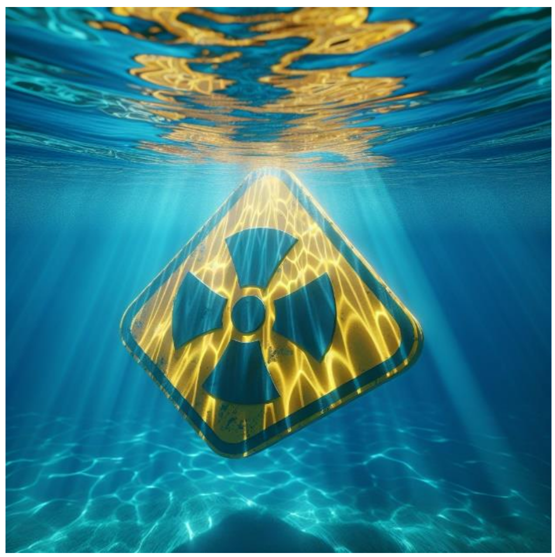
Navigating the Future: A Review of Nuclear Power in Decarbonizing Commercial Shipping



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Abstract

The marine industry must quickly reduce its carbon emissions to meet global climate goals. However, most traditional and alternative fuels cannot provide scalable, zero-emission propulsion across long distances. This review paper looks at how nuclear power, especially Small Modular Reactors (SMRs), may be used to reduce carbon emissions from commercial shipping. Using current changes in technology, the environment, the economy, and regulations, this research gives a whole picture of nuclear propulsion as a possible replacement for fossil fuels. According to Life Cycle Assessment (LCA) studies, SMRs have the lowest greenhouse gas emissions per unit of energy, beating biofuels, LNG, and new synthetic fuels by a wide margin. Advanced containment designs and probabilistic risk calculations show that modern maritime reactors can meet very high safety requirements. New business models like Reactor-as-a-Service (RaaS) and floating power agreements also show promise of getting into the market. Regulatory ambiguity and public image are still big problems, but coordinated international governance, demonstration initiatives, and getting stakeholders involved might help with gradual adoption. The study ends by saying that nuclear propulsion has the potential to change the marine energy picture and help the world move toward net-zero shipping, even if it is complicated and politically sensitive.

Keywords: *Maritime Decarbonization; Nuclear Propulsion; Alternative Marine Fuels*

Abbreviations

ABS	American Bureau of Shipping
CAPEX	Capital Expenditure
CDF	Core Damage Frequency
DNV	Det Norske Veritas
ECCS	Emergency Core Cooling Systems
EPR	Emergency Preparedness and Response
ETA	Event Tree Analysis
FNPP	Floating Nuclear Power Plants
FTA	Fault Tree Analysis
GHG	Greenhouse Gases
HLW	High-Level Radioactive Waste
HMI	Human-Machine Interfaces
IAEA	International Atomic Energy Agency
IMO	International Maritime Organization
LCA	Life Cycle Assessment
LEU	Low Enriched Uranium
LNG	Liquified Natural Gas
LOCA	Loss of Coolant Accident
LOHS	Loss of Heat Sink
LSFO	Low-Sulfur Fuel Oil
MSR	Molten Salt Reactor
NGO	Non-Governmental Organization
OPEX	Operational Costs
PWR	Pressurized Water Reactor
RaaS	Reactor-as-a-Service
SBO	Station Blackout
SMR	Small Modular Reactors
SNF	Spent Nuclear Fuel
TCO	Total Cost of Ownership
TRL	Technology Readiness Level
UNCLOS	United Nations Convention on the Law of the Sea

1 Introduction

The shipping sector is an important part of worldwide trade and a major source of GHG emissions. Commercial shipping is responsible for around 2.8% of the world's emissions (Lindstad et al., 2021). It is under increasing pressure to cut its carbon footprint in line with international climate goals, including the Paris Agreement, the EU's Fit for 55 legislation package, and the IMO updated GHG policy. To fully decarbonize by 2050, ships will need more than just better operations and alternative fuels. They will also need to change how they use energy.

There are several low- and zero-carbon marine fuels in development or in the early stages of deployment. These include biofuels, ammonia, hydrogen, and methanol. However, each of these fuels has its own set of technological, economic, and infrastructure challenges. These fuels frequently have problems with energy density, lifecycle emissions, safety issues, or availability throughout the world. In this light, nuclear energy, especially with the rise of SMRs and FNPPs, has come back into the discourse as a promising alternative for sectors that are hard to cut back on, like shipping.

Nuclear power has a number of unique benefits for marine decarbonization, including no direct CO_2 emissions, very high energy density, lengthy refuelling intervals, and not having to deal with complicated global fuel logistics. These traits make it an excellent option for large commercial vessels that travel on set routes, especially while infrastructure for alternative fuels is still developing. However, nuclear-powered commercial shipping is still mostly unexplored because of safety issues, regulatory ambiguity, public perception, and high capital expenditures, even though it has a long history in naval propulsion and a few early commercial experiments.

Recent events, including improvements in SMR designs, changing international rules, and the creation of marine nuclear working groups like NEMO and the NuclearDrive Consortium, show that nuclear propulsion may be closer to being commercially feasible than ever before (NEMO, 2024; Van Heek, 2025). Countries like China are aggressively building nuclear-enabled marine infrastructure. In Europe, classification societies and maritime safety organizations are looking into methods to safely employ nuclear power.

This review study looks at how nuclear power may help commercial shipping become less carbon-intensive. It looks at the history and present state of nuclear marine propulsion technology, the environmental and lifecycle effects of nuclear systems, and the main obstacles to deployment, such as regulatory, economic, and social concerns. The paper's goal is to give a complete picture of whether, when, and how nuclear energy might help the marine sector get toward net-zero emissions by looking at current research, legislative proposals, and industry roadmaps.

2 Methodology

This research employs a narrative review technique to critically evaluate the feasibility, obstacles, and ramifications of using nuclear propulsion, specifically via SMRs, in the commercial shipping industry. The main objective is to synthesize many aspects of literature from energy systems engineering, environmental assessment, risk analysis, economics, and policy to establish a comprehensive understanding of the subject and to pinpoint knowledge gaps that warrant more investigation. The article examines five interconnected subject domains: technical preparedness, environmental performance, safety and risk assessment, economic and commercial models, and institutional and social acceptability.

An exhaustive literature search was performed across many academic databases, including Scopus, ScienceDirect, Web of Science, and Google Scholar, to provide a comprehensive and multidisciplinary evidence base. The search strategy was directed by a collection of predetermined keywords and Boolean combinations, including "*nuclear propulsion*," "*maritime AND SMR*," "*nuclear AND shipping*," "*LCA AND nuclear OR maritime*," "*nuclear AND risk assessment*," "*floating AND nuclear power*," and "*nuclear AND regulation.*" These phrases were chosen to encompass the technological, environmental, and policy-related aspects of nuclear propulsion. The inclusion period was established from 2010 to 2025, with a specific focus on literature written in the previous five years to capture current technological developments and ongoing policy debates.

Alongside academic databases, pertinent studies and white papers were obtained from esteemed organizations and regulatory bodies. The entities included the IAEA, the IMO, and many classification societies such as DNV and Lloyd's Register. These sources were especially significant in addressing industry-driven advancements and the present condition of regulatory frameworks.

Literature was chosen for inclusion based on its pertinence to the study goals. Studies were included if they offered technical, economic, environmental, or regulatory insights about nuclear propulsion for marine applications, especially in a commercial setting. Priority was accorded to peer-reviewed journal papers and verified technical reports; however, selected conference proceedings and institutional publications were considered if they provided significant contributions. Sources that concentrated solely on military nuclear applications or showed insufficient technical rigor were omitted from the final dataset.

A total of 68 entries were initially found through databases and grey literature searches. Following the application of inclusion criteria and the elimination of duplicates or irrelevant entries during the title and abstract screening phase, 50 papers were selected for full-text examination. Subsequently, 13 papers were removed for lacking technical content, concentrating solely on military applications, or demonstrating inadequate relevance to the study aims. A conclusive compilation of 37 high-calibre sources was incorporated into the review, comprising peer-reviewed journal articles, technical reports, industry white papers, and institutional publications. Thematic analysis was conducted to derive essential insights across the five conceptual pillars of the study.

This integrative and thematic methodology enabled a comprehensive assessment of the viability of nuclear propulsion in aiding the marine sector's shift to low-carbon operations. It established a foundation for generating insights and suggestions rooted in technology advancements and systemic obstacles, pertinent to researchers, industry stakeholders, and policymakers.

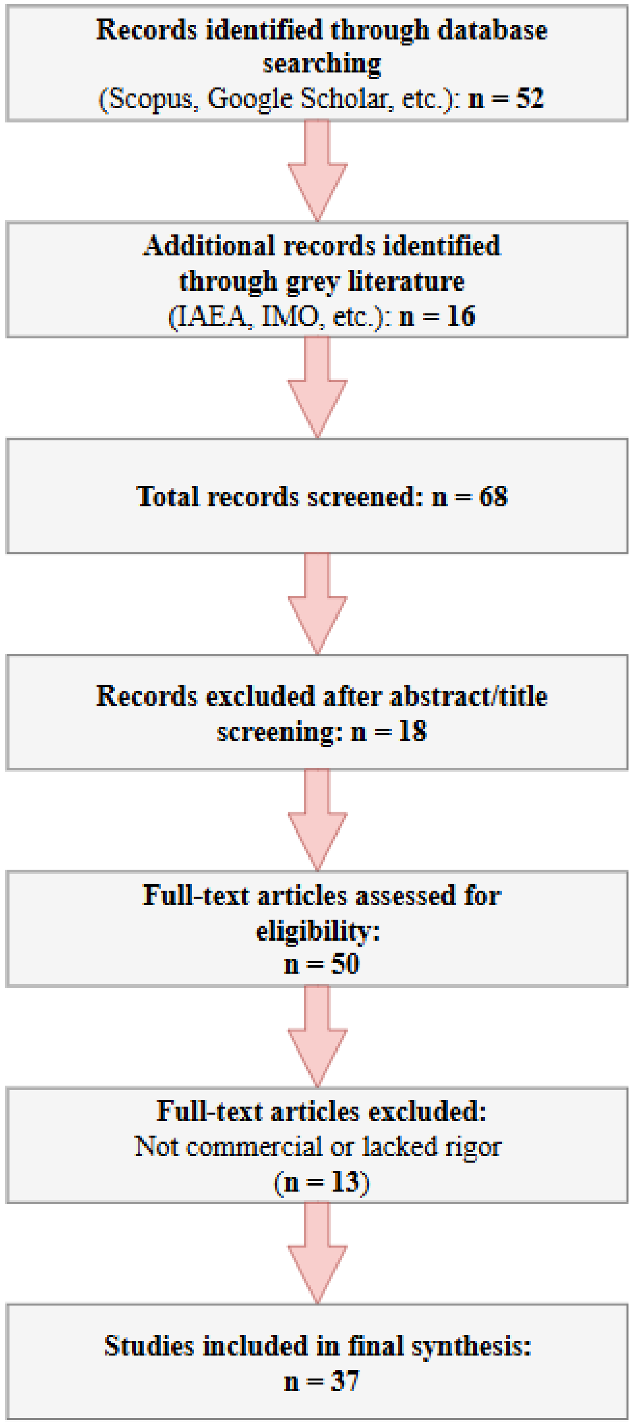

Figure 1. PRISMA-style flowchart depicting the literature screening and selection procedure

3 Nuclear Energy for Shipping – An Overview

Employing nuclear energy in vessels is not a new idea. Nuclear propulsion has been used in naval fleets since the 1950s. It is used in submarines, aircraft carriers, and icebreakers because it offers the best endurance, energy density, and operational independence. The Soviet Union was the first to build icebreakers. The U.S. Navy now has the world's biggest fleet of nuclear-powered ships (World Nuclear Association, 2025). These tests demonstrated that nuclear propulsion can operate effectively in challenging maritime environments and for extended periods.

However, in the business world, nuclear energy hasn't been used much. The NS Savannah (USA), Otto Hahn (Germany), and Mutsu (Japan) were among the first projects to explore whether nuclear propulsion might work for commercial ships. These ships were technically successful, but they were eventually taken out of service because of public resistance, high running expenses, and unresolved regulatory concerns (Hirdaris et al., 2014). Even so, these early instances provided us with important information on how to construct shipboard reactors, what safety standards to follow, and how to integrate them with maritime propulsion systems.

The rise in interest in marine nuclear energy is due to the creation of SMRs and FNPPs. These new-generation reactors have a number of benefits over older ones, such as being built in modules, having better passive safety measures, needing less fuel enrichment, and being able to be mass-produced (New Energies Coalition, 2025; EMSA, 2024). SMRs are being made for high-power applications in tight spaces, such as big container ships or bulk carriers. FNPPs can be used as stationary or movable offshore energy hubs to power port infrastructure or make e-fuels (Saltfoss, 2025).

Several groups are already working hard to find methods to make nuclear-powered shipping a business. The NEMO initiative and the NuclearDrive consortium in Europe want to make sure that legal and regulatory structures are in place to facilitate deployment at sea (NEMO, 2024). The IAEA has been a big part of promoting technical dialogue through its 2023 Vienna Symposium on nuclear maritime technologies (International Atomic Energy Agency, 2023). It also just started the ATLAS project to make a licensing framework for floating nuclear reactors (MNAG, 2025; Lloyd's Register, 2025).

These projects show that more and more people agree that nuclear energy, especially in its modular and scalable forms, might be the next clean way to power ships. But turning this promise into something that really works will need a lot of work in technical development, international legislation, safety regulation, and getting people involved.

Table 1. Chronological overview of significant milestones in the development of nuclear marine propulsion from 1939 to 2023
(Sources: World Nuclear Association, 2022; CORE POWER UK, 2023; Riviera, 2023; CORE POWER, 2024)

Year	Event
1939	Physicist Ross Gunn of the U.S. Naval Research Laboratory advocates for nuclear-powered submarines.
1946	The UK Royal Navy initiates research on nuclear propulsion technologies.
1951	The U.S. Congress authorizes the building of the USS Nautilus under the command of Captain Hyman G. Rickover.
1953	The first marine propulsion test reactor commenced operations in the United States.
1954	USS Nautilus is commissioned (30 September).
1955	The USS Nautilus commences sea testing on January 17, marking the start of a new epoch in naval combat.
	President Eisenhower advocated for a nuclear-powered commerce vessel as part of the "Atoms for Peace" project.
1956	The Soviet Union starts testing its first marine reactor.

1957	The Soviet Union launches Lenin, the first nuclear-powered surface vessel.
1958	The Soviet nuclear submarine K-3 Leninskiy Komsomol commences operations.
1959	NS Savannah, the first nuclear-powered merchant ship, is launched.
1960	USS Enterprise, the first nuclear-powered aircraft carrier, has launched.
	The UK's HMS Dreadnought, with a U.S. S5W reactor, is launched.
	Soviet K-19, the first SSBN, was commissioned.
1961	USS George Washington begins its first SSBN deterrent patrol.
1962	NS Savannah embarks on her maiden voyage.
	During the Cuban Missile Crisis, nuclear submarines played a pivotal role; the U.S. Navy has 26 nuclear subs operational, 30 under construction.
1963	USS Thresher submerges during deep dive trials—initiates safety redesigns.
1964	The German NS Otto Hahn nuclear merchant ship is launched.
	The NS Savannah reactor is uprated to 80 MWt.
1967	Soviet Project 667A (Yankee class) SSBN with 16 missiles is introduced.
1969	Japan launches NS Mutsu, an 8,000-tonne nuclear merchant vessel.

1972	NS Savannah was decommissioned after 10 years.
1975	U.S. Navy deploys third-generation reactor (S6G) in Los Angeles-class submarines.
1976	The USSR begins deploying third-generation submarine reactors.
1979	NS Otto Hahn is deactivated.
1980s	Peak Cold War era: USSR commissions 5–10 nuclear submarines per year from four yards.
1982	HMS Conqueror sinks ARA General Belgrano—only nuclear submarine kill in warfare.
1986	The Soviet Typhoon-class (the largest nuclear submarines) entered service.
	The Russian NS Sevmorput (nuclear-powered container/LASH ship) is launched.
1989	USS Tennessee, the first Ohio-class submarine with Trident II D5 missile, begins patrol.
1995	Russia introduces fourth-generation submarine PWRs (Severodvinsk class).
1997	Soviet/Russian total nuclear submarine builds reach 245—more than the rest of the world combined.
2000s	China and India officially enter the nuclear submarine community.
2015	NS Sevmorput returns to service following refurbishment.

2021	WANO initiates peer reviews for Russian nuclear icebreakers. AUKUS pact announced to support Australian nuclear submarine development.
2022	U.S. Department of Energy launches a 3-year study on offshore floating nuclear generation; NuScale and Prodigy begin SMR floating plant collaboration.
2023	Samsung and UK-based Core Power explore compact molten salt reactors for up to 800 MWe power barges; Japanese firms invest in Core Power's maritime nuclear R&D.
	Chinese Jiangnan Shipyard unveils the KUN-24AP, a 24,000 TEU container ship concept powered by a thorium molten salt reactor—the first of its kind.

4 Technological Readiness and Pathways

The shift from theoretical ideas to nuclear marine systems that can be used depends on how mature the technology is, how well it can be integrated, and if it meets the demands of maritime operations. Traditional large-scale nuclear reactors are still not practicable for commercial shipping, but the development of SMRs and FNPPs is a major step toward making marine nuclear technology possible.

4.1 Small Modular Reactors (SMRs)

SMRs have a modular design, passive security features, and power outputs that may be scaled up or down, usually between 10 and 300 MWe. These features make them great for use on big vessels that traverse the ocean, such as cargo ships, bulk carriers, and cruise liners (Hirdaris et al., 2014; New Energies Coalition, 2025). Modern SMR designs use improved PWR or MSR setups that are safe and take up less space (Park et al., 2024). Companies like CORE Power (UK), SALTFOSS (Denmark), Athlos Energy (Greece), and government-backed initiatives in China and Russia are working hard to make marine versions of land-based SMRs (CORE POWER, 2024; Saltfoss, 2025; Wang, 2025;CORE POWER, 2025)

These reactors can supply steady baseload power for propulsion and other systems on vessels, and they can run on their own for years at a time. A nice example could be a containership with an SMR that may run for 10 to 20 years without needing to refuel, which would make it less reliant on global refuelling facilities and lower its emissions from logistics.

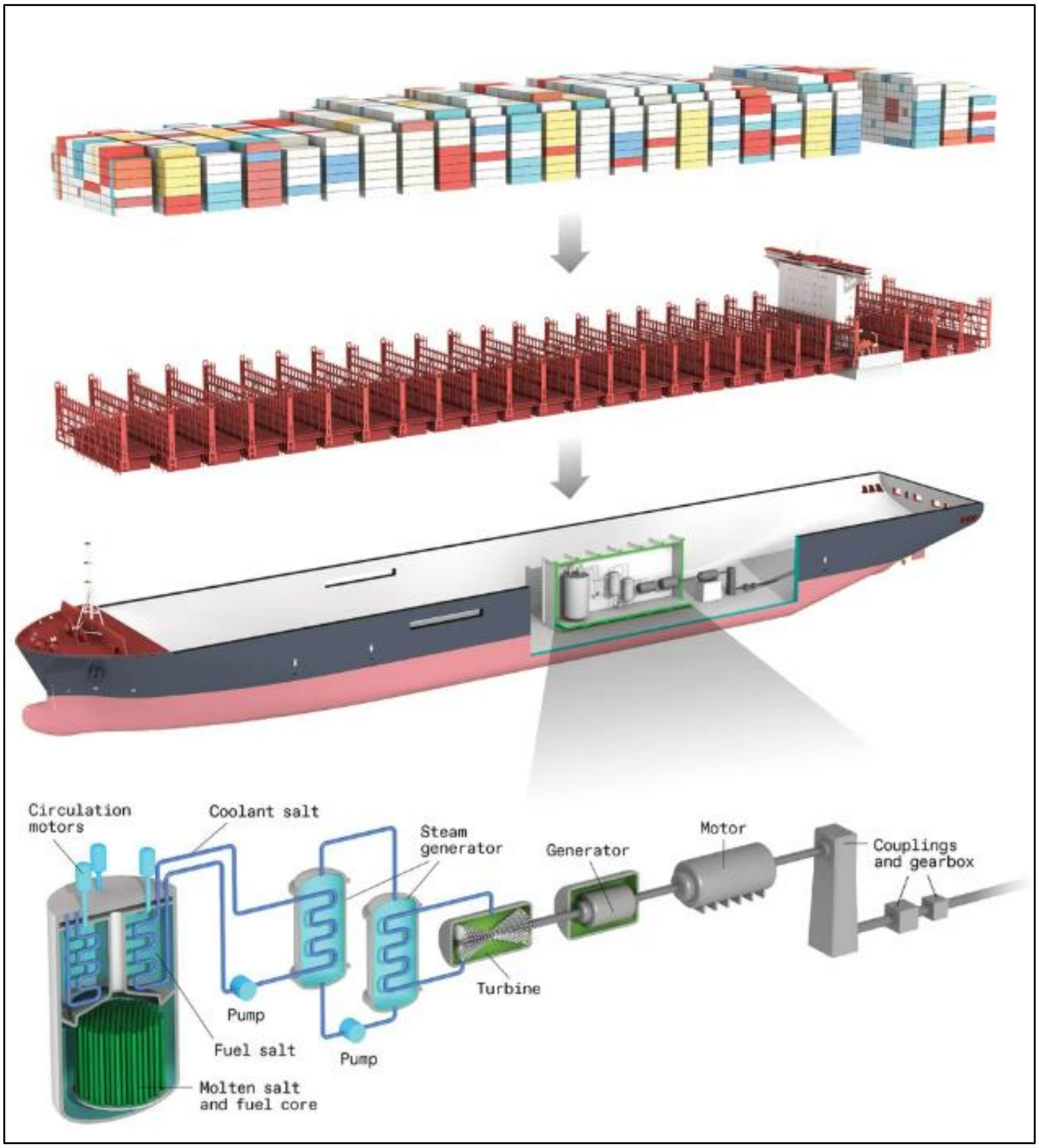

Figure 2. Illustration of a Molten Salt Reactor (MSR) powering a cargo ship (Source: Park et al., 2024)

4.2 Floating Nuclear Power Plants (FNPPs)

FNPPs go beyond propulsion to use nuclear energy for issues like port electricity, cold ironing, making synthetic fuel, and providing power for green corridors offshore. The Akademik Lomonosov, which Russia built in 2020, is the world's first commercial FNPP. It sends 70 MW of power to the isolated Arctic port of Pevek (Laskaris et al., 2025; EMSA, 2024). This accomplishment has brought back interest in movable or moored nuclear barges that might serve as clean energy hubs for coastal industrial or marine areas that can grow.

The IAEA's ATLAS Project, which began in 2024, aims to create a worldwide licensing framework for FNPP deployment. This will help overcome problems that have not yet been solved concerning regulation, insurance, and international responsibility (Lloyd’s Register, 2025). These steps are important for making nuclear marine infrastructure investments less risky and encouraging international pilot projects.

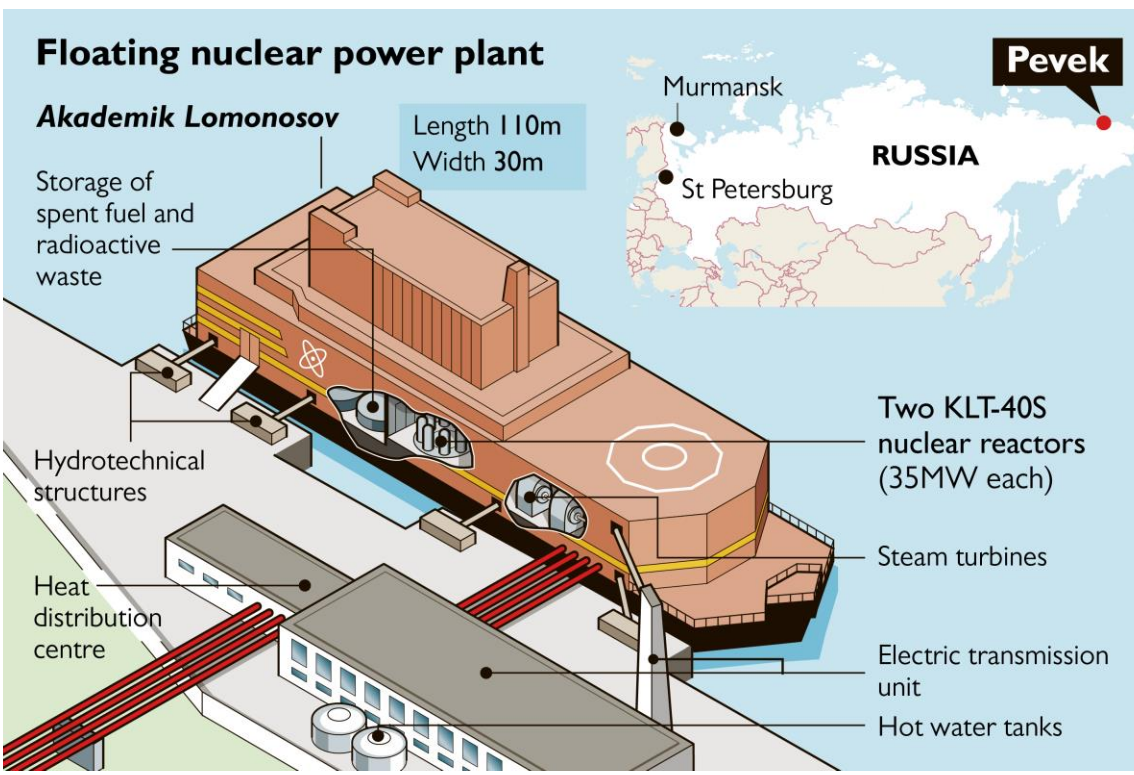

Figure 3. Schematic Illustration of Akademik Lomonosov FNPP (Source: The Times, 2018)

4.3 Integration Challenges and Readiness Assessment

Despite promising advances, significant challenges remain before full-scale commercial adoption. These include:

- **Design certification and classification**: No SMR has been certified for use aboard a commercial ship by any international classification organization yet; however, prototypes are being looked at (EMSA, 2024; NEMO, 2024).
- **Thermal-hydraulic coupling**: To combine reactor systems with maritime propulsion (particularly shaft or pod drives), you need specific control and redundancy architecture (Hirdaris et al., 2014)
- **Designing ships and adapting their hulls**: Shielding, weight distribution, and confinement all affect the structure of the ship and its stability.
- **Cybersecurity and control systems**: To achieve IMO safety requirements, marine reactors must be able to withstand both physical and digital assaults (U.S. Department of Energy, 2025).

Different types of reactors and uses have very different levels of TRLs. SMRs for land-based grids have achieved TRL 7–8; however, maritime SMRs are still at TRL 4–6, depending on how they are built. FNPPs like the Akademik Lomonosov are in use for business, but they are unique in terms of regulation, which makes it hard to know if they can be used in the same way in Western countries (New Energies Coalition, 2025).

Table 2. Comparison of Key SMR Designs for Maritime Use

SMR Developer	Reactor Type	Power Output (MWe)	Target Application	Status
SALTFOSS (Denmark)	MSR (Thorium-fueled)	50–150	Shipping and port power	Pre-commercial (Startup)
NuScale (USA)	PWR	77 per module	Land-based, potential marine adaptation	NRC-certified, commercial deployment by 2030
Rosatom / OKBM Afrikantov (Russia)	PWR	55	Icebreakers, FNPPs	Operational (e.g., *Akademik Lomonosov*)
China National Nuclear Corp.	PWR	125	Land-based, marine R&D	Construction phase (Hainan, China)

There will still be several demonstration projects between 2030 and 2035, and commercialization is likely to happen between 2040 and 2045, as long as there is continuing international cooperation and political will (International Atomic Energy Agency, 2023; Laskaris et al., 2025; Kim et al., 2024).

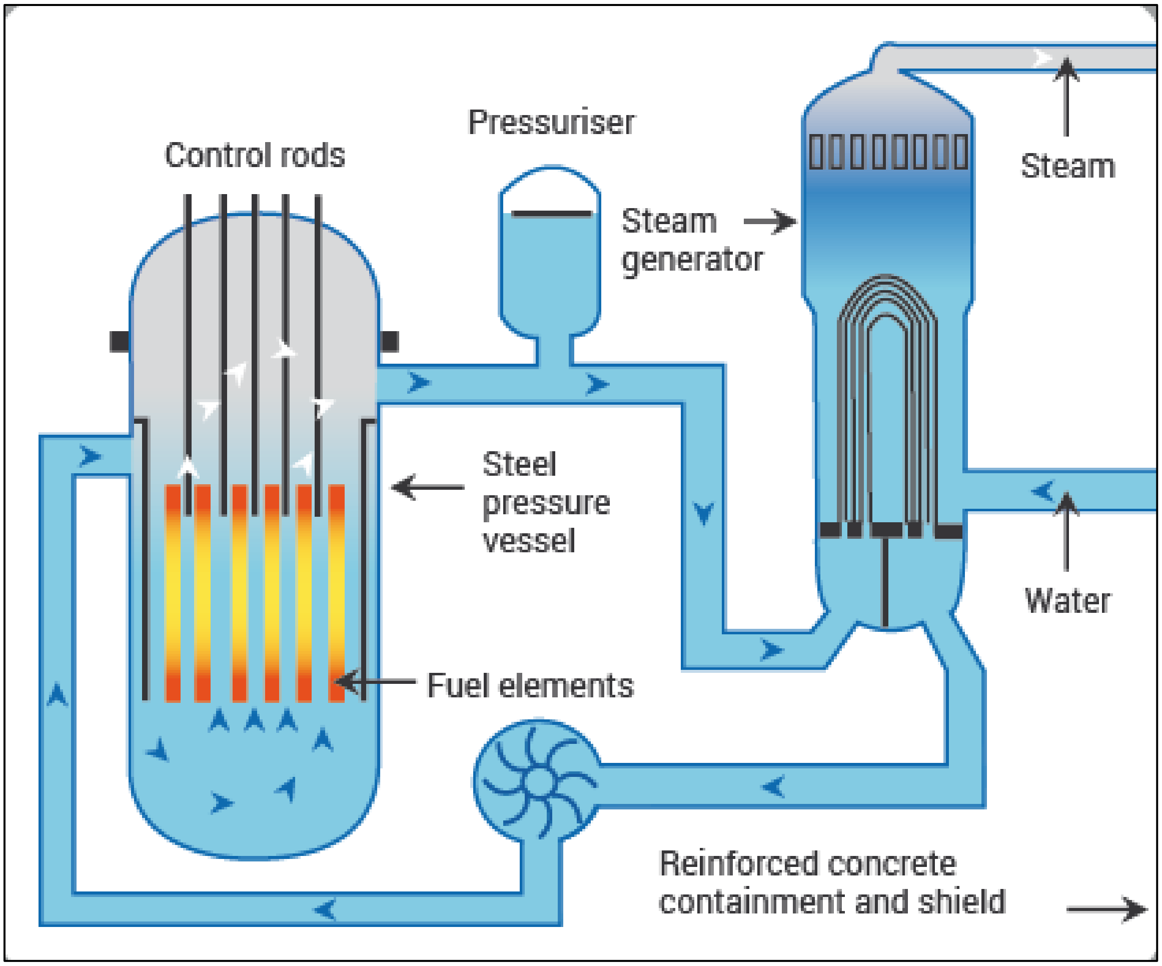

Figure 4. Pressurized Water Reactor (PWR) (Source: Kim et al., 2024)

5 Environmental Performance and Life Cycle Impacts

The environmental impact of nuclear-powered ships needs to be looked at across their whole life cycle, not just their emissions while they're running. Nuclear propulsion doesn't directly release GHGs while it's running, but a full assessment needs to look at all the steps involved, from uranium mining to fuel fabrication to reactor manufacturing to ship integration to operation to decommissioning to radioactive waste management.

5.1 Operational Phase Emissions

From an operational point of view, nuclear propulsion has a zero-emission profile for CO_2, NOx, SOx, and $PM_{10}/PM_{2.5}$ since the fission process doesn't generate any combustion gases. This trait is better for the environment than any carbon-based fuel, such as LNG, LSFO, or synthetic hydrocarbons. Also, nuclear propulsion does away with the requirement for carbon abatement technology like exhaust gas cleaning systems (scrubbers) or carbon capture equipment. This makes things even simpler and lowers the amount of energy needed on board (Bayraktar & Yüksel, 2023; EMSA, 2024).

5.2 Life Cycle Greenhouse Gas Emissions

In terms of LCA, nuclear energy exhibits one of the lowest cradle-to-grave GHG intensities among all propulsion options. According to Lenzen, (2008), nuclear LCA emissions are typically in the range of 10–20 gCO_2 Eq./kWh, considering mining, enrichment, construction, operation, and decommissioning. This value is comparable to wind energy and significantly lower than the life cycle emissions of hydrogen (especially from natural gas reforming), ammonia, and biofuels when fossil-derived energy inputs are considered (Bhattacharyya et al., 2023).

A normalized comparison of the amount of usable energy given to propulsion (kWh) shows that nuclear is better at reducing carbon emissions, especially for long-haul maritime routes, when combustion-based choices add emissions from fuel delivery. Also, because naval reactors may last for 15 to 30 years, the average GHG intensity goes down over time as the emissions from building the reactor and processing the fuel are spread out over that period.

5.3 Radioactive Waste and Environmental Risk Metrics

Radioactive waste is a particular environmental externality that comes with nuclear technologies. Nuclear waste, on the other hand, is very concentrated, easy to find, and protected by strict international rules. This is not the case with scattered GHG emissions from burning fuels. It is planned that HLW from maritime SMRs would be kept in reinforced casks on board and moved to onshore storage facilities or reprocessing plants every so often (Laskaris et al., 2025).

Studies like Tao et al., (2022) use event tree and fault tree analysis together with Monte Carlo simulation to figure out the chances of environmental risks happening in accidents like collisions, fires, or breaches of containment. These simulations show that even if a nuclear accident may have a big effect, the projected environmental damage (probability-weighted risk) is far lower than that of oil spills or LNG leaks in similar marine situations. Christian and Kang, (2017) go on to say that the chance of a catastrophic fuel cask failure during maritime transportation is less than 10^{-6} per cargo when IAEA-compliant transport measures are followed.

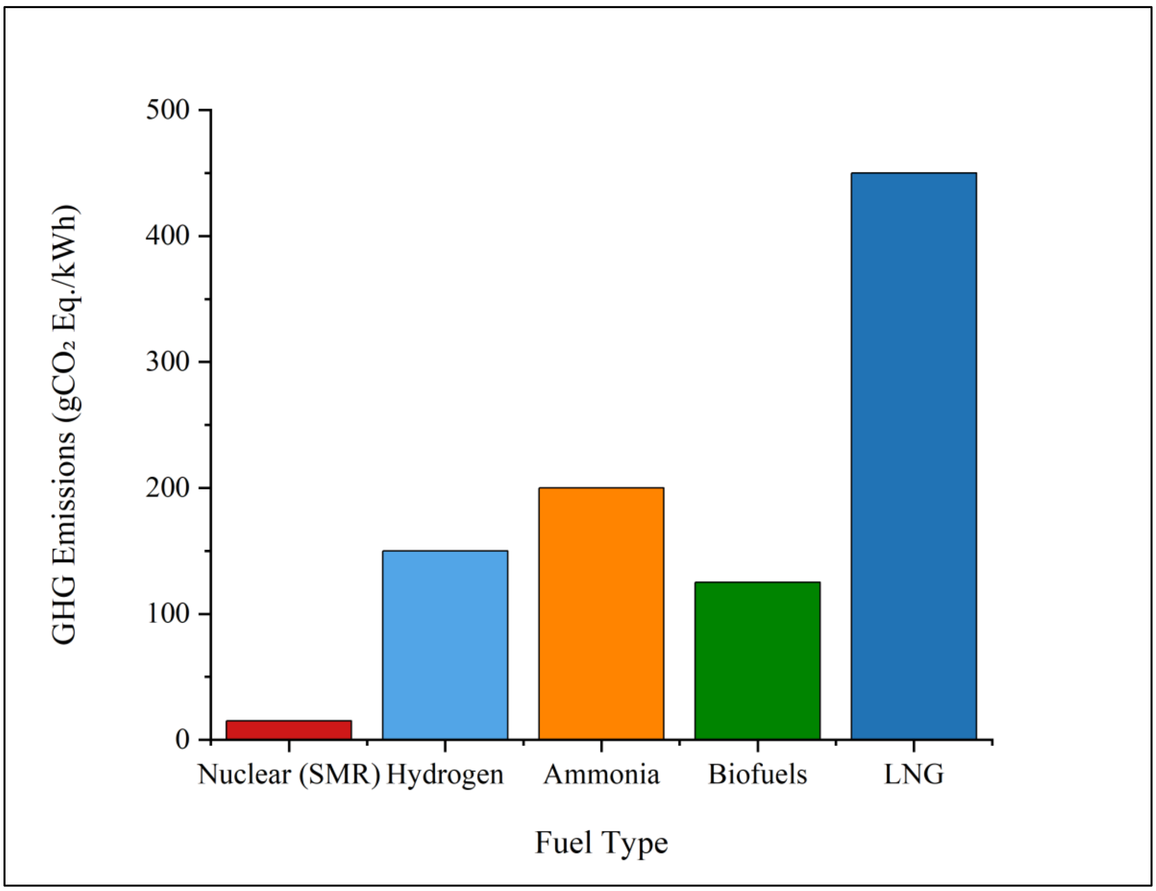

Figure 5. Estimated life cycle greenhouse gas emissions of selected marine fuels (Sources: Lenzen, 2008; Tao et al., 2022; Bhattacharyya et al., 2023; EMSA, 2024)

5.4 Comparative Environmental Profile of Marine Fuels

Table 3 presents a comparative analysis of nuclear propulsion and chosen alternative marine fuels, focusing on operational emissions, life cycle greenhouse gas emissions, and energy density. An illustrative comparison can also be found on Figure 5.

Table 3. Comparative Environmental Characteristics of Selected Marine Fuels
(Sources: Lenzen, 2008; Tao et al., 2022; Bhattacharyya et al., 2023; EMSA, 2024)

Fuel	**Operational GHG Emissions**	**Life Cycle GHG Emissions (gCO_2 Eq./kWh)**	**Energy Density (MJ/kg)**	**Notable Environmental Constraints**
Nuclear (U-235)	0	10–20	~700,000	Radioactive waste, low-accident-probability events
Hydrogen (Blue/Green)	0	100–200	~120	Leakage, production-related emissions, and flammability
Ammonia (Green)	~0 (NOx possible)	100–300	~18	Toxicity, NOx, fuel synthesis energy penalty
Biofuels	Low (depending on blend)	50–200	~40	Indirect land use, certification variability
LNG	Moderate (methane slip)	400–500	~50	Methane leakage, upstream GHGs, non-renewable source

In a nutshell, nuclear energy has a very competitive environmental profile in both the operational and life cycle dimensions, especially for large-scale maritime applications where fuel logistics and greenhouse gas intensity are important factors. Still, further study is being done in the following areas:

- Integration of probabilistic environmental risk models into global maritime LCA frameworks.
- Transparent treatment of decommissioning burdens and waste reprocessing pathways.
- Real-world case studies evaluating public health co-benefits of emission-free port operations using FNPPs.

There is a strong environmental argument for nuclear marine propulsion, but it must be put within a larger framework of technology, economics, regulations, and society so that policymakers and investors can make smart decisions.

6 Risk and Safety Considerations

Adding nuclear propulsion to commercial shipping creates a new risk environment that is different from both typical nuclear power facilities and conventional fuels. Naval reactors have an excellent safety record when they are used in the military, but when they are used in the commercial sector, they are subject to worldwide inspection, a wide range of operational profiles, and civilian regulatory control. This means that hazards need to be reevaluated freshly and thoroughly. This part talks about the technical safety structure of maritime SMRs, gives an overview of probabilistic risk modeling methods, looks at how to handle radiological consequences, and examines new problems like cybersecurity and physical protection.

6.1 Reactor Safety Systems and Marine Integration Challenges

Most modern SMRs that are being suggested for use at sea are based on integrated reactor design concepts. This means that the reactor core, steam generators, and pressurizers are all housed in one vessel. This small design makes the primary loop geometry easier, lowers the number of possible leak locations, and improves the safety features that are already there (Office of Nuclear Energy, 2023; EMSA, 2024).

Gravity-fed ECCS, natural convection for removing decay heat, and negative temperature coefficients are all examples of passive safety mechanisms that are built into modern naval reactor designs. These mechanisms are designed to keep the core cool and not become critical without any intervention from the operator or outside power during design-basis accidents like LOCA, LOHS, and SBO.

Additionally, marine-specific considerations must be addressed:

- Hull motion and pitch-roll dynamics necessitate the use of robust thermal-hydraulic designs to maintain coolant circulation.
- Seawater intrusion protection systems must isolate the primary loop and electrical equipment from corrosive or conductive environments.
- Shock and vibration resistance for core structures and instrumentation must comply with naval-grade standards.
- Radiation shielding must be optimized for space-limited shipboard environments while protecting crew and cargo.

The Russian RITM series, CORE Power's MSR idea, and SALTFOSS's thorium-based reactor all have these qualities; however, most are still at TRL 4–6 for use in the ocean.

6.2 Probabilistic Risk Assessment (PRA): Methods and Metrics

The nuclear power and maritime engineering fields have developed PRA methods that are used for quantitative risk evaluations of marine nuclear applications. Tao et al. (2022) provide a framework that combines:

- ETA for accident progression
- FTA for component/system failure probabilities
- Monte Carlo simulation to propagate uncertainty across thousands of accident scenarios

Tao et al. studied FNPP deployment scenarios and came up with a CDF of about 10^{-7} to 10^{-8} per reactor-year, which is similar to Generation III+ land-based reactors. Their model takes into account maritime dangers that are peculiar to each site, such as the chance of collisions in busy sea lanes, exposure to harsh weather, and mistakes made by people when moving ships in a harbour.

More sensitivity analysis found that SNF storage systems, electrical isolation of safety-critical instruments, and containment integrity under floods or tilt were major factors in the total risk. Christian & Kang (2017) also found similar results when they modeled radioactive leakage paths during SNF marine transit. They came to the conclusion that IAEA Type B(U) cask regulations provide a containment probability of more than 99.9999% even in the worst-case scenario.

6.3 Radiological Release Consequences and Emergency Preparedness

Radiological consequences in marine contexts are highly scenario-dependent but typically localized in extent due to:

- Small core inventories (relative to land-based reactors)
- Rapid containment heat dissipation due to ocean proximity
- Enclosed shielding geometry onboard vessels

In the worst-case circumstances of LOCA without enough core cooling, noble gases, volatile iodine, and cesium might be released. However, the integrity of the containment vessel, high burnup thresholds, and delayed decay heat release durations make it possible for emergency intervention to happen within reasonable time frames. Quantitative dose modelling (Christian & Kang, 2017) reveals that the public dosage stays within the 1 mSv/year regulation limit at a distance of 1 km, save in the most extreme multi-failure situations.

The IAEA recommends graded EPR for marine nuclear applications, including:

- Zone-based evacuation plans for ports of call
- Floating reactor-specific EPZs
- Onboard radiation detection and dosimetry systems
- Real-time coordination between port authorities, ship operators, and national nuclear regulators

The ATLAS Project (Lloyd's Register, 2025) is working hard to make the EPR and licensing standards for FNPPs the same. This will affect commercial ships that use SMR power in the future.

6.4 Security of Nuclear Material and Cyber-Physical Systems

It needs to deal with purposeful threats like cyber-attacks, piracy, and terrorism in addition to regular accident situations. Naval expertise is a good starting point for safety, but commercial nuclear ships will need more openness and collaboration across different jurisdictions for defence.

Marine SMRs will probably use LEU below the 20% U-235 level, which lowers the chance of spreading. Most designs also have sealed reactor cores that can't be accessed while the reactor is running. But nuclear ships must follow IAEA INFCIRC/225 Rev.5 for physical protection and the combined guidelines from the IMO and IAEA on nuclear transport security. In terms of cybersecurity, weaknesses come from:

- Digital control systems and HMIs
- GPS spoofing or AIS manipulation
- Remote shutdown commands if not adequately isolated

In order to keep maritime nuclear platforms safe, you must follow the IAEA NSS-17, the IMO's Resolution MSC-FAL.1/Circ. 3, and the cyber recommendations of classification societies like ABS and DNV.

Nuclear propulsion systems for ships are quite safe since they have excellent passive designs, small core inventories, and very good ways of figuring out how risky something is. Probabilistic risk studies show that the chances of core damage and radiation discharge are very low, thanks to strong physical and digital security measures. In a commercial maritime setting, nevertheless, safety assurance will need:

- Internationally harmonized regulatory frameworks
- Vessel-specific licensing and design certification
- Dedicated emergency response infrastructure
- Transparent public risk communication

Only by addressing these multidimensional safety challenges can nuclear shipping be accepted as a viable decarbonization solution on a scale.

7 Regulatory Landscape and Institutional Readiness

The adoption of nuclear propulsion in commercial shipping is still limited by both the lack of a uniform and effective international regulatory framework and the fact that the technology is not yet fully developed. Naval nuclear propulsion has always been controlled by secret military rules, but moving to civilian, commercial, and international waters brings with it new legal, institutional, and procedural needs that have not yet fully evolved or are not well organized.

This part looks at the present regulatory framework, points out important gaps, and talks about institutional efforts that are making it possible for nuclear-powered commercial ships and floating nuclear sites to be licensed, classified, and run safely.

7.1 Fragmentation of Existing Regulatory Frameworks

At the moment, there is no international law that deals with nuclear propulsion in commercial ships. There are many different laws that work together to make up the legal landscape. These include:

- **The International Maritime Organization (IMO)**: Oversees maritime safety and environmental regulations through instruments such as SOLAS (International Convention for the Safety of Life at Sea), MARPOL (pollution), and the ISPS Code (security). However, none of these explicitly address nuclear propulsion or reactor safety standards.
- **The International Atomic Energy Agency (IAEA)**: Sets safety standards and safeguards for nuclear materials and facilities, including guidelines for transport of radioactive material (IAEA SSR-6), emergency preparedness (GSR Part 7), and security (NSS-17). While these apply to nuclear cargo transport and land-based facilities, they are not tailored for nuclear propulsion or floating reactors.
- **The United Nations Convention on the Law of the Sea (UNCLOS):** Grants coastal states sovereign rights over territorial waters and exclusive economic zones but lacks clarity on how nuclear-powered merchant ships should be treated, especially in terms of innocent passage, port access, and jurisdiction in the event of an incident.
- **National Nuclear Regulatory Authorities**: Countries have the right to regulate nuclear activity in their waters and ports, leading to inconsistencies in acceptance, inspection requirements, and licensing pathways (NEMO, 2024; EMSA, 2024).

This legislative fragmentation generates ambiguity for classification societies, shipowners, insurers, and port authorities, therefore deterring investment.

7.2 Licensing and Flag State Responsibility

Under contemporary maritime law, the flag state is mostly responsible for making sure that ships registered under its flag follow safety and environmental rules. But now, no flag states have a civilian nuclear marine regulatory system in place, especially one that can license a mobile reactor and make sure it meets naval architecture criteria. Challenges include:

- Determining the competent authority to approve the reactor's nuclear design.
- Coordinating between maritime and nuclear regulatory bodies.
- Establishing protocols for inspection, radiation protection, waste handling, and emergency planning on board.
- Determining liability frameworks in case of cross-border radiological incidents.

The IAEA's ATLAS project, which started in 2024, attempts to solve these problems by working with member nations to create a common framework for licensing and overseeing FNPPs. This framework would be used as a model for nuclear-powered ships (Lloyd’s Register, 2025)

7.3 Role of Classification Societies and Industry Initiatives

Classification societies like ABS, DNV, and Bureau Veritas are very important for certifying the safety of ships. Some, like ABS and DNV, have started research programs and pre-normative rules for nuclear vessels. These projects focus on things like:

- Reactor containment integrity under maritime load conditions.
- Radiation zoning and crew protection.
- Redundancy and failure in marine reactor instrumentation and control.
- Ship survivability and accident response procedures.

However, comprehensive Class Rules for commercial ships powered by nuclear energy are still being worked on and need to be in line with both IAEA safety standards and IMO norms (NEMO, 2024; EMSA, 2024).

In parallel, industry-driven initiatives such as:

- NEMO (Nuclear Energy for Marine and Ocean Industries)
- NuclearDrive Consortium
- CORE Power – Southern Company – TerraPower collaboration

They are trying to bring together technology developers, regulators, and the shipping sector by pushing for demonstration projects and "regulatory sandbox" methods in some places, such as the UK, Norway, and the US.

7.4 Insurance, Liability, and International Conventions

Maritime nuclear propulsion introduces complex liability considerations under instruments such as:

- Paris Convention (1960) and Vienna Convention (1963) on nuclear liability
- Convention on Supplementary Compensation for Nuclear Damage (CSC)
- IMO Civil Liability Conventions (oil pollution, bunker spills, etc.)

None of these directly contemplate nuclear-powered commercial vessels. The uncertainty regarding:

- Who bears financial responsibility in the event of a reactor incident,
- How damage is attributed across borders, and
- Which jurisdiction governs such claims

makes it hard to underwrite because maritime insurers don't have any actuarial models or loss experience for nuclear propulsion situations right now. To move nuclear-powered shipping beyond the demonstration phase, this legal gap has to be filled EMSA, 2024); NEMO, 2024).

Even though it is becoming more technically possible and environmentally justified, institutions are still not ready for nuclear commercial shipping. There are holes in the rules when it comes to design certification, reactor licensing, international responsibility, flag-state governance, and emergency response protocols. Progress is underway through:

- Multilateral initiatives (e.g., IAEA ATLAS),
- Industry collaborations (e.g., CORE Power, SALTFOSS, NEMO, Athlos Energy)
- Pre-commercial classification society engagement,
- Port-state and pilot project proposals.

For nuclear-powered ships and FNPPs to be used safely and effectively, there has to be a coordinated governance approach. This should be led by both the IMO and the IAEA and include standardized safety protocols, unambiguous licensing procedures, and legally sound liability instruments.

Table 4. Summary of Regulatory and Institutional Frameworks Relevant to Nuclear-Powered Shipping

Domain	Entity / Instrument	Current Relevance	Gaps / Challenges
Maritime Safety	IMO – SOLAS, MARPOL, ISPS	Governs ship construction, pollution, and security	No provisions for nuclear propulsion, reactor containment, or radiological safety
Nuclear Safety	IAEA – SSR-6, GSR Part 7, NSS-17	Covers transport of radioactive material, emergency response, and security	Not tailored to mobile nuclear reactors or shipboard operation
Maritime Law	UNCLOS	Defines territorial waters, EEZ rights, and innocent passage	Ambiguity on the treatment of nuclear-powered merchant ships
National Regulation	Flag State & Port State Authorities	Jurisdiction over ship safety and environmental compliance	No nuclear maritime authority in place in most flag states
Classification	ABS, DNV, Bureau Veritas, etc.	Initiating nuclear vessel design studies and rule development	Full class rules for marine SMRs have not yet been formalized

Nuclear Liability	Paris & Vienna Conventions, CSC	Assigns liability and compensation for nuclear accidents	Applicability to nuclear ships is unclear; lacks unified maritime integration
Emergency Preparedness	IAEA – EPREV, GSR Part 7	Provides EPZ and radiological response guidance	No standardized marine-specific EPZ protocols or port coordination frameworks
Institutional Initiatives	IAEA ATLAS Project, NEMO, CORE Power Consortia	Advancing regulatory harmonization and licensing pathways	Still early stage; pilot regulatory models and sandbox testing needed

8 Economic Viability and Business Models

Nuclear propulsion has a very different cost profile than traditional marine fuels and other low-carbon choices. There are strong reasons to support nuclear-powered shipping from an environmental and operational point of view, but the financial feasibility of this type of shipping needs to be carefully looked at across the whole life cycle, from the initial investment and fuel expenses to compliance with regulations and decommissioning (Chou et al., 2022;Lenzen, 2008). This part looks at the economic structure of nuclear marine systems, how they compare to other strategies to reduce carbon emissions, and the new business models that may help make them work.

The CAPEX for nuclear propulsion is far greater than that of most other maritime propulsion systems, even those that are more traditional. The cost structure is based on the complicated process of building reactors, adding radiation shielding, having a lot of safety measures, and getting nuclear licenses. Current estimates say that a 100–150 MWe SMR made for maritime usage might cost between $800 million and $1.2 billion, not including the extra expenses of integrating it into a ship (Rahmanta et al., 2023). But the long service life of nuclear reactors and the fact that they don't need to buy fuel often can make up for this big initial cost.

Over time, OPEX for nuclear ships goes down a lot. Nuclear fuel reloads don't happen very often, usually every 10 to 15 years. Uranium has a high energy density; thus, ships may go around the world without needing to refuel. Nuclear propulsion systems not only almost eliminate fuel expenditures, but they also need less maintenance and wear and tear on their parts because SMRs always provide electricity (U.S. Department of Energy, 2025). Still, OPEX needs to include the costs of following the rules, keeping the crew safe from radiation, training the personnel, inspections, and insurance premiums that are specific to nuclear operations.

When compared to LNG, ammonia, and biofuels, nuclear propulsion shows that it is very competitive in terms of long-term TCO. Nuclear power has the largest initial capital cost, but it saves a lot of money on fuel logistics and can run on its own for more than ten years, while combustion-based alternatives can only run for a few weeks. In a market where carbon is limited and emissions pricing and fuel prices change a lot, nuclear propulsion is a solid and reliable choice (Rahmanta et al., 2023). Its lack of sensitivity to changes in the price of bunker fuel and the expenses of following GHG emissions and sulfur oxides rules makes it a good choice for long-haul, high-power marine routes.

New business structures are needed to make this potential a reality. Because of the legislative and technological issues involved, traditional shipowner-led finance models don't work well for nuclear systems. One such idea is the "RaaS" model. Similar to service-based frameworks in other fields, RaaS lets ship owners rent completely integrated nuclear propulsion systems from specialist suppliers instead of having to buy and maintain the reactor themselves. In this paradigm, the vendor is still in charge of important tasks like providing fuel, running the reactor, keeping it up to code, and eventually shutting it down. By centralizing nuclear knowledge and reducing liability risk, this method makes it much easier and cheaper for shipping firms to do business. It also makes it easier to follow nuclear safety rules by making sure that only qualified people oversee the high-skill, high-risk parts of running a reactor. The RaaS model is like other energy sector initiatives like Energy-as-a-Service (EaaS). It is thought to be a good way to speed up the use of SMRs in commercial shipping by allowing shipowners to use scalable, low-emission propulsion without having to have nuclear-specific skills.

In this approach, specialized vendors lease nuclear propulsion units to ship operators and are responsible for fuelling, maintenance, and following the rules (Wang, 2025). This makes it easier for shipping businesses to handle their finances and operations, and it brings together nuclear experts in one place. Floating nuclear infrastructure is another interesting idea. In this case, corporations run FNPPs near ports or industrial areas and sell energy through long-term power purchase agreements. Public-private partnerships that include SMR developers, marine operators, governments, and classification societies encourage these kinds of arrangements. These agreements make it possible for companies to invest together, create regulatory sandboxes, and share risk in early-stage deployments.

Even while there are evident economic and operational benefits, there are still problems. These include the high initial capital needs, the lack of insurance options, and the public's doubts, which will be discussed in the next section. Still, with smart investments and friendly regulations, nuclear shipping might become a cost-effective and environmentally friendly way to move things by 2050, when the world needs to cut down on carbon emissions.

Table 5. Comparative Economic Positioning (Sources: EMSA, 2024; Bhattacharyya et al., 2023; Laskaris et al., 2025)

Metric	Nuclear SMR	LNG	Ammonia	Biofuels
CAPEX	Very High	Medium	High	Medium
OPEX (Fuel + Maintenance)	Very Low	Medium	High	Medium–High
Energy Autonomy	>10 years	20–40 days	20–30 days	10–30 days
Fuel Price Volatility Risk	None	High	Very High	High
Regulatory Maturity	Low	High	Medium	Medium
Carbon Compliance Advantage	Very High	Medium	High	Medium

Table 6. Barriers and Enablers

Barriers	Enablers
High upfront capital costs	Long fuel autonomy and life-cycle cost advantages

Uncertainty in regulatory and insurance regimes	Initiatives like ATLAS and early engagement by class societies
Public perception and political resistance	Climate targets and security-of-supply pressures
Lack of precedent and pilot demonstrations	Strategic investment by nuclear vendors and maritime alliances

9 Public Perception and Policy Implications

The fact that more people are okay with nuclear propulsion in commercial ships has a big effect on policy, regulation, and market acceptability. The technological and economic arguments for nuclear shipping are getting stronger, but public opinion is still mixed and, in many places, negative. This is because people have historically linked nuclear technology with terrible catastrophes, and there isn't enough clear information on how to keep current reactors safe and minimize risks. So, changing how people see things is just as important as getting beyond technical and economic problems.

People's views on nuclear energy are typically molded by incidents from the past, such as Chernobyl and Fukushima. These views tend to stay the same even when reactor technology and safety regulations have come a long way. When it comes to shipping, this suspicion grows since nuclear-powered ships might be close to people living on the shore and in regions that are important for the environment. People don't know much about SMR designs, which have sophisticated passive safety mechanisms and are much less risky than regular reactors. Floating reactors or nuclear ships are also often linked to worries about their use in the military, geopolitical conflicts, and environmental damage in the case of accidents.

These ideas have real-world effects. Port administrations and coastal governments may not let nuclear-powered ships in or may put limits on them because of popular hostility or cautious legislative frameworks. For example, New Zealand has long had a policy against nuclear power, while various European ports have limited or forbidden access to nuclear-powered navy ships. International maritime law lets ships sail through without any problems, but port-state control and local government can decide whether nuclear ships can dock or get help. So, to be effective, deployment will need to follow international law and also include local stakeholders, environmental NGOs, and the public in a proactive way.

Policy tools and ways of talking about nuclear shipping can help change the story about it. Including nuclear propulsion in national and regional plans to reduce carbon emissions, especially for green corridors, can help it fit in better with climate goals. Pilot initiatives funded by the government that clearly show how safe and effective they are might help create trust and set examples for more widespread use. Carbon pricing systems that give low-emission technologies a boost will also make nuclear propulsion more competitive. Public-private partnerships and international cooperation, like those started by IAEA, IMO, and industry groups like CORE Power, can also make things more legitimate and lower the danger of politics.

In the long term, people will only trust the government if it is open, honest, and includes everyone in decision-making. Bridging the knowledge gap may be done through educational outreach, notably through schools and professional groups. For example, nuclear propulsion areas could be included in marine engineering and policy training. Comparative risk frameworks, which look at the emissions, health effects, and accident rates of nuclear systems compared to fossil fuels, can also help people talk about these issues in a more logical way.

Public opinion is still a big problem, but it can be overcome. Nuclear propulsion may become not only a technically and economically feasible choice, but also a socially acceptable answer within a larger framework for climate and energy transition if policies are aligned on purpose, stakeholders are included, and communication is based on facts.

9.1 Youth-Driven and Multilateral Policy Indicators: The Fusion-Quantum Interface

During the 2025 Youth 7 (Y7) Summit in Ottawa, young delegates in the Energy & Environment track presented a formal proposal under the pillar "Renewables Financing for Energy Security." This project focused on establishing a Renewable Energy Fund, funded by reallocating fossil fuel subsidies, to expedite the deployment and development of clean energy (Youth 7 Summit, 2025). The plan specifically promoted nuclear fusion as a prospective renewable technology, emphasizing its ability to function as a long-term facilitator of energy security, particularly for disadvantaged areas. This was a unique and deliberate support of fusion energy within youth policy, along with a wider generational transition towards high-risk, high-reward climate solutions.

This momentum was distinctly reflected in the 2025 G7 Summit in Kananaskis, Canada, when the Kananaskis Common Vision for the Future of Quantum Technologies was officially endorsed by the G7 chiefs of state (G7 Leaders, 2025). The statement highlighted quantum technologies as drivers of advancements in other vital areas, including energy. It explicitly recognized the significance of quantum computing, sensing, and control systems in advancing the feasibility of nuclear fusion, especially via improved plasma modelling, real-time confinement diagnostics, and magnetic field stabilization. This policy synergy between youth and G7 leadership demonstrates a distinctive confluence of next-generation energy research and development with digital innovation, presenting a novel framework for long-term decarbonization.

This is the inaugural occasion in which both Y7 and G7 platforms have directly linked quantum innovation with nuclear energy advancement. Previous announcements, such as the 2023 Hiroshima G7 communiqué and Y7 Italy’s 2024 proposals, briefly mentioned nuclear energy concerning resilience or net-zero transitions, but did not highlight fusion or digital enablers to this degree. The 2025 cycle signifies a definitive turning point, as policy stakeholders finally see the potential of fusion and its reliance on quantum progress as a unified, coordinated global goal.

10 Emerging Technologies: Fusion Propulsion in Maritime Shipping

10.1 Fundamentals of Nuclear Fusion

Nuclear fusion is a process in which two light atomic nuclei combine to create a heavier nucleus, resulting in the release of a substantial quantity of energy. This is the process that fuels stars, including the Sun, where fusion transpires under intense gravitational pressure and temperatures over 100 million degrees Celsius. On Earth, achieving fusion requires replicating extreme conditions through technology capable of generating and confining high-temperature plasmas (Barbarino, 2023).

Fusion usually happens in plasma, which is a state of matter when atomic nuclei and electrons are in a highly energetic, ionized form. In tokamak reactors, magnetic fields keep plasma in place so that deuterium and tritium, the most prevalent fusion fuel candidates, may collide with one another over and over again. The reaction makes helium and a neutron, which releases a lot of energy because of the tiny mass deficit, which is transformed to energy using Einstein's equation $E = mc^2$. Fusion is a safer and more sustainable technique to get nuclear energy than nuclear fission since it doesn't make radioactive waste that lasts a long time or has the risk of a meltdown (Stacey, 2010; Wesson, 2011).

10.2 Fusion Propulsion in Maritime Shipping

Fusion propulsion is getting more attention as a long-term energy option as the marine sector speeds up its attempts to cut carbon emissions to fulfill IMO goals of net-zero emissions by 2050. There is a lot of interest in alternative fuels like ammonia and hydrogen, but they are hard to store, have lower energy densities, and pose safety risks. Fusion, on the other hand, offers no emissions during operation, very high energy density, and very little radioactive waste, making it perfect for shipping across oceans (Barbarino, 2023; NT-Tao, 2025).

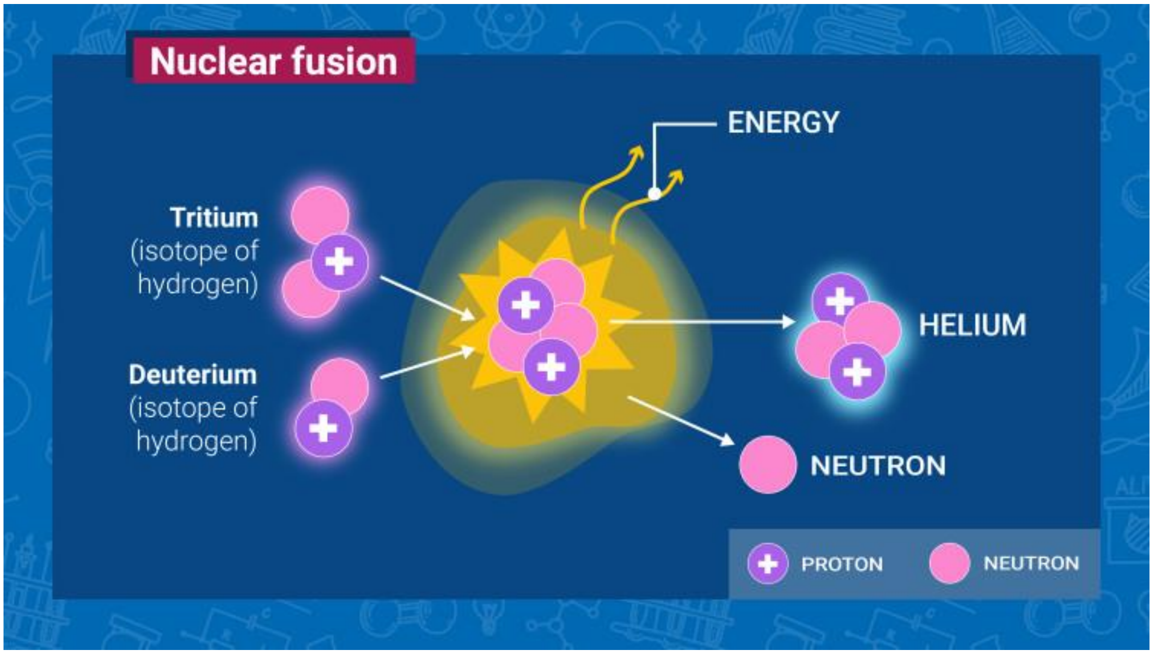

Figure 6. Illustration of nuclear fusion (Source: Barbarino, 2023)

Rheenen et al., (2024) did a thorough feasibility analysis using the Queen Mary 2 as a case study to look at how a small deuterium–tritium fusion reactor based on MIT's ARC design may be integrated. The idea reactor was scaled at about 200 MWe and was determined to fit in the vessel's current architecture, but it would need design changes for shielding and structural support. The main results showed that fusion could work on its own over long distances with no need for fuel, thanks to the lithium blankets that grow tritium on board. But there were several big problems, such as keeping the plasma stable in the changing circumstances at sea, managing vibrations, and sheltering the neutrons.

Simultaneously, technical advancements in the private sector are progressing fusion systems that may be suitable for maritime applications. The Israeli firm NT-Tao is creating ultra-compact, high-field fusion reactors that prioritize flexibility, quick deployment, and spatial efficiency—essential factors for integration aboard ships. NT-Tao's design philosophy diverges from large-scale reactors like ITER by prioritizing small, high-power-density units suitable for integration onto transportable platforms, including vessels (NT-Tao, 2025). These initiatives signify a wider trend towards portable fusion technology, which may provide a significant advancement in sustainable maritime propulsion.

Although fusion propulsion is a prospective option, its strategic potential is considerable. Ongoing investigation into compact reactor design, marine-specific integration, and adaptable regulatory frameworks may advance the feasibility of fusion-powered commercial boats. By synchronizing technical progress with policy preparedness and advancements in marine engineering, fusion might ultimately serve as a fundamental mechanism for decarbonizing global shipping fleets.

11 Conclusions

The necessity to decarbonize the marine industry is increasingly pressing, and nuclear energy is a technically advanced, ecologically sustainable, and economically viable solution for significant emission reductions in commercial shipping. This review study has analysed the viability of nuclear propulsion from several perspectives, like technological preparedness, environmental impact, safety, regulatory frameworks, economic considerations, and social acceptability.

SMRs characterized by their small design, passive safety mechanisms, and prolonged fuel cycles constitute the most feasible technical arrangement for naval use. LCA studies demonstrate that nuclear propulsion yields some of the lowest greenhouse gas emissions per kilowatt-hour, competing with and occasionally surpassing other alternative fuels in long-distance applications. Moreover, probabilistic risk assessment approaches demonstrate that the probability of catastrophic occurrences is exceedingly low, particularly with contemporary containment and redundancy measures implemented.

Notwithstanding these benefits, the implementation process is hindered by insufficient regulatory harmonization, institutional preparation, and market preparedness. Flag nations are now unprepared to authorize or oversee commercial nuclear vessels, and international legal frameworks lack precision regarding mobile nuclear applications. Insurance liability frameworks and classification society regulations must adapt to meet the specific needs of maritime nuclear propulsion.

Economically, although nuclear systems entail elevated initial expenditures, their enduring operational benefits and resistance to fuel price fluctuations provide significant lifespan savings. Business models, including RaaS, floating power purchase agreements, and public-private partnerships, offer viable pathways to mitigate investment risk and promote pilot-scale implementation.

The public's view continues to be the most unpredictable variable. Targeted communication, transparent supervision, and connection with global climate objectives may transform social narratives and establish credibility. Demonstration initiatives and deliberate implementation along green corridors might foster wider adoption.

The implementation of nuclear propulsion in commercial shipping is expected to occur in stages: commencing with near-shore demonstration units, progressing to deep-sea container and bulk carrier utilization, and ultimately evolving into a worldwide network of floating power nodes and zero-carbon shipping routes. Collaboration across sectors, encompassing maritime authorities, nuclear regulators, technology developers, financiers, and civil society, will be crucial to achieve this ambition.

Nuclear-powered commercial shipping is not a distant or theoretical notion, but a viable answer whose time may be imminent. It provides a pathway to carbon neutrality and establishes a basis for a transformative age in marine propulsion, rooted in safety, sustainability, and strategic vision.

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