit.

Table 3 presents these differences clearly, while Figure 1 visualises how operating at design speed compresses the required number of ships in each segment.

5.3. Fleet capacity effects under design-speed operation

Returning to design speeds under nuclear propulsion reduces required hours-under-way per ship and increases travel distance per unit time. Calculations show how many vessels are needed to maintain 2023 transport work at design-speed conditions. These results are summarised in Figure 1:

- Total ships required falls from 17,420 to 12,040 → a 31% reduction in fleet size.
- The largest capacity reductions occur in:
  - Containerships: ~3292 ships required (vs. 5075) → −35%
  - Tankers: ~4637 ships required (vs. 6594) → −30%
  - Vehicle carriers: ~517 ships required (vs. 677) → −24%
- Segments with already high speeds (e.g. small general cargo) show smaller reductions.

This is consistent with theory: reducing voyage time increases transport output per ship, allowing downsizing of the fleet even while holding demand constant.

The required number of vessels under design-speed operation is calculated as:

$$N_{\text{new}} = \frac{D_{\text{total}}}{v_{\text{design}} \times H_{\text{sea}}},$$

Table 3. Current actual, observed speed versus design speed for the various ship categories.

Ship types at the aggregate level	Observed speed	Design speed	Design speed span
Bulk carrier	10,69	14,00	13–15
Combination carrier	11,20	13,50	13–14
Containership	13,02	20,00	16–24 kn
Cruise passenger ship	13,90	22,50	20–25 kn
Gas carrier	13,36	17,50	16–19 kn
General cargo ship	10,14	15,00	14–16 kn
LNG carrier	13,82	19,00	19
Refrigerated cargo carrier	13,41	17,00	14–20 kn
Ro-ro cargo ship (vehicle carrier)	14,49	19,00	16–22 kn
Ro-ro passenger ship	15,68	19,00	16–22 kn
Tanker	10,92	15,50	13–17 kn
Weighted average	**11,49**	**17,35**	

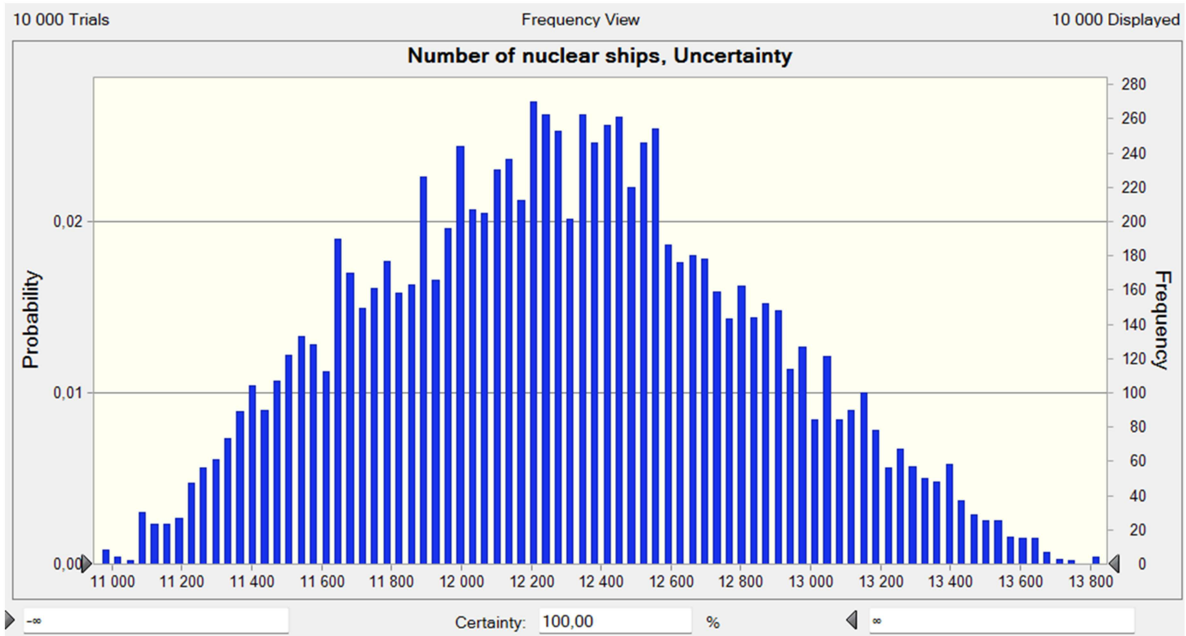


Figure 1. Number of nuclear-powered ships necessary to replace the current number of fossil ships of 17,420.

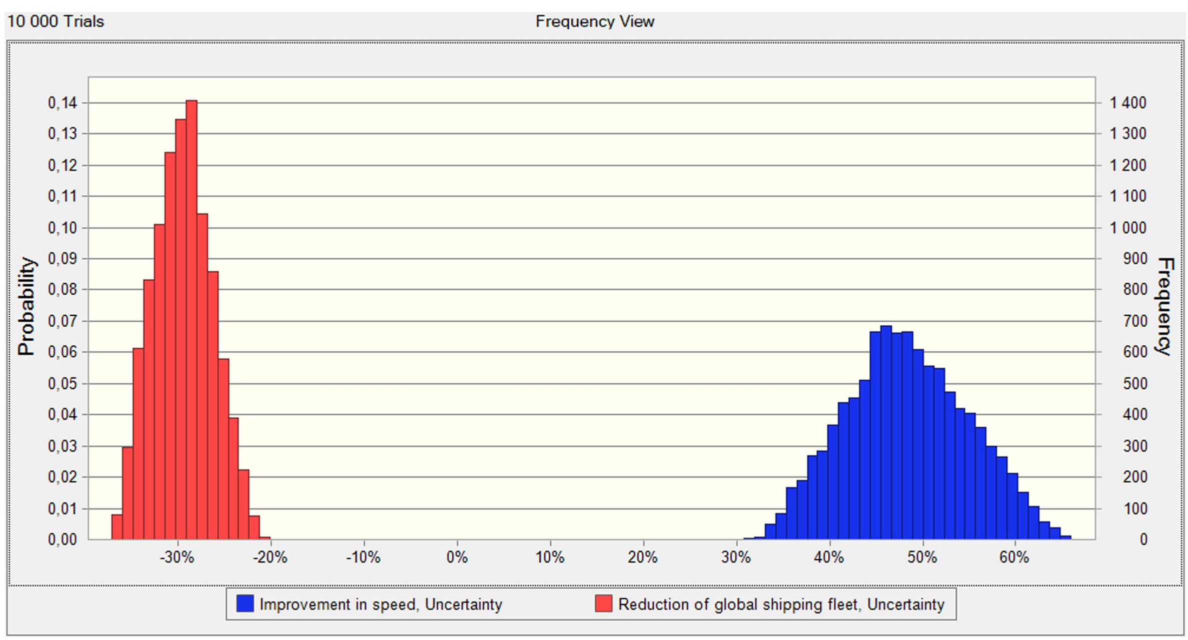


Figure 2. The improvement in speed and the subsequent reduction of the global shipping fleet as a consequence of nuclear propulsion given that the same amount of cargo is to be transported.

where D_{total} represents total annual transport distance (nm), v_{design} is design speed (knots), and H_{sea} is annual hours at sea per vessel.

Holding total transport work constant, higher design speed increases annual distance per vessel and reduces the number of ships required.

Figure 2 reinforces this relationship by demonstrating how a return to higher speeds realigns the fleet's operational profile. Ships that are currently constrained by high fossil-fuel costs become effectively 'over-deployed' once speed constraints are removed. The mechanisms driving these reductions are consistent with maritime economic theory:

- Higher speeds reduce voyage time, enabling each ship to complete more voyages per year.
- Productivity rises, so fewer ships are needed to deliver the same tonne-mile output.

A sensitivity analysis (shown in Figure 3) highlights that observed speed, design speed, and hours at sea are the dominant variables underlying fleet-size outcomes. This confirms the robustness of the model: Results are not driven by minor or unstable parameters but by fundamental operational characteristics.

5.4. Emissions outcomes under nuclear propulsion

Two emissions metrics are compared:

1. Old emissions per ship per year (fossil baseline).
2. New emissions per ship per year (nuclear scenario—with designed speed operated within each segment).

Total CO_2 emissions avoided: 978 million tonnes CO_2. Equivalent to 109% of baseline 2023 operational emissions in the dataset (because fleet size also decreases).

Key results:

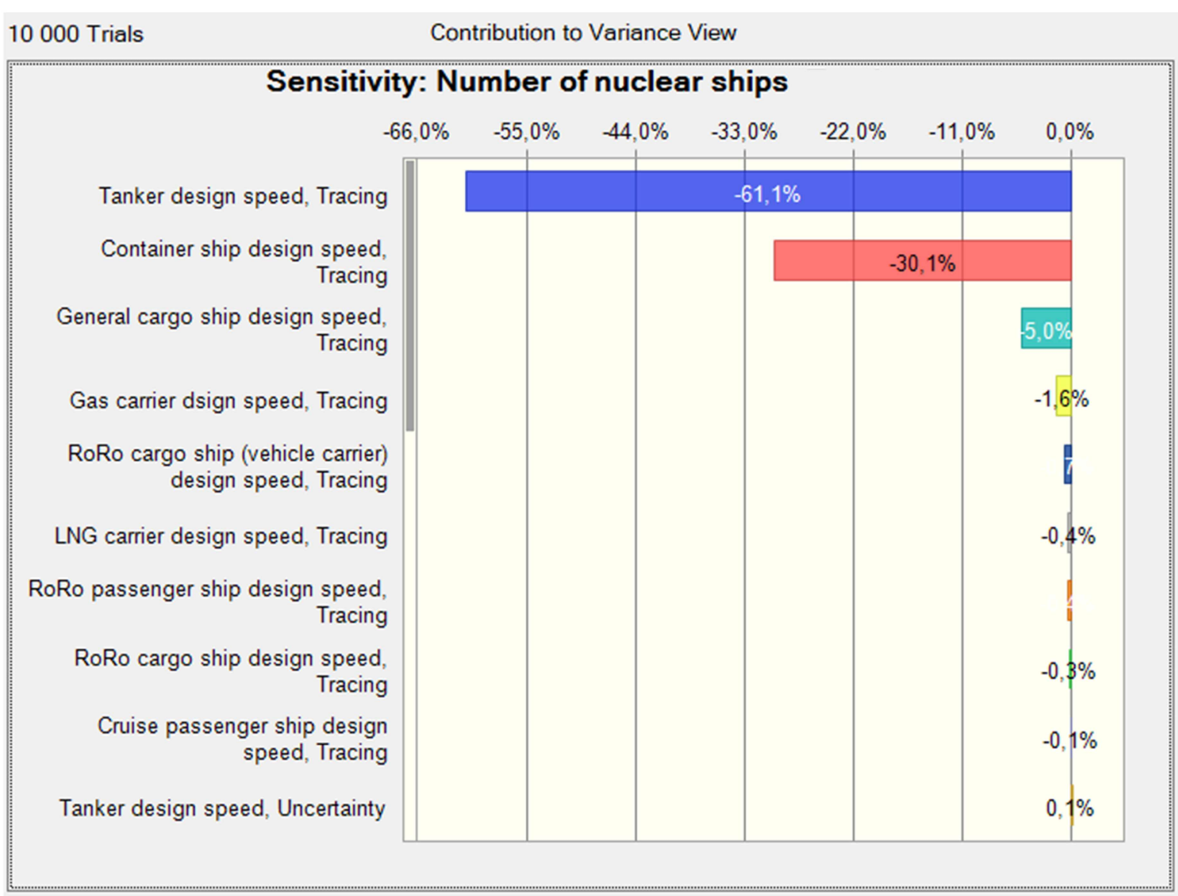


Figure 3. Sensitivity analysis to detect which variables in the global shipping fleet sample will drive the replacement of ships the most.

- Containerships alone avoid 415 million tonnes CO_2, ~42% of total avoidance.
- Tankers avoid 266 million tonnes CO_2.
- Bulk carriers avoid 82 million tonnes CO_2.
- Passenger and cruise ships avoid 46 million tonnes CO_2.

Combined, this represents a full elimination of fossil operational emissions for the dataset and an additional structural efficiency gain from higher speeds and fewer vessels. These results are illustrated in Figure 4, which shows CO_2 avoidance with designed speed.

6. Discussion

The results demonstrate that nuclear propulsion has the potential to initiate a structural reconfiguration of the global merchant fleet, driven not by environmental regulation alone but by fundamental shifts in economic incentives.

6.1. Reversal of the slow-steaming paradigm

Slow steaming has dominated shipping since 2009, motivated by fuel-cost minimisation, emissions constraints, and overcapacity absorption (Psaraftis and Lagouvardou 2023; Stopford 2009). Under nuclear propulsion, marginal fuel cost approaches zero, removing the economic logic behind slow steaming. This is consistent with earlier techno-economic studies showing that nuclear engines can operate efficiently across a wide speed range (Carlton, Smart, and Jenkins 2011; Kalimeris 2017). Therefore, nuclear propulsion does not merely decarbonise shipping, it reverses the operational logic that defines current fleet behaviour.

6.2. Fleet productivity and global capacity effects

A key and novel finding is that nuclear propulsion increases fleet productivity by enabling a return to design speeds while maintaining constant annual hours at sea. The resulting 31% reduction in required fleet size has several implications:

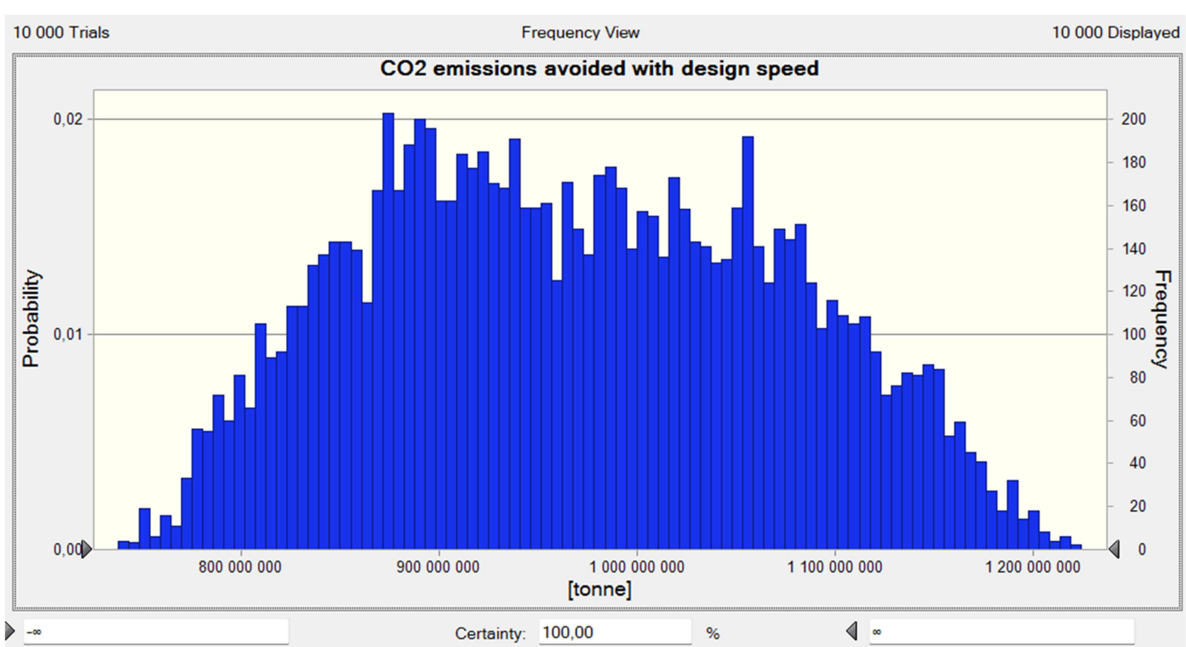


Figure 4. CO_2 avoided with designed speed.

1. Lower capital requirement for meeting global transport demand.
2. Reduced congestion in ports, canals, and chokepoints.
3. Lower inventory times and improved schedule reliability.
4. Increased tonne-mile delivery per ship.

This aligns with classical maritime transport models (Degiuli, Martić, and Farkas 2019; IMO 2024) showing that optimal speed is heavily influenced by marginal fuel cost. If marginal cost → zero, speed → design speed becomes rational.

6.3. Implications for decarbonisation pathways

The findings challenge mainstream decarbonisation scenarios (IRENA 2021; Laskar, Dowlatabadi, and Giang 2025; Li and Hu 2024), which often assume:

1. Continued slow-steaming as an emissions-reduction measure.
2. Increasing fleet size to meet trade growth.
3. Heavy dependence on synthetic fuels.

Nuclear propulsion bypasses these constraints by:

- Eliminating CO_2 emissions directly.
- Reducing the required number of ships, thus reducing embodied emissions from shipbuilding.
- Removing the need for large-scale electrofuel production for deep-sea transport.
- Increasing fleet productivity without additional tonnage.

Thus, nuclear propulsion appears both a decarbonisation accelerator and a system-efficiency enhancer, rather than an energy substitution mechanism alone.

6.4. Economic and market implications

Assuming nuclear vessels retain similar operating expenditures (OPEX) and achieve comparable net margins, the model suggests:

- Lower transport costs per tonne-mile due to improved productivity.
- Stronger competitiveness for operators adopting nuclear early.
- Potential for market bifurcation between nuclear and fossil fleets, with nuclear vessels capturing premium, time-sensitive routes.

These dynamics mirror early containerisation transitions, where step-changes in speed and reliability reshaped global trade patterns.

6.5. Limitations and future research

Several limitations provide avenues for further investigation:

- The model assumes ships instantly revert to design speed; real-world deployment may be phased.
- Operational CO_2 is set to zero; a full life-cycle analysis would include fuel-cycle and decommissioning emissions.
- Port capacity effects and port congestions are ignored in the model but are likely significant.
- Increased uptime of the ships due to less time spent on fuelling is ignored.
- The financial aspects of have a more asset light industry reducing the needs for investments and maintenance.
- Regulatory and public-acceptance barriers may slow adoption.

Despite these limitations, the analysis provides clear evidence that the operational logic of shipping is highly sensitive to the marginal cost of fuel, and nuclear propulsion alters that logic fundamentally even without considering the positive second-order effects related to reduced port congestions, increased uptime of ships related to less time spent fuelling, financial aspects and more. The study is therefore highly conservative. Given the positive results concerning nuclear propulsion, it seems clear that if nuclear propulsion can be established for commercial shipping it will have a disruptive effect on shipping. Perhaps on equal scale with the transition from sailing ships to powered ships more than hundred years ago.

Thus, the system boundary of this study is limited to operational-phase CO_2 emissions, consistent with the IMO DCS dataset and current EU ETS regulatory scope. Life-cycle emissions related to reactor construction, nuclear fuel cycle, decommissioning, and waste management are not included. Indirect effects are also ignored. These aspects represent an important area for future research but do not affect the structural fleet-productivity mechanism analysed here.

7. Conclusion

This study examined how nuclear propulsion could reshape global shipping not only by eliminating operational CO_2 emissions, but also by changing the economic logic that currently governs vessel speed and fleet deployment. While existing studies on shipping decarbonisation largely focus on alternative fuels, energy-efficiency measures, carbon pricing, or slow steaming within the fossil-fuel paradigm, this paper contributes by analysing a structurally different propulsion regime in which the marginal fuel-cost incentive for slow steaming is largely removed. In doing so, the study extends the literature on maritime decarbonisation and ship-speed economics by linking nuclear propulsion directly to fleet productivity, required vessel capacity, and system-level operational change.

Using the IMO DCS 2023 aggregated dataset, the analysis shows that slow steaming is not a marginal operational practice but a fleet-wide structural regime. The weighted-average observed speed in the analysed sample is 11.49 knots, compared with an estimated average design speed of 17.35 knots. This confirms a substantial speed gap across major ship segments, especially containerships and tankers, where fuel cost and emissions constraints strongly shape operational behaviour. The counterfactual nuclear propulsion scenario suggests that, if ships returned to design-speed operation while transport demand remained constant, the required fleet size could fall by approximately one-third. This finding adds to existing literature by showing that nuclear propulsion should not be understood only as an energy substitution pathway, but also as a potential productivity-enhancing regime shift.

The main contribution of the paper is therefore twofold. First, it provides an empirical fleet-level estimate of the speed gap between current operations and design-speed potential using IMO DCS-based operational data. Second, it demonstrates that the removal of voyage-dependent fuel costs could produce a significant 'fleet redundancy' effect, whereby fewer ships are needed to deliver the same transport work. This productivity effect represents an additional climate and economic mechanism that is rarely addressed in existing decarbonisation scenarios: fewer vessels over time may imply lower shipbuilding demand, reduced embodied emissions, lower congestion pressure in ports and chokepoints, and improved schedule reliability. These findings challenge decarbonisation pathways that implicitly assume continued slow steaming, increasing fleet capacity, and large-scale dependence on synthetic fuels.

At the same time, the results should be interpreted with caution. The analysis does not forecast the actual adoption of nuclear propulsion, nor does it claim that nuclear-powered shipping can be deployed without regulatory, financial, safety, liability, and public-acceptance challenges. The study assumes that nuclear propulsion becomes economically and institutionally viable at scale, and then evaluates the structural fleet-level consequences of that scenario. Several limitations remain. The IMO DCS dataset does not report design speed, requiring externally derived design-speed assumptions. Some ship segments contain missing or inconsistent activity data, which limits the precision of speed-gap and productivity estimates. The study also focuses on operational-phase CO_2 emissions and does not include full life-cycle impacts related to reactor construction, nuclear fuel supply, decommissioning, or waste management. In addition, dynamic market responses, phased fleet renewal, freight-rate adjustments, port readiness, and mixed-fleet transition pathways are outside the scope of the present model.

Future research should therefore develop vessel-level datasets that combine IMO DCS data with technical design-speed information from classification societies, commercial fleet databases, or ship-series specifications. Further studies should also compare nuclear propulsion with alternative fuels using full life-cycle assessment, model mixed-fleet transition pathways, and quantify indirect system effects such as port congestion, chokepoint capacity, inventory costs, and shipbuilding demand. Finally, more work is needed on regulatory design, liability frameworks, safety governance, and public acceptance, as these factors will determine whether the technical and economic potential identified in this study can be realised in practice.

Overall, the findings suggest that if nuclear propulsion becomes commercially and institutionally viable for deep-sea shipping, its impact could extend well beyond direct operational decarbonisation. By reversing the slow-steaming logic that has shaped shipping since 2009, nuclear propulsion could simultaneously eliminate operational CO_2 emissions, increase fleet productivity, reduce required fleet capacity, and reshape the operational architecture of global maritime trade. This makes nuclear propulsion a potentially disruptive decarbonisation pathway rather than a marginal alternative fuel option.

Acknowledgements

The work was supported by the NuProShip II project—the Research Council of Norway, grant number [336539].

Author contributions

CRediT: **Viktoriia Koilo-Gabillaud:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing; **Jan Emblemsvåg:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – review & editing.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

The data that support the findings of this study are available from the corresponding author, V.K., upon reasonable request.

References

Bhattacharyya, R., R. S. El-Emam, and F. Khalid. 2023. "Climate Action for the Shipping Industry: Some Perspectives on the Role of Nuclear Power in Maritime Decarbonization." *e-Prime – Advances in Electrical Engineering, Electronics and Energy* 4: 100132. https://doi.org/10.1016/j.prime.2023.100132.

Borén, C., M. Grifoll, and M. Castells-Sanabra. 2023. "Emissions Assessment of Container Ships Sailing under Off-Design Conditions." *Journal of Marine Science Engineering* 11: 1983. https://doi.org/10.3390/jmse11101983.

Carlton, J. S., R. Smart, and V. Jenkins. 2011. "The Nuclear Propulsion of Merchant Ships: Aspects of Engineering, Science and Technology." *Journal of Marine Engineering & Technology* 10 (2): 47–59. https://doi.org/10.1080/20464177.2011.11020247.

CE Delft. 2012. Regulated Slow Steaming in Maritime Transport An Assessment of Options, Costs and Benefits. Retrieved from: https://theicct.org/wp-content/uploads/2021/06/CEDelft_slow_steaming_2012.pdf.

Degiuli, N., I. Martić, and A. Farkas. 2019. "Environmental Aspects of Total Resistance of Container Ship in the North." *The Journal of Sustainable Development of Energy, Water and Environment Systems* 7(4): 641–655. https://doi.org/10.13044/j.sdewes.d7.0267.

Degiuli, N., I. Martić, and C. G. Grlj. 2024. "Slow Steaming as a Sustainable Measure for Low-Carbon Maritime Transport." *Sustainability* 16 (24): 11169. https://doi.org/10.3390/su162411169.

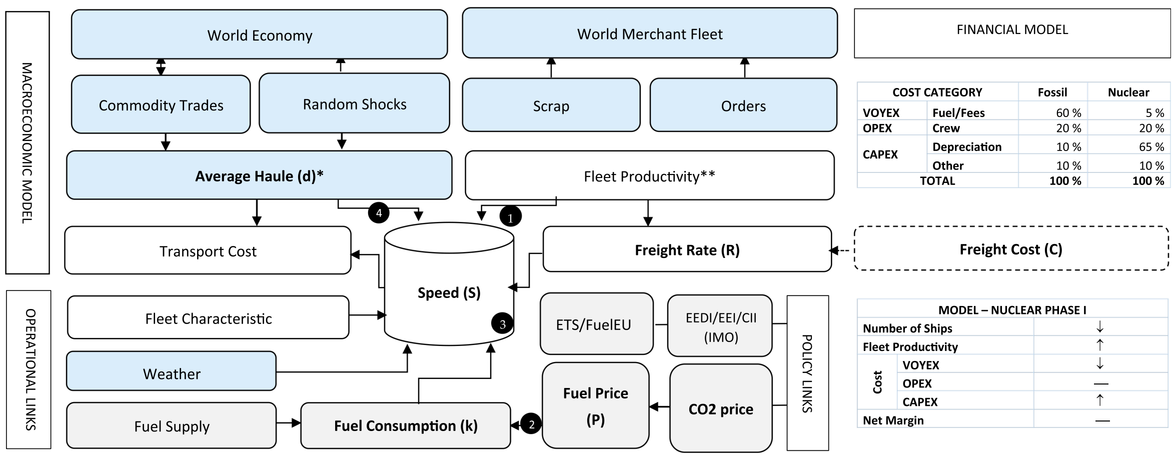
Degiuli, N., I. Martić, A. Farkas, and I. Gospić. 2021. "The Impact of Slow Steaming on Reducing CO2 Emissions in the Mediterranean Sea." *Energy Reports* 7: 8131–8141. https://doi.org/10.1016/j.egyr.2021.02.046.

DNV. 2024. Maritime nuclear propulsion – Technologies, commercial viability, and regulatory challenges for nuclear-powered vessels. Retrieved from: https://www.DNV.com/maritime/publications/maritime-nuclear-propulsion-download/.

Duong, P. A., J. Ha, C. Lee, and H. Kang. 2025. "Nuclear Propulsion for Merchant Ships: A Path to Sustainable Maritime Energy." *International Journal of Sustainable Energy* 44(1). https://doi.org/10.1080/14786451.2025.2579469.

Emblemsvåg, J. 2003. *Life-Cycle Costing: Using Activity-Based Costing and Monte Carlo Methods to Manage Future Costs and Risks*. Hoboken, NJ: John Wiley & Sons.
Emblemsvåg, J. 2021. "How Thorium-Based Molten Salt." *Marine Technology Society Journal* 55(1): 56–72. https://doi.org/10.4031/MTSJ.55.1.2.
Emblemsvåg, J. 2026. Powering Small Grids and Islands Using Floating Nuclear Power Plants In *Proceedings of the 15th International Conference of the Croatian Nuclear Society*. Zadar, Croatia: Pubøisher is Croation Nuclear Society (CNS), May 31 – June 3, 2026. Acceped for publication.
Emblemsvåg, J., C. Ordonez, C. G. Tamm, J. S. Ortigosa, Y. M. Colilles, and A. Pérez. 2024. *Final report of the Nuclear Propulsion for Merchant Ships I (NuProShip I) project*. Norges Teknisk og Naturvitenskapelig Universitet. Retrieved from: https://hdl.handle.net/11250/3174539.
Emblemsvåg, J., C. H. Ordóñez, C. Garrido Tamm, T. Strand, J. S. Ortigosa, and Y. M. Colilles. 2025. "Selecting Nuclear Reactor for Merchant Shipping." *Nuclear Technology*. 1–22. https://doi.org/10.1080/00295450.2025.2575544.
Emblemsvåg, J., T., Strand, H., Hammer, I., Salter, E., Joseph, A., Brachel, P., Vaddi, et al. 2020. Insuring nuclear-powered ships – clarifications and concepts for early demonstration projects. Accepted for publication in Frontiers in Marine Science.
EMSA. 2024. *Potential Use of Nuclear Power for Shipping*. Lisbon: European Maritime Safety Agency, Retrieved from: https://www.emsa.europa.eu/publications/reports/item/5366-potential-use-of-nuclear-power-for-shipping.html?.
Han, E. 2024. "Cases of Judicial Decisions Related to the Human Health Effects of Low-Dose Radiation in Korea." *Journal of Radiation Protection and Research* 49(4): 196–206. https://doi.org/110.14407/jrpr.12024.00339.
Holbert, K. E.. 2025. "A Review of Maritime Nuclear Reactor Systems." *Journal of Nuclear Engineering* 6 (1): 5. https://doi.org/10.3390/jne6010005.
IMO. 2018. Initial IMO Strategy on Reduction of GHG Emissions from Ships (MEPC 72, 2018, London. Retrieved from: https://www.imo.org/en/ourwork/environment/pages/vision-and-level-of-ambition-of-the-initial-imo-strategy.aspx.
IMO. 2024. Report of fuel oil consumption data submitted to the IMO Ship Fuel Oil Consumption Database in GISIS (Reporting year: 2023) (MEPC 82/6/38, Agenda item 6). Marine Environment Protection Committee, 82nd session. Retrieved from: https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Reporting%20year%202023.pdf.
IRENA. 2021. A pathway to decarbonise the shipping sector by 2050, International Renewable Energy Agency, Abu Dhabi. Retrieved from: https://www.irena.org/Publications/2021/Oct/A-Pathway-to-Decarbonise-the-Shipping-Sector-by-2050.
Jose, D. E. 2027. Experiences in Radiation Litigation in Israel In *Proceedings of the 21. conference of the Nuclear Societies*. Haifa (Israel): Publisher is International Atomic Energy Agency (IAEA).
Kalimeris, G. 2017. The Viability of Slow Steaming from a Supply Chain Perspective through a Break-Even Bunker Price Analysis In *Business Economics*. Erasmus School of Economics, Retrieved from: http://hdl.handle.net/2105/38040.
Kunze, C. D. 2022. The role of generation IV nuclear reactors in decarbonising international shipping: a multi-criteria decision making (MCDM) framework for matching potential decarbonisation pathways to different ship types and size. World Maritime University. The Maritime Commons: Digital Repository of the World Maritime University. https://commons.wmu.se/all_dissertations/2071/.
Laskar, I. I., H. Dowlatabadi, and A. Giang. 2025. "Expert Assessments of Maritime Shipping Decarbonization Pathways By 2030 and 2050." *Earth's Future* 13. https://doi.org/10.1029/2024EF005255.
Lee, C. Y., H. L. Lee, and J. Zhang. 2015. "Impacts of Slow Steaming on Schedule Reliability and Fuel Consumption." *Transportation Research Part E* 76: 176–190. https://doi.org/10.1016/j.tre.2015.02.004.
Li, W., and Z. Hu. 2024. "Pathways in the Governance of Shipping Decarbonization from Perspective of Balancing the Conflicting Interests." *Frontiers in Marine Science* 11. https://doi.org/10.3389/fmars.2024.1479528.
Notteboom, T., and P. Cariou. 2013. "Slow Steaming in Container Liner Shipping: Is There Any Impact on Fuel Surcharge Practices?" *The International Journal of Logistics Management* 24(1): 73–86. https://doi.org/10.1108/IJLM-05-2013-0055.
Psaraftis, H. N., and S. Lagouvardou. 2023. "Ship Speed Vs Power or Fuel Consumption: Are Laws of Physics Still Valid? Regression Analysis Pitfalls and Misguided Policy Implications." *Cleaner Logistics and Supply Chain* 7: 100111. https://doi.org/10.1016/j.clscn.2023.100111.
Rodrigue, J. P. 2024. *The Geography of Transport Systems*. 6th Edition 402. New York: Routledge. https://doi.org/10.4324/9781003343196.
Schøyen, H., and K. Steger-Jensen. 2017. "Nuclear Propulsion in Ocean Merchant Shipping: The Role of Historical Experiments to Gain Insight into Possible Future Applications." *Journal of Cleaner Production* 169: 152–160. https://doi.org/10.1016/j.jclepro.2017.05.163.
Stopford, M. 2009. *Maritime Economics*. 3rd Edition London: Routledge. https://doi.org/10.4324/9780203891742.
UNCTAD. 2025. Review of maritime transport. Staying the course in turbulent waters. Clarksons Research Services. Retrieved from: https://unctad.org/publication/review-maritime-transport-2025.
Wu, W. 2020. "The Optimal Speed in Container Shipping: Theory and Empirical Evidence." *Transportation Research Part E: Logistics and Transportation Review* 136: 101903. https://doi.org/10.1016/j.tre.2020.101903.
Zincir, B. A., B. Zincir, and Y. Arslanoglu. 2025. "Operational and Environmental Impact Analysis of Slow Steaming on Alternative Fuels." *Journal of Marine Engineering & Technology* 25: 1–15. https://doi.org/10.1080/20464177.2025.2550073.

Appendix



Note: **tonne km; **tonne km per deadweight; S is the optimum speed in km per day, R the voyage freight rate, p the price of fuel, k the ship's fuel constant, and d = distance.*

Color: *1. Grey: key elements of fossil fuel model that will be replaced with Freight Cost (C). 2. Blue: key elements of the model that we assume will stay constat. White: key models' elements that*

Figure A1. Projected development of the global merchant fleet under nuclear propulsion: speed-based scenario analysis.