

Marine nuclear power: back to the future

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Energy Transition

Decarbonization, Alternative Fuels

The decarbonization of maritime transport has become one of the greatest challenges of the global energy transition. Alternative fuels such as hydrogen, methanol and ammonia have physical, logistical and economic limitations that prevent their immediate and widespread development. In this context, nuclear energy is reappearing in the debate, not as a futuristic promise, but as a known, proven technology that has been deliberately relegated for decades for reasons unrelated to its technical viability. The high energy density of uranium, its ability to operate without direct emissions and its prolonged autonomy suggest that its role should be reconsidered in a scenario marked by increasingly demanding climate and energy independence targets and increasingly narrow margins for manoeuvre to implement realistic solutions.

This article analyses the advantages, limitations and conditions under which nuclear propulsion could be a strategic option for certain segments of commercial shipping. Far from proposing universal solutions, it explores recent advances in modular reactors, existing regulatory and legal barriers, and the key role of ports and social acceptance in any possible future deployment.

Energy needs and the capacity to meet them have shaped the development possibilities of societies, from primitive societies based on wood for cooking and heating to today's societies, which use a variety of **energy sources** and **vectors**. **Energy** is not just another commodity; its availability conditions the production and use of all other commodities, hence its importance in the functioning and development possibilities of societies.

A large part of the energy we consume is obtained from combustion processes which, in addition to energy, generate a series of by-products (such as carbon dioxide, nitrogen oxides and particulate matter) that have been proven to be harmful to human health and the environment.

Since humanity became aware of this fact, attention has been focused on the use of **energy technologies** that make it possible to reduce the associated emissions. Achieving this requires reducing and limiting the hydrocarbon combustion processes that currently account for the majority of propulsion in vehicles, aircraft, and ships. In the **decarbonization** process, light-mobility applications (automobiles) have begun the **transition** toward **electric-based technologies**, which would decarbonize the activity provided that the electricity used is generated from **renewable sources**. Heavy applications (aircraft and ships) require amounts of energy that are difficult to store in electrical systems (batteries) and therefore call for other types of **technological solutions**.

Focusing on **maritime mobility**, the most developed solutions currently are **synthetic fuels** such as **hydrogen** and its derivatives (**methanol** and **ammonia**). However, these fuels have certain limitations compared to conventional fuels that condition their applicability to the sector.

During the early stages of **nuclear energy** deployment, applications of this type were considered, but the practical and immediate advantages of using fossil fuels and a general moratorium on the technology limited these applications to very specific cases such as the propulsion of submarines and military aircraft carriers and a few civil applications. This article analyses the advantages and limitations of this technological solution.

Maritime decarbonization and the return of a long-delayed debate

In December 1953, the **President** of the **United States** delivered a speech to the **United Nations General Assembly** known as *Atoms for Peace*, in which he proposed an **international framework** to promote the **civilian use** of **nuclear energy** as an instrument of economic progress, international cooperation and peaceful development, as opposed to its exclusive association with military applications.

More than seven decades later, the **commercial maritime sector** faces a challenge of a different nature but comparable in magnitude: achieving deep **decarbonization** without compromising the **operational efficiency** or **economic viability** of **international trade**. In this context, **nuclear energy** reappears in the maritime debate not as a technological novelty, but as a historically known option that has remained on the sidelines of civil maritime transport development for primarily **regulatory**, **political** and **social** reasons.

Given that the goal is complete **decarbonization** of global **maritime transport**, is it reasonable to exclude in advance a technology that offers **zero emissions** in operation, an **energy density** far superior to any chemical fuel and a **range** compatible with the demands of ocean transport? The question does not imply immediate or widespread adoption, but it does force us to reconsider the current limits of the technological debate.

Nuclear propulsion in the **maritime sector** has operational experience in specialised naval and civil applications. In addition, the recent development of **modular reactors**, characterised by intrinsically safe designs and passive protection systems, has revived interest in their potential use in commercial applications other than power plants. However, its incorporation into **civil maritime transport** poses significant challenges in terms of **international regulation, civil liability, social acceptance** and **port management**, which to date have not been addressed in a systematic and detailed manner.

The energy challenge of large-scale maritime transport

International maritime transport is one of the fundamental pillars of the global **economy**, channelling around **80% of world trade** in terms of volume. This centrality explains why any transformation of its **energy base** has systemic implications that transcend the sector itself, affecting **supply chains, food security, market stability** and **industrial competitiveness** on a global scale.

From an energy perspective, **maritime transport** is characterised by a structural dependence on high-energy-density sources capable of sustaining continuous, high-energy-consumption operations over long periods, in isolated environments and with high reliability requirements. **Large ocean-going vessels** account for a substantial part of the sector's energy consumption and, correspondingly, its **emissions**.

This context forces us to recognise that the **decarbonization of maritime transport** cannot be addressed through a single technological approach. The diversity of **ship types, operational profiles** and **trade routes** requires a wide range of solutions, tailored to the specific characteristics of each segment. In this context, the *a priori* exclusion of certain energy options (for historical or psychological reasons) may unnecessarily limit the sector's ability to achieve its medium- and long-term climate goals.

The predominant response to this challenge has been centred on the development and deployment of **alternative fuels** from **renewable** or **low-carbon sources**, such as **methanol, ammonia** or **hydrogen**. While these options represent significant advances over the use of conventional fossil fuels, their widespread application in large-scale **maritime transport** presents significant physical and operational limitations that cannot be ignored.

Firstly, the **volumetric** and **gravimetric energy density** of these **fuels** is significantly lower than that of traditional marine fuels. This characteristic translates into the need to devote more space on the **ship** to fuel storage, with a direct impact on the ship's **design, available payload** and **economic efficiency** of operation. By way of illustration, a 24,000 TEU container ship on a single voyage between Shanghai and Valencia consumes approximately

5,500 tonnes of **marine fuel** (occupying around 5,600 m³), which is equivalent in energy terms to more than 1,800 tonnes of **hydrogen** (which in its liquid form occupies about 25,400 m³), some 11,000 tonnes of **methanol** or ammonia (which occupy approximately 13,900 m³ and 16,200 m³ respectively). As a reference, an Olympic swimming pool holds approximately 2,500 m³ of water. The equivalent mass of uranium would be 3 kilograms, which would occupy approximately 0.00014 m³, or less than half a soft drink can.

Secondly, the adoption of **new fuels** requires **global supply chains** that are not yet developed. Large-scale production of renewable synthetic fuels requires significant amounts of **clean energy, complex industrial infrastructure** and **international coordination** that is still in its early stages. From a **port** perspective, this implies very significant investments in new **storage, handling** and **safety infrastructure**, with long payback periods and high levels of economic and regulatory uncertainty. The absence of uranium reloading requirements during the ship's operational life makes **refuelling** facilities in **ports** unnecessary. The fuel would be loaded either at the reactor manufacturer's facilities or at the shipyard where the ship is built. It should be remembered that fuel elements have low radioactivity prior to use, which allows for a transport and installation process that is not overly complex, applying the appropriate safety standards already in place.

Added to these limitations is the issue of the **energy efficiency** of the system as a whole. In many cases, **alternative fuels** involve long energy conversion chains – **renewable electricity, hydrogen production, fuel synthesis, transport** and **end use** – with significant cumulative losses. For certain operating profiles, these losses can compromise the **economic and environmental viability** of the solution when analysed from a full life cycle perspective. Uranium exists in nature and is extracted from it. An enrichment process is necessary to increase the isotopic percentage of the fissile material. This process is the same as that required for conventional **nuclear power plants**, so it would be integrated into existing chains.

It is precisely in this area, defined by the physical limitations of **alternative fuels** in large-scale **maritime transport**, that **nuclear propulsion** begins to take on strategic importance. Its potential does not lie in replacing other technologies across the board, but in offering a specific solution for those cases where **energy density, autonomy** and **operational stability** are design requirements.

Nuclear propulsion in the maritime sector: state of the art and recent developments

Nuclear propulsion applied to **maritime platforms** is not an experimental development or an emerging technology in the strict sense. Since the mid-20th century, **nuclear reactors** have been used continuously in **naval applications**, especially in **submarines and aircraft carriers**, as well as in specialised **civilian fleets** such as icebreakers operating in the Arctic. These applications have demonstrated, over decades of cumulative operation, high levels of **reliability, availability** and **safety**, even in demanding and isolated operating environments.

Table 1 | Operational experience of civil nuclear-powered vessels

Name	Country	Period	Type / Experience
NS Savannah	United States	1962–1972	First nuclear-powered merchant ship built (Atoms for Peace programme). Power 74 MW (LWR). Capacity (14,000 tonnes and 60 passengers). It demonstrated technical viability, but costs and operational complexity made it unprofitable.
NS Otto Hahn	Germany	1968–1979	Experimental nuclear cargo ship. Built as a merchant ship and research platform. 38 MW reactor. Operated for 10 years before conversion to diesel.
NS Mutsu	Japan	1991	Experimental vessel. Sailed for 110 days, accumulating 2,320 hours of operation.
Lenin	USSR	1959–1989	First icebreaker and first civilian nuclear-powered ship in the world; multiple reactors and extended service.
Sevmorput	Russia	1988–2007; 2016–2023	One of four nuclear icebreakers currently in operation. 135 MW.

Source: *Historic survey on nuclear merchant ships, Nuclear Engineering and Design, 2015 and Rosatom*

However, these experiences cannot be directly extrapolated to **commercial maritime transport**. Traditional **naval reactors** have been designed according to specific defence criteria, in many cases using highly enriched **fuel** and operating regimes that would not be acceptable (or necessary) in a civil context. This difference partly explains why early attempts at **commercial application of nuclear propulsion**—such as the NS Savannah in the United States or the NS Otto Hahn in Germany—although technically successful, failed to establish themselves as **economically competitive solutions** in an environment dominated by **cheap** and **abundant fossil fuels**.

Illustration 1 | Lenin, first nuclear-powered icebreaker (1989)



Source: Rosatom, 2013

The current technological context, however, differs substantially from that which existed during those early experiments. Over the last two decades, the **nuclear sector** has undergone a significant evolution towards the development of **small modular reactors** and **micro reactors**, characterised by lower power outputs, standardised designs and a growing emphasis on passive and intrinsic safety. These developments have been driven both by the need to **reduce costs** and construction **times** and by the search for more flexible applications, including remote or off-grid environments.

Analyses by the Maritime Nuclear Application Group (Maritime Nuclear Application Group, 2022) identify precisely these **advanced reactors** as a potential opportunity for the **commercial maritime sector**, as they allow for configurations that are more compatible with the requirements of **civil vessels** in terms of size, weight and continuous operation.

From a **nuclear safety** perspective, **advanced reactors** incorporate **design** principles that seek to minimise the probability of radiological releases, even in severe accident scenarios. The elimination of the need for active cooling systems, the existence of **intrinsic safety systems** and the **integration of the reactor** into compact and robust containments are recurring elements in the concepts evaluated for **maritime applications** (). These characteristics are particularly relevant in an environment such as the **maritime sector**, where **operational simplicity** and **resilience** to adverse external conditions are very important factors.

The Idaho National Laboratory report (Idaho National Lab, 2025) emphasises that, from a **strictly technical perspective**, there are no fundamental **barriers** to the **use of advanced reactors** for the **propulsion of large commercial vessels**, provided that the intrinsic **safety** design criteria are adapted to **the maritime environment**. **Nuclear reactors** are designed to have a specific probability of core damage considering a range of situations that include site variables. These variables are different from land-based sites and updated **safety criteria** will be required to be included in the **reactor** design basis.

Classification societies have begun to play an important role as a technical interface between the **nuclear** and **maritime sectors**. Lloyd's Register (Lloyd's Register, 2025), among others, has developed preliminary guidelines for assessing the **risks, design requirements** and **certification processes** associated with **civil nuclear propulsion**, highlighting the need to adapt traditional classification approaches to a technology that introduces new vectors of risk and responsibility.

Despite these advances, the **degree of technological maturity** should not be confused with immediate readiness for **commercial deployment**. **Maritime nuclear propulsion** is at a stage where **reactor technology** is advancing faster than the **institutional frameworks** necessary for its adoption. The lack of demonstration projects, limited recent commercial operating experience and **international regulatory fragmentation** remain significant obstacles, reflected in the slow progress of **civil nuclear energy** in other areas.

Nevertheless, the current state of the art allows us to affirm that **nuclear propulsion** is not a technological hypothesis but a **technically viable** option, whose materialisation in the **commercial maritime sector** will depend less on disruptive scientific advances and more

on strategic decisions regarding **regulation, governance** and **social acceptance**. This observation reinforces the idea that the debate can no longer be limited to the question of whether the technology works, but rather how it could be responsibly integrated into the **global maritime industry**.

Strategic advantages of nuclear propulsion for certain segments of commercial shipping

The analysis of **nuclear propulsion** in **commercial maritime transport** makes perfect sense when approached as a specific solution. As highlighted above, the diversity of **the maritime sector** (in terms of **ship size, operational profile, routes, required speed** and **operating regime**) makes it advisable to select the best **technological solution** for each area of use. In this context, the main contribution of **nuclear propulsion** does not lie in its ability to generalised ly replace other alternatives, but in offering clear advantages in those segments where **energy requirements** are more demanding. It should be noted that these advantages do not materialise uniformly across the entire **fleet**. For **small** or **medium-sized vessels, short routes** or **flexible operational profiles**, solutions based on **alternative fuels** or **partial electrification** may be more appropriate from a **technical** and **economic point of view**. However, for segments with higher **energy consumption** and greater **operational complexity, nuclear propulsion** has attributes that are difficult to replicate with other technologies, which justifies its consideration as a strategic option within the set of available solutions.

The first of these advantages is the virtually total elimination of greenhouse gas emissions during ship operation. Unlike alternative fuels of chemical origin, whose carbon footprint depends largely on production processes, **nuclear energy** allows the **ship's operation** to be directly decoupled from the **emissions** associated with **energy consumption**.

A second strategic advantage is **prolonged energy autonomy**, which is a distinguishing feature compared to any chemical fuel. **Advanced reactors** evaluated for **maritime applications** allow for operating cycles of several years (even the entire operational life of the ship) without the need for **refuelling**, eliminating dependence on **bunkering infrastructure**, reducing exposure to **supply chain** disruptions and simplifying **operational planning** on long-haul routes.

From an **economic standpoint, nuclear propulsion** also offers greater **energy cost** stability throughout the **ship's life cycle**. While fossil and alternative fuels are subject to high price volatility, influenced by geopolitical, regulatory and resource availability factors, the cost of **nuclear fuel** represents a relatively small fraction of the total cost of generation. This characteristic reduces the uncertainty associated with the operation of **the ship** and facilitates long-term financial planning, an aspect that is particularly relevant for assets with useful lives of more than twenty or thirty years.

The Idaho National Laboratory study shows that, under certain capital and operating cost assumptions, **nuclear propulsion** can be economically competitive with fossil or synthetic

fuel alternatives, especially when considering scenarios of progressive increases in carbon prices or the introduction of emissions-related tax mechanisms. As a **capital-intensive technology**, it benefits from the low interest rates that characterise the modern economy.

In addition, the integration of **nuclear propulsion** opens the door to complementary functionalities that go beyond propulsion itself. These include the possibility of supplying **electrical power** to **auxiliary systems**, or even exporting **electricity to port** during **stopovers (reverse OPS)**, which has been identified as a potential vector for creating additional value for certain **ship profiles** and **port-**. While these applications require specific **regulatory** and **technical developments**, they illustrate the multifunctional nature of **nuclear energy** in the **maritime environment**.

Consequently, the discussion on **nuclear propulsion** in **commercial shipping** should not be framed in terms of total replacement, but rather **technological complementarity**. Its value lies in covering those niches where conventional alternatives have structural limitations, thus contributing to a more realistic and robust **decarbonization** that is aligned with the operational demands of **global maritime trade**.

Regulatory, legal and operational barriers to the adoption of commercial nuclear propulsion

Despite the **strategic advantages** identified, the incorporation of **nuclear propulsion** into **commercial maritime transport** faces a set of **structural barriers** beyond the technological sphere. These barriers are mainly **regulatory, legal** and **operational**.

From a **regulatory standpoint**, the existing maritime regulatory framework recognises the possibility of **nuclear-powered merchant ships**, but does so on the basis of instruments developed in a technological and political context very different from the current one. The main reference point is the Code of Safety for Nuclear Merchant Ships, adopted by the International Maritime Organisation (IMO) in 1981 (IMO, 1981). This code, which is non-binding and was developed in a **technological and industrial scenario** very different from the current one, was conceived primarily as a **guiding framework** without constituting a complete regulatory regime, including general principles for the design of floating nuclear facilities. The very approach of the code shows that its application is largely subject to the legislation of the **flag state of the ship** and to **bilateral agreements** with the countries where the ports involved are located, which reinforces **regulatory fragmentation** and highlights the **absence** of a specific **harmonised international framework** for the commercial operation of **nuclear ships**.

This regulatory obsolescence is exacerbated by the fragmentation of responsibilities between different levels of authority. **Nuclear regulation** is the responsibility of national nuclear authorities, which operate under legal frameworks designed primarily for fixed land-based facilities within a single jurisdiction. The inherent mobility of **merchant ships** therefore introduces a complexity in terms of licensing, supervision and regulatory compliance

that is not addressed by the nuclear regulations in force in most countries with **nuclear energy** regulations.

Studies and technical documents by the International Atomic Energy Agency (IAEA) (IAEA, 1968) emphasise that, although there is a **consolidated international framework** for **nuclear safety, radiation protection, safeguards and civil liability**, these instruments were designed for **land-based nuclear facilities** or **military nuclear vessels**. In particular, the IAEA itself recognises that the operation of **nuclear reactors** on board **merchant ships** introduces unique constraints that are not fully covered by existing **international conventions**, requiring specific assessments and *ad hoc* agreements between states to ensure equivalent levels of **safety** and **security**.

At **the port level**, the **absence** of **harmonised procedures** for authorising **port calls, nuclear inspection** by states or coordinated emergency management is one of the main sources of **regulatory uncertainty**. Added to this situation is the issue of **civil liability and insurance**, which represents one of the most significant obstacles from a commercial viability perspective. The lack of a clear framework articulating the interaction between **the maritime and nuclear spheres** makes it difficult to structure viable insurance systems for **commercial nuclear ships**, as pointed out in analyses by Lloyd's Register and the Maritime Nuclear Application Group.

From an **operational point of view**, **nuclear propulsion** poses specific requirements in terms of **crew training, qualifications and organisation**. The safe operation of a **nuclear reactor** requires highly qualified personnel with specific training and certification processes that are not currently integrated into **maritime training** frameworks.

Ports are emerging as relevant **players** in this **regulatory framework**. The acceptance of nuclear-powered **ships** implies the adaptation of **emergency plans, safety procedures, communication protocols** and **incident response capabilities**, even though the probability of a radiological event is extremely low. The **absence** of internationally **harmonised criteria** can lead to unilateral decisions to restrict access, complicating the operational framework and reducing predictability for **shipowners** and **operators**.

Taken together, these **barriers** should not be interpreted as definitive arguments against **nuclear propulsion**, but rather as symptoms of an institutional **gap** between **technological evolution** and existing **administrative systems**. As the Idaho National Laboratory report emphasises, the main challenge for the commercial adoption of **nuclear propulsion** is not the lack of technical solutions, but the need to develop **regulatory frameworks that are consistent**, predictable and **socially** and **economically** acceptable.

Social acceptance, risk perception and the role of ports

Beyond regulatory and operational barriers, the long-term viability of **nuclear propulsion in commercial shipping** is conditioned by **social acceptance** and **risk perception**. Unlike other emerging energy sources, nuclear power carries a symbolic and political burden that

directly influences public decision-making, especially in densely populated port environments with high social visibility.

Numerous studies have highlighted the divergence between the **technical risk** associated with **nuclear operation**, particularly in advanced designs with passive safety systems, and the risk perceived by the public. This gap is amplified in the **maritime environment** by the **mobility of ships**, their proximity to urban areas during **stopovers**, and concerns about possible cross-border impacts. The Idaho National Laboratory report emphasises that public acceptance is one of the most decisive factors for the implementation of **maritime nuclear technologies**, on a par with **economic** or **regulatory feasibility**.

In this context, **ports** are not only **logistical infrastructures**, but also spaces for direct interaction between **maritime activity**, the **city** and **public opinion**. The possible presence of **nuclear-powered ships** in **commercial ports** requires a redefinition of the port's role in **risk management**, **communication and institutional coordination**. This includes the integration of the **nuclear dimension** into **port emergency plans**, **specific training** for authorities and response services, and the **establishment** of transparent and comprehensible **information channels** for the public.

Experience gained in other areas of the **energy transition** shows that social acceptance is not achieved through isolated technical arguments, but through processes based on **transparency**, **anticipation** and the **participation** of the **actors involved**. In the case of **maritime nuclear propulsion**, this logic is even more relevant, given that decisions taken by a limited number of states or ports can have an impact on **trade routes** and the **global competitiveness of the sector**.

In a scenario marked by **climate urgency**, pressure on **energy systems** and the need to ensure **resilient supply chains**, the **social perception of nuclear energy** may undergo significant transformations, especially if it is presented as part of a coherent approach to **sustainability** and not as an imposed technological exception.

Conclusions

The **decarbonization** of **international maritime transport** poses a structural challenge that cannot be addressed with single solutions or technological simplifications. The diversity of **operational profiles**, **ship types** and **trade routes** requires a pluralistic approach, based on the complementarity of solutions and a rigorous assessment of their respective limitations and advantages.

In this context, **nuclear propulsion** cannot be considered an immediate or universal solution for the **commercial maritime sector**. However, it is also unreasonable to exclude it *a priori* from technical analysis. The limitations imposed by the use of **alternative fuels** in certain large-scale and long-haul segments, together with the **technological maturity** achieved by **advanced reactors**, give **nuclear energy** significant potential that deserves to be evaluated on technical criteria and not solely on the basis of the psychological perception of risk.

The analysis developed in this article shows that the **main barriers** to the adoption of nuclear propulsion at sea are not technological in nature, but rather **institutional, regulatory and social**. The lack of alignment between the **maritime and nuclear frameworks**, uncertainty regarding **civil liability and insurance**, and the absence of clear **port acceptance mechanisms** are the real **bottlenecks** to its eventual development.

Recognising this reality does not imply promoting the immediate adoption of **commercial nuclear ships**, but rather integrating **nuclear propulsion** into the long-term strategic thinking of the maritime sector. Doing so would make it possible to anticipate scenarios, develop **coherent regulatory frameworks** and avoid hasty decisions in a future marked by greater climate restrictions and less technological room for manoeuvre.

Ultimately, the question is not whether **nuclear propulsion** should replace other energy alternatives, but whether **maritime transport** can afford to do without an option that, for certain uses, offers attributes that are difficult to replicate. As has happened at other key moments in energy history, the challenge is to approach the debate with rigour, responsibility and a long-term vision, before circumstances force us to do so under less favourable conditions.

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