WHEN TRUST MATTERS

MARITIME NUCLEAR PROPULSION

Technologies, commercial viability, and regulatory challenges for nuclear-powered vessels

WHITE PAPER

Contents

Project team

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FOREWORD

As the drive for decarbonization becomes more urgent, the world stands in need of solutions that can meet the moment. This extends to shipping – an industry which provides the backbone to world trade but where ambitious decarbonization targets have been set and increasingly proactive regulations are being implemented.

Decarbonization is no longer a distant ambition but an immediate necessity, an obligation, and a formally agreed objective. Every viable pathway must, therefore, be carefully considered, including those previously deemed improbable.

Nuclear propulsion, once regarded as a distant prospect, is now under active consideration as a real option for the commercial maritime fleet. Shipyards and shipowners are exploring its potential and weighing the promise of virtually emission-free power against the complexity of introducing such a transformative technology into commercial fleets.

This technology carries inherent risks. Its acceptance will depend not only on technical performance but also on the confidence of the public it serves. In this context, independent and competent assurance becomes indispensable. It is the mechanism by which risks are managed, trust is built, and credibility is earned. Assurance is not simply a safeguard – it is an enabler of progress.

The maritime sector benefits from a long-established system of classification societies that harmonize technical rules, provide independent verification, and bridge the gap between regulation and operation. This framework enables the development and assessment of new technologies, including nuclear propulsion, within a coherent and internationally recognized assurance structure.

No comparable system exists in the land-based nuclear sectors, where regulatory responsibilities are fragmented and primarily nationally defined. The experience and institutional frameworks of the maritime classification system therefore offer a unique foundation for enabling civilian nuclear propulsion – creating a model of harmonized oversight that could inspire broader approaches to innovation in other high-risk, high-value technologies.

This report explores the technologies, commercial viability, and regulatory challenges that frame the future of nuclear propulsion. It seeks to provide clarity in a complex field and to support informed decisions on whether, and how, this option can play a responsible role in shaping the future of maritime transport.

As the maritime industry navigates the complexities of decarbonization, nuclear propulsion presents both a formidable challenge and a transformative opportunity. Whether this technology becomes a cornerstone of future fleets will depend on our collective ability to manage its risks, earn public trust, and establish robust assurance frameworks.

This report aims to equip stakeholders with the insights needed to evaluate this option responsibly, to innovate with integrity, and to shape a sustainable future for global shipping.

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EXECUTIVE SUMMARY

As the shipping industry faces mounting financial and regulatory pressures to decarbonize, nuclear propulsion is increasingly viewed as a potential solution, offering the promise of stable, predictable energy costs, enhanced operational flexibility, and reduced reliance on traditional bunkering infrastructure.

While no civilian maritime nuclear facilities have been commissioned in over four decades, shifting environmental, technological, regulatory, and commercial dynamics are reigniting interests and highlighting the transformative role that nuclear power could play in the maritime industry over the coming decades. This white paper describes the current state of play of nuclear maritime propulsion and emphasizes the need for technological innovation, regulatory clarity, and economic feasibility.

Although nuclear propulsion and its supporting infrastructure are not yet commercially viable, past operating experience offers valuable insights for the path ahead.

Almost all previous commercial projects – vessels such as Savannah, Otto Hahn, and Mutsu – operated using pressurized water reactors (PWRs), which required extensive monitoring and active safety systems to manage transients. This reactor type typically demands a large, highly skilled crew, increasing operational costs and posing commercial challenges for shipowners.

Many military vessels have also been deployed with nuclear propulsion technology. However, their relevance to future commercial projects is considered limited, due to the differing technological and commercial realities of these vessels.

With these considerations in mind, this white paper outlines the preferred characteristics of reactor concepts currently being developed for marine use. All maritime nuclear technologies will differ from land-based equivalents due to some key characteristics, such as mobility, exposure to harsh sea conditions, and operational profile. Further, maritime installations will vary significantly depending on their purpose – propulsion (nuclear-powered ships, NPSs) or power generation (floating nuclear power plants, FNPPs.

Design choices such as single versus dual reactors involve trade-offs between cost, space, reliability, and power availability. Smaller, standardized reactors may offer advantages for merchant shipping, especially if they feature passive safety systems and minimal crew requirements. Low-pressure systems and Generation IV or heat-pipe reactors could be preferred for their inherent safety and reduced complexity compared to traditional PWRs.

Marine reactors must be compact and designed for infrequent refuelling – ideally aligned with other required maintenance activities such as dry-docking to minimize impacts on ship availability. Refuelling logistics are confined to specialized ports, and global nuclear fuel supply chains face pressure due to geopolitical shifts. The reactor's purpose – mechanical propulsion or electric power – determines the system configuration, with steam turbines or nuclear-electric setups offering different benefits. Higher fuel enrichment levels may be necessary to meet operational demands, and online refuelling could reshape current limitations.

Ultimately, reactor technology selection hinges on balancing safety, efficiency, and operational feasibility. Several projects in different countries are already underway with differing approaches to fuel, coolant, and safety.

Translating these concepts into commercial reality requires more than technical innovation, however.

A cost-effective and proven nuclear fuel cycle, tailored for maritime use, must be developed by the industry. This includes establishing clearly defined roles and responsibilities across the supply chain, from fuel production and reactor integration to loading, exchange, and disposal.

Crucially, storage and disposal of spent nuclear fuel are fundamental to the functionality and credibility of the supply chain. Reactor design and fuel type will directly influence these requirements, and these factors must be addressed before any operating license is granted. As part of this, provisions for the whole maritime fuel cycle – including long-term waste management – are essential, not only for regulatory compliance but also for advancing public acceptance.

As technology and supply chains evolve, they must be rigorously tested under maritime conditions. Due to the high-risk potential and the need for public acceptance, this includes verification and assurances of major components, such as reactor systems, fuel logistics, and port infrastructure to ensure safe and efficient installation, operation, and maintenance at sea.

The development of a commercial maritime nuclear industry also needs to be supported by a predictable and internationally accepted regulatory framework. Organizations such as the IMO and IAEA must lead efforts to establish standards for fuel management, ship construction, and operational protocols. Classification societies will play a critical role in enabling global adoption, helping to overcome the fragmented nature of the land-based nuclear industry and fostering a standardized maritime approach.

The regulatory landscape for nuclear shipping will likely exceed what the maritime industry is accustomed to, opening the door to multiple future system configurations. By identifying key actors, their mandates, and the need for coordination, regulatory roadmaps outlined in this white paper offer essential guidance. As roles multiply, clarifying interfaces becomes increasingly important – something these roadmaps help address by mapping key interdependencies.

Safety, security and non-proliferation remain paramount. Future installations must be designed to withstand collisions, groundings, and external threats such as sabotage or piracy. Remote monitoring and advanced communication capabilities will be essential, along with rigorous cybersecurity measures.

Technological advancements, particularly in digitalization – encompassing automation and communication – are helping to overcome longstanding challenges. These innovations may enhance safety, reduce costs, and support transparent monitoring and cybersecurity, factors which are all critical for both public confidence and international oversight.

The success of future maritime nuclear installations will also depend on the development of compelling business models. These must reflect the commercial realities of shipping and provide a clear understanding of total cost of ownership, especially across the entire fuel cycle.

Cost-competitiveness could be significantly enhanced through modular and standardized approaches, which streamline construction, simplify maintenance, provide independent assurance, and facilitate regulatory approval across jurisdictions.

Progress is being made. The integration of Generation III+ and IV reactor technologies, along with the rise of small modular reactors (SMRs), may enable shorter construction times, greater standardization, and improved safety. These developments may also support reduced crew requirements and operational efficiencies, strengthening the business case for nuclear propulsion.

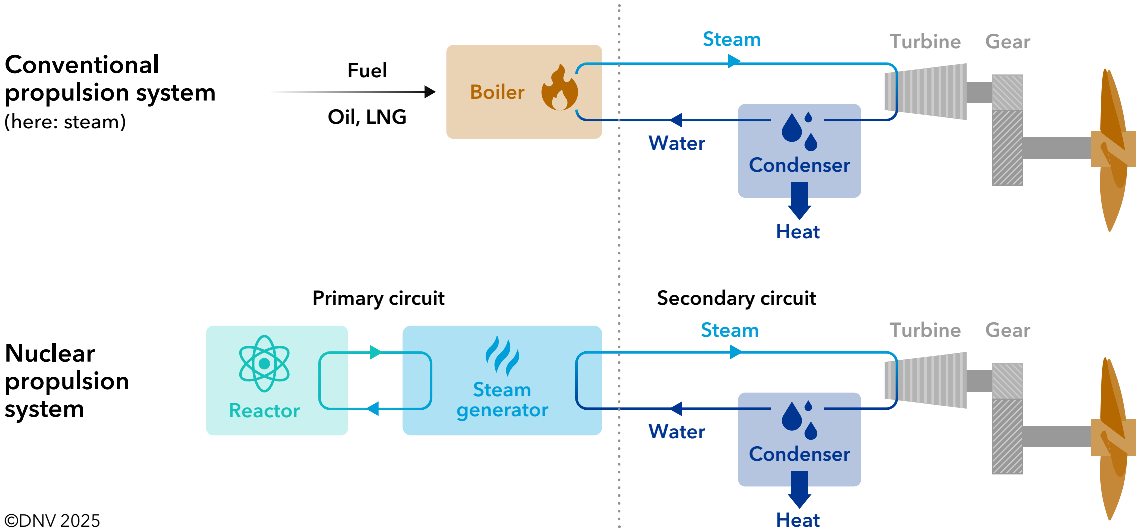
Reactor costs are a key factor. DNV case studies presented in this paper show that nuclear can outperform other technologies under both low and high fuel price scenarios. A reactor cost below USD 18,000/kW could be competitive if full decarbonization is achieved by 2050, while costs below USD 8,000/kW could be viable even without full decarbonization.

Realizing the potential of nuclear propulsion in maritime requires more than technological readiness. It demands coordinated global action, involving a wide range of actors across the maritime industry, regulators, and society in general.

With strategic investment and international collaboration, nuclear energy could become a cornerstone of the maritime energy transition, delivering safe, efficient, and zero-emission propulsion for the global fleet.

FIGURE 0-1

Transfer of heat for nuclear reactor



1 INTRODUCTION

Currently, no commercial nuclear facilities are in operation on civilian ships or offshore platforms anywhere in the world. Yet, from an economic point of view, several compelling arguments support their potential, notably low and predictable energy costs, albeit with high investment costs. As this is a technology that produces no emissions, the climate and environmental benefits are also clear (DNV, 2023) (DNV, 2024). From an operational perspective, nuclear propulsion enhances flexibility by making higher speeds economically feasible, even for larger vessels, while the reduced need for bunkering infrastructure could have a major impact on the global fleet.

This raises the pivotal question: how might these opportunities be realized across the world?

The aim of this paper is to describe the state of play of international commercial activities utilizing nuclear fission for propulsion or power generation at sea, and to provide a basis for developing a strategy to combine two commercial industries with little historical cooperation. The paper is divided into four parts.

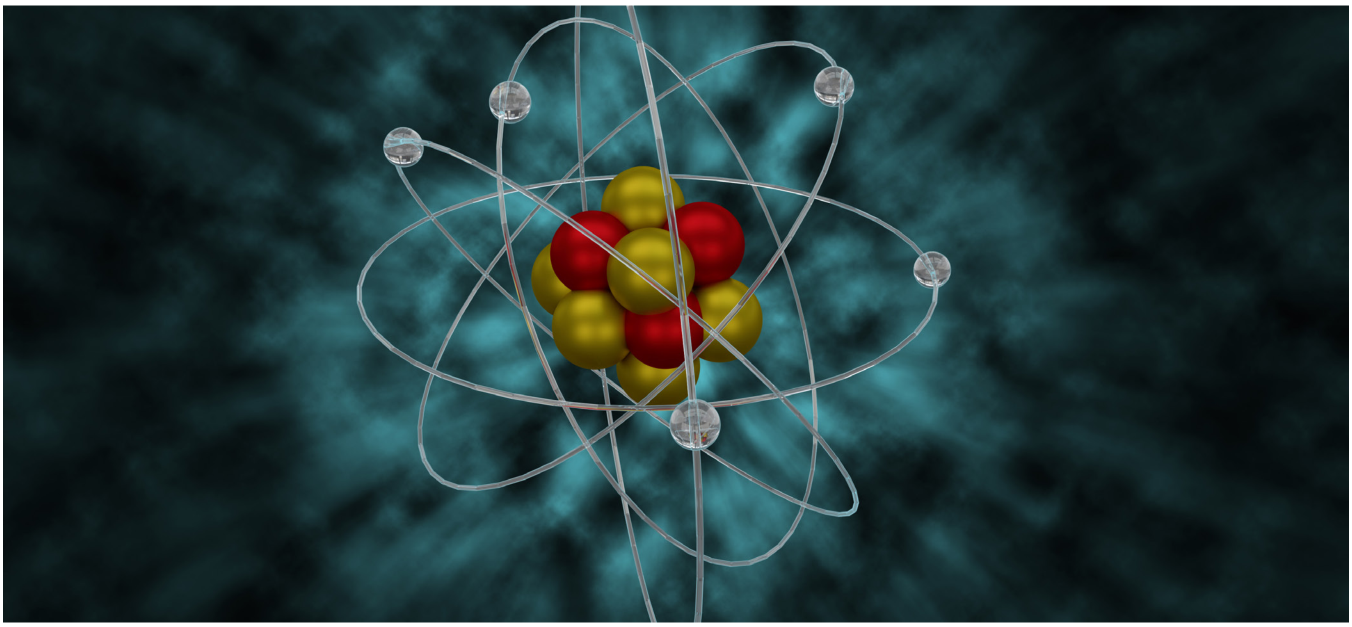
First, in Chapter 2 we describe the history of maritime nuclear propulsion, providing a brief overview of experiences with nuclear-powered civilian merchant ships and other relevant activities. In this chapter, we also introduce the maritime fuel cycle and outline the principle key elements that are relevant to this, including the 'front end' (activities before the reactor, such as fuel production and delivery) and 'back end' (post-use management, including potential reprocessing and final disposal of waste products that cannot be reused).

Secondly, in Chapter 3, we examine the readiness of civilian nuclear propulsion technologies, comparing them to land-based counterparts, while examining preferred properties and candidate technologies, such as pressurized water reactors (PWRs), small modular reactors (SMRs), molten salt reactors, lead-cooled reactors, high-temperature gas reactors, and heat-pipe reactors.

The realization of commercial nuclear propulsion is also dependent on non-technological factors, and in the third part of the paper, in Chapter 4, we provide a detailed overview of the regulatory frameworks that will be required for a functioning nuclear propulsion industry to be internationally recognized, and to enjoy a high level of public acceptance. This will involve multiple national and international actors and will depend on close cooperation between all parties.

Finally, the successful emergence of a commercial maritime nuclear propulsion industry will hinge on viable business models and costs, and these factors are analysed in Chapter 5. Business models must address different factors such as ownership, leasing, crew size, and supply-chain management, while cost competitiveness will depend on the ability of the industry to implement standardization, mass production, and efficiency manning.

These factors are all clarified through a detailed case study, presented in Chapter 6, where we simulate the potential cost levels marine nuclear reactors will need to achieve for nuclear propulsion to be relevant for the merchant fleet, and how this may affect the introduction of the technology in international shipping.



2 CIVILIAN MARITIME NUCLEAR PROPULSION: BACK AGAIN?

Highlights

- Early merchant nuclear ships demonstrated technical feasibility but lacked commercial success, and no civilian maritime nuclear facilities have been commissioned for more than 40 years.
- The maritime nuclear fuel cycle encompasses all stages from 'front end' to 'back end' and includes uranium mining, enrichment, fuel fabrication, reactor operation, and spent fuel management.
- Maritime infrastructure must adapt to the demands of the maritime fuels cycle, with specialized yards and ports for nuclear operations.
- While much experience can be gleaned from nuclear-propelled vessels for military purposes, their relevance to future commercial maritime nuclear installations is limited

Shipping's experience with nuclear-powered vessels remains limited.

While some large countries, above all the US, United Kingdom, France, Russia, and China, today utilize nuclear energy extensively in both the civilian and military sectors, the development of both onshore power generation and maritime nuclear propulsion did not proceed as expected at the beginning of the nuclear age. Apart from exploratory tests in Russia, no civilian maritime nuclear facilities have been commissioned for more than 40 years.

However, nuclear is re-emerging as an option for fossil-free energy. This has also extended to the maritime industry, where nuclear energy has gained renewed interest, both as a means of power generation on sea-based platforms and for nuclear propulsion systems (DNV, 2023) (DNV, 2024).

There are numerous examples today of new actors demonstrating interest in nuclear energy in shipping. The UK took the initiative in 2022 to accede to the Nuclear Code (see Chapter 4), one of the few relevant international legal instruments. (Mandra and Ovcina, 2022). China is described as a pioneer in the application of nuclear technology to decarbonize shipping (Wang and Quiwen, 2025), and the Chinese shipbuilding company Jiangnan Shipbuilding Group has demonstrated its efforts to make progress in the design of nuclear-powered merchant ships (Mandra and Ovcina, Offshore Energy, 2023). Major shipbuilding companies in South Korea have taken several initiatives that demonstrate their intentions and expertise in the field of merchant nuclear shipping (World Nuclear News, 2025; Nautical Voice, 2025). Additionally, as described in the next chapter, several reactor manufacturers in other countries are exploring how their technology can be utilized in merchant shipping.

A central component of all future developments in maritime nuclear propulsion will be the nuclear reactors, an integrated part of a comprehensive technological system known as the nuclear fuel cycle. Before considering the technical, commercial, and regulatory aspects of maritime nuclear propulsion, this fuel cycle is described below, together with the most relevant experiences and technical data from the very first nuclear merchant vessels.

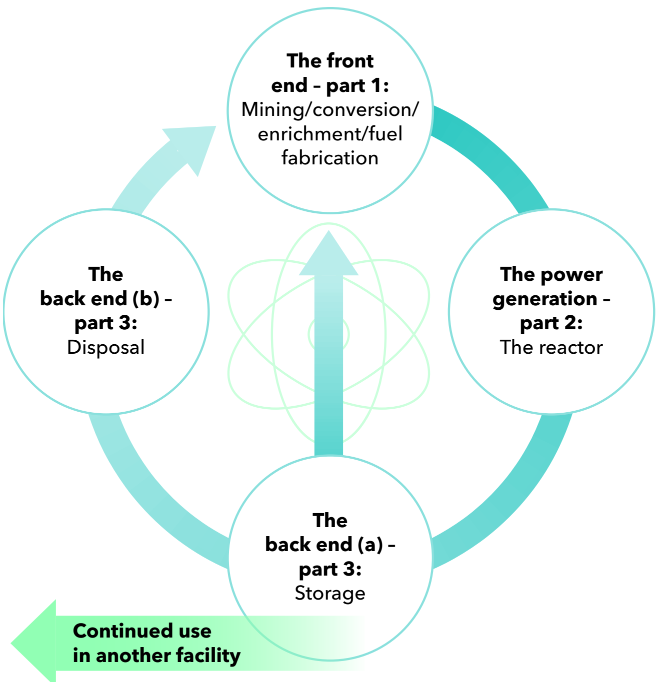
2.1 The maritime nuclear fuel cycle – in perspective

Historical experiences suggest that, in the early stages of maritime nuclear development, conventional PWR technology – water-cooled like most land-based reactors – was the preferred choice for naval vessels and other exploratory projects. Savannah, entering service in 1962, demonstrating the-then US President Eisenhower's 'Atoms for Peace' initiative, was the first ever nuclear-powered cargo-passenger ship. This was later followed by the German Otto Hahn and the Japanese Mutsu, all three vessels using PWR-type reactors (Schøyen and Steger-Jensen, 2017).

Following the initial phase of the 1950s and 60s – an era that ushered in the so-called nuclear age, including the launch of the first nuclear-powered ships - the expansion of nuclear energy levelled off in the 1980s and 90s, both in terms of number of plants and energy generated, with only Russia continuing to commission nuclear-powered vessels for civilian use.

FIGURE 2-1

The maritime nuclear fuel cycle (uranium-based)



©DNV 2025 Source: World Nuclear Association, 2025

Regarding the now decommissioned exploratory vessels from the US, Germany, and Japan, the land-based fuel cycle was used with some adaptations for use at sea. Although maritime applications have distinct requirements for fuel and supporting infrastructure, none of these countries established a truly dedicated maritime fuel cycle at that stage.

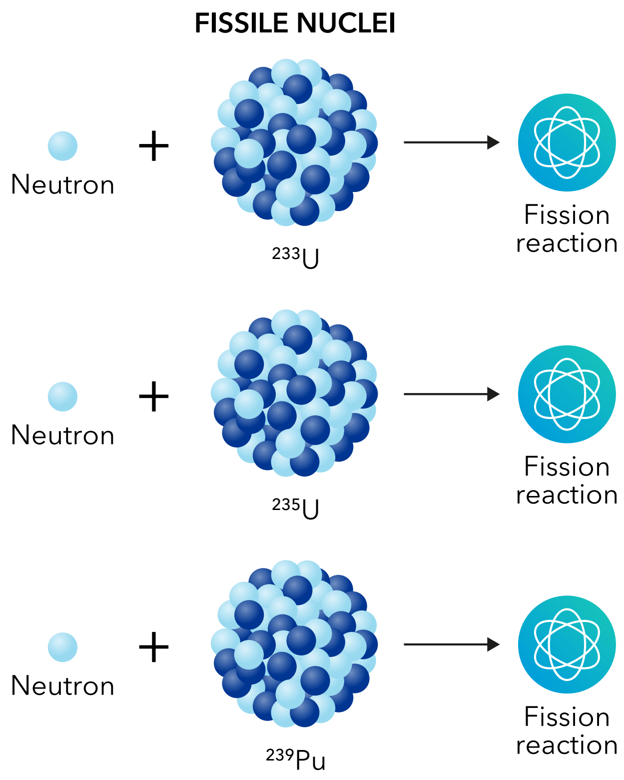
The principal elements of a maritime fuel cycle are outlined in Figure 2-1, traditionally divided into a 'front end' (activities before the reactor, such as fuel production) and a 'back end' (post-use management, including potential reprocessing and final disposal of waste products that cannot be reused).

Industrially, the initial stages of the maritime nuclear fuel cycle – such as mining and milling – are identical to those used for land-based reactors. However, fuel production processes, including qualification and fabrication, typically need to be tailored to the specific reactor type and its intended maritime application. In the longer term, the maritime nuclear fuel cycle will diverge significantly from its land-based counterpart, with shipyards and ports emerging as key physical and logistical differentiators.

The only country which has pursued a maritime fuel cycle on an industrial scale is Russia. Ten nuclear-powered ships have been constructed – all part of the Russian icebreaker fleet, operating out of a permanent base in Murmansk – in addition to one floating power plant, currently in operation in Pevek, in the Russian far east. The icebreaker fleet, formally owned by the Murmansk Shipping Company, has been used primarily by the Russian Government for many years.

FIGURE 2-2

The most relevant fissile isotopes for nuclear fuel



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2.1.1 The front end – the fuel technology

Fuel is the most fundamental component of a nuclear system, containing the fissile material which provides the energy needed. The fissile material in the fuel can be a uranium isotope - uranium-235 (U-235) or uranium-233 (U-233) – or plutonium-239 (Pu-239), as described in Figure 2-2. U-235 is fissile, and the only fissile isotope found in nature, while U-233 can be made (produced) in a reactor from thorium-232 (Th-232). Mindful of the difference from fissile materials, Th-232 is therefore called 'fertile', as described in Figure 2-3. There are other important groups of material; U-238, like Th-232, is fertile because it can be converted into the fissile isotope Pu-239 by absorbing neutrons. Uranium ore, which is mined, contains only 0.7% U-235, which is why nuclear fuel is usually enriched to a higher proportion of U-235 – 3-5% U-235, i.e. an increased enrichment level.

For civilian purposes, fuel with an enrichment level below 20% is the only option, as higher levels are considered an unacceptable proliferation risk. Nuclear fuel for commercial land-based power plants is often referred to as low-enriched uranium (LEU), which indicates an enrichment level of about 3% to 5%. In contrast, some countries, such as the US, only use fuel enriched up to 90% where compactness is beneficial or potentially decisive for the purpose of the facility, as for their military vessels.

Since higher enrichment can lead to more compact cores, a form of HALEU (High-Assay Low-Enriched Uranium) is a starting point for many of the new fuel types for candidate civilian marine reactors. While higher enrichment can offer significant operational advantages, it also raises concerns around cost and security of supply. Fuel qualification can also be a challenge, especially if the aim is to use fuel enriched to more than the 3% to 5% U-235.

The Russian case is also important to illustrate the role of enrichment in nuclear fuel. Russian cargo ship Sevmorput, commissioned in 1988, reportedly used 90% enriched fuel, although the cost of this remains unknown (Reistad, Mærli and Bohmer, 2005).

2.1.2 The operation of civilian nuclear reactors at sea

The fission process itself takes place in the fuel – when in a nuclear reactor. Fission produces neutrons, fission products, and substantial amounts of energy. The released neutrons go on to split new uranium atoms, leading to a sustained chain reaction in the reactor that enables it to operate at constant power. The energy – or the heat – released can be utilized in a controlled manner.

FIGURE 2-3

Creation of fissile materials in reactors

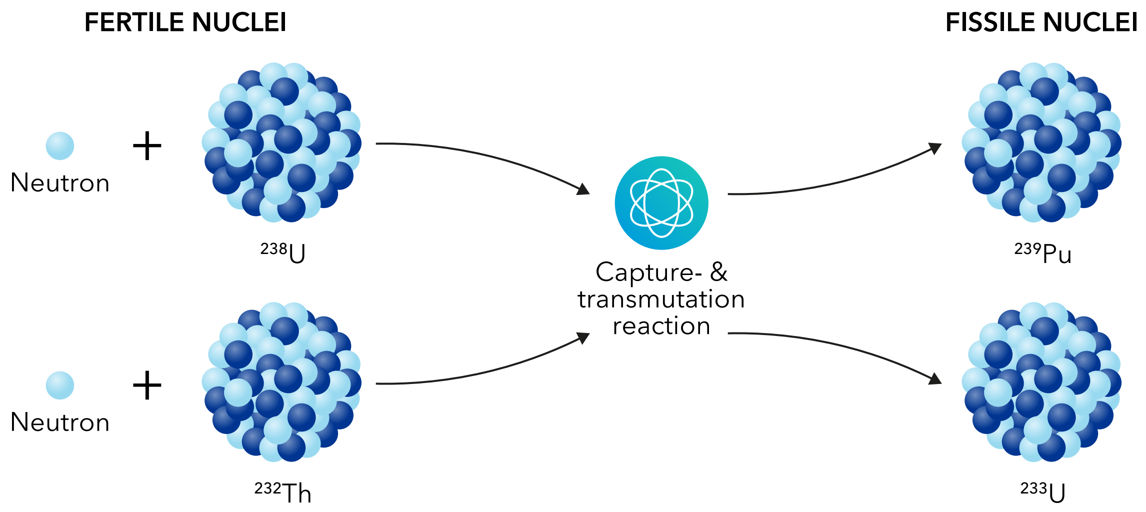
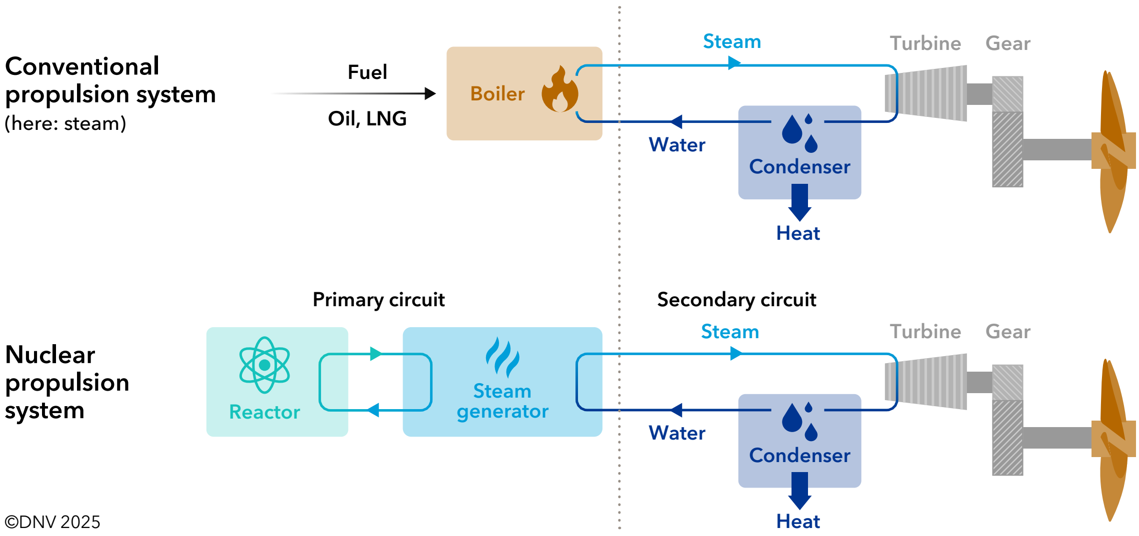


FIGURE 2-4

Transfer of heat for nuclear reactor



A fission reaction can occur with both fast neutrons, coming directly from the fission process, and slow (thermal) neutrons, slowed down using a moderator. The various materials used to regulate the fission reaction by slowing down neutrons share a common characteristic: they consist of light elements. Examples include heavy water, ordinary water, and graphite - as illustrated in Figure 2-4. Together with the material that transports the heat to the turbine (coolant) – helium, heavy water, water, a type of salt or metal (lead), as seen in Figure 2-4 – these properties determine the type of reactor.

In a fast reactor, the neutrons are never slowed down, which allows for more compact core design. However, this potentially makes the fission reaction more complex to control and, as a result, few fast reactors have ever been put in operation. With fast reactors, breeding of fissile material – production of more fissile material than consumed – is also feasible, though more relevant for land-based facilities where fuel can be handled more readily than at a mobile seagoing nuclear facility.

The rated power of a ship reactor can be in the range from 1 MW[1] up to as large as required, keeping in mind that the largest ship installations of propulsion and auxiliary power are up to 100 MW.[2]

Almost all operating experience at sea has been gained in the operation of PWR-type reactors – thermal reactors water-cooled and water-moderated. PWRs remain the only reactor type with a broad maritime track record and commercial attributes, supported by a variety of qualified fuels and standardized materials, and by quality assurance processes used globally.

Regarding the three exploratory vessels, Savannah's performance, safety record, and fuel economy were good, but she was not commercially successful compared with fossil-fuelled ships, as her cargo space was limited, her specialized crews numbered more than three times those of a conventional merchant ship, and subsequently her operation costs far exceeded the costs for conventional merchant ships (GAO, 1970). Similarly, Otto Hahn and Mutsu were taken out of operation relatively soon after launch, being considered experimental from the very beginning.

The development of Russian icebreaker reactors ran in parallel with submarine reactor programmes, both based on the PWR design. Icebreakers served as a technical test bed for submarine reactors, particularly in demonstrating feasibility. However, the extent to which these designs align with civilian priorities, such as transparency, proliferation resistance, safety, and cost-efficiency, is not well documented. As a result, their relevance to future merchant nuclear shipping remains difficult to fully assess.

The Russian floating reactor vessel Akademik Lomonosov is based on the KLT-40 reactor, which emerged from the icebreaker programme, and is also a PWR-design. Today, the US company Lightbridge is promoting a commercial fuel design for civilian power reactors that utilizes the Russian ship fuel design used in the Sevmorput metallic uranium-zirconium alloy fuel core, where the fuel is co-extruded and metallurgically bonded to a zirconium alloy cladding (Lightbridge, 2025).

What was then Soviet Russia also had an experimental phase with nuclear-electric propulsion, with the first icebreaker Lenin featuring nuclear-electric auxiliary systems. While Savannah was nuclear-electrically powered, Russian icebreakers have primarily relied on nuclear-mechanical propulsion.

2.1.3 The back end of the maritime fuel cycle

The most critical element of the back end of the maritime nuclear fuel cycle is the management of spent fuel, which contains the majority of the radioactivity. Due to the distinct operational profiles of shipboard reactors compared to land-based facilities, spent fuel characteristics and burn-up rates differ, requiring tailored handling strategies.

Spent fuel must be stored for extended periods to allow for adequate cooling before further processing. As such, an interim storage facility is a prerequisite for operating a commercial nuclear fleet. The optimal approach would integrate nuclear operations with scheduled maintenance, necessitating a well-coordinated supply chain and supporting infrastructure. This includes designated shipyards and ports equipped to manage these specialized requirements under secure and controlled conditions.

A fundamental aspect of reactor and fuel design is whether reprocessing is considered an integral part of the fuel economy or fuel cycle for the reactor technology in question. Reprocessing means that the fissile materials from the spent fuel elements are reused. If spent fuel is not reprocessed, it is referred to as an open fuel cycle (or a once-through fuel cycle), as indicated in Figure 2-1.

The reprocessing – or the recycling – of fuel elements has been a long-term goal for parts of the industry for many years, even as strong objections have been raised due to the risk of proliferation (Fetter and Hippel, 2019). As a result, this process is only pursued by a few countries, even though it is a prerequisite for some technologies, especially advanced ones, to be industrially and commercially viable. The process itself is relatively complicated as, in most cases, the spent fuel must be handled remotely or with strong shielding, with inherent risk of release.

Produced fission products, such as caesium and strontium, are highly radioactive substances which form key constituents of spent nuclear fuel. Most of the radioactivity produced by nuclear fuel is contained in these fission products, which pose the greatest radiation risk. The operation of the reactor continually generates spent fuel and radioactive waste which must be actively managed on board and regularly removed from the ship.

The time between fuel changes should ideally be optimized to minimize costs. A fundamental goal is that fuel changes should occur during scheduled maintenance intervals and have minimal impact on overall ship availability. The fuel in the reactor is normally only changed at dedicated ports or yards, with relevant infrastructure, including the necessary licenses. Refuelling involves the handling of highly radioactive substances and should only be carried out by trained personnel in specialized facilities.

When using a generic fuel type (e.g. pebbles or a homogeneous mixture), it is possible to reuse the fuel or the uranium materials in a larger plant on land. Therefore, the marine fuel cycle may include the option to reuse the fuel after use in a maritime installation, as indicated in Figure 2-1.

One option being considered is online refuelling. In this case, the nuclear reactor is designed so that fresh fuel can enter the reactor during operation. This can introduce additional complexity in terms of safety and security but also adds an important layer of flexibility.

2.2 Are non-civilian marine nuclear vessels relevant?

While there are currently no commercial nuclear vessels worldwide, many military vessels are in operation. However, the relevance of military ship propulsion technology to future maritime nuclear installations is dependent on several factors, with limited relevance, at least on a purely technical level.

Notably, the technological foundation of at least the US naval reactors differs significantly from that of other navies and from commercial nuclear power systems. These are extremely compact and operate at high-power densities; up to 200 MWth/m^3 with a volume of around 1 m^3. The technology has been developed for over 70 years and is one of the world's best kept secrets. Today, it features life-time cores lasting approximately 40 years, enrichment levels exceeding 90%, and advanced fuel geometries with extreme reliability. High power densities require efficient heat dissipation from the reactor core. In contrast, other nations, like France, have decided to use low-enriched fuel with lower power densities in their naval reactors.

The quest for robustness has made all nuclear navies use water as the preferred coolant even if, for example, liquid metal instead of water could also alleviate the high-power densities. In fact, the decision in favour of water-cooled and water-moderated reactors marked a pivotal breakthrough for this technology in the military context.

While the relevance of military ship propulsion technology to civilian propulsion technology is limited to the US, an important question is how this dynamic will evolve for other countries developing their nuclear fleets. For example, like France, China is historically known to have used low-enriched fuel in its submarines. As China seeks to strengthen its strategic global position, it can be assumed that it will prioritize similar characteristics to those of the US military vessels, prioritizing aspects such as core life, endurance, and capabilities at great depths in its propulsion efforts.

This raises a key question internationally: how might the potential development of civilian propulsion reactors be affected by a future military build-up in this area? For some countries, such as South Korea and Brazil, that do not have access to highly enriched material and place a larger emphasis on adherence to current international norms discouraging its use, the distinction between the military and civilian sectors could be less pronounced than for nations like the United States.

With respect to propulsion systems, the US experimented in early years with nuclear-electric configurations, as the preferred choice for its first vessels. However, all subsequent US naval vessels have adopted nuclear-mechanical propulsion, although some auxiliary power systems continue to be powered by electricity generated from reactor installations.

3 CIVILIAN NUCLEAR PROPULSION TECHNOLOGY READINESS

Highlights

- Maritime nuclear installations differ from land-based plants in mobility, exposure to sea conditions, and operational profiles.
- Preferred reactor properties include compactness, long refuelling intervals, inherent safety, and robust supply chains.
- Candidate technologies include PWRs, gas-cooled reactors, molten salt reactors, lead-cooled reactors, and heat-pipe reactors.
- Companies in multiple countries are developing reactors for maritime use, with varying approaches to fuel, coolant, and safety.
- Technology readiness is shaped by regulatory, commercial, and societal factors.

Maritime nuclear installations differ from land-based nuclear facilities in at least three different aspects: the installation is not stationary; the installations are exposed to the movements of the sea; and the installations have different operational aspects (variable energy requirements and loads in different environments) than land-based reactors. As these conditions can impact different nuclear technologies in different ways, it is essential to treat technology as an independent factor.

To assess the state of play of maritime nuclear technology, we begin by outlining the preferred characteristics of reactor concepts currently being developed for marine use. This includes an examination of how these concepts are related to the fuel technologies and the complete maritime fuel cycle. In general, these characteristics are dependent on the intended use, including the type of vessel involved. Nevertheless, they provide some useful guidance on the range of properties required for maritime nuclear applications.

Several of the relevant characteristics, including reliability, proliferation, and accident risk, are dependent on the specific reactor type and scale. Each of these properties requires a separate assessment, as would be the case when designing and licensing the system, taking external factors into account. These factors include societal, commercial, and industrial ones not directly related to the general technical properties discussed in this chapter.

There is uncertainty as to what the design features of future maritime nuclear facilities in international commercial operation will look like, and this will only become clear when specific initiatives are presented with their own background and external factors. Some of the design features that will be important for assessing technological readiness are already known, but not always to what extent. The requirements for the whole fuel cycle, including spent fuel management and the recent global challenges for nuclear supply chains, need to be given proper consideration.

3.1 What are the preferred properties?

Table 3-1 presents a selection of design features for maritime nuclear facilities, focusing on two main types of nuclear maritime installations: NPSs and FNPPs.

While FNPPs are not within the main scope of this paper, the contrast to NPS is relevant, as it underscores how propulsion differs from power production. For example, characteristics such as available space and operation under extreme conditions will not be as important and fundamental to safety for FNPPs as for NPSs. The operation of nuclear installations like these for power generation (FNPPs) is unlikely to include production activities during transport and, to minimize the risk of fuel diversion, may not even include facilities for the removal of fuel from the reactor.

There are valid arguments supporting both single-reactor and dual-reactor configurations for NPSs. Cost, weight, and space generally increase with the number of reactors, representing a disadvantage. Robustness and reliability – and available nominal power – may increase with the number of reactors; however, two reactors may affect the availability factor negatively for the ship as such.

Regarding the size of the reactor(s) in nominal power (MW), previous assessments have indicated that about 40 MW may prove sufficient for a 15,000 TEU vessel (DNV, 2023). The question arises as to whether a series of smaller reactors, standardized and installed in a multi-reactor configuration, would be more suitable for merchant shipping than a single large propulsion reactor. The option of a series of smaller reactors is also relevant when considering other reactor types, having few or no moving parts and a robust power and heat generation system, and not requiring, for example, a specialized crew.

Given the need to minimize complexity and prioritize inherently safe designs with passive safety features, low-pressure systems may be preferred for NPSs. This preference aligns with the use of Generation IV-type reactors, or even heat-pipe reactors, as alternatives to the historically dominant PWR designs in maritime applications.

Overall, commercial reactors deployed at sea should be more compact than land-based plants. The mobility aspect significantly affects the fundamental design, particularly in the selection of fuel and reactor technology, and the logistics of efficient refuelling. Refuelling can only take place in designated shipyards equipped with necessary infrastructure and trained personnel.

Cost and security of supply are also important factors, especially as global nuclear fuel supply chains are already limited and shrinking due to the growing need for independence from the well-supported Russian enrichment industry. Pressure and temperature are also fundamental to the complexity of the system: high pressure and high temperatures require greater effort to achieve and demonstrate safety.

The purpose of a marine nuclear facility – whether for propulsion or power generation – influences the choice of reactor technology and propulsion principles. When considering a nuclear-powered vessel, a mechanical system

– such as steam turbines using water as the conventional working fluid of a nuclear reactor – may be preferable. This setup allows for direct connection to the ship's propeller shaft, representing a nuclear mechanical configuration. In a nuclear-electric system, the nuclear reactor generates heat, which is then converted into electrical energy to power electric propulsion systems.

If the overall purpose of the facility is to provide power, as with FNPPs, the assessments will certainly be different, but it is not obvious in which direction. This is because when weighing up different reactor technologies, other aspects may dominate the final decision, as can be seen below.

A vital property is the time between refuelling, which should be at least five years to fit a normal dry-docking schedule, preferably longer. However, online refuelling, as described above, may provide a different perspective on this issue. Higher enrichment levels, as discussed in Chapter 2, may be essential to meet operational and design requirements, such as time between refuelling.

TABLE 3-1

Preferred properties for maritime nuclear installations (technology)

<table>
<tr><th colspan="3">Selected design properties</th><th>Important aspect related to NPS</th><th>Important aspect related to FNPP</th><th>Note (joint properties)</th></tr>
<tr><td rowspan="6">Component 1: Technology</td><td rowspan="2">Front-end issues</td><td>Enrichment</td><td>Trade-off between planned routes, time between refuelling, relevant sites for maintenance.</td><td>Dependent on location, but with similar requirements as land-based installations.</td><td>Trade-off between enrichment levels and burn-up vs. fuel cost, refuelling time, and supply chain issues.</td></tr>
<tr><td>Fuel fabrication</td><td>Well-proven and tested fuel, with established back-end systems. Reliable fuel supply. High degree of safety.</td><td>Well-proven and tested fuel, with established back-end systems. Reliable fuel supply. High degree of safety.</td><td>Assurances of supply fundamental. Candidate fuel technology – TRISO (TRIstructral-ISOtropic).</td></tr>
<tr><td rowspan="2">Power generation</td><td>Reactor number/ size, also physical properties (tonnes, m^3, MW)</td><td>Cost vs. space/reliability/ operational redundancy (as compact as possible). One or two reactor units. Shielding fundamentally important for weight, footprint and crew safety.</td><td>Reliable power production vs. cost/ reliability/ power generation redundancy. External factors (ex. availability factor for power production). Several (more than one). SMR-equivalents (up to 300 MW). Less strict space limitations.</td><td rowspan="2">High-temperature systems have higher efficiency than water-based systems. NPS and FNPP involve different trade-offs in fundamental characteristics (nominal power, number of reactors, physical size, weight, etc.) because their overall purposes and functions differ.</td></tr>
<tr><td>Power conversion, efficiency and reliability</td><td>Nuclear-electric provides flexibility, though less simple (nuclear-mechanical). Benefits of direct cycles (gas-turbines vs steam turbines). Steam turbines require more space and have less flexibility regarding placement (horizontal/ vertical). Reliability should be competitive with traditional ship engines. Minimal complexity in operation (low pressure).</td><td>High-temperature systems efficient. Level of reliability dependent on requirements for power deliveries.</td></tr>
<tr><td rowspan="2">Back-end fuel cycle issues</td><td>Refuelling frequency/ burn-up</td><td>As high/long as possible (min. 5 years, at least in line with major maintenance periods, preferably longer).</td><td>As high/long as possible (in line with power need, major maintenance periods, preferably longer).</td><td rowspan="2">The need for reprocessing will influence back-end requirements.</td></tr>
<tr><td>Spent fuel storage and disposition</td><td colspan="2">The acceptability of on-site spent fuel storage/on-line refuelling must be assessed.</td></tr>
</table>

3.2 Candidate technologies and projects

A limited number of nuclear reactor technologies relevant for maritime installation exist today. This is primarily due to the limited number of combinations of fuel, coolant and, if relevant, moderators for the reactors.

Fundamentally, the physical principles and material properties limit the scope. Table 3-2 includes suggested combinations of fuel, coolant, and moderators, divided into conventional, advanced, and other nuclear reactors. However, several projects or candidate reactors have been left out as being mainly for land-based generation, even if promoted for other purposes.

While conventional reactor technologies dominate historical merchant nuclear projects, several advanced technologies are emerging among the candidate technologies and projects, as seen in Table 3-2. These involve other types of nuclear fuels and coolants; for example, metals, molten salt, or other components to cool the process or enable efficient fission.

For options that are not based on light water, the path forward is complicated, as all materials used in the reactor as well as the fuel itself must be qualified for the entire fuel cycle (before, during, and after operation). Together with the material qualification, an overall design must be prepared that describes the necessary fabrication, construction, testing, and performance of the safety-related structures, systems, and components. A proposed non-light water design must be accompanied by a recognized methodological basis involving; event-specific analytical methods, reactor coolant analytical methods, core design methods, and reactivity control methods.

A closer examination of the advanced reactor technologies demonstrates the importance of fundamental physical and chemical properties in shaping design choices. Among these, metal-cooled fast reactors (currently only lead-cooled designs are pursued for maritime use) and molten-salt reactors are two of the six reactor technologies proposed by the Generation IV International Forum for further development. This offers several advantages. The use of salt or lead as a primary coolant enables high outlet temperatures that allow for higher thermal-electric conversion efficiencies.

Additionally, operation at atmospheric pressure removes the need for complicated pressure vessels. Unlike sodium, which Terrapower is currently pursuing as a coolant for its land-based SMR, lead does not undergo any exothermic reactions with either water or oxygen, and its high boiling point eliminates the risk of coolant boiling and void formation during normal and most accident scenarios, a key safety advantage over water. Lead-cooled reactors can be designed with a large variety of nominal power outputs, including the hundreds of megawatts required for nuclear power plants or the tens of megawatts appropriate for decentralized grids and propulsion. The obvious downside is the need to keep the coolant at constant high temperature to prevent clogging.

Several properties associated with lead as coolant, such as high efficiency, atmospheric pressure, and high boiling point, are also relevant for molten salt reactors. The main feature of molten salt reactors is their use of a salt, typically fluoride or chloride, as a primary coolant, due to its excellent thermal properties, which make it highly effective for transporting and storing heat. Depending on the specific design, the molten salt will contain either a dissolved fuel (homogeneous) or solid TRISO fuel elements (heterogeneous), and possibly also compounds enabling it to act as a moderator, meaning SMRs can be designed as thermal or fast reactors.

Heat-pipe reactors represent a novel class of nuclear reactor technology, notably because, historically, they have not been counted among the GEN-IV list of designs and not typically discussed for maritime applications. However, this has recently changed with the UK-based commercial company Core Power bringing this technology forward as one of its candidate technologies for FNPPs, see Table 3-2 (Power C., Benefits of the Heat Pipe Reactor, 2025).

Heat-pipe reactors principally consist of a solid matrix in which holes are drilled to hold fuel rods and heat pipes. Currently, no heat-pipe operating designs exist with power outputs in the megawatt range. Originally developed for use in outer space, they are now also being considered as a potential replacement for diesel generators in remote locations such as islands, decentralized grids, and military bases (Yan, Wang and L.G.Li, 2020). The fuel used is typically UN or TRISO particles (HALEU), or U-Zr alloys. The original versions developed for space were designed as fast reactors. However, more recent activities, such as those by Core Power, have focused on models with thermal spectra.

Table 3-2 also features an overview of companies engaged in the development of reactors relevant or purpose-made for civilian nuclear vessels. As shown, these companies cover the whole range of technologies. Table 3-2 also lists several reactor concepts designed for civil maritime use that are still under development.

Based on the technical concepts proposed in the scientific literature, it is notable that attention is primarily on reactor technologies and their basic properties, while lesser consideration is given at this stage to the fuel cycle associated with the reactor types, and the explicit maritime requirements regarding reactor technology, such as crew, competence, security, and safety. In addition, just a few models are considered exclusively for maritime nuclear installations.

The selected reactor concepts also point in different directions when it comes to efficiency, safety, security, and non-proliferation. Additionally, broader considerations, such as economic feasibility, political priorities, and alignment with regional industrial capabilities and resource availability will play a critical role in shaping reactor selection for maritime applications. While proprietary and commercial activities are likely underway in various countries, a more comprehensive assessment is needed to understand the relevance and the importance of the different properties within the relevant context.

TABLE 3-2

Candidate reactor and fuel technology types for civilian marine reactors (both NPS and FNPP)

	Conventional nuclear [3]	Advanced nuclear				Other
Reactor type (type) (thermal/ fast)	**Pressurized water reactors (PWR)**	**High/very high-temperature reactors (VHTR)/(HTR)**	**Molten salt cooled reactors (MSCR)**		**Liquid metal-cooled reactors (LMCR)[4]**	**Heat-pipe reactors**
	Thermal	**Thermal**	**Thermal**	**Fast**	**Intermediate/ fast**	**Thermal**
Nominal power (MWt/ type (SMR/ micro-reactor/nuc. battery)	Above 20/SMR	Above 10/SMR, microreactor, nuclear battery	Above 10/SMR, microreactor	SMR, microreactor	Above 10/SMR/ microreactor	Up to 5/nuclear battery
Coolant	Water	Gas-cooled (helium) (single phase)	Fluoride salt	Chloride salt	Lead	Sodium or equivalent
Moderator	Water	Graphite	Graphite, other materials			Graphite, other materials
Fuel technology (materials/ geometry (heterog. / homog.)	UO2/ ceramic fuel (HALEU)/ rods (heterog.)	TRISO (HALEU) (heterog.)	TRISO (HALEU)/ pebble fuel (heterog.)	Liquid fuel (homog.)	Ceramic/ metallic/ rods (heterog.)	UN/ U-Zr alloys/ rods (heterog.)
Reactor vendor/maritime companies/ country of origin/relevant projects (a selection)	• KEPCO (News, 2020) • Prodigy (Floating Nuclear Reactor Project Set for 2030 Debut in Canada, 2024)	• HOLOS (Hologen, 2025) • BWXT (BWXT, 2022) • Nano Nuclear Energy (form. Ultrasafe) (energy, 2025)	• Kairos Power (Power K., 2025) • Seaborg Technologies (Seaborg, 2025) (liquid fuel) • Jiangnan shipyard (NucNet, 2024) (liquid fuel)	• Naarea (Naarea, 2025) • Core Power (Terrapower) (Power C., 2025)	• Newcleo (NewCleo, 2025)	• Westinghouse (eVinci) in coop. with Prodigy (Westinghouse, 2025) • Core Power (Terrapower) (Power C., Benefits of the Heat Pipe Reactor, 2025)

4 INTERNATIONAL AND NATIONAL AGREEMENTS AND REGULATIONS

Highlights

- Maritime nuclear installations require compliance with both maritime and nuclear regulatory frameworks.
- Safety, emergency preparedness, security, safeguards, and non-proliferation are central regulatory concerns.
- International organizations, including the IMO, IAEA, and NEMO, are working toward harmonized standards.
- Flag states, classification societies, and port/coastal states play critical roles in certification and oversight.
- Regulatory roadmaps and licensing processes are complex and may require coordination across jurisdictions.

The consideration of the technology framework, with emphasis on candidate reactor and fuel technology types for civilian marine reactors, has highlighted properties that should be adapted for use in maritime installations, and appropriately regulated as the technology advances towards deployment and commissioning. Land-based power reactors and fuel facilities around the world are subject to stringent regulation, driven by widespread awareness of the unexpected and unprecedented accidents which have taken place over the years.

An example may illustrate the number of dimensions related to the regulatory challenges. All nuclear material, including any type of nuclear fuel, is subject to continuous oversight under the 'safeguards' system administered by the IAEA, due to the risk of proliferation. Any nuclear fuel present, on land or in a vessel, also constitutes a significant security risk, with oversight of this being the responsibility of the national regulator. Safety dimensions, such as the risk of release and radiation exposure, are also the responsibility of the national regulator, together with any emergency preparedness measures needed at yards and in ports.

Looking at some of the requirements for dealing with these characteristics – safety, security, safeguards, non-proliferation, and emergency preparedness – at an aggregated level in a regulatory context, as shown in Table 4-1, the broad scope and fundamental role of the regulations becomes clear. Achieving international recognition of nuclear installations at sea – through a coordinated system of national and international regulations – is essential for enabling commercially viable nuclear shipping.

Looking at some of the preferred characteristics for safety, safeguards, security, non-proliferation, and emergency preparedness at an aggregate level, as shown in Table 4-1, the foundation lies in modern reactor designs with enhanced safety features, and modern means of communication and systems that transparently assure all relevant stakeholders that they are compliant in all respects. Reactor compartments should be restricted as much as possible, aligning with designs that support remote monitoring and, potentially, the application of some autonomous functions. In any case, due to their inherent mobility, any nuclear maritime installation should also require a high level of remote monitoring, fulfilling

TABLE 4-1

Preferred properties for maritime nuclear installations (overall safety)

	Main design properties	Important aspect related to NPS	Important aspect related to FNPP	Note (joint properties)	Reference to relevant regulatory system
Component 2: International and national framework	Safety (also including environmental issues)	Modern safety levels (Gen III/ Gen IV), emphasis on inherent safety, passive measures. No significant consequences when sinking (all types of environments).	Modern safety levels (Gen III/ Gen IV), emphasis on inherent safety, passive measures. No significant consequences when sinking (all types of environments).	Main difference regarding safety may be the need for, or the level of, surveillance (active parameters), e.g. inherent safety mechanisms.	IMO requirements, IAEA recommendations, national regulations.
	Emergency preparedness	Oversight and communication of status for all relevant situations, as part of an agreed bilateral/international system.	Oversight and communication of status for all relevant situations.		IMO requirements, IAEA recommendations, national regulations.
	Safeguards	Establish an international transnational system for accountancy and control.	Present system adequate.	IAEA with requirements for monitoring.	IAEA requirements, with provisions in national regulations
	Security	Limited or no access to reactor facilities when at sea, also fresh and spent fuel.		Possible conflicting concerns regarding safety vs. security needs to be evaluated for NPSs.	IAEA recommendations, national regulations.
	Non-proliferation	Fuel compositions and materials not attractive for proliferation.	Fuel compositions and materials not attractive for proliferation.	20% U-235 a given limit; detailed assessment needed (value chain (front and back ends)).	IAEA recommendations, national regulations.

broad obligations for communication capabilities, as well as high levels of cybersecurity requirements to meet general emergency preparedness requirements. This calls for a previously uncharted combination of maritime and nuclear regulations, as further described below, where draft regulatory roadmaps with the main actors are listed.

The walk-through below focuses on regulatory frameworks. However, several initiatives exist to facilitate co-operation and development in this area, spanning national, regional, and international levels and covering research and development, industrial efforts, and regulatory advancement. To support nuclear and shipping regulators in developing appropriate standards and regulations for the construction, operation, and decommissioning of nuclear maritime installations, the Nuclear Energy Maritime Organization (NEMO) was recently established. The mandate of the IAEA – the main player on an international level for land-based technology – also covers maritime nuclear installations, as all peaceful efforts are within its defined scope:

> "The Agency shall seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world. It shall ensure, so far as it is able, that assistance provided by it or at its request or under its supervision or control is not used in such a way as to further any military purpose."
>
> *(IAEA, 1957)*

This international nuclear framework, which in most areas is loosely coordinated by the IAEA, a UN organization, recommends principles, tasks, and responsibilities, while the detailed assessments and regulatory approvals, for example in relation to safety, security, and non-proliferation, are the responsibility of the national framework. This also includes the licensing process. The recommended measures are implemented according to national preferences and practices, so harmonization of regulations is a major unresolved issue that hinders the international scaling of nuclear power plants. One of the IAEA's main

roles is to monitor the stockpile of fissile material spent in the reactor and remaining in fresh fuel; promote nuclear energy; set safety standards to protect health and minimize hazards; and, to provide support services to facilitate the establishment and use of radiation and nuclear energy.

Considering the regulatory frameworks at different levels, the overall conclusion is that the recently initiated efforts to revise the international regulatory frameworks are fundamental to the future maritime nuclear industry and to ensure a safe maritime fuel cycle. However, additional efforts are needed on the national level of relevant countries to support research and development in this area. Bilateral agreements can facilitate and accelerate implementation. Nuclear regulators need to clarify with shipping authorities and classification societies how to establish a licensing system for nuclear ships. The regulatory roadmaps below provide an understanding of the relevant actors, their main tasks, and the importance of coordination interaction. They also underscore that sufficient time is required for all the relevant stakeholders to make progress in a coordinated way.

4.1 Existing regulatory frameworks

Regulatory frameworks around nuclear and maritime activities vary in nature. For maritime activities, there is a well-functioning system with defined roles for international organizations, national governments, classification societies, shipowners, and shipyards in international and national jurisdictions. This backdrop may serve as a starting point for the consideration of a future regime for the construction and operation of nuclear ships.

The United Nations Convention on the Law of the Sea (UNCLOS, 1982) establishes the overarching rights and obligations for nuclear-powered ships. The International Convention for the Safety of Life at Sea (SOLAS) and International Convention for the Prevention of Pollution from Ships (MARPOL) address safety management, emergency preparedness, and environmental protection, with these also applicable to nuclear ships. Nuclear-powered ships thus in principle have the same rights of innocent passage and freedom of navigation as conventional ships in territorial seas, straits, and the high seas. Furthermore, the Code of Safety for Nuclear Merchant Ships (CSNMS) (1981) provides design, construction, operation, and certification guidance for nuclear-powered vessels. However, the provisions for civil nuclear shipping in the SOLAS Convention include basic requirements for a certain type of reactor – the PWR, as is the case for CSNMS code.

Several other instruments, international and regional, exist, such as the International Ship and Port Facility Security (ISPS) Code, which established an international framework for co-operation between governments, government authorities, local administrations, and the shipping and port industries to identify security threats and take preventive action against security incidents affecting ships or port facilities in international trade.

As far as the role of governments is concerned, an important obligation lies with the flag states and the coastal states, with particular emphasis on port states. Several of the basic requirements for flag states are laid down in the SOLAS Convention: for example, the issuance of a Nuclear Passenger Ship Safety Certificate or a Nuclear Cargo Ship Safety Certificate, i.e. an approved operating manual and an approved safety assessment. The flag state certification also contains considerations for adequate liability cover. On the other hand, coastal states may impose non-discriminatory safety requirements and regulate access to their ports, including emergency preparedness measures, as they deem appropriate. In addition to flag states, coastal and port states also play an important role in verifying compliance with international safety, security, and environmental standards. There are international and regional agreements to harmonize the way inspections are carried out so that ships are treated uniformly. Due to the international nature of shipping and its historical background, classification societies also fulfil the role of an independent third-party organization with a global presence vis-à-vis both the shipyard and the shipowner in the design, construction, and operation of the ship. In this way, global organizations such as the major class societies support internationally uniform enforcement of the maritime safety framework that is essential for regulating a global business such as shipping.

The framework conditions for the regulation of nuclear facilities on land are different. All types of nuclear technology are heavily regulated within a national framework, with only a small proportion being regulated by international bodies. After the Second World War, the nuclear sector grew rapidly in both the civilian and military sectors. As the activities associated with these facilities were seen as a significant risk, and at the same time the industry was considered sensitive, and fraught with many controversial aspects, societal control – regulation – was anchored in national regulatory bodies with national jurisdiction, often dealing with specific elements arising from particular national concerns that also result from socio-cultural specificities ('the way we do it here'). With the growing number of countries involved in nuclear activities, the international framework, which summarizes national responsibilities in conventions, has evolved into a broad-based system covering nuclear safety and security, including waste and spent fuel management, as well as insurance, safeguards, and non-proliferation. Existing regulations are often limited to land-based facilities, but in some cases cover all types of activity, including those at sea.

4.2 Regulatory roadmap – the maritime-nuclear regulatory nexus

The regulatory aspects of nuclear shipping are likely to go beyond what the industry is used to, allowing several alternatives for the future maritime-nuclear system. By identifying the key players, their mandate and the need for interaction, these elements, compiled in the context of regulatory roadmaps, provide an overview and guidance for the way forward. As the number of roles increases, the need to clarify the interfaces also grows, and regulatory roadmaps have been established to improve the understanding of the interdependencies. (Reistad and Ovrum, 2025).

First, we can recapitulate on the previous parts of this paper in which - both indirectly and explicitly - some risks to which the vessel and reactor(s) may be exposed need to be analysed and justify the need for interaction. Examples of issues that need addressing are, inter alia:

- Protection against damage from collision and grounding and for recovery after sinking. This also includes also detailed considerations on the environment when a vessel sinks and the recovery option is gone.
- Additional means of propulsion and power supply. Events requiring an emergency shutdown of the reactor must be anticipated, and it is not acceptable that an emergency results in the loss of any of the vessel's major functions which must be available to operate it in an acceptable manner in the event of a reactor shutdown.
- Security and sabotage. In modern terms, this means that all associated risks, i.e. terrorism, piracy, etc., must be included in the assessment.
- Alarms and control system. All interactions between the nuclear control system and the ship's other propulsion/control systems shall be analysed and it shall be demonstrated that all appropriate mitigation measures are in place and that there are no unacceptable risks.

The nuclear regulatory basis introduces a key role – the licensee. In Figure 4-1, a regulatory roadmap for the licensee for the approval of an NPS is described. The licensee holds overall long-term responsibility for the nuclear installation and its fuel, and is subject to legally-binding requirements regarding organizational quality, safety and security competence, and financial solidity. These requirements are significantly more demanding than those currently applied to yards or shipowners in the conventional shipping industry. The introduction of such a role may seem of minor importance; however, this may have wider implications for business models, further discussed in the next chapter.

At the heart of this work is first and foremost the nuclear regulator. A regulatory roadmap for the nuclear regulator, for the approval of an NPS, is described in Figure 4-2. While any reactor will at one level of development be subject to a licensing process of a national nuclear regulator, a first step is to clarify if there really is a legislative mandate provided for this regulator. As part of the international nuclear conventions and recommendations, it is assumed that all nuclear reactors will have a licence issued by a national nuclear regulator to be allowed to operate. The questions are to what extent this licensing process will be recognized by other similar agencies, and what is the scope of additional licensing efforts relevant for the operation of the nuclear-powered vessel, that will have to be performed. A licensing authority normally commissions a technical support organization (TSO) to carry out the detailed technical analysis required to ensure safe design, safe operation, and all associated activities. Fundamental questions for the realization of maritime nuclear installations are therefore: Is there national legislation for maritime nuclear installations? Is there a national regulatory authority with a clearly defined role for maritime nuclear installations? Has a TSO been established?

In Figure 4-3, the regulatory roadmap describes the flag administration's key role in making initial clarifications on how regulations should be applied to an NPS. As the role

FIGURE 4-1

A regulatory roadmap for NPS: Responsible organization/licensee

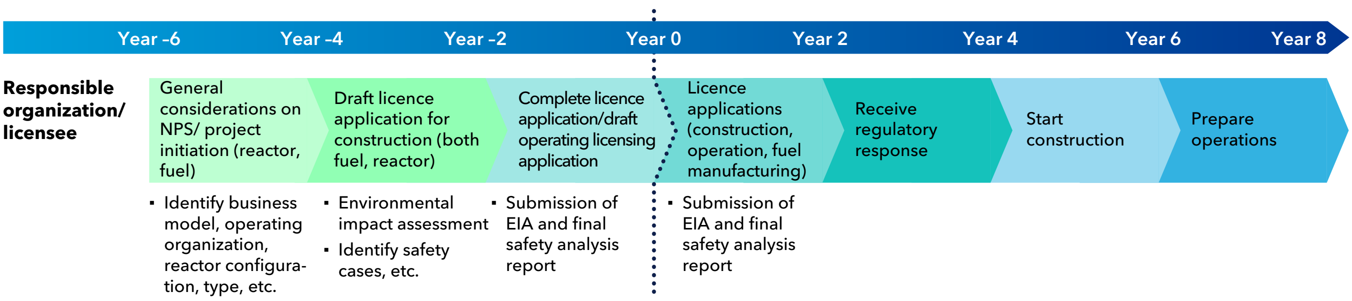


FIGURE 4-2

A regulatory roadmap for NPS: Nuclear regulator(s)

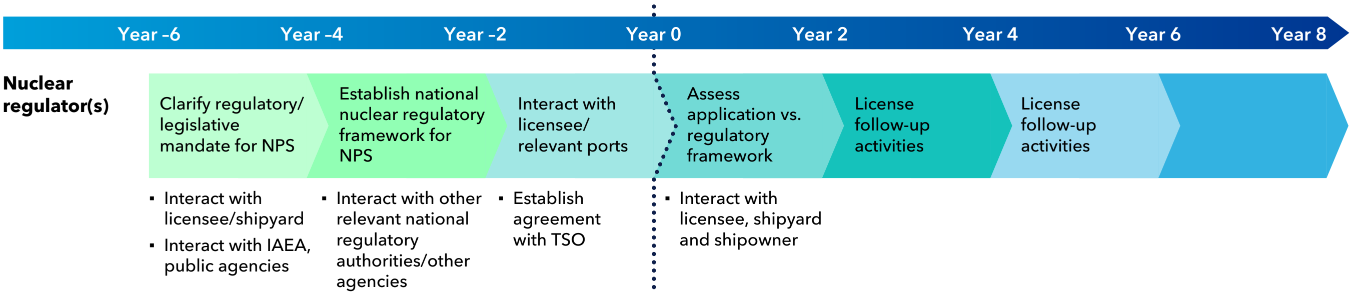
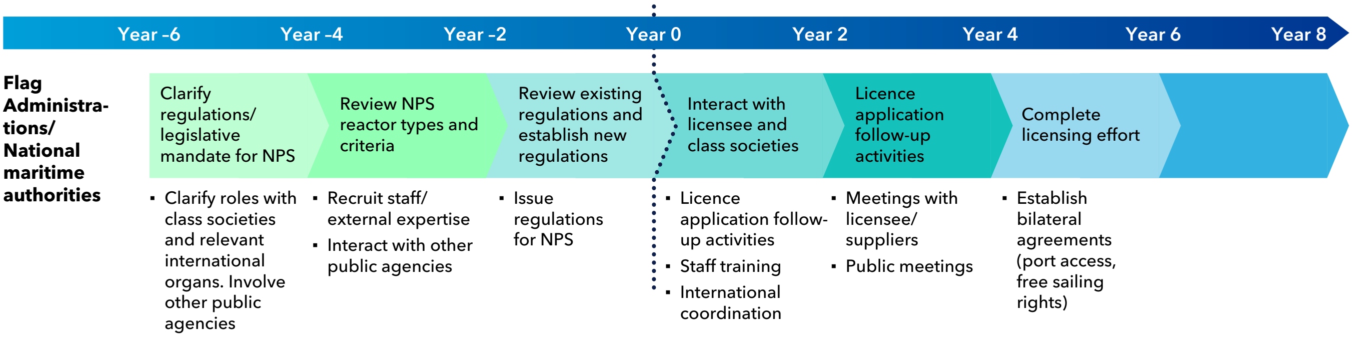


FIGURE 4-3

A regulatory roadmap for NPS: Flag administrations / national maritime authorities



of the flag administration is to issue a safety certificate in accordance with SOLAS Chapter VIII or equivalent, the flag administration must be willing and able to fulfil this role, which is recognized by coastal and port states. The competence and capacity of the flag State may be supplemented by delegation of authority to classification societies recognized by the flag State. This may depend on what level of development we are considering; FOAK may only be feasible with a few flag states as highly specialized skills are required and recognition by other parties is necessary; NOAK may be feasible through a different process as the basic requirements have already been established. The need for domestic expertise, both technical and regulatory, may suggest that significant domestic nuclear activities are an implicit prerequisite for establishing adequate competence as a flag State for nuclear ships.

Classification societies may play a key role alongside regulatory authorities in the design and construction of nuclear-powered vessels, particularly since responsibility for the vessel and reactor may rest with different organizations in different countries. Figure 4-4 presents a regulatory roadmap for classification societies, illustrating how developing a class guideline can serve as an initial step in the process. The unique role of classification societies may facilitate overcoming major obstacles in the goal to develop a truly international, standardized industrial base for nuclear merchant shipping, in contrast to the prototype nature of the land-based nuclear industry. However, other aspects for the realization of maritime nuclear installations are, taking the roles discussed above into account, how should the interaction between the nuclear regulatory authority, the TSO and the classification society be organized? Is the classification society a potential TSO in this regard?

As the maritime regulatory framework is based on international binding conventions defining roles outside the national framework, this is addressed separately in the regulatory roadmaps. The effort has begun in the IMO; the IMO's Maritime Safety Committee decided this year to update the relevant sections of the SOLAS and CSNMS noting that the current framework is outdated. There are alternatives for approval of nuclear ships if the revision of the CSNMS is delayed, for example the alternative design process, which will, however, take a long time overall. In this respect, bilateral agreements may play a role, as already proposed (Valiaveedu, Edmonds and Honson, 2025). If the IAEA takes the initiative to establish the Atomic Technology Licensed for Applications at Sea (ATLAS) initiative in 2025, this will be a step of fundamental importance for the advancement of maritime nuclear installations (IAEA, 2024).

FIGURE 4-4

A regulatory roadmap for NPS: Classification society

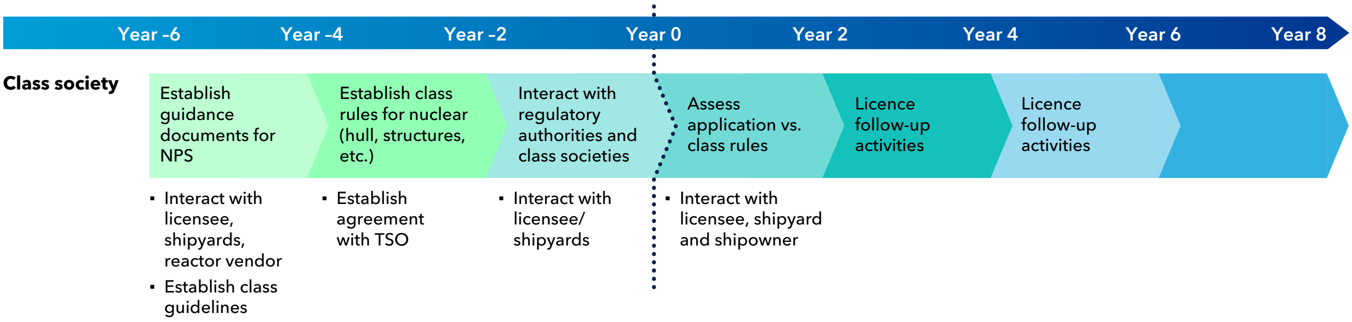
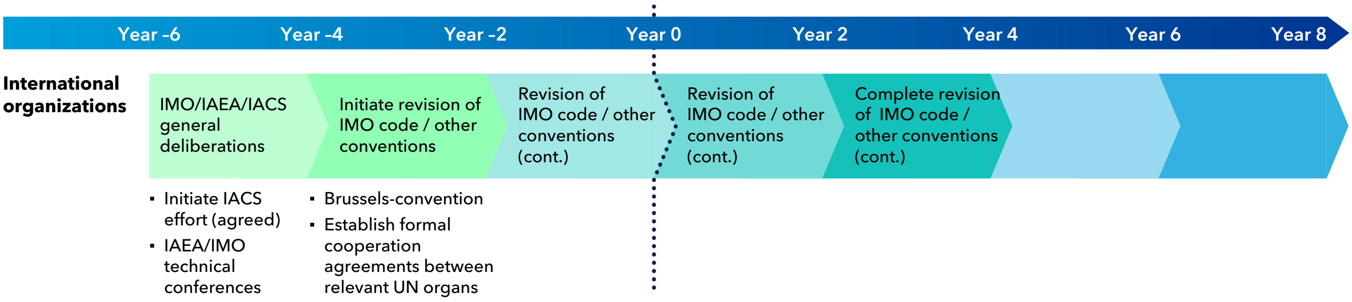


FIGURE 4-5

A regulatory roadmap for NPS: International organizations



The activities and timelines for a regulatory roadmap for NPS are shown in the figures above. Year 0 is the date on which the licence holder submits the licence application to the nuclear regulatory authority. The various steps for the licence holder, the nuclear regulator, the flag state administration and the national maritime authorities are, if not self-evident, well known and recognized for an activity that carries significant risks and attracts a lot of attention, not to mention the potential involvement of various coastal states, especially port states. The crux of the matter – and the potential advantage for making the process more effective – lies in the interaction between the roles.

The timetables indicate that it will take more than a decade to conceptualize, design, and build such a power plant. Even though the processes have already been initiated with several key players in the most important flag states in various projects, the steps described in the regulatory roadmaps must still be carried out overall, as the mobility of an NPS introduces several new safety aspects into the international system. Without a clearly defined effort by all relevant parties, this can take significantly longer than for a land-based installation. While the process can take between 5 and 10 years if the technology and concept are known and familiar, this can be extended to between 15 and 20 years if the technology and concept are new, there is a lack of national resources and competencies, and there is no agreement on how to harmonize the licensing system for nuclear and maritime installations. Harmonization efforts are essential in defining roles, responsibilities, and interactions between regulators and industry stakeholders, helping to streamline the finalization of key elements such as safety and environmental impact assessments.

The role of flag administrations and classification societies in the maritime sector is comparable to the role of the nuclear regulatory authority for nuclear installations. The nuclear regulator is concerned with the reactor and its potential impact on the environment, while the flag administrations and classification societies have a similar focus on the safety of the crew, the ship, and the environment. Although the safety code has rarely been applied to nuclear ships, the documents mentioned above – an approved operating manual and a safety assessment – are similar in principle to those required as the basis for a

licence application submitted by the nuclear regulatory body for land-based installations. A nuclear licence, at least traditionally for land-based reactors, serves as an information basis for all relevant stakeholders. It is crucial that port state control guidelines and regimes harmonize their regulations and requirements for such installations. If this is properly coordinated with the port states, the penalties for operating mobile reactors may not be so high after all. Classification societies can make the difference in this area.

The development of small modular reactors (SMR) can provide relevant perspectives on how and why nuclear energy needs to be made more cost-effective while further improving safety in line with the international framework. A preliminary conclusion of the regulators is that the way of working still needs to be changed to efficiently implement SMR projects worldwide (IAEA, 2023).

Regulators may need to engage earlier with the supply chain and associated accreditation initiatives to allow suppliers to progress the design and manufacturing of safety-related components, even before a licence holder is established. Several smaller reactors with a high degree of standardization can play an important role in reducing the licensing burden for the reactor and the vessel, considering the tiered approach. Therefore, the role of classification societies, which represent a new entity in the nuclear landscape, is crucial in facilitating the necessary standardization and harmonized implementation of the safety requirements required for a mobile vessel or facility.

As mentioned earlier, another big unknown in this picture is the progress within international maritime organizations. The continued efforts of key international organizations such as the IMO and the IAEA to formulate objectives and recommendations in this regard are of paramount importance and place emphasis on a harmonized approach to ensuring safety in the maritime fuel cycle.

5 BUSINESS MODELS AND COST

Highlights

- Business models must address ownership, leasing, crew size, and supply-chain management.
- Cost competitiveness hinges on standardization, mass production, and efficient manning.
- Recent land-based nuclear projects show wide cost variation, creating significant uncertainty for nuclear applications
- Mass production and standardization of SMRs offer potential for significant cost reduction and could enable business cases.

This paper has identified the technologies under consideration and the components for regulation and oversight, but what are the relevant business models for maritime nuclear facilities and, crucially, what is the actual total cost of a commercial maritime nuclear facility?

Some of the most relevant factors for the business model, including costs, for a general project, without knowing the ship segment or country of origin, are collected in Table 5-1, which, in addition to costs, covers roles (ownership) and properties relevant for the availability and reliability of the vessel.

One element that has not been adequately addressed in any study to date is consideration of how to maintain a small number of operating personnel, particularly on NPSs in international trade. The size and competence of the crew are important issues in modern shipping, where crew size has gradually decreased, with increased autonomy both in parts of the ship and for the ship itself also a consideration. Historical and existing nuclear ships, including naval vessels, have had large crews in line with the approach described above for early civilian ships. The reactor in current use, namely the PWR, requires extensive monitoring and several types of remedial action in the event of transients, as the passive approach to safety is mostly a modern feature. This, in turn, may require a larger crew with a wide range of skills related to the reactor, potentially making this type of reactor less suited for use in a cost-efficient and cost-saving shipping industry. While the PWR-type reactor is still an important candidate for future small modular reactors (SMRs) onshore, potential manning needs have not yet been described and may influence the outcome.

Another issue to consider more closely when establishing business models is supply-chain management. For historical reasons, Russia has a major influence on the supply chains of land-based nuclear energy, especially on enrichment services, and proposals are being made for the world to be less dependent on Russia in the future (Erdemir, 2022). As enrichment above 20% is a route to weapons-grade materials, a similar concern exists with reactors, which can be used to produce plutonium in case of extremely low-enriched fuel. Therefore, in the maritime nuclear fuel cycle, the various export control frameworks come into play, particularly regarding Russia, where various sanctions are in place. This applies to both the front end and the back end of the fuel cycle, and to reactors that are designed for maritime use.

TABLE 5-1

Preferred properties for maritime nuclear installations (business models and cost)

	Main design properties	Important aspect related to nuclear-powered ship (NPS)	Important aspect related to floating nuclear power plant (FNPP)	Note (joint properties)
Component 3: Business models/costs	Simplicity and standardization	Emphasis on simplicity (basis for reliability and robustness to maximize availability factor for propulsion and minimize risk). Minimize risk parameters (high pressure/temperature).	Emphasis on high efficiency (to increase time needed between fuel changes), in addition to reliability and robustness (Gen III/ Gen IV). The most efficient design involves high-temperature processes.	
	Low cost and efficient manning	Minimization of crew size and on-site competence (implications for the control systems and level of complexity).	Minimization of crew size and on-site competence, but not at the expense of power generation.	SMR, with more than 30+ employees per unit, is probably beyond the scope of NPSs.
	Ownership (leasing vs. owning)	Leasing in line with shipping industry mindset (no large capital costs), due consideration must be given to the role of the licensee vs. ownership.	Shifts liability and responsibility. FNPPs operating on a different time scale than NPSs, less relevant.	

Developing a maritime nuclear fuel cycle as described in Chapter 2 therefore involves not only the rebuilding of key elements required for maritime installations but also ensuring that these efforts are resilient across diverse future geopolitical scenarios, particularly as the industry transitions away from current supply dependencies.

In summary, in the absence of operational maritime nuclear facilities, there is a lack of understanding of the relevant cost estimates, i.e. value propositions, and supply-chain management issues encompassing all elements of the maritime fuel cycle. A business model that considers the full scope of this cycle needs to be created along with cost estimates. Significant expansion of the global fleet assumes that certain price thresholds (price per kW) are met, as identified below. The international nature of shipping and its focus on cost competitiveness requires standardized and industrialized production of SMRs for nuclear merchant shipping to succeed, in contrast to the prototype nature of the land-based nuclear industry up to now.

5.1 How to operate maritime nuclear installations?

A fundamental aspect of the maritime industry is its deeply commercial nature. Over the centuries, shipping has developed into a global ecosystem driven by private shipowners and shipyards together with an extensive network of traders, brokers, and specialized service providers. This spans all aspects of vessel operation, from fuels and equipment to cargo and crew, reflecting the industry's long-standing role in global commerce.

In contrast, the nuclear industry is relatively new, its origins tracing back to the scientific breakthroughs made just before and during the Second World War. It is often characterized as a global industry that is highly regulated and imperfectly competitive. It is technologically sophisticated, involves a high proportion of first-of-a-kind (FOAK) projects, requires large long-term financial commitments, and has a symbiotic relationship with governments (Rubio-Varas, Torre and Connors, 2022). However, as the shipping industry increasingly turns to the nuclear industry for solutions and the nuclear industry identifies the maritime industry as a potential market, it stands to reason that maritime nuclear installations will be built on commercial terms.

As outlined in Chapter 4, the licensing framework for nuclear operators requires that each nuclear installation or activity be overseen by a designated operator organization. This entity must be a legally recognized body within the national context, which has the responsibility to acquire a licence. A licence must be granted for the reactor and the fuel to be used in it, as well as for all production facilities relevant to the manufacture of the reactor, its components, fuel, and the fabrication processes, in addition to the relevant yards, including those used for fuelling and refuelling.

At the centre of a licensing system is a licensee, namely a responsible operator, whose role is central to the oversight of future maritime nuclear installations. The intuitive licence holder, using today's models for reactors and maritime installations as templates, would be the shipowner or a similar entity. However, the organizational structure of a shipowner bears little resemblance to that of a land-based nuclear power plant licensee. While the latter has extensive technical expertise, operational capabilities, and a long-term perspectives – including responsibilities for waste management issues, including the spent fuel elements, and the decommissioning of the reactor – there is an open question how a shipowner may handle such stringent requirements when operating conventional maritime technologies, which will definitely affect the potential for trading the vessels, for example.

A central consideration for the commercial operation of a future nuclear fleet is, therefore, the establishment of an appropriate business model adapted to the technology used, with an organizational element covering all aspects required for a competent operator. This entity may also play an important role in the construction, operation, and decommissioning of the nuclear installation, having the competence to assist in all plant modes and all phases of the operation and decommissioning of the installation. One proposal, where the ultimate consumer of energy enters the picture as more of customer than an operator, is the development of a Solution Provider (Aparicio and Parsons, 2023). The Solution Provider shall be a service provider which either develops the technology itself or is closely linked to the manufacturer, with the main task of creating an integrated solution for the customer, namely the delivery of power services on a mobile platform. The Solution Provider should possess the required competence for operation and maintenance and have procedures in place to manage fuel supplies and end-of-life responsibilities. This proposal is similar to the trend towards servitization seen in several industries and pioneered in aviation with Rolls-Royce Power-by-the-Hour contracts for engines. Such solutions have the benefit of incentivizing optimization of maintenance and operations with the manufacturer / solution provider, and have led to highly reliable and cost-effective aircraft engine operations (Wood, 2021).

5.2 What does nuclear propulsion cost?

The total cost structure of a land-based nuclear power plant – covering site preparation, foundation work, grid connection, and control buildings – differs significantly from the cost of a reactor system (reactor, shielding, power conversion, and more) designed for a nuclear-powered ship. In the maritime context, several support systems are already included in the ship, reducing the scope and cost of external infrastructure. There are, however, differences between how land-based nuclear plants and marine installations will affect the costs. Due to the lack of data for maritime nuclear facilities, the following discussion draws on the experience of land-based power

USS Gerald R. Ford nuclear-powered aircraft carrier. Picture courtesy of Hendrik Brinks reactors. The costs for nuclear power plants on land are assessed below, where we consider historical cost overruns and analyses related to the potential for cost reduction.

5.2.1 High spread in actual costs for recent land-based large nuclear power plants

Actual costs[5] of recent land-based large-scale nuclear reactors exhibit a great span, ranging from 2,000–3,000 USD/kW[6] in China and South Korea to 14,000–16,000 USD/kW in the US and UK, with Finland and United Arab Emirates in between at 6,000–7,000 USD/kW (IEA, 2025). Compared with the initial budgets and estimates, the European and US reactors have exhibited cost overruns in the range 76% to 190% after adjustment for inflation as described in Table 6-2. Arguably, South Korean costs for land-based facilities might be more representative than Western costs for nuclear propulsion in merchant vessels.

Several factors are contributing to the higher costs of nuclear power projects in Europe and the US. One of the most significant is the extensive schedule overruns. For example, Olkiluoto 3 was initially projected to take 4 years but ultimately required 18 years to complete. These delays not only inflate construction costs, but also substantially increase the financial costs due to compound interest accrued during construction. Reactors for these projects have – despite years of accumulated experience – largely been FOAK one-off projects, coupled with an immature nuclear construction industry which disintegrated over 30 years due to the general absence of newbuild activity. For example, there has been a lack of qualified workers to produce nuclear-grade steel and concrete.

Furthermore, the reactor designs for these projects were generally immature and underwent changes after construction had begun. In short, much trial and error has been applied in constructing these projects. Nonetheless, cost overruns have partly been exaggerated in the media as the initial budgets were not properly adjusted for inflation in some cases. Table 6-2 shows inflation adjusted initial budgets for these recent European and US projects. It should be noted that Vogtle 3&4, for example, experienced 76% cost overruns, not 2x to 3x as reported in some places. In general, for these projects in the US and Europe, high capital costs have contributed significantly to inflated costs, as reactors are CAPEX intensive and many projects have been delayed by several years.

It should also be noted that costs for land-based nuclear power plants include not only the reactor costs, but also all auxiliary costs. These include on-site surface buildings for the reactor, turbines and electrical systems, subsurface structures and tunnels, roads and rails, operations buildings, spent fuel storage pools, various plant equipment such as fire detection systems and fire protection, and much more. In a maritime application, some of these costs may already be included in the cost of the hull or else not relevant for a ship, although other costs for ships may apply.

5.2.2 Reasons for high costs in the US and Europe and cost cutting opportunities

One of the main reasons for the low productivity on the nuclear power plants Summer and Vogtle in the US, was the low productivity of craft labourers. For example, it was found that these workers were unproductive during 75% of scheduled working hours, primarily due to construction

TABLE 5-2

Budgets and actuals for selected recent nuclear projects, highlighting the actual cost overruns of US and European projects after inflation adjustments of the initial estimates and keeping the original currencies

	Initial budget (10^9)	Inflation adjusted (10^9)	Inflation factor	Actual/ recent estimate (10^9)	Actual increase (%)	Gross MW	Actual cost/ kW (10^3)	Initial budget/ kWe (10^3)
Olkiluoto 3	3.2 EUR (2003)	5 EUR (2022)	1.52	11 EUR (2023)	110	1600	6.9 EUR	3.1 EUR
Flamanville 3	3.3 EUR (2007)	4.8 EUR (2022)	1.45	13.2 EUR (2024)	175	1600	8.25 EUR	3 EUR
HPC, UK	18 GBP (2016)	23.7 GBP (2024)	1.32	46 GBP (2024)	194	3200	14.4 GBP	7.5 GBP
Vogtle 3&4	14.3 USD (2008)	21 USD (2023)	1.47	37 USD (2023)	76	2500	14.8 USD	8.4 USD
Saeul 1&2							2.5 USD	

FIGURE 5-1

Cost reduction potential (Figure reused by courtesy of (Bolisetti et al., 2024))

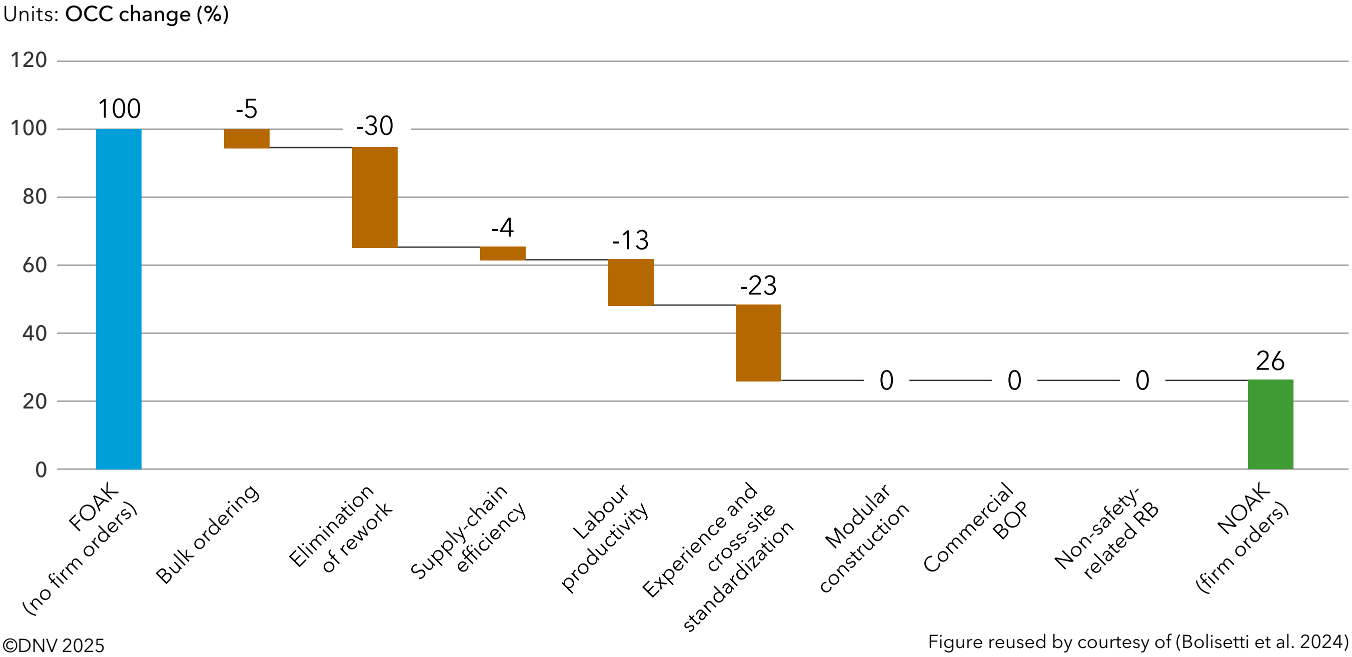


Figure reused by courtesy of (Bolisetti et al. 2024)

management and workflow issues, including lack of material and tool availability, overcrowded work areas, and scheduling conflicts between crews of different trades (Eash-Gates et al., 2020). The productivity in the general construction industry in the US has declined by 14% since the 1970s while productivity[7] levels in the nuclear construction industry have experienced a drop of more than 50% for nuclear steel and 90% for nuclear concrete (Eash-Gates et al., , 2020).

The good news is that there are ample opportunities for cutting future costs as the nuclear industry and workforce is re-established. With developed expertise, more efficient supply chains, and design refinements, the cost and time it takes to develop subsequent reactors should be reduced. Mass production of standardized reactors will allow for economies of scale, in addition to learning rates, and, according to Bolisetti et al., (2024), has the potential to cut costs by a factor of 4 (75% reduction) as the workforce gains experience and rework is eliminated. Figure 6-1 illustrates where costs could be cut to achieve a 75% reduction.

Standardization of nuclear programmes is a key factor for reducing construction costs (Angel, 2015). Mass production implies production of many reactors with the same reactor design and workforce and should lead to the creation of a mature supply chain and skilled workforce.

In China, Japan, and South Korea, shorter construction schedules have been reported in cases where the same engineering company led projects in multiple countries (Buongiorno et al., 2018).

Finally, cutting construction time significantly impacts total costs. For example, a loan with 7% interest rate will double the level of debt over 10 years. Both Flamanville 3 and Olkiluoto 3 had schedule overruns in this range. Streamlined mass production in a factory, in turn, reduces financial risk, further cutting costs. The introduction of governments and state-owned utilities as investors can also reduce capital costs. State-owned utilities are the main investors in China, Russia (Rosenergoatom), and South Korea (KEPCO) (Angel, 2015). In France, the state is proposing to offer the state-owned utility, EDF, a zero-interest loan to build new nuclear power plants (Reuters, 2024).

5.2.3 The cost opportunity of mass-produced SMR/MMR – in a shipyard

A growing share of investment is expected for SMRs over the next 25 years (IEA, 2025). No SMRs have recently been built, but there are numerous designs in the pipeline. Cost estimates in meta-studies for land-based SMRs range from 5,000 USD/kW to 9,000 USD/kW (2024) for Between-of-a-Kind (BOAK[8]) SMRs (Abou-Jaoude et al., 2023) while the South Korean SMART SMR is estimated at

10,000 USD/kW (IAEA, 2020). In the IEA Net Zero Emissions scenario (IEA, 2025), the costs are reduced in all countries, and to below 2,500 USD/kW in China already by 2040.[9]

Cost estimates for SMRs and Large Modular Reactors (LMRs) diverge, reflecting different assumptions about economies of scale. Some studies argue that LMRs benefit more from economies of scale and are therefore more cost-effective (Krellenstein et al., 2024) (Steigerwald et al., 2023; Stewart and Shirvan., 2022) while other meta-analyses find no significant cost difference between SMRs and LMRs (Abou-Jaoude et al., 2023). Similarly, older studies of actual costs did not find any clear evidence of cost differences as a result of scale for large versus small reactors. In fact, findings indicated that larger reactors had longer construction times (Valsdottir, 2025). Longer construction times tend to increase debt and thus financial costs, offsetting scale advantages, such as less concrete and steel per kW installed for a large versus a small reactor.

Arguably, economies of scale achieved through mass production and shorter construction times associated with SMRs in large factories, could outperform economies of scale achieved through building large reactors. One of the reasons for this is that fixed costs such as licensing and construction of a factory for mass production can be distributed over many units. As an example, production of many identical reactor units can change licensing from individual approval to type approval. Other types of economies of scale may include financing (large customers may be more creditworthy); purchasing (lower

prices on steel, concrete, and components when buying large quantities); more specialization of labour in large factories; and investments in new production techniques and advanced equipment such as robot welders (AK&M, 2023). This is not the same as 'learning rates', which come in addition to scale effects. As for MMRs, cost estimates are even more uncertain (Nichol and Desai, 2019), but heat-pipe technology like Westinghouse's eVinci could be a game changer due to its simple design, compact size, and low weight (Boyd, 2024).

Given the observations and reasons for cost overruns of recent European and US nuclear projects, a shipyard, in particular, theoretically has some advantages compared with the construction site of a one-off land-based nuclear power plant, assuming the reactors will be industrially mass produced and installed at the yard. First, a shipyard is more like a factory with assembly lines. The best yards have a trained, well-organized, and permanent work force and yard management, factors which are likely to lead to significant cuts to the 75% idle time and rework experienced in some historical land-based projects. Second, mass production of standardized reactors for a relatively standardized fleet of vessels can lead to more of a type-approval approach, further reducing construction time and financial risk.

Table 5-3 provides a comparison of the investment alternatives of a conventional and a nuclear vessel using the total cost of ownership calculated as the net present value of the costs (CAPEX and OPEX) of each ship; see Annex for details on this simplified case study calculation.

The High, Medium, and Low CAPEX figures are identical to the actual costs per kW in Table 6-2: Vogtle 3&4 (USA), Olkiluoto 3 (Finland), and Saeul 1&2 (South Korea), respectively. For Olkiluoto 3, EUR is converted to USD using an average 2024 rate of 1.08. The Ultralow alternative assumes that the actual South Korean costs (for large reactors, not SMRs) can be further reduced from 2,500 USD/kW to 1,500 USD/kW by economies of scale in terms of mass production on an assembly line. According to Bolisetti et al., (2024) this might be achievable. The other investment assumptions are listed in Annex.

In (DNV, 2024) a range of prices for fossil fuels and carbon-neutral fuels is presented. Today, and in a situation without decarbonization, conventional fuel prices are estimated to be around 500 USD/t, while carbon-neutral fuels required for conventional vessels to decarbonize are estimated to cost 1,000 to 2,300 USD per tonne of VLSFO equivalent. The proposed IMO Net-Zero Framework includes a CO_2 price per tonne of up to USD 380, equivalent to a fossil-fuel price including penalty of about 1,700 USD/t.

While a number of challenges and unresolved issues have been discussed in earlier chapters in this paper, nuclear vessels may have other cost advantages, such as that higher speeds can be economically viable for nuclear vessels, as the nuclear fuel costs are low compared to CAPEX, and a stable fuel cost known in advance through leasing of a nuclear reactor can reduce the risk premium of uncertain fuel costs going forward for non-nuclear ships. As for higher speeds, many vessels sail below design speed today due to GHG emissions regulations. Nuclear vessels could operate at today's design speeds without regulatory penalties due to GHG emissions. Nuclear vessels could also be designed for higher speeds, but this could increase CAPEX.[10] A high speed requires, for example, more installed power, and a stronger hull, shaft and propeller.

Another assumption is that a future commercial nuclear reactor will not need a significant increase in the number of crew on board. This is also related to how the safety and security will be arranged, and how maintenance will be organized in relation to the concept of operation and potential port calls. As pointed out above, access to the reactor compartment or fuel storage may not be permissible under operation in any case.

TABLE 5-3

Break-even fuel cost for nuclear and conventional – equivalent VLSFO cost per tonne yielding the same net present value of costs for a given reactor CAPEX

Item	High	Medium	Low	Ultralow
Reactor cost (USD/kW)	14 800	7 400	2 500	1 500
VLSFO equivalent cost (USD/t)	2 500	1 300	500	340

6 SIMULATING NUCLEAR PROPULSION IN MERCHANT SHIPPING

Highlights

- Detailed assumptions for cost modelling include CAPEX, OPEX, vessel size, operational parameters, and financial modelling.
- Comparison of nuclear and conventional vessels includes crew costs, fuel consumption, construction timelines, and discount rates.
- Break-even reactor costs for competitiveness: < 18,000 USD/kW (decarbonized fleet), < 8,000 USD/kW (conventional fuels).

In the previous chapters, we outlined some of the elements that need to be addressed to realize nuclear propulsion, for nuclear energy in shipping to be internationally recognized, enjoy a high level of public acceptance, and be commercially viable. We also outline how the business infrastructure, shipowners and shipyards, and an extensive community of traders, brokers and various support functions for all types of ships, fuel, equipment, cargo, and personnel will need to mature to accommodate nuclear propulsion in merchant shipping worldwide.

In this chapter, we investigate what cost levels marine nuclear reactors will need to achieve for nuclear propulsion to be relevant for the merchant fleet. A case study for a nuclear-powered ship and simulations of nuclear propulsion as part of the global fuel mix are presented, together with the identification of cost targets for the nuclear industry to strive towards to be able to compete with other marine fuels.

In the 2023 edition of DNV's Maritime Forecast to 2050 a case study was performed for a 15,000 TEU container vessel, see Figure 6-1. The case study examined what annual leasing costs for nuclear propulsion – with corresponding interest rates and CAPEX – could compete with other proposed solutions to decarbonize the case study vessel. The price scenarios were chosen based on historical prices for land-based nuclear propulsion as the cost of nuclear propulsion is highly uncertain, as seen in the new analysis in Chapter 5. The lower price scenario of 4,000 USD/kW (2023 dollars) represents approximately mid-price historically, while the relatively higher price scenario at 6,000 USD/kW represents a slightly higher price historically, though both are below the Medium level identified above. The results, presented in (DNV, 2023) show that for the case study ship, nuclear propulsion was able to compete against the other technologies in the 4,000 USD/kW-price scenario when comparing the net present value. In the 6,000 USD/kW price scenario, nuclear became competitive when the emission regulations tightened and approached net-zero emissions.

In the 2024 edition of DNV's Maritime Forecast to 2050 report, the potential uptake of nuclear propulsion in the world fleet was modelled using DNV's Pathway model, simulating ship by ship, year by year – a more complex model than the simplified case study presented here. In one of the four scenarios presented in the report, nuclear propulsion was available from 2040 at a cost of 8,000 USD/kW (2024 dollars) (DNV, 2023). The cost of nuclear in the 2024 report was raised compared to the high-cost scenario of 2023 by increasing the high-cost scenario somewhat and taking inflation into account.

The model allowed for a reactor module size of 15,000 kW (DNV, 2024) where ships in the model can then choose to have one or more reactors, each module with the same annual leasing cost. In Figure 6-2 we see uptake of nuclear from the first year if it is available. What is not shown in the figure is that nuclear propulsion in the model was chosen by the ships in segments with large engines, such as container vessels, large bulk carriers, large RoRo vessels, vehicle carriers, and large cruise ships.

FIGURE 6-1

Annual costs and net present value for the high nuclear and low nuclear scenarios (DNV, 2023) – the grey band is the range of costs over five fuel price scenarios for conventional and dual-fuel LNG/methanol/ammonia versions of ship

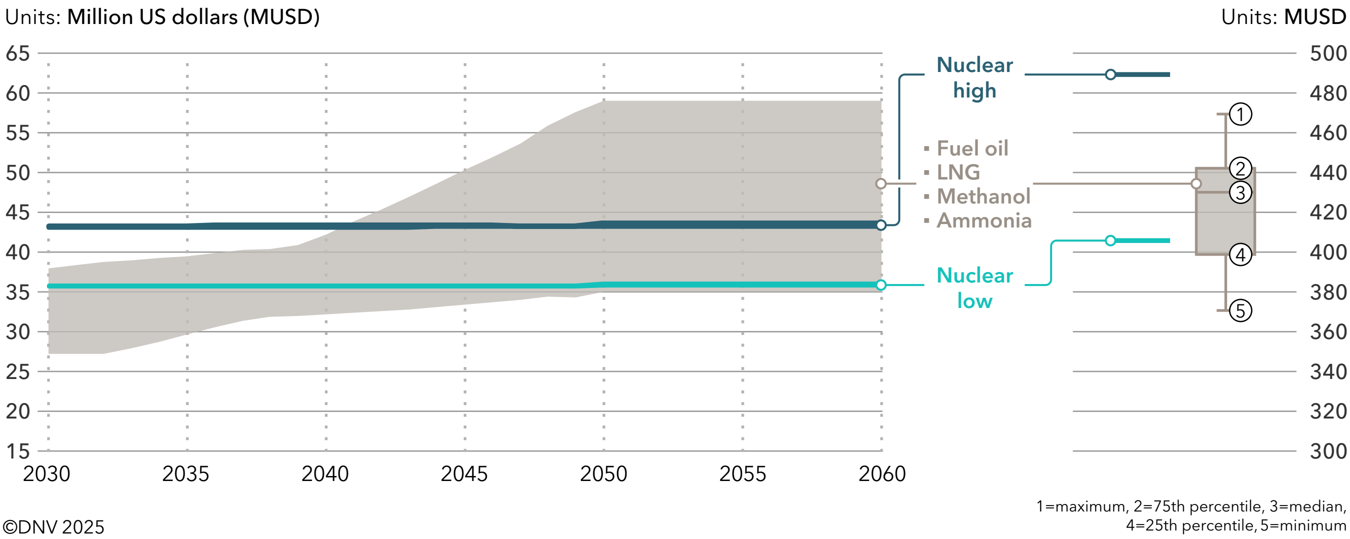
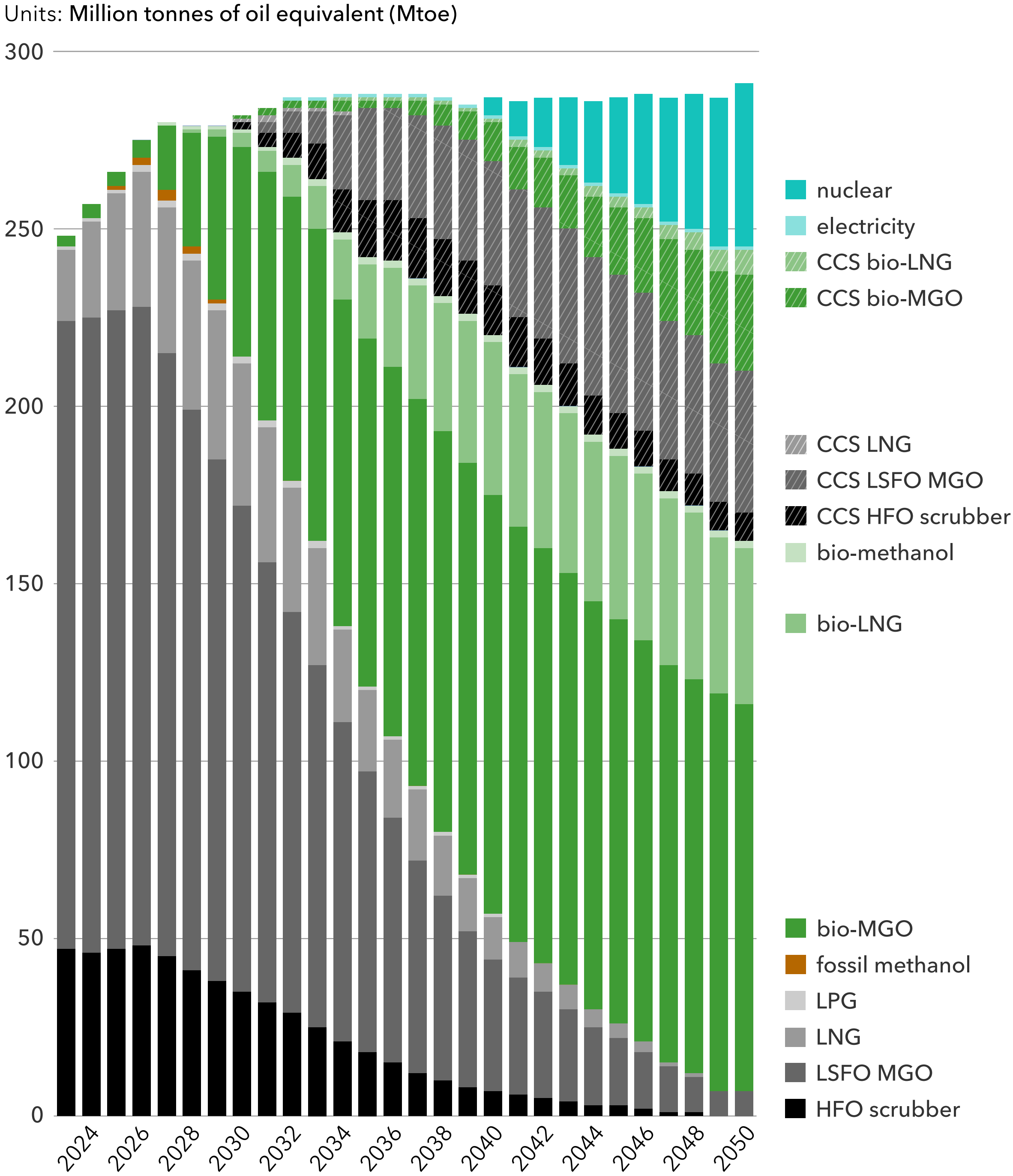


FIGURE 6-2

A possible scenario for fuel mix in a world fleet achieving net zero by 2050 – previously published scenario 1 from 2024 edition of DNV's Maritime Forecast to 2050 report



The cost of nuclear reactors for ships is highly uncertain, as mentioned in Chapter 5. We have therefore investigated the relevance of nuclear propulsion at higher costs, as a sensitivity study. The same scenario inputs were used as in the scenario from DNV's Maritime Forecast to 2050 report (DNV, 2024), but with increasing costs related to nuclear propulsion. Another uncertainty which will affect the business case for nuclear propulsion is the rate at which the world fleet is able to decarbonize. The results of this sensitivity study, where we vary the specific CAPEX of nuclear reactors for ships and the degree to which the world fleet is decarbonized by 2050 are found in Table 6-1 below. The share of world fleet is here calculated based on cost criteria.

For an optimistic scenario where the world fleet reaches the IMO's goal of net-zero emissions from shipping by 2050, these figures indicate that the cost of nuclear can increase to 18,000 USD/kW before it is almost completely outcompeted by other technologies for this set of assumptions. For a specific CAPEX of 8,000 USD/kW, nuclear propulsion achieved a 15% share of the world fleet fuel mix. For a scenario where the decarbonization trajectory of the world fleet is less strict, with decarbonization in 2070, we see, as expected, a lower uptake of nuclear propulsion at with the same price of 8,000 USD/kW, with the technology almost completely out of the fuel mix at the 15,000 USD/kW price. Lastly, we tested whether nuclear propulsion had any prospect in a future without decarbonization. The result of this was that at the specific CAPEX of 8,000 USD/kW, nuclear is only installed on a limited share of the world fleet, close to 1%.

With respect to the assumption, if the cost per kW for a typical SMR is applicable for a ship-size reactor, there are a number of considerations to be taken forward. As stated in Chapter 3, small reactors are inherently less efficient than large ones because of the higher ratio of core surface area to volume in the smaller versions. However, due to the lower risk, the regulatory requirements are considerably lower for smaller reactors, following a 'graded approach' to safety for these (IAEA, 2021). In this assessment, the figures have thus not been adjusted for any of the aspects.

These studies give some insight into the cost levels at which nuclear propulsion for ships could be competitive against other decarbonization solutions. Faster decarbonization ambition improves the business case for nuclear, allowing for uptake in our model at relatively high reactor costs, while if decarbonization is slower than the goals set today, the cost of nuclear reactors will have to reach significantly lower values than the costly land-based reactor projects in Europe today.

TABLE 6-1

Sensitivity study of degree of nuclear in the 2050 world fleet fuel mix as functions of specific reactor CAPEX and degree of world fleet decarbonization

Decarbonization trajectory scenarios	Nuclear CAPEX in USD/kW	Share of world fleet energy consumption using nuclear propulsion by 2050
Net zero by 2050	6 000	21.2%
Net zero by 2050	8 000	15.7%
Net zero by 2050	18 000	3.8%
Net zero by 2070	8 000	10.3%
Net zero by 2070	15 000	2.9%
No decarbonization	8 000	1.4%

ANNEX: INVESTMENT ASSUMPTIONS FOR NUCLEAR AND CONVENTIONAL VESSELS

Assumptions for simplified case study presented in Chapter 6

Some of the assumptions in this annex are based on the case study in (DNV, 2023), such as the annual VLSFO consumption and round trips per year, which in turn are based on an annual sailing distance of 94,000 nm. Other assumptions are as follows:

- Engine costs are included in hull costs for fossil vessels.
- The operational speeds are assumed to be equal for fossil and nuclear vessels, i.e. no faster transport with a nuclear vessel. This implies that the hull costs for the nuclear ship are like the hull costs for the nuclear ship.
- The cargo capacity is assumed equal. A nuclear plant occupies more space than a ship engine, but on the other hand, fossil fuel tanks occupy a large space on a fossil ship.
- The itinerary is assumed equal, i.e. the same sailing distance per year.
- Nuclear reactor costs: it is assumed that the costs include the whole nuclear plant part of the ship, such as steam turbines, power generation systems, etc.
- Operational costs: nuclear-only additional cost of 2.5 MUSD/year for crew[11] and nuclear fuel, including paying into a fund for decommissioning and storage for spent fuel. Only fuel costs are included for a conventional vessel, while other OPEX is assumed to be equal for conventional and nuclear ships. Operational costs are for 30 years, starting with the year construction is completed.
- Construction times are assumed equal (three years) when reactor mass manufacturing has reached the same level of maturity as hull manufacturing.
- CAPEX is divided into equal instalments per year. As an example, the CAPEX is 150 MUSD for the conventional vessel, or 50 MUSD/year over the three construction years.
- The discount rate assumed is equal at 8% for both conventional and nuclear vessel investment. We argue that in a mature, steady-state construction of nuclear vessels, the major investment risk is future freight rates, not construction delays or cost overruns.

TABLE 7-1

Investment assumptions for both conventional and nuclear vessel: engine CAPEX is included in hull costs for the conventional vessel

Item	Amount
CAPEX hull (MUSD)	150
Construction time (yrs)	3
Lifetime (years)	30
Roundtrips/year	4.5
Discount rate WACC (%)	8
Container capacity (TEU)	15 000
Nuclear OPEX costs/ year (MUSD)	2.5
VLSFO consumption per year (tons)	25 000
Nuclear reactor power (MW)	42

Operational costs are divided into OPEX (including crew costs) and fuel costs, assuming fuel costs constitute 20% of OPEX, based on uncertain figures from literature, with fuel cost estimates ranging from 2% for a light-water reactor to 45% in meta studies (Abou-Jaoude et al., 2023). Crew costs for a nuclear vessel vs. a conventional vessel will be much higher unless there is a high degree of automation and remote monitoring and control of the nuclear engine. Current information indicates very large workforces of land for based SMRs, for example 75 employees for GE-Hitachi's BWRX-300 300MW reactor (Reuters, 2025). A main assumption in the modelling presented in this paper is that a future commercial nuclear reactor will not need a significant increase in the number of crew on board.

Assumptions for 2023 case study of nuclear-powered ship in Maritime Forecast to 2050 report

We constructed High Nuclear and Low Nuclear scenarios, by assuming a cost for the 42 MW reactor (including initial fuel), then we calculate a leasing cost based on an annuity loan over the ship's lifetime with 8% interest for the CAPEX. An assumption was made for OPEX, based on the fact that OPEX[12] includes refuelling, remote monitoring, decommissioning funds, and extra crew costs or external competence, amounting to an additional 2.5 MUSD. As a concept of operation for these vessels is taken forward, this assumption has to be further evaluated, also taking into account potential resources on land to cover, for example, accident management. The annual leasing cost, including both CAPEX and OPEX, is then used in the FuelPath model to calculate the case study economics.

- High Nuclear scenario
  - Specific CAPEX, 6,000 USD/kW
  - CAPEX, 252 MUSD
  - Annual cost for CAPEX 22.2 MUSD, and for OPEX 2.5 MUSD
  - The annual leasing cost is high, 24.7 MUSD.

- Low Nuclear scenario
  - Specific CAPEX, 4,000 USD/kW
  - CAPEX, 168 MUSD
  - Annual cost for CAPEX 14.8 MUSD, and for OPEX 2.5 MUSD
  - The annual leasing cost is low, 17.3 MUSD.

Assumptions for 2024 simulation of nuclear-powered ships in world fleet in Maritime Forecast to 2050 report (DNV, 2024)

When included in scenario results of the future fuel mix, the nuclear share of the mix is represented as the amount of VLSFO that conventional ships would have used instead of nuclear. The main modelling features are:

- nuclear is allowed from 2040.
- only reactor sizes of 15 MW will be available.
- nuclear ships can use MGO as fuel for any remaining energy needs: if, for example, they have 20 MW of installed power in total, 15 MW can be nuclear, while 5 MW comes from MGO-powered auxiliary engines.
- reactors are assumed to be leased, with annual leasing cost calculated as annual downpayments on an annuity loan with 8% interest over 15 years:
  - reactor CAPEX of 8,000 USD/kW
  - with an additional 2.5 MUSD in annual OPEX covering additional crew/remote monitoring, refuelling and fuel decommissioning
  - for a total annual leasing cost of 16.5 MUSD per 15 MW reactor

LIST OF ABBREVIATIONS

BOAK	Between-of-a-kind (between FOAK (First-of-a-kind) and NOAK (Nth-of-a-kind))
CAPEX	Capital expenditure
CSNMS	Code of Safety for Nuclear Merchant Ships
FNPP	Floating nuclear power plant
FOAK	First-of-a-kind
HALEU	High-assay low-enriched uranium
HEU	Highly Enriched Uranium (above 20%)
HTGR	High-temperature gas-cooled reactor
IAEA	International Atomic Energy Agency
IMO	International Maritime Organization
ISPS	International Ship and Port Facility Security
kW	kilowatt
LC/RT	Levelized Cost per Roundtrip
LMCR	Liquid metal cooled reactor
MARPOL	International Convention for the Prevention of Pollution from Ships
MGO	Marine gas oil
MSCR	Molten salt cooled reactor
MUSD	Million US Dollars
MW	Megawatts
NOAK	Nth-of-a-kind
NPS	Nuclear-powered ship
NPT	Non-proliferation Treaty
OCC	Overnight construction costs, the costs of labour and materials excluding interest during construction
OPEX	Operational expenditure
PWR	Pressurized Water Reactor
SOLAS	Safety of Life at Sea
tHM	tons heavy metal (e.g. amount of fuel)
UNCLOS	United Nations Convention on the Law of the Sea
VLSFO	Very low sulphur fuel oil

END NOTES

1 While terms such as megawatt electrical (MWe) and kilowatt electrical (kWe) are commonly used in the nuclear industry, for purposes of alignment with the wider maritime industry, we have changed these to MW and kW in all cases throughout this paper.

2 In nuclear engineering it is common to divide between the thermal power output of the reactor (kWth) and the electric power output (kWe) after energy losses energy conversion system, most commonly a steam turbine. Thermal efficiencies are typically in the low thirties but can reach above 40 percent.

3 All historical merchant ships, all naval nuclear vessels (in 5 countries), all active Russian vessels and FNPP (KLT-40)).

4 Russian submarines (Alfa-class), US submarine (SEAWOLF)

5 Actual costs include overnight construction cost (OCC) and the Interest During Construction (IDC).

6 For nuclear power plants, reactor power is typically given in both thermal output (kWth) and in electric power output (kWe). We use kWe as the power for both nuclear-electric and nuclear-mechanical propulsion, although there will be some differences in efficiencies of power conversion.

7 The productivity for steel and concrete are measured as the volume of steel and concrete deployed per labour hour.

8 BOAK is somewhere in between FOAK (First-Of-A-Kind) and NOAK (N'th-Of-A-Kind).

9 Admittedly, NZE is not the most plausible scenario at the moment. However, the NZE scenario indicates the cost reduction potential.

10 LR claims «very fast steaming at negligible cost increase» in their «Fuel for thought: nuclear report (2024), p. 26.

11 Current nuclear crew size may be around 60. Our assumptions include much higher automation levels onboard ships than in current land-based nuclear plants. Also, it is assumed no specific security crew or guards on a ship. So, a 50/50 split between crew and fuel costs are assumed in the 2.5 MUSD/year OPEX costs.

12 Typical costs for decommissioning fund and fuel are USD 10 per megawatt hour (MWh) of electric energy produced. The case study reactor produces 132,000 MWh annually.
https://www.oecd-nea.org/jcms/pl_30490/full-cost-workshop-4-defining-plant-level-costs

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