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The economics of nuclear propulsion for containerships

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ABSTRACT

The maritime shipping sector, which accounts for 80% of global trade by volume, faces a significant challenge in decarbonising. This article examines the economic competitiveness of nuclear containerships, drawing on current industrial and academic literature on nuclear power integration in maritime shipping. First, we analyse the design and operational characteristics influenced by nuclear power adoption and identify key barriers to its deployment. Second, we develop a scenario-based model to assess the economic competitiveness of nuclear-powered containerships compared to conventional and alternative fuel systems, using the Levelised Cost of Transport as the primary metric. We show that nuclear power applied to containership propulsion may represent an economically competitive solution in specific scenarios characterised by high cruising speeds and favourable CAPEX for nuclear reactor engines. The learning process of building and operating nuclear containerships might play a key role in making this technological option economically viable at scale.

1. Introduction

Maritime transport plays a central role in the modern economy, with 80% of international trade by volume and 50% by value carried out on water (UNCTAD, 2022). The sector is responsible for approximately 3% of global GHG (*greenhouse gas*) emissions (Faber, 2021), with a 20% increase over the last decade (UNCTAD, 2023). Policymakers are urging industry stakeholders to reduce GHG emissions by implementing new regulatory frameworks. Examples are the European Union's ETS (*Emission Trading Scheme*), which was extended to commercial ships in 2024 (European Commission, 2024a), and the IMO's (*International Maritime Organization*) EEXI (*Energy Efficiency Existing Ship Index*) and CII (*Carbon Intensity Indicator*) indicators, which also came into practice in 2024 (IMO, 2021). Containerised shipping is crucial to maritime transport, particularly for the transportation of consumer goods. Although containerships represent only 13% of cargo vessels by deadweight tonnage (DWT), they account for 66% of goods transported by value (Notteboom et al., 2022; UNCTAD, 2023, p. 30). Given the operational characteristics of containerships, the shipping industry has identified several alternatives (e.g., methanol and ammonia) as potential substitutes for conventional fuel-oil propulsion systems (Tu et al., 2024).

Despite advancements in adopting alternative fuels, the maritime industry continues to explore complementary solutions, with growing interest in nuclear propulsion systems. Traditionally limited to military and research vessels, nuclear propulsion is now the subject of Memoranda of Understanding and feasibility studies specifically focused on containerships, conducted by major industry players, such as Maersk (Cooper, 2024), CSSC (Mandra, 2023), Fincantieri, RINA (RINA, 2023), Lloyd's Register, Hyundai Heavy Industries, and Zodiac Maritime (Lloyd's Register, 2024; World Nuclear News, 2024). Additionally, specific organisations, such as Core Power, aim to develop a Small Modular Reactor (SMR) for maritime applications (Core Power, 2024). Only a few feasibility studies, mainly addressing technical implementation, have examined the specific design features and cost drivers affected by adopting nuclear propulsion (Carlton et al., 2011; de Vries et al., 2024; Hirdaris et al., 2014). The scientific literature on the application of nuclear technologies for maritime propulsion predominantly addresses specific barriers, particularly regulatory challenges (Q. Wang et al., 2023a, 2023b) and technical implementation issues (Drosińska-Komor et al., 2022; Hirdaris et al., 2014; Peakman et al., 2019). Comprehensive economic assessments remain largely absent, despite representing a fundamental dimension for innovation and investment decisions. In contrast, such evaluations are well established in the academic literature on the deployment of the aforementioned alternative fuels (Ammar, 2019; Louvros et al., 2023; Seo et al., 2024; Wu et al., 2022).

This article aims to address this research gap by investigating the economic competitiveness of deploying a nuclear-powered containership. In particular, we will address the following research question: Which scenarios make nuclear-powered containerships economically

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competitive compared to modern state-of-the-art propulsion system solutions?

2. Literature review

2.1. Maritime shipping sector background

Containerships are designed to transport 20-foot (TEU) or 40-foot (FEU) standardised containers (International Chamber of Shipping, 2024). The total number of TEUs transportable is generally used as a volume measure of containerships and to classify containerships: following the classification used by US Department of Agriculture (2024) feeders are containerships carrying less than 3000 TEUs, Panamax between 3000 and 5300 TEUs, Neo-Panamax between 5300 and 12500 TEUs, Very-Large Container Vessels/Ships (VLCV/VLCS) between 12500 and 18000 TEUs while containerships carrying over 18000 TEUs are defined Ultra-Large Container Vessels/Ships (ULCV/ULCS). Park and Suh (2019) highlight that the market is gradually shifting towards higher capacity to exploit economies of scale. On the other hand, VLCV and ULCV introduce additional complexities compared to smaller vessels: they do not fit through Panama Canal, they are limited to specific ports (and consequently specific routes) able to accommodate their dimensions and they entail higher complexity in the loading and unloading of containers, which must be positioned thoughtfully to ensure accessibility when needed, considering that routes of these containerships are multi-stops (Park and Suh, 2019).

Traditionally, the shipping industry is characterised by a mix of ownership and chartering practices, with fleet ownership shares ranging from 6.1% to 62.5% across companies (D'Agostini et al., 2019, p. 77). More broadly, these organisational choices are embedded in the cyclicality and cost structure of shipping markets, as discussed in the standard maritime economics literature (Stopford, 2010). Containerships are built by a limited number of companies, mainly in the Far East. Thus, major players include CSSC in China, Mitsubishi Heavy Industries, Imabari Shipbuilding and JMU in Japan, Hyundai Heavy Industries, Samsung Heavy Industries and Hanwha Ocean in South Korea, as well as a minor exception being JSC United Shipbuilding Corporation in Russia (Menon, 2020). These companies build the ship's hull (referred to as the "body") and then fit an outsourced propulsion system, with a few exceptions, such as Mitsubishi H.I. (Mitsubishi Heavy Industries Ltd, 2024). Among the most notable engine producers, excluding Mitsubishi H.I., are MAN Energy Solutions SE in Germany (MAN energy solutions se, 2024a) and Wärtsilä in Finland (Wärtsilä, 2024a). Regarding the market standard for containerships, fuel-oil engines are widely used to allow vessels to operate at up to 25 kn (knots), which is equivalent to nautical miles per hour (Rodrigue, 2020). Engine power varies considerably with ship size, ranging from a few MWe for small feeders to 90/100 MWe for 24000 TEU ULCV (The Maritime Executive, 2023). Before 2020, most containerships used HFO (*Heavy Fuel Oil* also known as bunker fuel), because of its low cost and the lack of strong regulations on emissions of nitrogen oxides (NOx) and sulphur dioxide (SO2) by the IMO, except in specific areas of the globe called *Emission Control Areas* (Bengtsson et al., 2011). Starting in January 2020, the IMO introduced a more stringent regulation, called MEPC328(76), on the sulphur content of maritime fuels, limiting it to 0.1% m/m within ECAs and 0.5% m/m outside of them (IMO, 2021, p. 57). This decision indirectly limited HFO, which generally has a sulphur content of 1% m/m to 1.5% m/m when not paired with a scrubber to remove sulphur from exhaust gases. Thus, the decision paved the way to a broader implementation of VLSFO (*Very Low Sulphur Fuel Oil,* max 0.5% m/m) and ULSFO (*Ultra Low Sulphur Fuel Oil,* max 0.1% m/m) (Bee, 2025), which reached 67% and 2% share of the bunker fuels market, respectively, after only 6 months from the introduction of MEPC328(76). The share of HFO and MGO (*Marine Gas Oil*) shrank to 15% and 16%, respectively (VPS, 2020).

Generally, fuel oil consumption is influenced by two main variables: the ship's dimensions (specifically engine power) and, more importantly, speed (Rodrigue, 2020). Commercial vessel speeds can range from 12 knots (the lowest technical speed) to 25 knots, affecting fuel consumption exponentially (Rodrigue, 2020). This relationship is well known throughout industry operators and widely exploited to reduce costs of operations: after 2008 crisis, shipping companies, driven by increased costs and lower revenues, collectively diminished cruising speed from 22/25kn, which was considered "normal speed", to 19kn or lower, a practice commonly called "slow steaming" (Vakili et al., 2023). Today, this practice is highly established in the market because the marginal increase in revenue from faster deliveries does not offset the significantly higher fuel costs (Notteboom et al., 2022). Given the significantly lower fuel consumption, slow steaming helps reduce costs and emissions. Thus, this practice is consolidating further due to the wave of environmental regulations being implemented (Pelić et al., 2023). This trade-off between service speed, fuel consumption, and operating economics is a well-established feature of liner shipping operations (Stopford, 2010).

To reach the net-zero objective around 2050, IMO introduced worldwide EEDI (*Energy Efficiency Design Index*), EEXI (*Energy Efficiency Design Index for Existing Ships*) and CII (*Carbon Intensity Indicator*) measures (IMO, 2021). At a regional level, the EU also introduced a significant framework for decarbonising maritime shipping. Starting in 2024, the EU extended ETS to include cargo and passenger ships over 5000 GT (i.e., 550 TEU), including almost the entirety of the containership market. This well-known scheme obliges shipowners to source allowances on the market for each ton of CO_2 directly emitted by their vessels' operations (European Commission, 2024a).

Furthermore, the EU introduced the FuelEU Maritime mechanism in 2025. This mechanism targets a yearly average reduction in GHG intensity for a ship or a fleet (European Commission, 2024b). If the vessel does not meet the requirements, authorities impose sanctions and envisage harsher penalties for multi-year violations (European Commission, 2024b). Lloyd's Register (2023) estimates that a fleet of ten non-compliant vessels (handy bulk carriers) would pay up to 277 M€ in penalties over five consecutive years of sanctions. The fundamental point is that sanctions against a fleet can be offset by adding alternative-fueled vessels. Following (Lloyd's Register, 2023) example, adding a single zero-emission vessel to the fleet could offset the entire fleet's GHG deficit, allowing the shipowner to avoid sanctions altogether.

2.2. Alternative fuels

Increasing pressure from evolving environmental regulations forces the maritime industry to explore alternative propulsion systems to reduce emissions. Thus, the shipping industry (DNV, 2022; Lloyd's Register, 2023; Q. Wang et al., 2023a; T. Wang et al., 2023) has identified the following solutions: Methanol, Ammonia (both as a combustion engine and as a fuel cell), Methane, Biofuels, Liquified Natural Gas, Liquefied Petroleum Gas, Hydrogen fuel cells, Pure electric, and Nuclear (direct propulsion or nuclear electric propulsion). As of today, the industry considers ammonia and methanol among the most promising options for substituting fuel oil for containerships (Lloyd's Register, 2023; T. Wang et al., 2023).

Methanol application as a marine fuel started in 2012 with the commercialisation of the first methanol dual-fuel engine, which runs on methanol and fuel oil, the MAN B&W LGIM by Man Energy Solutions SE (MAN energy solutions se, 2021). Methanol started to gain more interest from the industry as a possible substitute for VLSFO in a post-MEPC328 (76) (IMO, 2021) shipping market (Ammar, 2019; DNV, 2018). Despite over a decade of commercialisation, only a handful of vessels run exclusively on methanol, given the prevalence of dual-fuel solutions (T. Wang et al., 2023). Methanol is comparable to fuel oil in terms of the type of emission components, but lower emission factors are observed (ClassNK, 2024). Furthermore, methanol has a lower calorific value than fuel oil (ClassNK, 2024) and, consequently, methanol-propelled ships require larger fuel tanks (IMO, 2016; Rivarolo et al., 2023).

The application of ammonia as a marine fuel is a relatively recent idea (T. Wang et al., 2023). Given its potential "zero-carbon at the point of use" status (Alnajideen et al., 2024; Bilgili, 2021; Cai et al., 2023), extensive research has been conducted (Machaj et al., 2022; T. Wang et al., 2023), and engine producers have started commercialising their first solutions (MAN energy solutions se, 2024b; Wärtsilä, 2024b). When combusted under optimal conditions, ammonia emits only nitrogen and water vapour, while NOx, N_2O, and ammonia slip may be produced if conditions are not appropriately controlled (Li et al., 2021; Mashruk et al., 2024). In this study, ammonia is treated as "zero carbon" only with respect to direct CO_2 emissions (consistent with ETS-like CO_2-only framing).

However, ammonia has a lower calorific value, even lower than methanol (ClassNK, 2024), requiring larger fuel tanks (Rivarolo et al., 2023). While ammonia propulsion and bunkering are progressing, large-scale availability of low/zero-carbon ammonia and the associated infrastructure and regulatory framework remain under development; ammonia is therefore treated here as a forward-looking benchmark rather than an immediately deployable solution.

Adopting methanol or ammonia as a fuel results in modifications to containership design and operations, primarily due to the need for larger fuel tanks, enhanced safety measures, and increased CAPital EXpenditures (CAPEX). Methanol fuel tanks are generally 2.5 to 2.8 times larger in volume than the ones for fuel oil, and ammonia fuel tanks are up to four times larger (DNV, 2022, p. 60). This is because the fuels have a lower calorific value than VLSFO (ClassNK, 2024). Furthermore, higher security measures concerning the design and operation of the ship are needed due to the relatively dangerous nature of these fuels compared to VLSFO, especially for ammonia, which is also corrosive compared to other fuels of interest (DNV, 2022). Adopting methanol and ammonia propulsion systems is associated with CAPEX increases of approximately 14.4% and 21.2%, respectively, compared to conventional fuel oil systems (Tu et al., 2024, p. 10).

2.3. Nuclear propulsion

Using nuclear power as a propeller for merchant shipping is a relatively old idea (World Nuclear Association, 2025). Along with the first navy nuclear submarines, ships and icebreakers implementations, research studies and pilot implementations were conducted by the USA, Germany, Japan and Russia (Patel, 2024a) to apply nuclear reactors, specifically PWRs (Pressurised Water Reactors), as engines of merchant vessels between the 1950s and the 1980s (Freire and Andrade, 2015). These projects aimed to demonstrate the technical feasibility of the solution and to study operational barriers (Khlopkin and Zotov, 1997). Except for Russia's Sevmorput, which is still in operation (Vessel Finder, 2024), all vessels were repurposed with fuel oil engines after a few years of service or decommissioned due to the high operational cost, which proved hardly competitive in the market (Patel, 2024b).

In recent years, the development of SMRs has created a new wave of interest in nuclear-powered vessels, particularly containerships (Cooper, 2024; CORE POWER, 2023; C. CORE POWER, 2024; Mandra, 2023; Moore, 2023; RINA, 2023; World Nuclear News, 2024, 2025). Considering SMR's power output is generally 10-300 MWe (Liou, 2023), they fit the power needed by containerships. From a practical point of view, building a nuclear-powered containership means replacing the engine, auxiliary engine and related components, generally alimented by fuel oil, with an SMR to power the ship through electrical power or, concerning the propulsion only, through direct powering of the propeller (Peakman et al., 2019) while also considering the standard optimisation problematics of a containership subject to complex dynamics that may impact the reactor functioning (Fitriyani et al., 2008). The new wave of nuclear interest led to new research on nuclear reactor designs for marine nuclear power, with different concepts being developed for MSRs (Lee et al., 2023) and SCWRs (Rahman et al., 2020).

A key characteristic of ship design and operation affected by the implementation of nuclear power aboard a containership is cargo volume. Optimising cargo volume is crucial in the shipping industry, particularly for containerships (Wilson and Roach, 1999). As Schøyen and Steger-Jensen (2017) noted, the first generation of nuclear-powered cargo ships suffered from reduced cargo capacity due to the heavy shielding and safety systems required. Carlton et al. (2011) suggest that modern merchant vessels could face similar space constraints.

Several concepts for maritime nuclear propulsion target extended service lives (often cited around 50 years in the literature), although this remains a design objective rather than evidence from civil commercial deployment (World Nuclear Association, 2025), which is twice the design life of most maritime engines, which is typically 25 years (Akan and Kiraci, 2023; DNV, 2022; Global Maritime Forum, 2022). The nuclear propulsion system should consequently be positioned on a new hull at the end of the life of the previous one, increasing the economic viability of the solution (World Nuclear Association, 2025), or the ship should be refurbished to last another 25 years. Another key difference between nuclear-powered and conventional fuel oil cargo ships lies in their refuelling and maintenance cycles, which directly impact their operational lifespans. As discussed by Bhattacharyya et al. (2023), nuclear power offers extended operational cycles between refuelling, allowing ships to spend years at sea without docking for fuel (CORE POWER, 2024). Some SMR concepts target very long refuelling intervals or sealed-core operation over the vessel's service life. However, refuelling requirements are design-specific and should be interpreted as design targets rather than established practice for civil commercial maritime applications (Patel, 2024a). Looking more at the maintenance side, it is minimal compared to traditional engines (Lloyd's Register, 2024), and can be effectively carried out in parallel with refuelling operations every 10-15 years (RINA, 2023), leading to a further increase in time availability. Even though more extended downtimes are required when refuelling and maintenance are performed (Hirdaris et al., 2014), fuel oil containerships require major cyclical maintenance. Long refuelling intervals also allow for lower exposure to market volatility in fuel costs (Bhattacharyya et al., 2023; Emblemsvåg, 2021), which is very high for petroleum derivatives (Bacon and Kojima, 2008). Nonetheless, refuelling also poses concerns among scholars because of the port infrastructure needed, which, as of today, is primarily limited to military bases (Drosińska-Komor et al., 2022; Hirdaris et al., 2014) and because of waste management and disposal, which is an added burden for ship operators compared to combustion engines (Emblemsvåg, 2021).

The choice of a nuclear propulsion system influences speed. In maritime combustion engines, speed is exponentially related to fuel consumption, and, consequently, cruising speed drastically affects OPEX costs (Rodrigue, 2020). Lloyd's Register (2024) and Vergara and McKesson (2002) emphasise that nuclear power can support higher operational speeds without the fuel cost limitations of combustion engines, even possibly allowing the creation of a market niche of high-performance cargo vessels (Schøyen and Steger-Jensen, 2017), which failed in the past (Koman, 2019). On a fleet analysis basis, higher speeds on a significant number of ships may even allow reducing the number of ships in operation, while maintaining an equal service level (Carlton et al., 2011).

CAPEX and OPEX costs differ significantly from nuclear and more conventional solutions. Nuclear reactor CAPEX is 10 to 30 times (Abou-Jaoude et al., 2024) that of an equivalent fuel oil engine. This should be carefully considered when evaluating the economic feasibility of such ships (Emblemsvåg et al., 2024; Lloyd's Register, 2024). Furthermore, additional expenses are to be accounted for the reactor's decommissioning and initial regulatory compliance costs at the end of life (Freire and Andrade, 2015; Schøyen and Steger-Jensen, 2017), thereby offsetting the effect of CAPEX (ULC Energy, 2024). Considerable savings are expected in fuel costs, both from a consumption point of view (Emblemsvåg et al., 2024; Schøyen and Steger-Jensen, 2017) and from a market stability point of view (Dracoulis and Spence, 2023;

Emblemsvåg, 2021), enabling more precise forecasting of OPEX (Egieya et al., 2023; Emblemsvåg, 2021). However, Hirdaris et al. (2014) call attention on crew costs for such ships, which would increase compared to fuel oil implementations: the nuclear propulsion requires a crew with specific training which may take up to a year (Lange, 1990), bringing additional costs not only on the training itself, but also on the wage of sailors which will consequently be raised given the specific competences and the riskier environment (Peakman et al., 2019). Finally, there are potential savings from carbon pricing schemes (Maritime Nuclear Application Group, 2022) and, more generally, from GHG-related compliance costs, given that nuclear reactors do not emit any GHG. Table 1 summarises the key elements of the technologies discussed.

2.4. Economic feasibility of nuclear containerships

Vergara and McKesson (2002) conducted a feasibility study of nuclear propulsion for a small 1432 TEU high-performance cargo vessel, including an economic viability analysis with a similar fossil-fuel high-performance ship, considering both CAPEX and OPEX (fuel costs, insurance, crew, and port access). They found a strong relationship between nuclear power's viability and its CAPEX. Still, the cost of fossil fuel has a considerable impact. Hirdaris et al. (2014) feasibility study on a SMR-powered Suezmax tanker focuses on more technical and risk-related analyses of the considered ship, leaving the economics of the solution to future research (Jin and Bang, 2024).

A life-cycle cost analysis based on power plants estimates is carried out by Emblemsvåg (2021) for a Thorium Molten Salt Reactor (TMSR) application on an Aframax tanker, stating that "*the economic performance is about $70 million better over a 30-year period*" compared to combustion engine technologies, and 9 years of operation are needed for TMSR to become cost-effective compared to HFO. A qualitative example of cost assessment for containerships can be found in Lloyd's Register (2024) which considers a range (high-low) estimation of CAPEX and annual OPEX for a sample of containerships (14000 – 15000 – 20000 – 24000 TEUs) on the Asia-Europe trade corridor, fitted with a 70 MWe nuclear reactor. The results give a rough idea of the scale of investment, but no comparison is made with fuel oil containerships.

The most comprehensive work on the economic assessment of nuclear-powered cargo ships, analysing a 20000 TEU containership and a bulk carrier, is de Vries et al. (2024). This work performs a "*speed--dependent total cost of ownership*" analysis to understand the economic feasibility of cargo vessels under different operating conditions, creating a scenario-based analysis with the main scenario elements (Bood and Postma, 1997): speed and useful life of the reactor. In particular, the reactor containership analysis was carried out without a specific nuclear design because the technical impact of the type was deemed limited. The ship is a 20000 TEU containership fitted with a 512.6 MWe, an enormous figure compared to normal containerships, which generally have engine powers under 100 MW (Kistner et al., 2024), needed to accommodate the high-speed scenarios considered by the authors. Among the CAPEX, the authors considered estimates for reactor purchase and auxiliary systems, while OPEX was estimated as fuel costs, operations & maintenance costs, and voyage costs (port and canal dues). By assumption, decommissioning costs were not considered, as the vessel's decommissioning costs are comparable across the different technologies. Nuclear reactor decommissioning costs, mainly covered by Nuclear Decommissioning Trust Funds accumulated during the useful life, were not considered for the sake of simplicity in the analysis. Shipping income was calculated through historical freight rates on the chosen round trip to obtain a total cost of ownership. Freight rates highly influence the results, while reactor CAPEX plays a less substantial role within the range investigated. Nuclear engine installation on a containership has a potentially competitive total cost of ownership only in high speeds.

More recently, Kim et al. (2025) presented a conceptual design and techno-economic assessment of a 15,000 TEU Neo-Panamax containership powered by an SMR of approximately 70 MWe. Their scenario analysis varies key cost drivers (e.g., reactor manufacturing cost, nuclear fuel cost, and carbon tax assumptions) and complements ship-level results with a fleet-level comparison, highlighting that the higher operating speeds enabled by nuclear propulsion may reduce the number of vessels required to maintain a given service frequency on a representative route. Their findings corroborate the importance of reactor CAPEX and operating speed as first-order drivers of nuclear competitiveness.

Apart from strictly economic considerations, other significant barriers must be considered in the evaluation:

- **Public opinion/perception** and related matters, such as port/canal restrictions driven by public opposition, may eventually hinder the ship's existence (Lloyd's Register, 2024; Q. Wang et al., 2023a) and, and its ability to travel and operate freely (Schøyen and Steger-Jensen, 2017).
- **The regulatory** framework is complex and fragmented due to its dual nature (Maritime Nuclear Application Group, 2022). National

Table 1
Summary table of propulsion systems' characteristics.

	Bunker fuel	Methanol	Ammonia	Nuclear smr	Bibliography
Year of first commercial ship inauguration	Market standard	2015 2023 for a containership	2024 2026 for a containership	Yet to be commercialised	(Habibic, 2024; State Of Green, 2023; Supplychainbrain, 2024; Wärtsilä, 2015)
Number of ships >5000gt worldwide (on service + on order)	~37000	~200 (~30 on service)	~20 (1 on service)	0	(Classnk, 2024, P. 16)
Number of retrofit-ready ships (on service + on order)	N/a	~270	144 ammonia-fueled vessels and 302 ammonia-ready vessels	0	AMMONIA ENERGY ASSOCIATION (2025)
Emission components	- high co_2 - moderate sox - moderate nox	- medium/high co_2 - moderate sox - moderate nox	- nox - N_2O - NH_3	N/a	EUROPEAN COMMISSION (2023)
Emission factors for direct emissions [tco_2/tfuel]	3.151 (ldo)	1.375	0	0	EUROPEAN COMMISSION (2023)
Lower calorific value [Mj/Kg]	40.2	19.9	18.6	Depends on design considered	(Classnk, 2024, P. 30)
Engine life [yr]	25	20-30	20-30	~50	(AKAN AND KIRACI, 2023; WORLD NUCLEAR ASSOCIATION, 2025)
Propulsion system requirements	- medium space - limited security measures	- large space - moderate security measures	- large space - moderate security measures	- moderate space - very high security measures	(Dnv, 2022; Lloyd's Register, 2024)

regulatory frameworks are also to be considered (Lloyd's Register, 2024).

- **Insurance and liability** are indirectly related to the complex regulatory framework (Sam et al., 2023) and thus highly uncertain (Savini, 2022). While conventional marine insurance markets can price many operational risks, civil nuclear liability is typically made insurable through statutory frameworks (e.g., the U.S. Price-Anderson system) (NRC, 2021). For nuclear-powered merchant shipping, a broadly implemented international liability and compensation regime is currently absent; notably, the 1962 Brussels Convention on the Liability of Operators of Nuclear Ships has not entered into force (NEA, 1962). Consequently, coverage limits, premiums, and financial responsibility requirements for early nuclear-powered containership projects are likely to be project-specific and remain highly uncertain.
- **Finance***,* which is related to the ability to finance the construction of such ships, in particular, the high CAPEX cost (Bhattacharyya et al., 2023)

Furthermore, barriers and challenges out of the scope of this work mentioned by scholars are technical implementation problems (Bayraktar and Yüksel, 2023; Lloyd's Register, 2024; Maritime Nuclear Application Group, 2022; Q. Wang et al., 2023b), non-cooperative political environment (Bhattacharyya et al., 2023; Wang et al., 2024), movement of nuclear material (Lloyd's Register, 2024), disposal of nuclear waste (Peakman et al., 2019), difficulty in training the crew (Bayraktar and Yüksel, 2023; Egieya et al., 2023; Peakman et al., 2019).

3. Model development

This article uses a metric based on the levelised cost concept (Friedl et al., 2023) for scenario analysis. Comello et al. (2021) define LCXM (Levelised cost per X-mile) as "*the unit cost of a transportation service, such as a ton- or passenger-mile delivered*" highlighting how it could also be applied to "*any kind of transportation service (passenger and cargo)*". LCXM is an arrangement of the general Levelised Cost formulation reported by Friedl et al. (2023). Another important concept used in this work is the learning rate. The concept is closely related to the learning curve (Argote and Epple, 1990), which we may define as the "*constant percentage of unit cost decrease for each doubling of experience*" (McDonald and Schrattenholzer, 2001). Learning rates are widely used in economic analyses to reflect the optimisation of a process (and, consequently, its cost reduction), thanks to experience gained from producing multiple units (Gonsalves and Upadhyay, 2021; McDonald and Schrattenholzer, 2001; Rogner et al., 2008). In this paper, "experience" refers to cumulative production and deployment volume (i.e., the cumulative number of reactor units manufactured and installed for a given design, including repetition in the supply chain and assembly). The learning rate formulation is used here as a stylised sensitivity to represent potential FOAK-to-NOAK cost reductions. However, we recognise that a constant percentage cost decline does not apply indefinitely, as learning may saturate and/or occur via step changes associated with manufacturing scale-up and factory investments.

3.1. Model design and assumptions (ASMs)

Five "scenario-elements" are considered for the definition of scenarios:

- The chosen propulsion system: VLSFO, methanol, ammonia, or nuclear-electric.
- the chosen cruise speed: 17kn, 19kn, 22kn, 25kn.
- The amount of carbon tax: In an ETS-like approach, a carbon tax is paid on the direct CO_2 emissions of the vessel. Accordingly, non-CO_2 exhaust pollutants (e.g., NOx/N_2O and ammonia slip) are outside the scope of the pricing mechanism implemented in the model. Multiple values ranging from 0 $\frac{\$}{t_{CO_2}}$ to 3000 $\frac{\$}{t_{CO_2}}$ are chosen. In this range, two important values are 74 $\frac{\$}{t_{CO_2}}$, which is the current cost of emission allowances (Tradingeconomics, 2024) and 210 $\frac{\$}{t_{CO_2}}$, which is the cost of emission allowances forecasted by (BloombergNEF, 2024) to be reached in 2035.
- The value of engine CAPEX for the nuclear propulsion: average case, unfavourable case and favourable case.
- A learning rate for nuclear propulsion CAPEX of 9.5% as indicated for SMRs (Abou-Jaoude et al., 2024, p. 109). Nuclear propulsion CAPEX values are taken from the SMR-only subset of Abou-Jaoude et al. (2023) as a range of overnight cost estimates (excluding FOAK-specific RD&D, licensing and financing), and the same overnight-cost convention is applied to conventional, methanol and ammonia engines. The learning-rate analysis should therefore be read as a sensitivity on overnight CAPEX.

Building on (Friedl et al., 2023) general formulation and (Comello et al., 2021) considerations on the suitability of the levelised cost concept application to cost of transport evaluations, we define Levelised Cost of Transport (LCOT) as "the cost incurred by the containership-owning operator to transport one TEU (Twenty-foot Equivalent Unit, 20-foot container) for a distance of 1000 nautical miles". In defining the LCOT, we also build on the long-standing use of ton-mile-based metrics in transport and maritime economics. Early applications include Stevens' 19th-century cost-per-ton-mile formulation for rail (Batts, 1976) and analysis of the commercial performance of merchant steamers as discussed by Duru (2017). Our LCOT thus represents a container-specific extension of this established ton-mile framework to TEU-nautical-mile transportation services. Using LCOT, the objective is to identify the propulsion system (Nuclear, VLSFO, Methanol, and Ammonia) with the best economic performance in each identified scenario, across the "scenario-elements" mentioned above. The decomposition of ship costs into capital-related costs, operating (fixed) costs, and voyage/variable costs follows standard conventions in maritime economics (Stopford, 2010). Formally, adjusting (Friedl et al., 2023) formulations to fit the specific needs of this work, we define LCOT as:

$$LCOT(k) = w(k) + f(k) + c(k) \cdot \Delta \tag{1}$$

In (Friedl et al., 2023)'s formulation variable k represents the non-discounted yearly output of the system, which in this work will be the number of TEU transported per year multiplied by the nautical miles travelled per year.

The first component w represents the time-averaged unit variable cost or variable:

$$w(k) = \frac{k \cdot \sum_{t=0}^{T-1} w_t \cdot (1+r)^{-t}}{L(k)} = \frac{\sum_{t=0}^{T-1} w_t \cdot (1+r)^{-t}}{L} \tag{2}$$

The numerator represents the total discounted future variable cost, assuming output k obtained in period t *with* $0 \le t \le T-1$ where T represents the containership useful life's w_t represents the unit variable OPEX in period t. Variable OPEX in this model is composed of the cost of fuel and the cost of carbon tax. The denominator represents the total discounted output attainable over the entire planning horizon T, which in this work is the number of TEUs transported in the useful life, multiplied by the nautical miles travelled in the useful life. Furthermore, the original formulation considers that a x_t component represents a degradation factor of the performance in terms of the output of the interested system. We pose $x_t = 1$ considering a non-degrading output.[1] Considering this, the levelising factor is affected in its formulation with respect to (Friedl et al., 2023):

$$L(k) = L\cdot k = \sum_{t=0}^{T-1}(1+r)^{-t}\cdot k \tag{3}$$

The time-averaged unit fixed cost and the unit cost of capacity are formulated as follows:

$$f(k) = \frac{\sum_{t=1}^{T} F_t(k)\cdot(1+r)^{-t}}{L(k)} \tag{4}$$

$$c(k) = \frac{v(k)}{L(k)} \tag{5}$$

where $F_t(k)$ is the total fixed operating cost in period t that is required for a facility scaled to size of k and $v(k)$ denotes the initial capacity investment expenditure for a facility scaled to size of k units of production capacity.

To reflect the payment of income taxes, the *LC* includes a tax factor that acts as a multiplier on the unit cost of capacity:

$$\Delta = \frac{1-\alpha\cdot\sum_{t=0}^{T}\hat{d}_t\cdot(1+r)^{-t}}{1-\alpha} \tag{7}$$

Here, α represents the effective corporate income tax rate and $\hat{d}_t$ is the share of the initial investment that can be written off in a period t as a depreciation. For simplicity and generality (fiscal considerations are out of scope), we assume $\alpha = 0$, Therefore, $\Delta = 1$ [2]and a consequent final formulation of LCOT which is:

$$LCOT(k) = w(k) + f(k) + c(k) \tag{8}$$

Fig. 1: provides a conceptual representation of our cost model. The complete list of assumptions is presented in the Appendix.

We selected a 12,000 TEU Neo-Panamax containership to apply our cost model. By assumption, any eventual dimensional differences required to accommodate the different systems are considered to have a negligible effect on the model's variables. The Neo-Panamax class holds the largest share (33%) of the market in terms of total capacity and the second-largest share (18%) in terms of absolute number, behind feeders, which are of no interest given their limited size (US Department of Agriculture, 2024). To have a complete overview of the assumptions made for the model application, please refer to the “Appendix” section. Technology-specific data are presented in

Table 2, other inputs are the following:

- Ship size: 12,000 TEU - See ASM1 (Assumptions 1) in the appendix
- Propulsion power: 70 MW (Cepowski, 2017, p. 98), ASM2-3
- Hull CAPEX: 120.450 M$ (Daniel et al., 2022), ASM4-5
- Space utilisation: 70% (Sea-Intelligence, 2023), ASM31
- Time utilisation: 98.4% Based on (US Department of Agriculture, 2024), ASM32
- Discount rate 9.3% (GuruFocus, 2024; Vishawakarma, 2023), ASM34
- Inflation fixed OPEX 1.74% (Drewry, 2024) annual inflation calculation, ASM19
- Port Productivity: 210 CMPH (Achterkamp, 2019), ASM33
- Average trip length 8,174.8 nmi (Freight Mango, 2024; SEA-DISTANCES, 2024), ASM35

4. Results and discussions

This section presents and discusses the results of the model application for the different scenarios. We quantified each scenario's propulsion system from an economic perspective based on LCOT values. In the columns, we presented different values for carbon tax cost, and in the rows, we presented different values for cruising speed. At the same time, each table represented a different value of nuclear propulsion engine CAPEX. Four other scenarios (one illustrated in each figure) were analysed in depth by applying a learning rate to nuclear propulsion CAPEX. Production volume is plotted on the X-axis against achieved LCOT on the Y-axis.

4.1. Results without a learning rate

Starting from the nuclear CAPEX average - value scenarios (Table 3), nuclear is economically competitive at maximum-speed scenarios with a substantial carbon tax, indicating the possibility of its introduction shortly for high-speed transport niches. When considering unfavourable nuclear CAPEX value scenarios (Table 4), nuclear is not economically competitive in any of the identified scenarios, due to the high impact of CAPEX on LCOT. When considering favourable nuclear CAPEX value scenarios (Table 5), nuclear is economically competitive in many scenarios, even at lower speeds and carbon tax values.

To investigate relevant scenarios, we then fixed specific parameters to represent the situation graphically. The graphs plot the results obtained from the LCOT scenario analysis given a specific carbon tax value. Each solid line represents a different propulsion system, while the dotted lines represent the uncertainty range caused by the uncertainty on the CAPEX of nuclear containerships. On the X-axis, we considered speed, and on the Y-axis, LCOT, so the graph focuses on the effect of speed on LCOT. Figs. 2 and 3 present speed as a variable because it is the one that most affects LCOT. Break-even points between different propulsion systems indicate the speed at which the LCOT is equal for the two systems and, as such, the costs incurred by the operator are equal. The descending curves for nuclear indicate that operators would have clear incentives to use high speeds to maintain a high service level at negligible cost. The ascending curves for other propulsion systems indicate that operators face a trade-off between service level and costs. A different level of carbon tax would move the curves of combustion systems affected by carbon levies (VLSFO and Methanol) up or down.

Considering today's conditions in terms of allowances costing 70 $\frac{\$}{t_{CO_2}}$ as a fixed input (Fig. 2), nuclear is hardly competitive compared to the status quo represented by the usage of VLSFO, even in the low CAPEX favourable case, where only for “high” speed (22 and 25 knots) scenarios the LCOT is lower than that of VLSFO. Considering the projected cost of emission allowances in 2035 (220 $\frac{\$}{t_{CO_2}}$) as a fixed input (Fig. 3), nuclear results in being generally more competitive than VLSFO in “high” speed (22 and 25 knots), average and favourable engine CAPEX scenarios

In average-engine CAPEX scenarios, nuclear is the optimal solution only for 25 knots scenarios and emission allowances from 220 $\frac{\$}{t_{CO_2}}$ above, meaning the cutoff in emission allowances is between 150 $\frac{\$}{t_{CO_2}}$ and 220 $\frac{\$}{t_{CO_2}}$ scenarios. In the unfavourable engine CAPEX scenarios, nuclear is hardly the optimal solution compared to the other options. Even with a wider price range for ETS allowances, nuclear would not be competitive with ammonia because neither is affected by carbon levies. In the favourable engine CAPEX scenarios, the nuclear option is competitive across a wide range of speeds (22-25 knots), while being almost as competitive as ammonia in high allowance-cost scenarios (19 knots). Methanol never becomes competitive. Methanol's LCOT is lower than VLSFO's LCOT, but only for high carbon tax scenarios where ammonia or

[1] Degradation factor is introduced in the formulation to ensure a higher degree of generality and applicability of LCOT for future developments but is assumed to be equal to 1 for the sake of this work's simplicity.

[2] Tax factor is introduced in the formulation to ensure a higher degree of generality and applicability of LCOT for future developments, but is assumed to be equal to 1 for the sake of this work's simplicity.

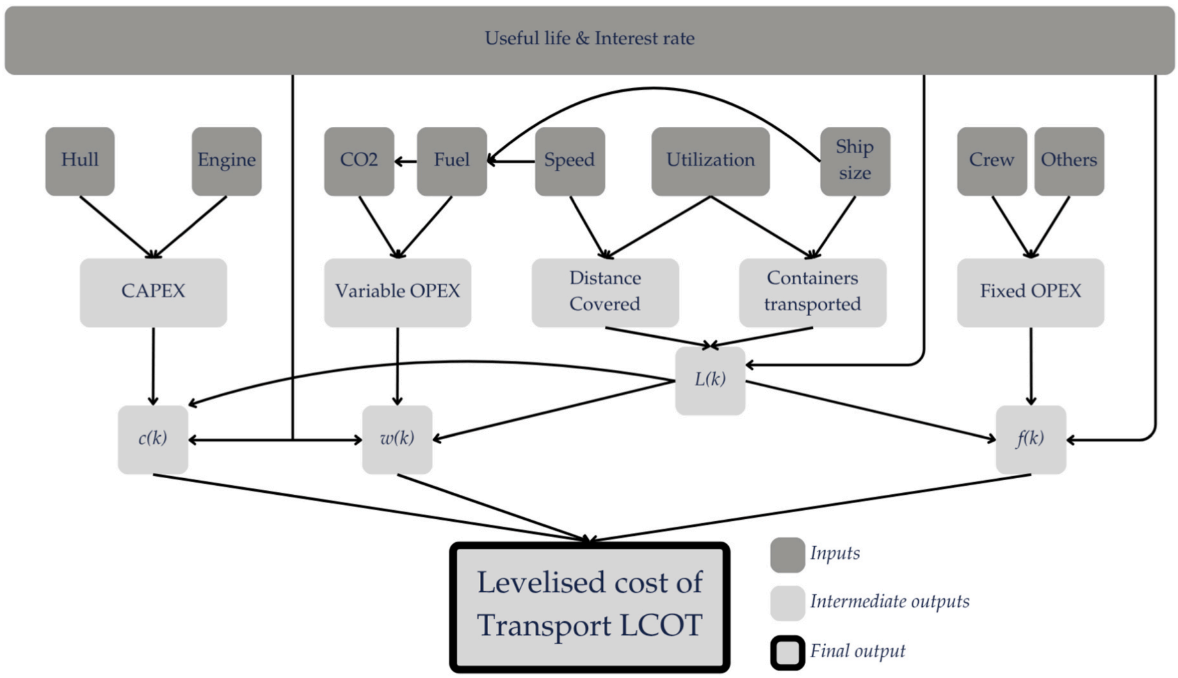

Fig. 1. Model representation.

nuclear LCOT are lower than methanol's LCOT. This can be explained by the fact that methanol is ≈ 40% more expensive than VLSFO when accounting for their different calorific values, while methanol is ≈ 12% less carbon-intensive.

4.1.1. Scenario analysis for fuel consumption

Given the fixed-value approach used for many variables, we performed additional calculations to evaluate a more conservative nuclear fuel consumption rate scenario. In particular, based on (Sadegh-Noedoost et al., 2020, p. 17), we considered the reactor core to contain 9,28 t of nuclear fuel and, based on (IAEA, 2020, p. 5), we considered a fuel replacement rate of one-third of the total fuel in the core over 12 months, giving a consumption of 3,09 t/year. This is in line with the considerations presented in the literature review of a multi-year fuel cycle. As Fig. 4 shows, nuclear fuel consumption has a tangible effect on nuclear propulsion performance and, ultimately, on its economic competitiveness, but at this rate of consumption, nuclear remains a viable solution across multiple scenarios according to this model's results (see Fig. 5).

4.2. Analysis with learning rate

Section 4.1 illustrates the effects of speed and carbon cost on the feasibility of a nuclear-powered containership in a static manner, without accounting for learning-by-doing. This analysis does not account for the potential efficiency gains from building multiple nuclear-powered containerships. Consequently, to make our analysis more comprehensive, we introduce a 9.5% learning rate, as indicated by (Abou-Jaoude et al., 2024) for SMRs, on the engine CAPEX of the nuclear-powered containership. Given the added complexity of introducing learning rates, we analysed four selected scenarios we considered particularly interesting to understand their effects. We selected the following scenarios:

1. Today's emission allowances cost and 19 knots speed
2. 2035 emission allowances cost and 19 knots speed
3. 2035 emission allowances cost and 25 knots speed
4. Today's emission allowances cost and 25 knots speed.

Scenarios 1 and 4 represent current conditions, with 19 knots the most common “slow steaming” speed and 25 knots the ideal speed for nuclear power under the assumption of constant fuel consumption. Meanwhile, scenarios 2 and 3 represent the forecasted market situation in 2035 with two different cruising speeds.

Figs. 6–9 show that the learning rate may significantly affect the competitiveness of nuclear propulsion, both in low-speed scenarios, where it guarantees the solution's higher long-term competitiveness, and in high-speed scenarios, where it strengthens nuclear's position. Specifically, the results of scenarios 3 and 4 further reinforce the considerations regarding speed and demonstrate that few production units would even bring the unfavourable case closer to economic competitiveness at higher speeds. To further enrich our analysis, we also applied a conservative learning rate of 4.75%, half the value reported by scholars. We specifically report below the results of the two most important scenarios:

5. Today's emission allowances cost and 19 knots speed (4.75% learning rate, see Fig. 10).
6. 2035 emission allowances cost and 25 knots speed (4.75% learning rate, see Fig. 11).

The following figures report results, showing that the impact of a lower learning rate is not negligible; however, overall, it does not significantly affect the conclusions drawn from the previous results.

The analysis shows that scenarios that consider nuclear propulsion and speeds below 25 knots are logically debatable. High speeds guarantee a higher service level (at equivalent conditions) and a lower lead time, which, for combustion engines, comes at an increased cost, meaning the analysis of different speeds is necessary and must be evaluated by shipping companies through a cost-benefit analysis. On the other hand, nuclear propulsion paradoxically offers lower costs for higher speeds, given that variable OPEX for nuclear represents a minor component of the cost profile, meaning a nuclear containership operating at full speed would guarantee a higher service level at lower cost. A nuclear containership owner would have clear incentives to operate only at the vessel's maximum design speed, at which nuclear is feasible compared to other solutions. Our findings are also consistent with recent

Table 2
Technology-specific data.

VARIABLE	U. MEASURE	VLSFO	METHANOL	AMMONIA	NUCLEAR
ENGINE CAPEX	$	34,750,000	39,760,000	42,120,000	≈376,700,000 (FAVOURABLE CASE) ≈691,700,000 (AVERAGE CASE) ≈1,017,600,000 (UNFAVOURABLE CASE)
		Based on (Alzayedi et al., 2022), ASM9	Based on (Tu et al., 2024), ASM10	Based on (Tu et al., 2024), ASM11	Based on (Abou-Jaoude et al., 2023), ASM12
END-OF-LIFE ENGINE MARKET VALUE	$	0	0	0	0
		ASM15			
CREW COST	$/day	3,749	3,749	3,749	3,749 + 26,082
		Based on (Bologna, 2010), ASM16-19			Based on (Abou-Jaoude et al., 2024), (Bologna, 2010) ASM18-19
OTHER FIXED OPEX	$/day	12,526	12,526	12,526	12,526 + 26,082
		Based on (Bologna, 2010), ASM16-19			Based on (Abou-Jaoude et al., 2024), (Bologna, 2010) ASM18-19
FUEL COST	$/ton	608	433	466	2,500,000
		Based on (Ship&Bunker, 2024), ASM21	Based on (Methanex, 2024), ASM22	Based on (Edwardes-Evans et al., 2024) ASM24	(de Vries et al., 2024), ASM25
USEFUL LIFE	YEARS	25	25	25	25 (50 ENGINE)
		(Akan and Kiraci, 2023) ASM13-14			(World Nuclear Association, 2025), ASM13-14
EMISSION FACTOR	t_{CO_2}/t_{fuel}	3.151	1.375	0	0
		(European Commission, 2023), ASM36			
LOWER CALORIFIC VALUE	MJ/kg	40.2	19.9	18.6	N&A
		(ClassNK, 2024), ASM37			
LEARNING RATE ENG CAPEX	-	0%	0%	0%	9.5%
					(Abou-Jaoude et al., 2024), ASM 40

Table 3
Propulsion system with the lowest LCOT -Nuclear average case scenarios.

<table>
<tr><td colspan="2" rowspan="2"></td><td colspan="14">CARBON TAX [$/TONCO₂]</td></tr>
<tr><td>0</td><td>50</td><td>60</td><td>70 (2024)</td><td>100</td><td>150</td><td>220 (2035)</td><td>250</td><td>500</td><td>750</td><td>1000</td><td>1500</td><td>2000</td><td>3000</td></tr>
<tr><td rowspan="4">SPEED [KN]</td><td>17</td><td colspan="8" rowspan="3">VLSFO</td><td colspan="6" rowspan="3">AMMONIA</td></tr>
<tr><td>19</td></tr>
<tr><td>22</td></tr>
<tr><td>25</td><td colspan="6">VLSFO</td><td colspan="8">NUCLEAR</td></tr>
</table>

conceptual work on SMR-powered containerships, which highlights that the operational value of nuclear propulsion may be amplified in high-speed regimes, not only at the vessel level but also through potential fleet-level effects (e.g., fewer ships required to sustain a given service frequency), thereby strengthening the economic rationale for operating closer to maximum design speed (Kim et al., 2025).

5. Conclusions

Decarbonising the maritime shipping sector represents a significant

Table 4
Propulsion system with the lowest LCOT -Nuclear unfavourable case scenarios.

<table>
<tr><td colspan="2" rowspan="2"></td><td colspan="14">CARBON TAX [$/TONCO₂]</td></tr>
<tr><td>0</td><td>50</td><td>60</td><td>70 (2024)</td><td>100</td><td>150</td><td>220 (2035)</td><td>250</td><td>500</td><td>750</td><td>1000</td><td>1500</td><td>2000</td><td>3000</td></tr>
<tr><td rowspan="4">SPEED [KN]</td><td>17</td><td colspan="8" rowspan="4">VLSFO</td><td colspan="6" rowspan="4">AMMONIA</td></tr>
<tr><td>19</td></tr>
<tr><td>22</td></tr>
<tr><td>25</td></tr>
</table>

Table 5
Propulsion system with the lowest LCOT -Nuclear favourable case scenarios.

<table>
<tr><td colspan="2" rowspan="2"></td><td colspan="14">CARBON TAX [$/TONCO₂]</td></tr>
<tr><td>0</td><td>50</td><td>60</td><td>70 (2024)</td><td>100</td><td>150</td><td>220 (2035)</td><td>250</td><td>500</td><td>750</td><td>1000</td><td>1500</td><td>2000</td><td>3000</td></tr>
<tr><td rowspan="4">SPEED [KN]</td><td>17</td><td colspan="8" rowspan="2">VLSFO</td><td colspan="6" rowspan="2">AMMONIA</td></tr>
<tr><td>19</td></tr>
<tr><td>22</td><td colspan="2">VLSFO</td><td colspan="12" rowspan="2">NUCLEAR</td></tr>
<tr><td>25</td><td colspan="2">NUCLEAR</td></tr>
</table>

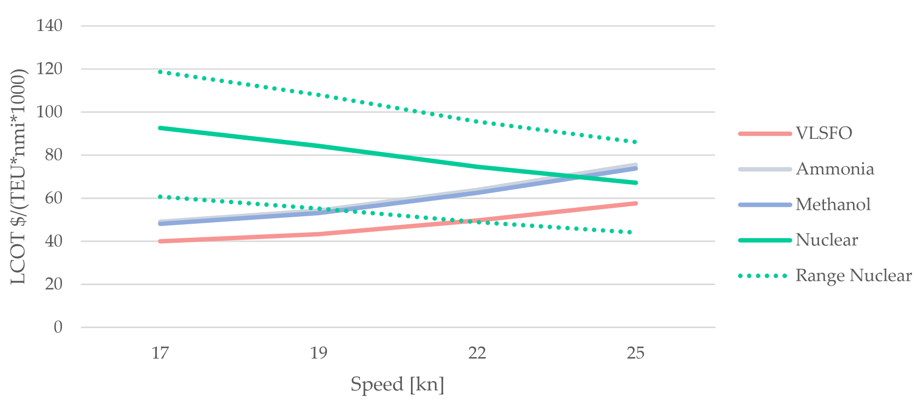

Fig. 2. LCOT with today's carbon levies cost.

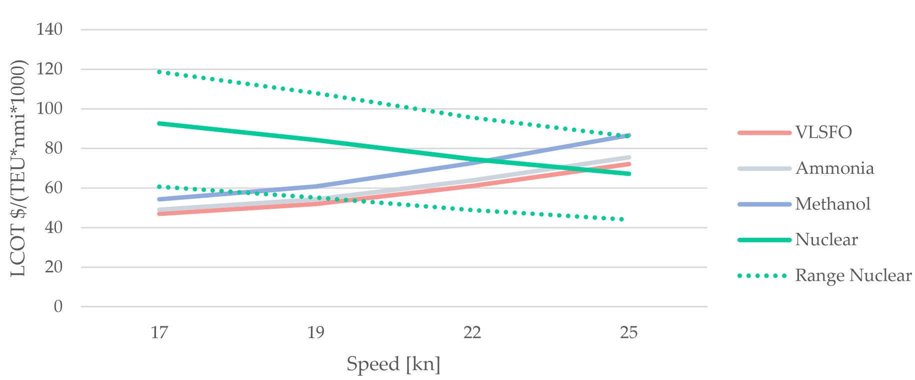

Fig. 3. LCOT with 2035 forecasted carbon cost.

challenge. Both scholars and industry practitioners are actively exploring a range of decarbonisation pathways to identify technologies capable of addressing this pressing issue. Among the options under consideration, SMRs stand out as a particularly promising solution. This

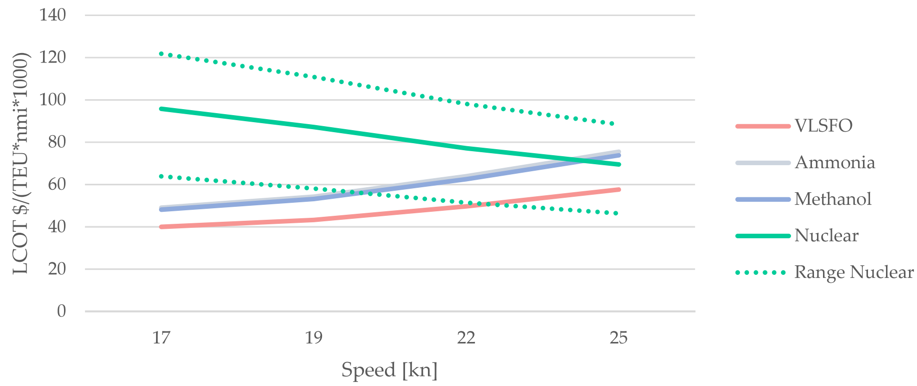

Fig. 4. LCOT with today's carbon levies cost and higher nuclear fuel consumption.

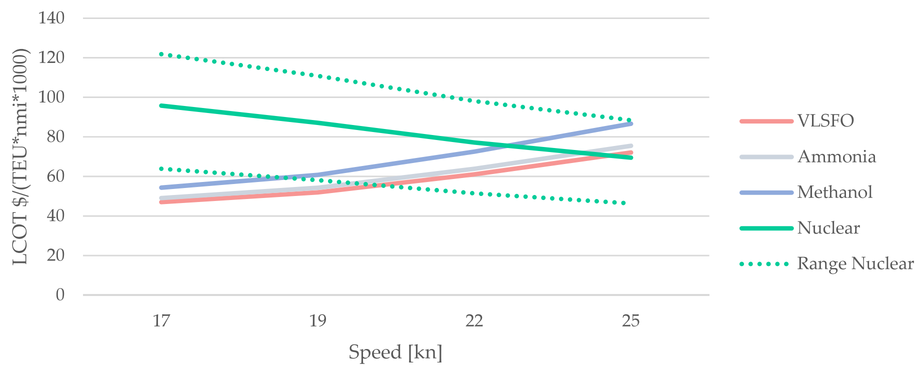

Fig. 5. LCOT with 2035 forecasted carbon levies cost and higher nuclear fuel consumption.

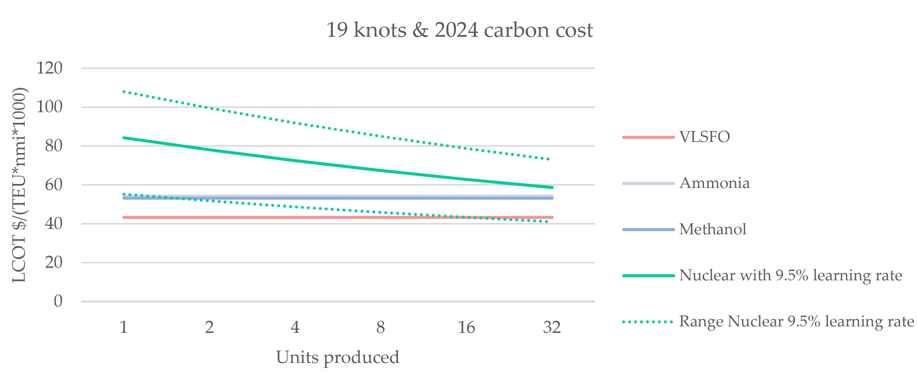

Fig. 6. Scenario 1 - Today's emission allowances cost and 19 knots speed.

Fig. 7. Scenario 2 - 2035 emission allowances cost and 19 knots speed.

Fig. 8. Scenario 3 - 2035 emission allowances cost and 25 knots speed.

Fig. 9. Scenario 4 - Today's emission allowances cost and 25 knots speed.

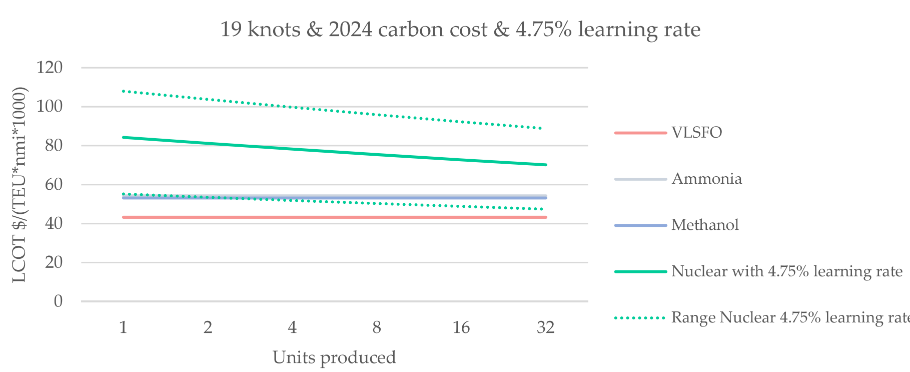

Fig. 10. Scenario 5 - Today's emission allowances cost, 19 knots speed and 4.75% learning rate.

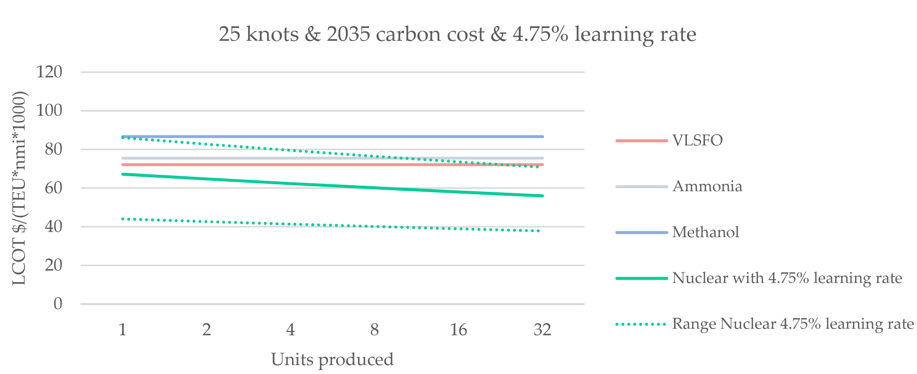

Fig. 11. Scenario 6 - 2035 emission allowances cost, 25 knots speed and 4.75% learning rate.

study aims to investigate the economic competitiveness of deploying a nuclear-powered containership.

Compared to other decarbonisation pathways, such as adopting ammonia or methanol as marine fuels, nuclear propulsion has a greater impact on the technical characteristics and cost structure of containerships. Implementing nuclear propulsion is expected to moderately reduce cargo volume (by approximately 1.5% to 2%) due to additional weight, the consequent need for more ballast tanks, and the reactor's shielding. The useful life of an SMR reactor is expected to be 50 years, double the standard useful life of containership hulls and engines (25 years), allowing the reactor to be used on two different hulls during its useful life. Additionally, nuclear-powered vessels require less frequent refuelling and maintenance, potentially increasing time utilisation rates. Speed management of a nuclear-powered containership would differ significantly from that of a traditional fuel-powered containership, given the clear incentive to operate at full speed, which could affect shipowners' fleet management strategies. CAPEX is radically affected by the introduction of a nuclear propulsion system, leading to an increase in the cost of propulsion between 10 and 30 times compared to the status quo. On the other hand, lower OPEX is expected, specifically due to lower fuel costs, for lower consumption and price stability compared to combustion fuels, even though crew-related costs are expected to rise.

This study presents a model to economically evaluate decarbonisation pathways for containerships based on scenario analysis, levelised cost indicators, and learning rate dynamics. The findings indicate that CAPEX assumptions for nuclear propulsion systems are critical in determining economic viability. Under the unfavourable CAPEX scenario, nuclear propulsion is never the preferred option. In the average CAPEX scenario, nuclear becomes competitive at 25 knots when considering post-2035 carbon allowance price projections. Under the favourable CAPEX assumption, nuclear propulsion proves economically viable across most 25-knot and several 22-knot scenarios. The learning rate analysis further reinforces these findings, demonstrating that nuclear propulsion is clearly economically competitive at a cruising speed of 25 knots. Conversely, at 19 knots, the risk of incurring higher costs than alternative solutions remains substantial.

The main limitation of this work is that technical implementation problems and solutions, as well as the legal framework, were not considered, given its managerial approach, and, as such, should also be investigated to identify the most suitable reactor technology for this implementation. Furthermore, this work overlooks other types of cargo ships, such as tankers, which may be effectively fitted with a nuclear propulsion system, and the possible implementation should be investigated. Estimations and assumptions about OPEX are generally based on limited literature on the topic; thus, it may be expected that a further revision will be needed in future work. Economic considerations should also be revised to generalise the model's results further; for example, real escalation is not discussed throughout the text. In addition, nuclear-specific third-party liability and insurance arrangements, potentially shaped by future statutory or international regimes, are not explicitly quantified and are treated qualitatively as an uncertainty/barrier (Stopford, 2010). Finally, we do not analyse the strategic choices of specific operators, because publicly available information is insufficient to support a rigorous, evidence-based assessment of those cases. Future research should investigate the limitations of this work to enhance the academic and industrial understanding of nuclear-powered cargo ships. An in-depth study of the most suitable SMR design from an economic perspective should be performed, along with research on financing and business models for such ships.

CRediT authorship contribution statement

Giorgio Locatelli: Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Nicolò Guglielmetti:** Writing – review & editing, Writing – original draft, Validation, Investigation, Formal analysis, Data curation. **Giacomo Dei:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis. **Valeriia Skliarenko:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Giorgio Locatelli, Giacomo Dei reports financial support was provided by Horizon Europe. This project has received funding from the Euratom Research and Training programme, a complementary funding programme to Horizon Europe, under grant agreement No 101060920 If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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APPENDIX

Complete collection of model design assumptions.

Table 6
List of assumptions for model design.

ID	Focus	Assumptions
ASM1	Scenarios	Learning rate is applied only to nuclear engine CAPEX. VLSFO is already well developed and thus cannot have a learning rate by theory. Methanol and ammonia, instead, have a learning rate for engine CAPEX by theory, considering the relative technology novelty. Nonetheless, given the marginal contribution of engine CAPEX to the LCOT of said technologies, we decided to exclude their learning rates from the analysis.
ASM 2	LCOT formula	the first period of operation will coincide with the year of capital expenditure $t = 0$
ASM 3	LCOT formula	$x_t = 1$ to consider a non-degrading output. This is coherent with the context of analysis, considering that ship volume and the average trip are not affected by time through the useful life
ASM 4	LCOT formula	$\alpha = 0$. Zero corporate tax situations are generally unrealistic. Nevertheless, $\alpha \neq 0$ would introduce significant variability in the results based on the country considered and consequently distort the underlying analysis, reducing the level of generalisation
ASM 5	CAPEX	"Engine" CAPEX component includes all the propulsion related components of the ship and the auxiliary engine, "hull" CAPEX component includes all the remaining parts of the ship

(*continued on next page*)

Table 6 (*continued*)

ID	Focus	Assumptions
ASM 6	Fixed OPEX	The "Others" component includes stores and lubricants, routine maintenance/repairs, insurance, and general/administrative costs, consistent with the standard operating-cost breakdown discussed in Stopford (2010, p. 225). This item reflects conventional marine insurance; nuclear-specific third-party liability cover is not separately modelled due to limited public data.
ASM 7	Variable OPEX	Carbon Tax calculation is based on the EU's ETS allowances model. Consequently, only direct CO_2 emissions are accounted and only 50% of emissions are accounted for the calculation of the allowances needed (European Commission, 2024a).
ASM 8	Variable OPEX	No ETS transition phase (European Commission, 2024a) is considered. The model applied is the one described in ASM7 from $t = 0$
ASM 9	Utilisation	Utilisation is both in terms of time utilisation (thus considering the average time spent not travelling and not in port to load/unload) and space utilisation (meaning the share of cargo volume occupied by containers)
ASM 10	Exclusion	Container handling costs, port and canal dues are excluded because of the non-fixed route approach followed.
ASM 11	Exclusion	Allowances for nitrous oxides are excluded, even though envisioned by European Commission (2024a), because of the lack of data on costs
ASM 12	Exclusion	Extraordinary maintenance is excluded because of the general impossibility of estimation given the wide variety of interventions that can be performed.

Complete collection of data, model application assumptions, and bibliography.

Table 7
Data collection assumptions and bibliography used in the model application.

ID	Focus	Assumptions and/or bibliography
ASM 1	Ship Size	Ship size is decided a priori. Eventual dimensional differences needed to accommodate the different systems are considered to have a negligible effect on the model's variables
ASM 2	Propulsion power	Propulsion power needed is estimated to be 70 MW based on (Cepowski, 2017). The existence of an engine of this power for each decarbonisation pathway is taken as a assumption.
ASM 3	Propulsion power	Nuclear-electric propulsion power needed by the ship is taken as the MWe production of the reactor. No efficiency loss is considered
ASM 4	CAPEX	CAPEX cost is divided into hull capex (including all components different from the propulsion) and engine capex (including the whole propulsion system)
ASM 5	Hull capex	Hull capex cost is estimated starting from a shipbuilding average cost of 125mln $ for 11000-13000 TEU containerships in 2022 (Daniel et al., 2022), subtracting the cost of a fuel oil engine (see ASM 9) and then actualising the amount to 2024 (see ASM39)
ASM 6	Decommissioning costs and Scrap value	No decommissioning costs or scrap value for the hull were considered
ASM 7	Decommissioning costs and Scrap value	No decommissioning costs or scrap value for the engine were considered
ASM 8	Units of measure	LDT of the ship is calculated based on TEU. TEU is first transformed in DWT through regression from Abramowski et al. (2018) and then from DWT to LDT through coefficient presented in Sanchez and Pereira (2019).
ASM 9	Engine CAPEX	Capex of fuel oil engine estimated as 460 $^{\$}/_{kW}$ multiplied by the engine power (Alzayedi et al., 2022)
ASM 10	Engine CAPEX	Capex of methanol engine estimated as 14.4% more expensive than the fuel oil one (Tu et al., 2024)
ASM 11	Engine CAPEX	Capex of ammonia engine estimated as 21.2% more expensive than the fuel oil one (Tu et al., 2024)
ASM 12	Engine CAPEX	CAPEX of nuclear engine estimated from (Abou-Jaoude et al., 2023, p. 45), isolating NOAK SMRs values only and considering median and 99.3 percentile limits of the sample of estimations, resulting in 7466 $^{\$_{2019}}/_{kW_e}$ (median) for the average case, 10984 $^{\$_{2019}}/_{kW_e}$ for the unfavourable case, 4066 $^{\$_{2019}}/_{kW_e}$ for the favourable case. The symmetric nature of the uncertainty band given by the choice of the normal distribution can be considered as a limitation of this work. Values presented in Table 2 are obtained considering a 70 MW_e reactor (Table 2, ASM 2) and actualisation of values presented above (Table 2, ASM 19)
ASM 13	Useful life	Useful life of hull (All propulsion) and engine (except nuclear) is estimated at 25 years (Akan and Kiraci, 2023). Useful life for nuclear propulsion only is estimated at 50 years (World Nuclear Association, 2025).
ASM 14	Useful life	The model takes into consideration a 25-year containership useful life for all scenarios. LCOT calculations are performed on a 25 useful life. This considered, nuclear propulsion scenarios would entail a positive value for the engine at the end of life of the containership, considering useful life for nuclear propulsion is estimated to be 50 years (Table 2, ASM 13), but, considering ASM 7, this positive value was not introduced in the model which does not account for Decommissioning Trust Funds either
ASM 15	End-of-life engine value	Considering ASM 6, 7, 8, 14, value of the engine at the end of life is put equal to 0 for all systems
ASM 16	Fixed OPEX	Crew cost for combustion engine scenarios estimated from Bologna (2010) and actualised through cost factor (see ASM 39)
ASM 17	Fixed OPEX	Other fixed operating costs for combustion engine scenarios estimated from Bologna (2010) and actualised through cost factor (see ASM 39)
ASM 18	Fixed OPEX	Nuclear propelled containership total fixed OPEX is given, in a conservative way, by ASM 16 + ASM 17 + 136 $^{\$}/_{kW_e*yy}$ for the reactor fixed OPEX, "moderate" estimation from Abou-Jaoude et al. (2024). In particular, we estimated the operational costs of a nuclear containership to be the sum of the operational costs of a combustion engine ship (presented in ASM16 and ASM17) and the operational costs of a comparable SMR as presented by (Abou-Jaoude et al., 2024) (moderate estimation), including dedicated personnel and maintenance for the reactor. This approach guarantees a conservative estimation of fixed OPEX, given that no possible efficiencies and overlaps between the two estimations are considered.
ASM 19	OPEX	Inflation for operating costs except fuel during useful life is estimated through Drewry Ship Operating Index (Drewry, 2024). The value considered is the average of the index as indicated by Drewry between 2008 and 2022
ASM 20	Variable OPEX	No efficiency factors considered
ASM 21	Variable OPEX	For fuel oil engine, utilisation of VLSFO exclusively, with price as average of Global 20 Ports Average index in the period 01/08/24-01/11/24 (Ship&Bunker, 2024)

(*continued on next page*)

Table 7 (*continued*)

ID	Focus	Assumptions and/or bibliography
ASM 22	Variable OPEX	For methanol engine, price given: average cost of methanol contracts for Europe, Asia, China in the period 12/23-11/24 (Methanex, 2024)
ASM 23	Variable OPEX	For ammonia engine, utilisation of grey ammonia (produced by natural gas) only. This choice was made from an economic point of view, given that EU ETS, as of the time of this work, accounts for direct CO_2 emissions only (European Commission, 2024a). Considering that carbon emissions are found only in the production of ammonia and not in its usage (considering good burning conditions), EU ETS costs are entailed by ammonia producer only. This means that ammonia users, as of today, have an economic incentive in using grey ammonia for its cheaper price. The effect of carbon taxes paid by the ammonia producer on the price of grey ammonia was not considered, as this would be outside the scope of this work. However, not considering any increase in the price of ammonia leads to a conservative approach towards the analysis of nuclear, which is appropriate for this work.
ASM 24	Variable OPEX	For ammonia engine, price of fuel given: cost of grey ammonia price is average of average price in Black Sea, Middle East, Far east, US and northwest Europe in the month of September 2024 (Edwardes-Evans et al., 2024)
ASM 25	Variable OPEX	For Nuclear-electric, price of fuel estimated by (de Vries et al., 2024)
ASM 26	Variable OPEX	Fuel consumption for fuel oil is calculated through regression from (Vancouver Fraser Port Authority, 2018). The model fitted to Clarkson data of 1,350 records is: $\textit{Fuel consumption}\frac{tons}{day} = 0.000074(\textit{ship size in TEU})^{0.635}\cdot(\textit{speed in knots})^{2.883}$. The model replicates the fuel consumption of the Clarkson data with an average deviation of about 0.5%.
ASM 27	Variable OPEX	Fuel consumption for methanol, by assumption, follows the same regression as fuel oil, after adjusting for the different lower calorific value (see ASM 37)
ASM 28	Variable OPEX	Fuel consumption for ammonia, by assumption, follows the same regression as fuel oil, after adjusting for the different lower calorific value (see ASM 37)
ASM 29	Variable OPEX	Nuclear propulsion system fuel consumption is only moderately influenced by speed (Vergara and McKesson, 2002). Given this, by assumption, we consider equal consumption of nuclear fuel at all speeds, 1.75 tons/year derived from (Nuclear-Power, 2024) which is a conservative figure considering that, elaborating on Abou-Jaoude et al. (2024), a consumption of 1.56 tons/year can be estimated for a PWR producing 70 MWh all year round and consumptions in the order of 0.3 tons/year for HTGR and SFR technology SMRs
ASM 30	Variable OPEX	No inflation is considered on the cost of any fuel. This is because cost of petrol derivatives (and thus fuel oil) is highly volatile (Bacon and Kojima, 2008) and hardly reduceable at a linear inflation rate. Consequently, also inflation on other fuels is not considered to ensure equal conditions.
ASM 31	Utilisation	Space utilisation is derived from (Sea-Intelligence, 2023), data from November 2023
ASM 32	Utilisation	Time utilisation is derived from the average share of idle containerships in the world fleet (US Department of Agriculture, 2024), data from march 2022. The assumption at the base is that every ship in the fleet has similar idle time. Maintenance is not considered
ASM 33	Port Productivity	Port productivity is calculated from Achterkamp (2019) considering 6 cranes at 35CMPH/crane
ASM 34	Discount rate	As discount rate, we decided to use the average WACC of the 10 biggest shipping companies in the world. Starting from the list of 10 biggest shipping companies (Vishawakarma, 2023), the WACC is retrieved for the ones for which it is available (8/10) from GuruFocus (2024) (accessed 21/05/24) and the average is calculated. This approach is used to estimate a discount rate that could be used by operators in the evaluation of the investment
ASM 35	Route	To evaluate the output of the containership in a year, we decided on a fixed route setting. The fixed route is a fictitious route, its length is given by the average of 5 of the busiest routes in the world as presented by Freight Mango (2024). The length of each of these routes is then calculated through SEA-DISTANCES (2024) and SeaRates (2024)'s calculators. The average is taken as the reference route for this work. Given the scope of this work, for simplicity, no intermediate stops were considered along the route.
ASM 36	Emission factors	Emission factor of fuel oil (Light Fuel Oil taken as a reference) and methanol from (European Commission, 2023)
ASM 37	L. calorific value	Lower Calorific Values from ClassNK (2024)
ASM 38	Exchange rate	Exchange rate euro dollar 1.0807 average 12 months 01/09/23-01/09/24 (European Central Bank, 2025). When not specified, dollars as of 01/03/2024
ASM 39	Indexes	Cost factors considered: OPEX 2008-2022 Drewry Ship Operating Index 2008-2022 (Drewry, 2024) 2022-2024 average of Drewry Ship Operating Index 2008-2022 (Drewry, 2024) CAPEX Ship and Boat Building Producer Price Index 2008-2024 (Federal Reserve Bank of St. Louis, 2024)
ASM 40	Learning	Learning rate nuclear 9.5% (Abou-Jaoude et al., 2024)

Acronyms and uncommon units of measure

ASM = *Assumption*
CAPEX = *Capital Expenditure*
CMPH = *Container Moves per Hour*
DWT = *Deadweight Tons*
ETS = *Emission Trading Scheme*
FEU = *Forty-Foot Equivalent Unit*
FOAK = *First Of A Kind*
GHG = *Greenhouse Gases*
GT = *Gross Tons*
HFO = *Heavy Fuel Oil*
IAEA = *International Atomic Energy Agency*
IMO = *International Maritime Organization*

kn = *Knots*
LCOT = *Levelised Cost of Transport*
LCXM = *Levelised Cost per X-Mile*
LDT = *Light Displacement Tons*
MSR = Molten Salt Reactor
nmi = *Nautical Miles*
NOAK = *Nth Of A Kind*OPEX = *Operational Expenditure*
PWR = *Pressurised Water Reactor*
SCWR = Super Critical Water Reactors
SMR = *Small Modular Reactor*
TEU = *Twenty-Foot Equivalent Unit*
TMSR = *Thorium Molten Salt Reactor*
ULCV/ULCS = *Ultra-Large Container Vessel/Ship*
ULSFO = *Ultra Low Sulphur Fuel Oil*
VLCV/VLCS = *Very-Large Container Vessel/Ship*
VLSFO = *Very Low Sulphur Fuel Oil*

Data availability

Data will be made available on request.

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