OSM Thome

evigo

ADVANCED NUCLEAR IN MARITIME

Pilot Report - Feasibility Study

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Green Shipping Programme

Abstract

The maritime industry faces the challenge of decarbonising its operations. While there are several solutions for short sea operations, deep sea operations—responsible for over 85% of maritime carbon emissions—present more significant challenges and limitations. Various studies have examined ammonia, methanol, and biofuels, and now a detailed investigation into nuclear alternatives should be conducted. The goal of this Green Shipping Programme pilot study has been to perform a techno-economic and safety analysis of advanced nuclear energy technology as an initial step towards potential implementation. The scope includes evaluating whether new advanced nuclear energy technology can be responsibly used in the maritime industry by examining the technology, safety aspects, design impact, cost considerations, scaling potential, and a high-level timeline for possible implementation. Potential primary obstacles to its realisation will also be identified.

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Introduction

This report examines the feasibility of advanced nuclear energy technology for maritime applications, emphasizing its potential to decarbonize shipping operations, particularly in deep-sea contexts. The study assesses various aspects including technology, safety, cost, and regulatory frameworks.

The maritime industry faces significant carbon emissions challenges, especially in deep-sea operations, which contribute to over 85% of maritime emissions. Nuclear energy provides zero CO_2 emissions during operation, positioning it as an environmentally friendly energy source for ocean-going vessels. Historical examples of nuclear merchant ships offer valuable lessons for future applications.

The feasibility study is conducted through collaboration among several stakeholders across the maritime industry. This collaboration focuses on public opinion, technology assessment, environmental impacts, and financial aspects. Public acceptance is essential for integrating nuclear technology into maritime operations. Safety concerns, such as emergency planning and radiological hazards, must be addressed to gain public trust.

The study underscores the necessity for a comprehensive regulatory framework governing nuclear shipping, encompassing both national and international regulations. Current SOLAS regulations primarily address PWR reactors, requiring adaptations for other reactor types. The project evaluates the economic implications of nuclear propulsion, considering factors such as capital costs, operational expenses, and potential return on investment. Preliminary findings indicate competitive advantages as emissions regulations become stricter.

Recommendations include specialized training for personnel operating nuclear-powered ships, highlighting the need for regulatory guidelines tailored to maritime nuclear environments. The study suggests that with appropriate investments and regulatory support, nuclear propulsion could significantly contribute to the maritime sector's decarbonization goals by 2050.

Conclusions from the study

- The report presents an overview of many of the challenges to overcome for a nuclear propelled ship.
- Opinion polls on nuclear power have registered a shift in favour of nuclear, and through a questionnaire-based poll among professionals and experts in various segments of the Norwegian maritime industry, we have found a nuanced and often cautiously optimistic outlook on nuclear propulsion as a possible contributor to decarbonizing shipping.
- By comparing thorough analyses on land-based nuclear power with well-to-wake emission factors for conventional and alternative maritime fuels, we find that only the very best alternative fuels produced under very favorable conditions can compete with the very low GHG emissions factor of nuclear propulsion.
- Nuclear energy is included in the EU taxonomy – it is considered green – on the conditions that international safety standards are followed, that there are operational disposal facilities for low-level waste, and that there is a detailed plan to have in operation by 2050 a disposal facility for high-level waste.
- Nuclear risks, and thereby also use of nuclear fuel, are excluded in marine insurance policies and for it to change, international agreements and conventions needs to be developed. In addition to

such developments the insurance industry will independently have to consider whether such risks are something they are prepared to cover and mapping of the risks will be an important step in this process.

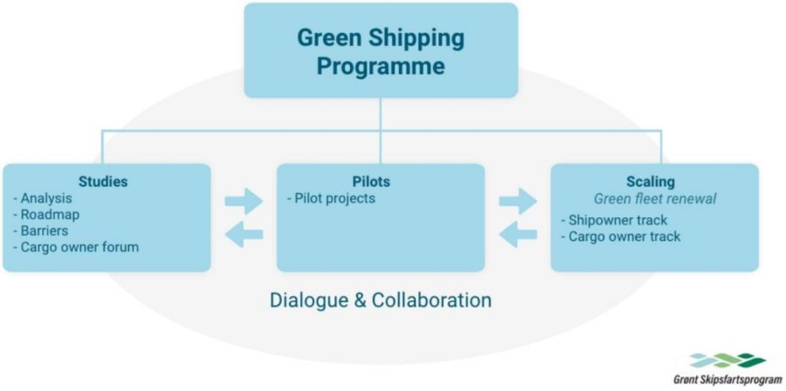
- In a case study using an exisiting ship, owned by Maran Shuttle Tankers, we found suitable reactor technologies and sizes matching the requirements of DP Shuttle Tanker operations. No showstoppers were identified to have these technically integrated in the engine room layout.
- Nuclear merchant ships are not only subject to regulations from IMO, flag and class – the maritime regime – but also the nuclear regime: IAEA and national nuclear regulatory bodies.
- The IMO's SOLAS ch.VIII with a corresponding code from 1981 provides rules for nuclear ships using one reactor type, and it is in need of being updated.
- For the last few years, Norway has accepted 30-40 visits per year from nuclear propelled vessels, most commonly nuclear-powered submarines.
- 2024 was a very important year for nuclear power internationally, marked by groundbreaking news and a growing enthusiasm for nuclear power, with big tech moving into nuclear for data centres, US passing law simplifying licensing, and the first Gen IV reactor in US being licensed for construction.

Green Shipping Programme partners

This report is a product of collaboration in its true sense. OSM Thome is the project owner, and the feasibility study is carried out under the umbrella of the Green Shipping Programme.

OSM Thome is a company specializing in Ship Technical Management, Crew Management, and other Marine Services. The crew is considered a key asset, with an emphasis on ensuring the quality of their services, equality, and ethics. Equipped with training and experience, OSM Thome manages a diverse fleet that includes Offshore, Tankers, and Dry/Bulk vessels. The company applies knowledge from advanced projects to all types of vessels. OSM Thome aims to be transparent in ship management, communicating clearly with customers about costs and potential issues. The company has a solid financial position, making it a stable partner for customers, partners, and stakeholders. OSM Thome provides a range of marine services while adhering to core values and environmental standards.

The Green Shipping Programme (GSP), a public-private partnership, aims to advance the Norwegian government's maritime strategies and plans. The programme's vision is to develop and strengthen Norway's goal to establish the world's most efficient and environmentally friendly shipping. GSP was first established in January 2015 under the name "the Green Coastal Shipping Programme", consisting of 16 private companies and organisations, as well as two government ministries. In the spring of 2019, the program changed its name to the Green Shipping Programme to state its international ambitions. As of 2025, the programme includes 112 private companies and organizations as well as 16 public observers. The Green Shipping Programme is financed partly by public allocations from the State budget of Norway and partly by the members themselves

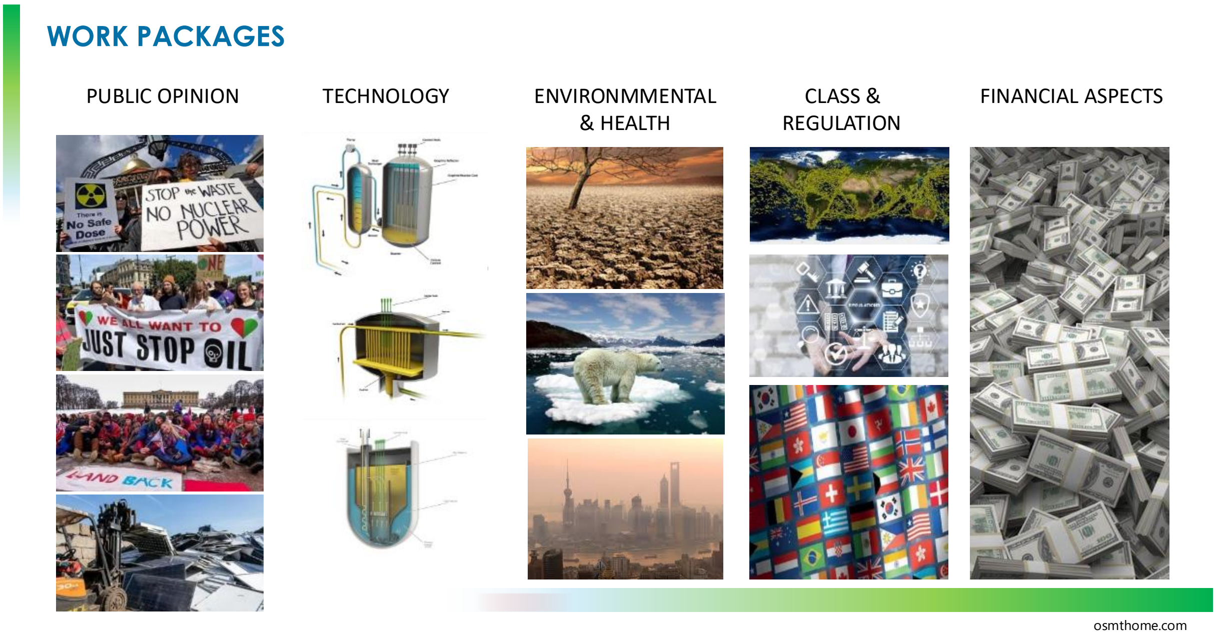


Project Partners and Contributors

The following partners from GSP have participated in the project, together with companies from the maritime supply industry that have put in many hours and significantly contributed to the findings.

Work Processes

The project work was divided into a series of Work Processes, which all have separate chapters in this report.



Contributors to individual Work Packages:

WP 1) PUBLIC OPINION – The work package owner is the University South-Eastern Norway (USN). Other participants are, Norsk Kjernekraft AS, Norwegian University of Science and Technology (NTNU), DNV, Skuld, and OSM Thome

WP 2) TECHNOLOGY - The work package owner is NTNU. Other participants are, Maran Shuttle Tankers, Utkilen AS, Sinoceanic Shipping, Wallenius Wilhelmsen, Wilhelmsen, Shearwater GeoServices AS, Hurtigruten, Lerøy Havfisk, Knutsen OAS, ABB, DNV, Brevik Engineering, and OSM Thome

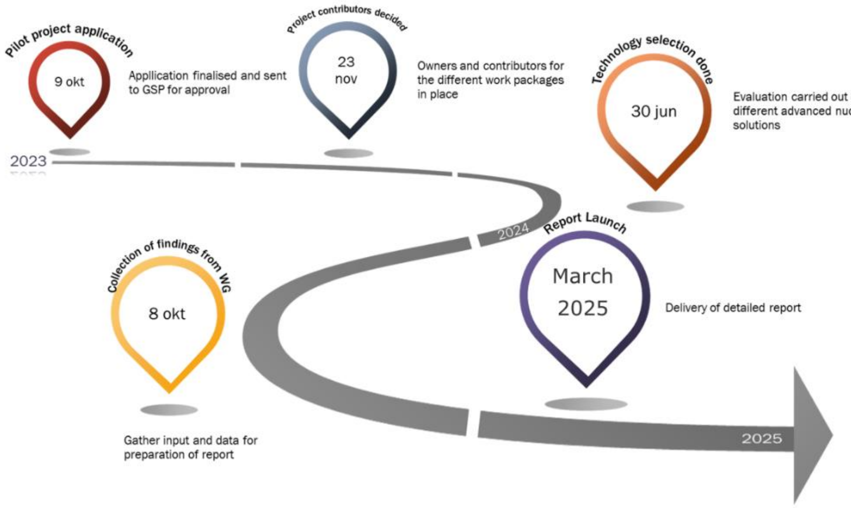
WP 3) ENVIRONMENTAL and HEALTH - The work package owner is NTNU. Other participants are, SINTEF Ocean, DNV, Shearwater, and OSM Thome

WP 4) CLASS and REGULATION – The work package owner is DNV. Other participants are, NTNU, Norwegian Maritime Authorities, Norwegian Coastal Authorities, Skuld, Norsk Kjernekraft AS, Shearwater, and OSM Thome

WP 5) FINANCIAL ASPECTS – The work package owner is OSM Thome. Other participants are, NTNU, Nors Kjernekraft AS, KLP, DNB, Sparebank 1 Nord-Norge, and Sparebank 1 Midt-Norge

The pilot project proposal was presented to GSP 9th October 2023 and presented for acceptance of partners. The project was formally accepted by GSP at the same date. The work to identify potential partners then started and the interest was significant. The formal kick-off meeting was held at DNV on 23rd November where work tasks were discussed, and the individual contributors agreed on what work to carry out.

Partners and contributors delivered their input in timely fashion so that the analysis work and preliminary conclusions could be made. The work with reporting could start as planned on 2nd January 2024 and was presented for GSP in May 2025.



Work Process 1, Public Opinion

A crucial part of all activities involving nuclear technologies is having an open and constructive dialogue with the public. As all nuclear activity has in general been of public interest, several projects have historically failed by not sufficiently acknowledging the need for open and honest communication at an early enough stage. Most famously in maritime applications, the Japanese nuclear ship Mutsu leaked fast neutrons on its maiden voyage in 1974, causing concern among local inhabitants, port authorities, and fishermen, which resulted in the ship being denied return to its homeport, the city of Mutsu.

In this chapter we first have a short introduction to nuclear power (WP 1.1), then discuss challenges for marine nuclear and safety of nuclear power (WP 1.2-1.3), before briefly introducing (WP 1.4) advanced reactor types. We present results from other studies on the public opinion of nuclear power (WP 1.5) and present results of work done in this pilot project on the opinions of the Norwegian maritime industry on using nuclear power (WP 1.6).

WP 1.1) Nuclear Energy's Role in the Zero-Carbon Transition

Nuclear energy is crucial to the global energy mix's transition to zero-carbon energy. It produces no greenhouse gas emissions during operation and is one of the cleanest energy sources available. Nuclear power generates one-third of the world's carbon-free electricity, playing a vital role alongside renewables in reducing greenhouse gas emissions from using fossil fuels without carbon capture and achieving climate goals.

Nuclear energy is released when a Uranium-235 atom undergoes nuclear fission. In a nuclear reactor, this energy is used to generate heat, which produces steam to drive a turbine and generate electricity.

Uranium is mined and processed from the Earth's crust. Naturally occurring uranium consists of about 0.7% Uranium-235, while the fuel used in nuclear power plants is enriched to 3-5% Uranium-235 to sustain a controlled fission reaction.

Inside a nuclear reactor, fission occurs within the reactor vessel, where Uranium-235 nuclei are bombarded with neutrons. When a uranium nucleus absorbs a neutron, the nucleus becomes unstable and can split, releasing energy, additional neutrons, and other fission products. These newly released neutrons can strike other uranium nuclei, triggering a self-sustaining chain reaction. This controlled process is carefully regulated using a moderator (such as water, heavy water, or graphite) that slows down the neutrons, making it easier for them to split Uranium-235. Control rods absorb excess neutrons to maintain a stable energy output.

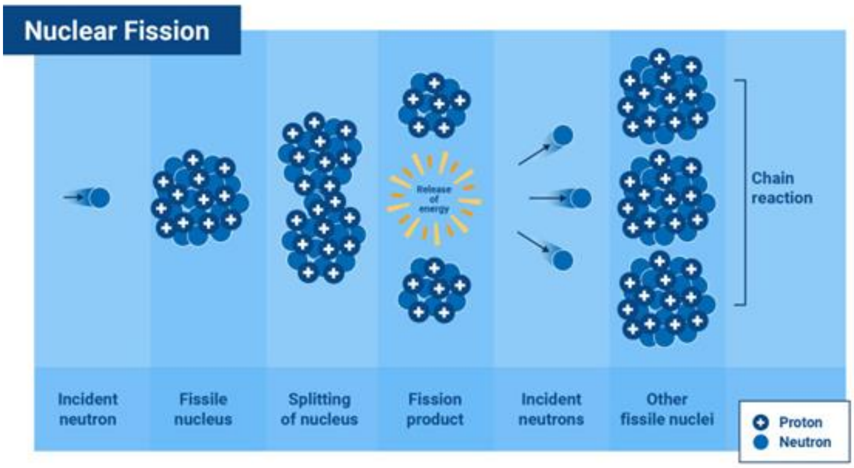


Figure 1 Nuclear fission, https://www.iaea.org/newscenter/news/what-is-nuclear-energy-the-science-of-nuclear-power

Spent fuel from nuclear reactors can be reprocessed, e.g., in a chemical process, and used again, as it still contains vast amounts of energy. However, not all nuclear power plants reprocess spent fuel. Reprocessing is expensive, technologically complex, and politically sensitive due to proliferation risks. Most countries store spent fuel instead of reprocessing it. Nuclear waste can be stored deep underground in stable rock formations or shielded buildings[1].

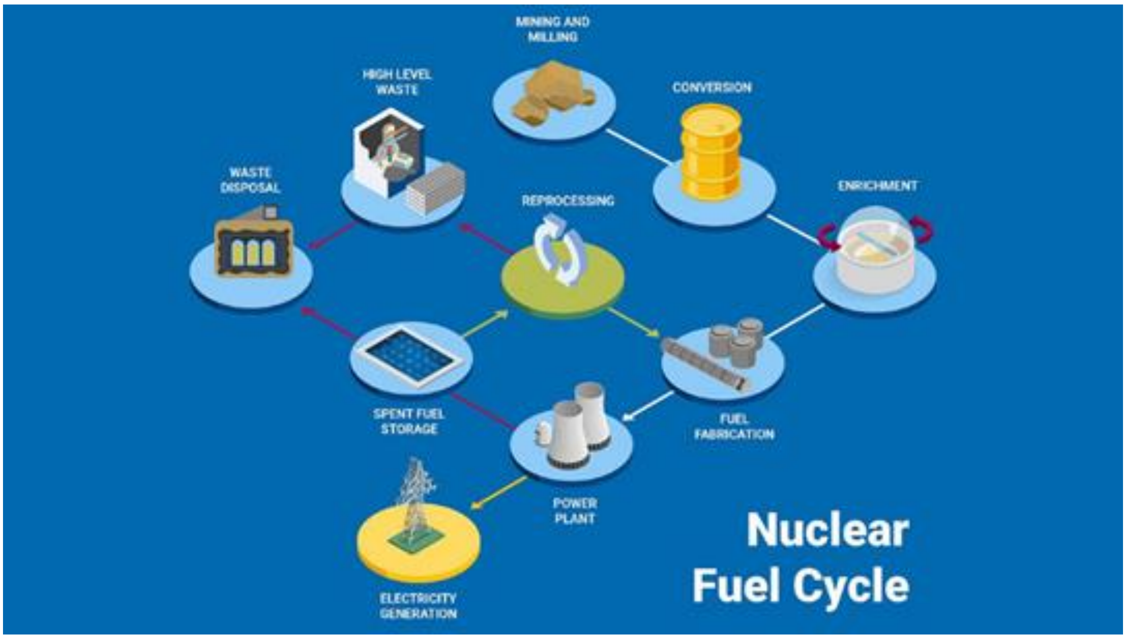


Figure 2 Figure nuclear fuel cycle, https://www.iaea.org/newscenter/news/what-is-nuclear-energy-the-science-of-nuclear-power

[1] https://www.iaea.org/newscenter/news/what-is-nuclear-energy-the-science-of-nuclear-power

WP 1.2) Challenges of Nuclear Propulsion in Commercial Shipping

The integration of nuclear technology into commercial shipping presents several uncertainties. Regulatory frameworks and licensing processes may take time to adapt to emerging technologies, often delaying implementation until safety and security risks are thoroughly assessed and mitigated. There are also uncertainties surrounding the cost and duration of crew education and training for commercial nuclear shipping (Morland & Schøyen, 2023).

Key safety concerns associated with nuclear reactors on ships include limiting the emergency planning zone to reduce potential consequences in the event of an incident, managing radiological hazards in both maritime and port environments, and addressing risks related to collisions, groundings, or sinkings.

Security is another major factor influencing public perception of maritime nuclear applications. Given ships' mobility and involvement in international trade, concerns arise regarding threats such as piracy, targeted attacks, or the illicit use of nuclear materials. Ensuring continuous protection against security risks while operating in international waters and foreign ports remains a considerable challenge (Senemmar & al., 2024).

WP 1.3) Public Acceptance and Safety of Nuclear Power

Although nuclear power has faced public scepticism, it remains the safest energy source based on fatalities per terawatt-hour (TWh) produced (Pioro, 2023). This includes major atomic incidents such as Three Mile Island, Chernobyl, and Fukushima. Compared to solar, wind, and hydroelectric power, nuclear energy results in fewer deaths per TWh. Fourth-generation nuclear reactors (and Gen III+) have advanced safety features, including passive safety mechanisms that reduce the need for human intervention to prevent accidents (S. Adumene, 2022).

While radioactive exposure poses risks at high doses, the health impact at very low doses is minimal (Lips & al., 2021). Norwegian radiation regulations limit occupational ionizing radiation exposure to 20 mSv annually[2]. In US naval nuclear-powered ships, radiation exposure for crew members is extremely low. Since 1958, no U.S. Navy personnel have exceeded 20 mSv annually, with the average yearly exposure being just 1.03 mSv[3] [8]. For comparison, natural background radiation in Norway alone averages 5.2 mSv per year (Johnsen & Morland, 2025).

[2] *Forskrift om strålevern og bruk av stråling,* FOR-2016-12-16-1659, 2016. § 32

[3] WNA. "Nuclear-Powered Ships." World Nuclear Association. https://www.world-nuclear.org/information-library/non-power-nuclear-applications/transport/nuclear-powered-ships.aspx (accessed 29th of March 2024).

Table 1 Occupational Ionizing Radiation Exposure Limits

Regulation	Radiation Workers
United States (NRC 10 CFR 20.1201)	50 mSv (5 rem) per year
U.S. Navy (Internal Guidelines)	20 mSv (2 rem) per year
European Union (Euratom Directive 2013/59)	20 mSv (2 rem) per year (averaged over 5 years, max 50 mSv in 1 year)
Norway (Norwegian Radiation Protection Regulations)	20 mSv (2 rem) per year

Despite nuclear power's low objective risks, developing new technologies depends heavily on public acceptance. If the public perceives the risks of a technology in its early stages as too high, strong opposition can arise. This opposition may hinder technology development, even if it offers clear benefits to its stakeholders (Wróbel, 2022). Many associate nuclear energy with atomic weapons and historical nuclear accidents such as Three Mile Island, Chornobyl, and Fukushima. Any nuclear-related incident could further reinforce these concerns (Yfantis, 2021) (IPPC, 2014). To gain public trust, advanced nuclear reactors' safe and efficient operation must be demonstrated comprehensively before integrating into maritime applications.

According to the European Maritime Safety Agency (EMSA) report on the potential use of nuclear energy, low investment, and public acceptance readiness levels represent significant obstacles to adoption. These challenges stem from difficulties securing financial support and public doubts regarding safety, environmental impact, and regulatory compliance[4].

Since economic feasibility is often the determining factor for implementing new technologies, nuclear reactors' high Technology Readiness Level (TRL) must be complemented by progress in these other critical areas.

WP 1.4) Advancing Reactor Technologies for Maritime Decarbonization

Public concern toward new technologies remains a key challenge. While PWRs (Pressurized water reactors) currently have the highest readiness level, other reactor types - HTGRs (High-temperature gas-cooled reactors), LFRs (Lead-cooled Fast Reactors), and MSRs (Molten Salt Reactors) possess considerable potential. HTGRs, LFRs, and MSRs require further investment appeal and community acceptance advancements to overcome safety, feasibility, and financial viability concerns. With targeted investments

[4] European Maritime Safety Agency (2024), Potential Use of Nuclear Power for Shipping, https://www.emsa.europa.eu/

and proactive public engagement, these advanced reactor technologies could gain broader acceptance and emerge as viable solutions for the maritime sector's decarbonization and modernization efforts[4].

Table 2 highlights the readiness and feasibility levels of various reactor technologies. It uses a scale from 1 to 9, where 1 indicates the lowest level of preparedness and 9 is the highest.

Table 2 Readiness and feasibility levels of various reactor technologies, with courtesy of EMSA https://www.emsa.europa.eu/

Category	PWR	MSR	LMCR	VHTR/HTGR	FBR	LFR
Investment Readiness	8	4	5	4	5	4
Community Readiness	7	2	4	2	4	2
Technical Maturity	Developed	Emerging	Mature	Emerging	Mature	Developing
Investment Attractiveness	High	Moderate	Moderate	Low	Moderate	Low
Community Support Level	Medium	Low	Medium	Low	Medium	Low
Ship Integration	4	1	4	2	3	3
Bunkering & Port Readiness	4	2	2	4	3	2
Propulsion Compatibility	2	1	1	1	2	1
Fuel Handling Readiness	5	5	5	5	4	4
Energy Conversion Efficiency	2	2	2	2	3	3
Risk Level (Community)	2	2	2	2	3	2
Long-Term Scalability	High	Moderate	High	Moderate	Moderate	Low
Environmental Impact	Low	Moderate	Moderate	Moderate	Low	Low

"SMRs are defined today as nuclear reactors with a power output between 10 megawatts electric (MWe) and 300 MWe. They integrate higher modularization, standardization, and factory-based construction by design to maximize economies of series (or the "series effect"). The different modules can then be transported and assembled on-site, leading to predictability and savings in construction times"[5].

Research into the potential use of Small Modular Reactors (SMRs) for deep-sea shipping is gaining attention due to the sector's decarbonization challenges. Given the variety of reactor concepts available, it is essential to establish clear selection criteria to identify the most suitable options. One approach is to apply Generation IV reactor requirements, which could enhance political acceptance among multiple flag states and facilitate the harmonization of licensing frameworks for nuclear-powered shipping.

To support this effort, researchers have developed a structured selection process that includes 11 exclusion criteria and 26 selection criteria, covering aspects from nuclear engineering to regulatory and political considerations. However, the effectiveness of this approach will ultimately depend on the quality of the reactor designs it identifies.

Additionally, access to comprehensive cost data remains a significant challenge, influencing the feasibility of nuclear propulsion in commercial shipping. Extensive research is being conducted to develop safe and efficient reactor technologies for nuclear-powered ships. As part of these efforts, the Generation IV Forum reviewed more than 130 reactor designs and identified six promising concepts for further investigation. These advanced reactor types enhance nuclear energy's efficiency, safety, sustainability, and cost-effectiveness. The selected designs include HTGRs, LFRs, and MSRs, each offering potential benefits for maritime applications. This ongoing research reflects a commitment to refining nuclear

[5] NEA, "Small Modular Reactors: Challenges and Opportunities," 2021. [Online]. Available: https://www.oecd-nea.org/jcms/pl_57979

technology to meet the specific challenges of marine propulsion while addressing public concerns about safety and environmental impact (Emblemsvåg & al., 2024).

WP 1.5) Public Opinion on Nuclear Energy

Nuclear power is receiving increasing public and political support as a reliable energy source[6]. Recent global surveys indicate that public support for atomic energy significantly outweighs opposition. Across 20 surveyed countries, nearly one and a half times more people favor nuclear power than oppose it. In 17 countries, atomic energy enjoys net support, with China and India demonstrating some of the most substantial backing—over three times higher than the opposition [7].

Nuclear power is more favored than other energy sources, such as onshore wind, biomass from trees, or gas with carbon capture and storage (CCS). Public preference for atomic energy ranks second only to large-scale solar farms, with a quarter of respondents believing their country should prioritize nuclear development. Individuals with a technology-neutral and optimistic outlook on climate change solutions tend to prefer atomic power strongly.

Reliability is the most valued energy attribute, and nuclear power is widely regarded as the most dependable thermal energy source. Approximately two-thirds of respondents perceive atomic energy as highly reliable, a rating that surpasses biomass and gas[8].

However, misconceptions about nuclear emissions persist, with over half of respondents believing that atomic energy generates substantial greenhouse gases. In contrast, in countries that have previously phased out nuclear power—such as Germany, Japan, South Korea, and Sweden—nuclear power is now perceived as a leading solution for reducing energy costs.

Concerns over safety and waste disposal remain prevalent, with 79% of respondents expressing some level of concern regarding nuclear safety. Despite this, safety apprehensions do not strongly correlate with opposition, as a larger share of those who express concern still support atomic energy rather than oppose it[7].

Figure 3 illustrates public opinion on nuclear energy across 20 surveyed countries. Respondents were asked the question: "*From what you know about [nuclear energy], to what extent, if at all, do you support or oppose using [it] to generate electricity in your country?*" They were given six response options: strongly oppose, tend to oppose, neither support nor oppose, tend to support, strongly support, and don't know.

The data highlights the percentage of respondents in each country who fall into these categories, providing insights into the level of support or opposition toward nuclear energy for electricity generation.

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[6] M. B. Brugidou, Jérémy "A return to grace for nuclear power in European public opinion? Some elements of a rapid paradigm shift," 2023. [Online]. Available: https://www.robert-schuman.eu/en/european-issues/0662-a-return-to-grace-for-nuclear-power-in-european-public-opinion

[7] Opinion. "Flertall for atomkraft i Norge." Opinion. https://www.opinion.no/innlegg/flertall-for-atomkraft-i-norge (accessed 13/03, 2025).

[8] R. O. M. W. Nelson, "Public Attitudes toward Clean Energy." [Online]. Available: https://www.radiantenergygroup.com/

Countries are ranked by net support (total support and opposition), revealing significant variations in public attitudes worldwide.

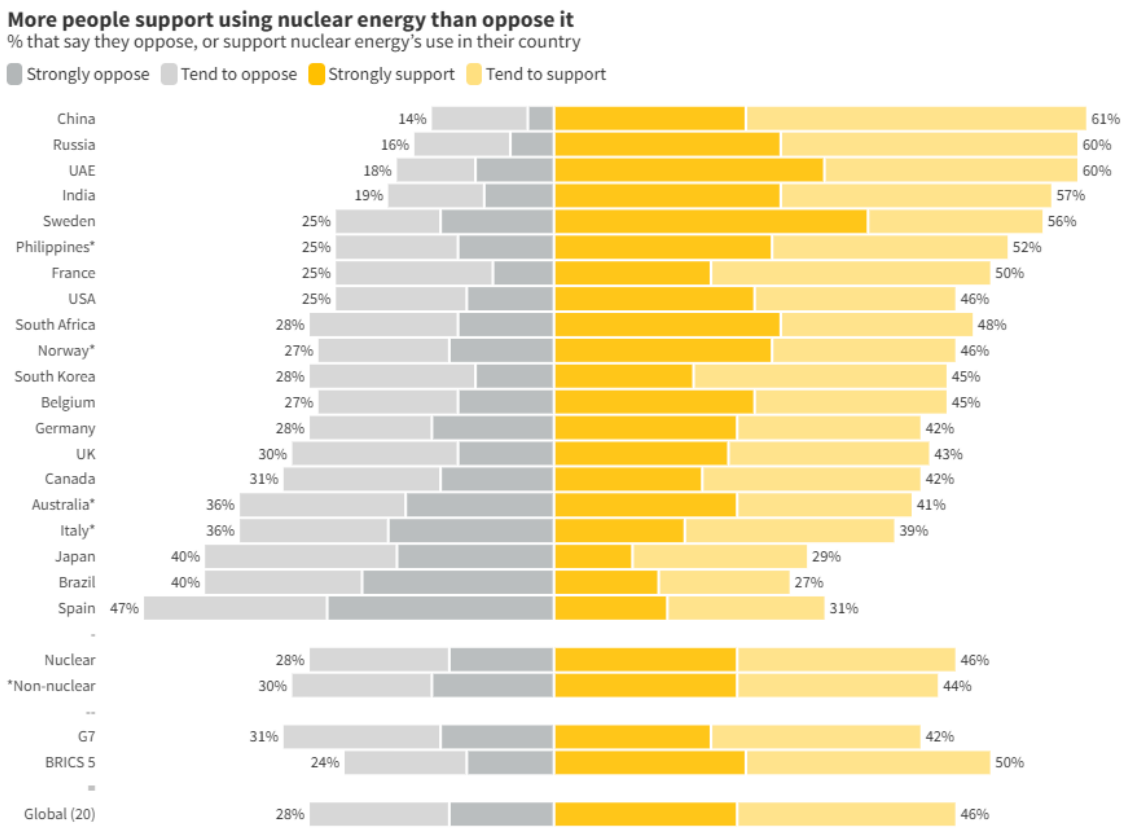

Figure 3 Courtesy of Radiant Energy Group, as featured in its Public Attitudes Toward Clean Energy Index 2023. info@radiantenergygroup.com

The study also revealed a correlation between the level of knowledge about nuclear power and whether respondents were positive or negative towards its use. The results suggest that those with the most knowledge about nuclear power is more positive towards this form of energy than those without knowledge about nuclear energy[8].

Opinion conducted a survey in January 2023 among a nationally representative sample of 1,003 people. The survey is part of Opinion's Social Monitor, which regularly explores current issues in Norwegian society.

The results show that 51% of Norwegians support the development of nuclear power in Norway, 37% oppose it, and the rest are undecided. Overall, more Norwegians are positive than negative toward atomic energy.

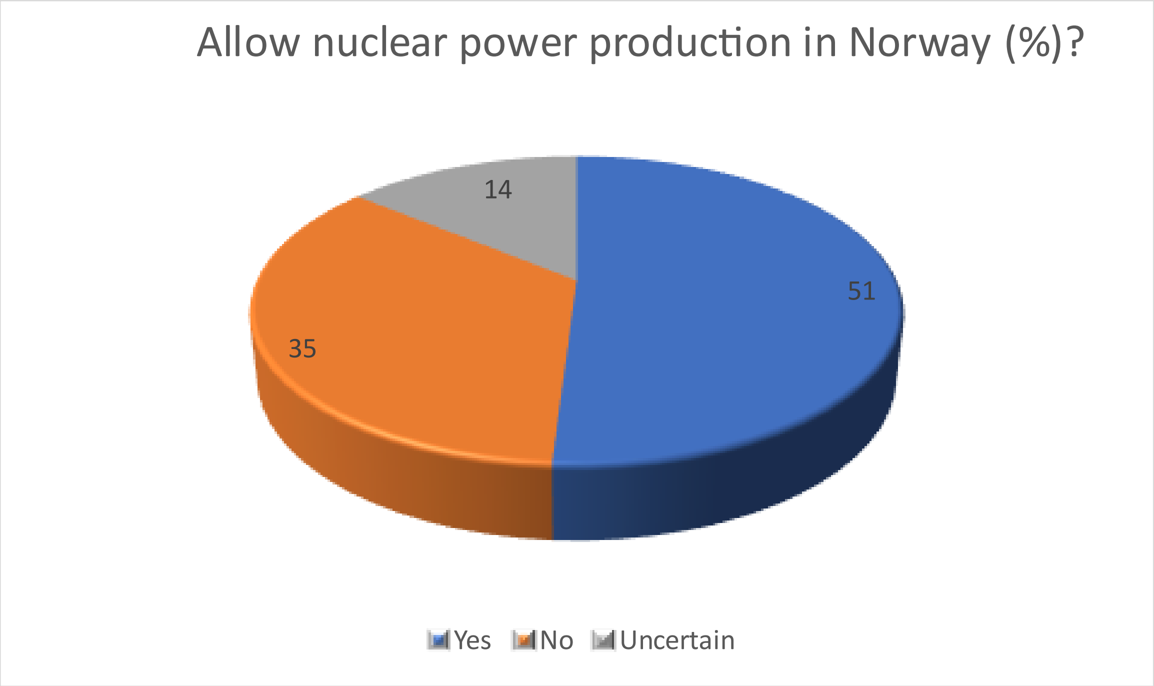

Figure 4 Opinion on nuclear power in Norway. (Adapted from OPINION)
https://www.opinion.no/innlegg/flertall-for-atomkraft-i-norge (accessed 13. March, 2025)

Support for nuclear power spans across political parties, with the highest support among Fremskrittspartiet (73%), followed by Venstre (63%), Høyre (58%), Rødt (52%), and Miljøpartiet De Grønne (49%). Senterpartiet and SV voters are the most opposed[7].

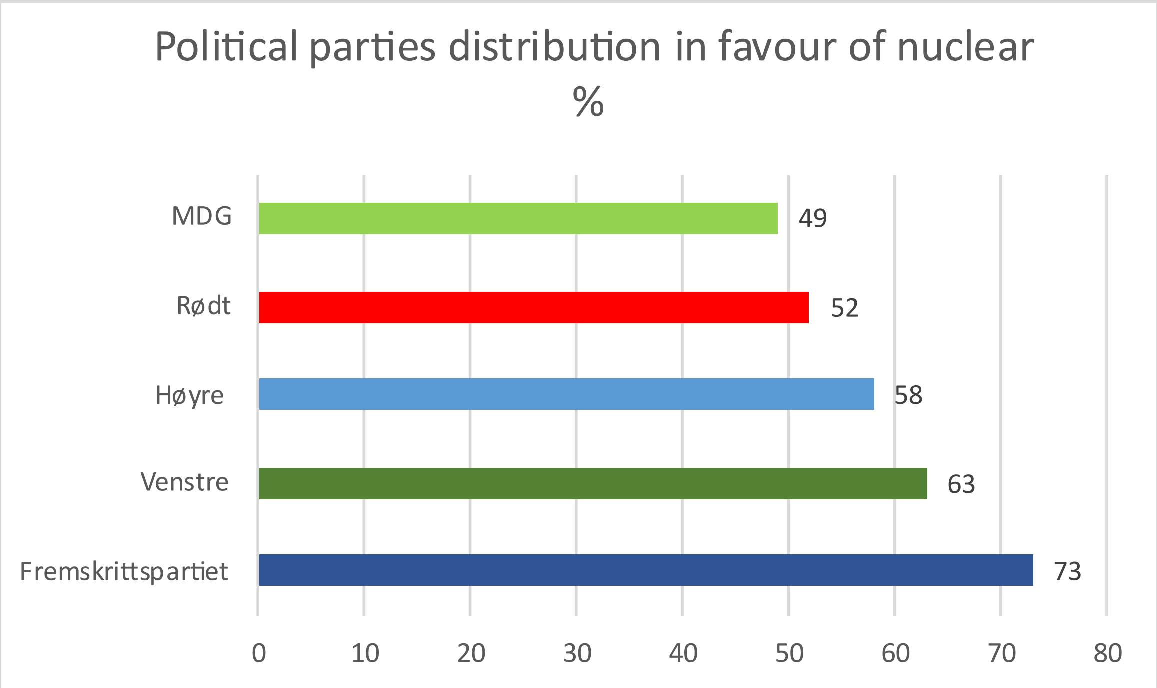

Figure 5 Political Opinion on Nuclear Energy. Adapted from OPINION
https://www.opinion.no/innlegg/flertall-for-atomkraft-i-norge (accessed 13. March, 2025)

WP 1.6) Exploring nuclear propulsion, insights from Norwegian industry stakeholders

In this chapter we present the findings from a questionnaire-based study conducted by a university student as part of an academic research project. The aim of the investigation was to explore the attitudes and perceptions of stakeholders in the shipping industry regarding the potential role of nuclear propulsion in reducing greenhouse gas emissions.

The data was collected through a structured questionnaire distributed via email to a targeted group of professionals and experts across various segments of the maritime sector. A total of 70 respondents participated, offering valuable insights into both the perceived opportunities and the barriers associated with the implementation of nuclear-powered ships.

The following summary provides an overview of the main findings and reflects a nuanced and often cautiously optimistic outlook on nuclear propulsion as a possible contributor to achieving the IMO's climate goals.

Contribution to IMO targets

Most respondents see nuclear power as either essential or an important contributor to reaching the IMO's target of net-zero emissions by 2050. While 39% considered nuclear propulsion indispensable, a slightly larger group (49%) saw it as a key part of a wider portfolio of energy sources, including solar and wind. A minority expressed scepticism about the technology's readiness or necessity by 2050, with several commenting that deployment could come too late to impact the current climate goals.

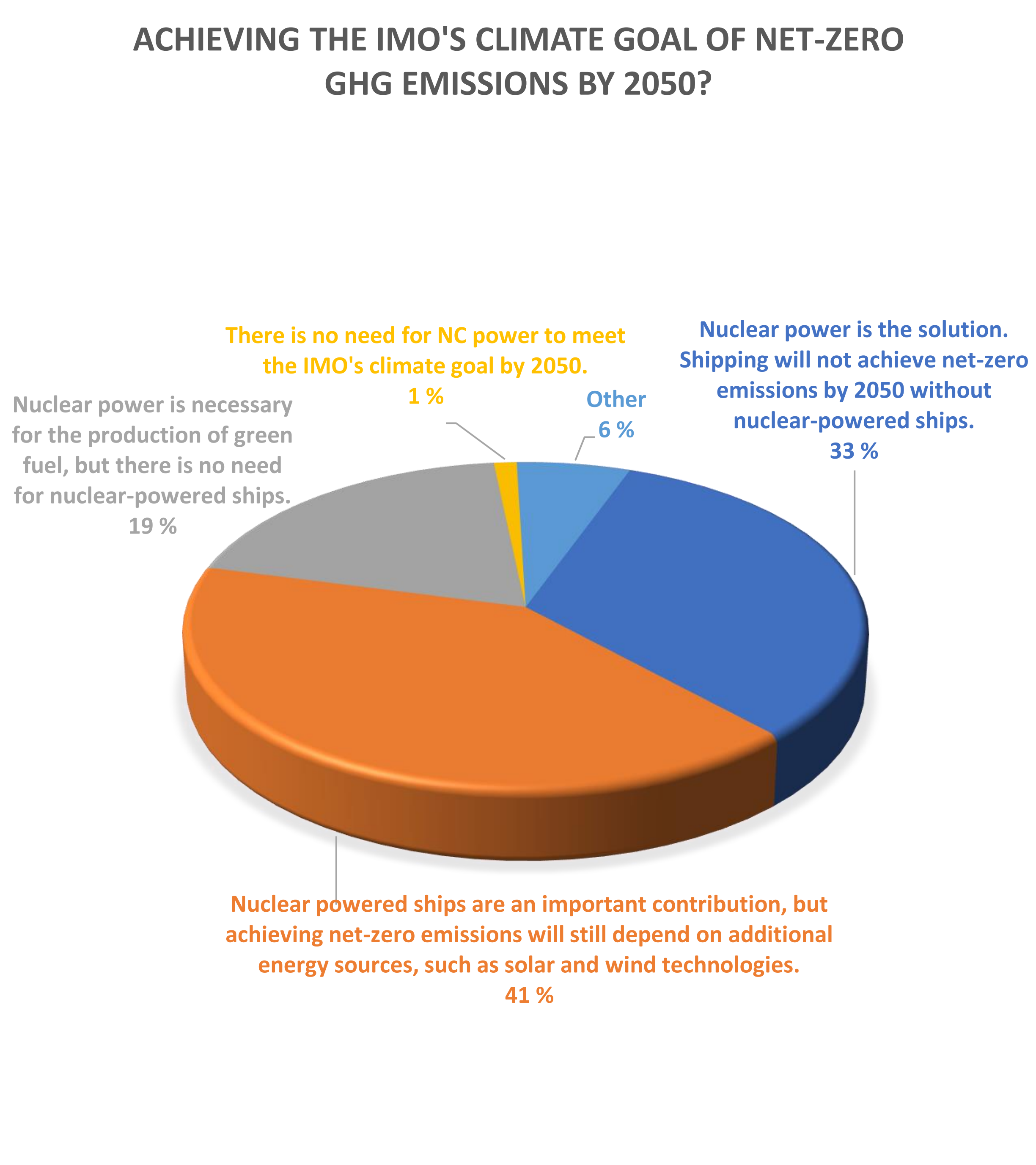

Figure 6 Answers to survey.

Interest and knowledge

Interest in the topic is considerable. A large portion of the respondents (76%) indicated they are either "interested" or "very interested" in nuclear propulsion. Importantly, no one expressed outright opposition to the concept. However, many respondents acknowledged that their knowledge of modern nuclear technology, such as Generation IV reactors and the comparison between uranium and thorium fuel, is limited, with only 23% claiming to be up to date on the subject.

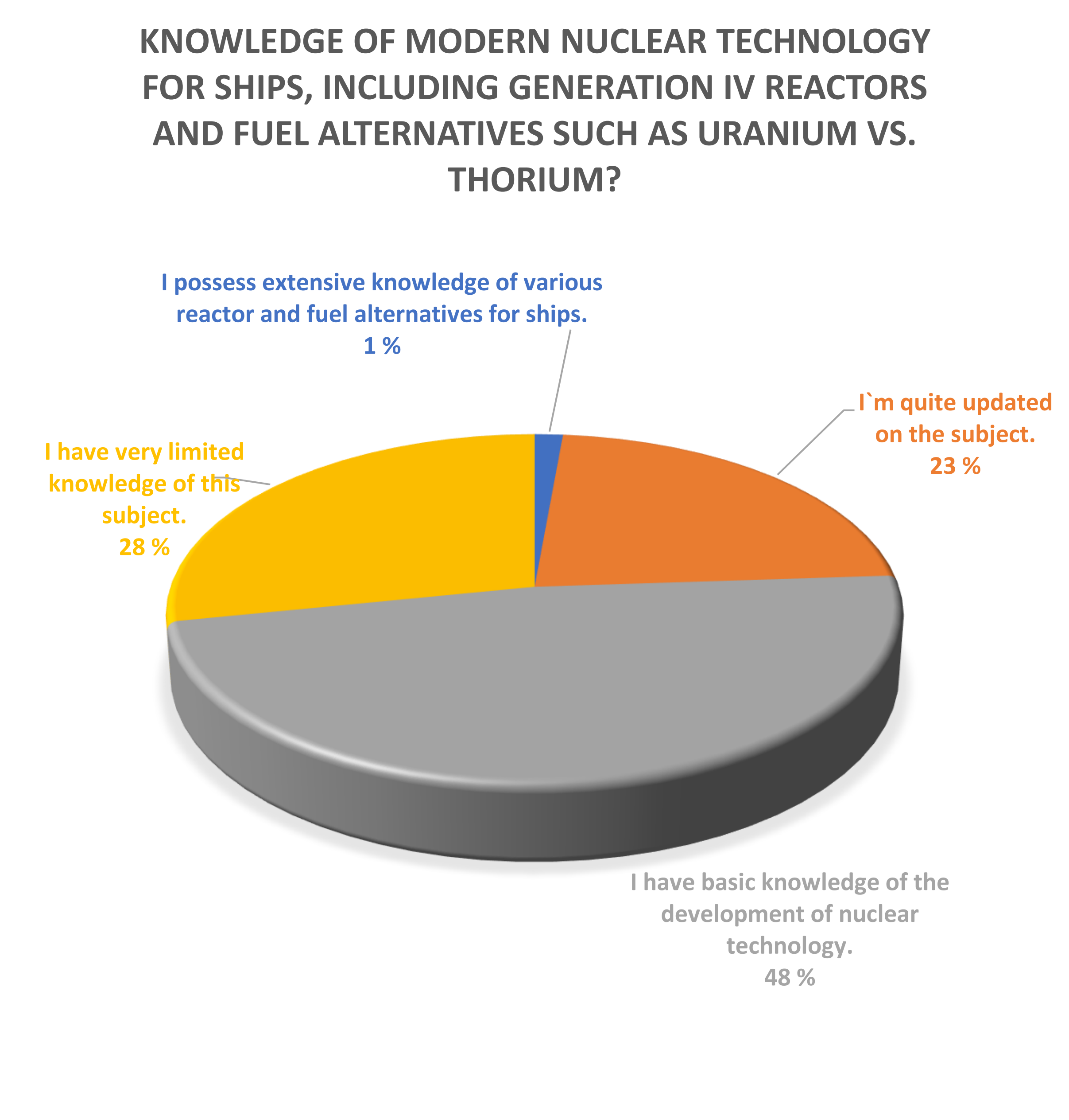

Figure 7 Answers to survey.

Future role

There is a widespread belief (60%) that nuclear energy will play a role in the future, both for land-based power and for ship propulsion. Respondents generally agree that adoption at sea depends on technological advancement, regulatory development, and public acceptance. The most frequently cited barrier to implementation was legislative: the absence of clear and modern international regulations. Safety concerns and the management of radioactive waste were also prominent issues, although several noted that advanced reactor designs could significantly mitigate these risks.

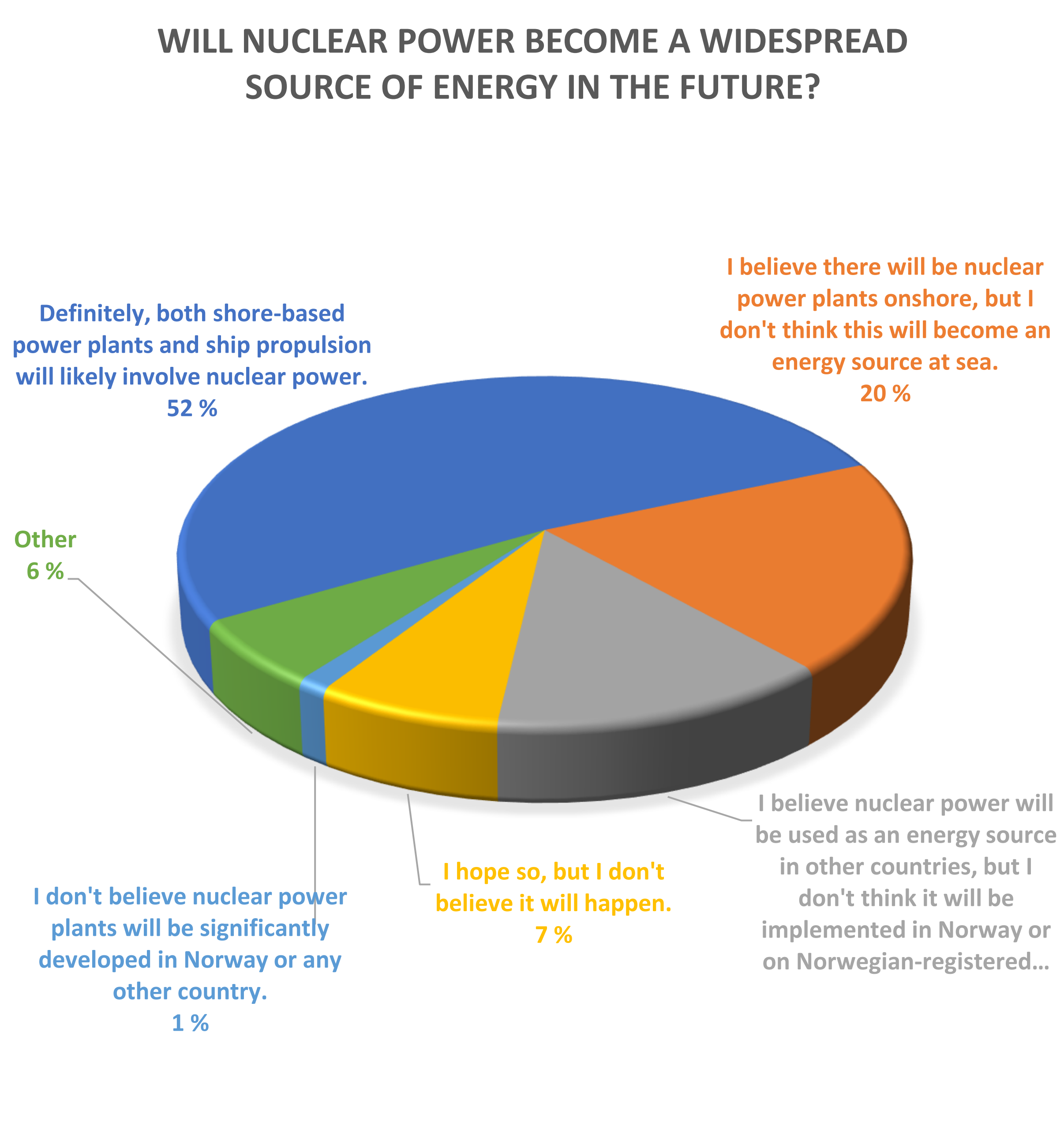

Figure 8 Answers to survey.

Comparison with other green alternatives

When comparing nuclear propulsion to other green alternatives, opinions varied. Some considered nuclear power the most dangerous, while others thought it carried equal or even lower risks compared to fuels like ammonia or battery power. There was a recognition that every fuel source has its own hazards, and the safety of nuclear propulsion would depend mainly on proper reactor design and risk management.

Economy

Economically, opinions were nearly split between those who saw high capital costs as a barrier and those who believed in the favourable long-term cost efficiency of nuclear-powered ships. Some emphasized that nuclear propulsion may only be feasible for large shipping companies capable of absorbing high initial investments, or for vessels with long lifespans and consistent routes.

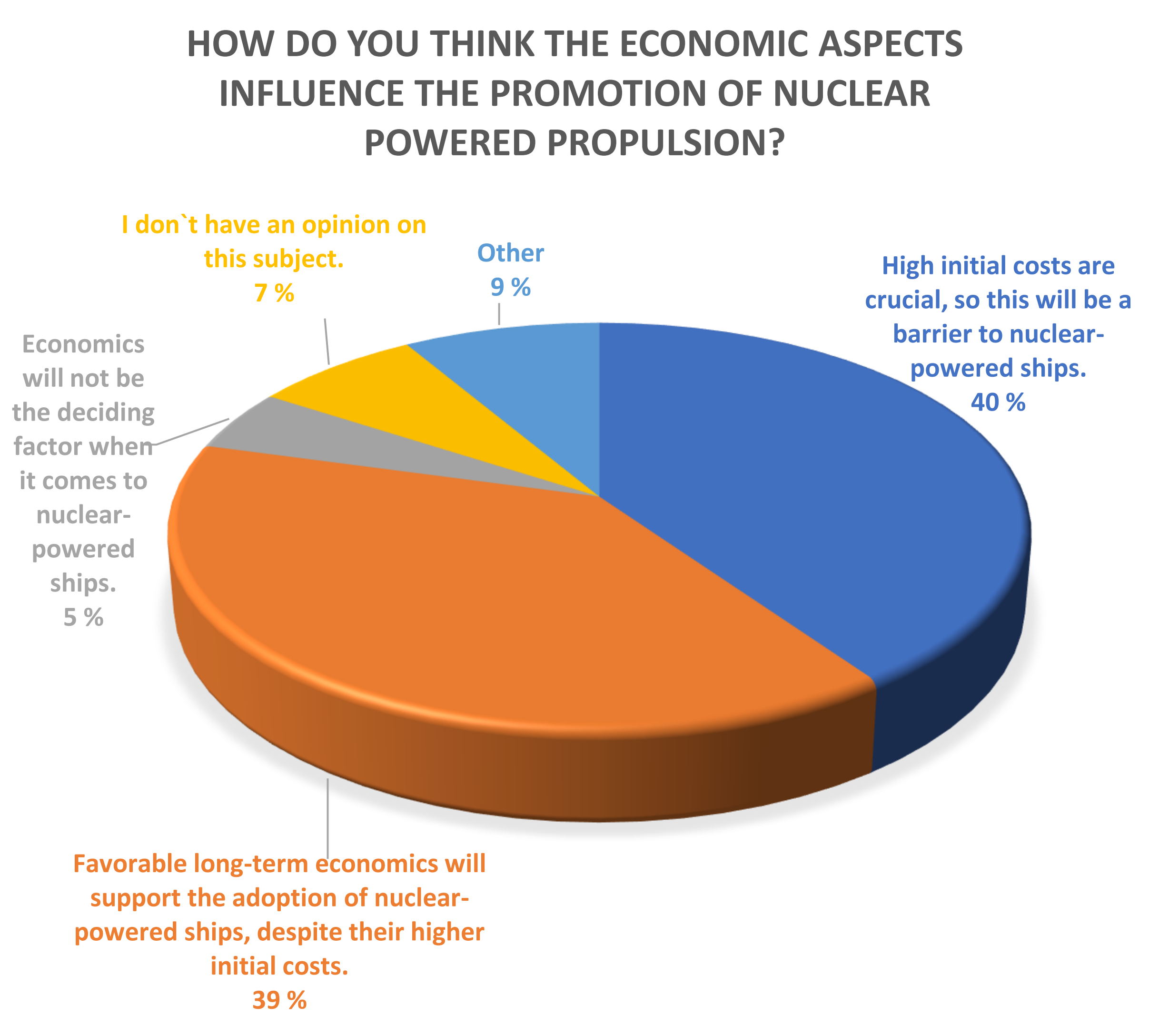

Figure 9 Answers to survey.

Obstacles and challenges

Public perception emerged as a significant obstacle, particularly for nuclear-powered cruise ships. The majority believed passengers would be wary of traveling on such vessels, citing safety concerns and general aversion to nuclear technology. However, many also expressed the view that attitudes could shift over time with better education and demonstrated safety.

Waste handling was acknowledged as a challenge, though not an insurmountable one. Many respondents thought that modern reactors produce less hazardous waste and that the volume generated by ships would be manageable, especially if handled in specialized ports.

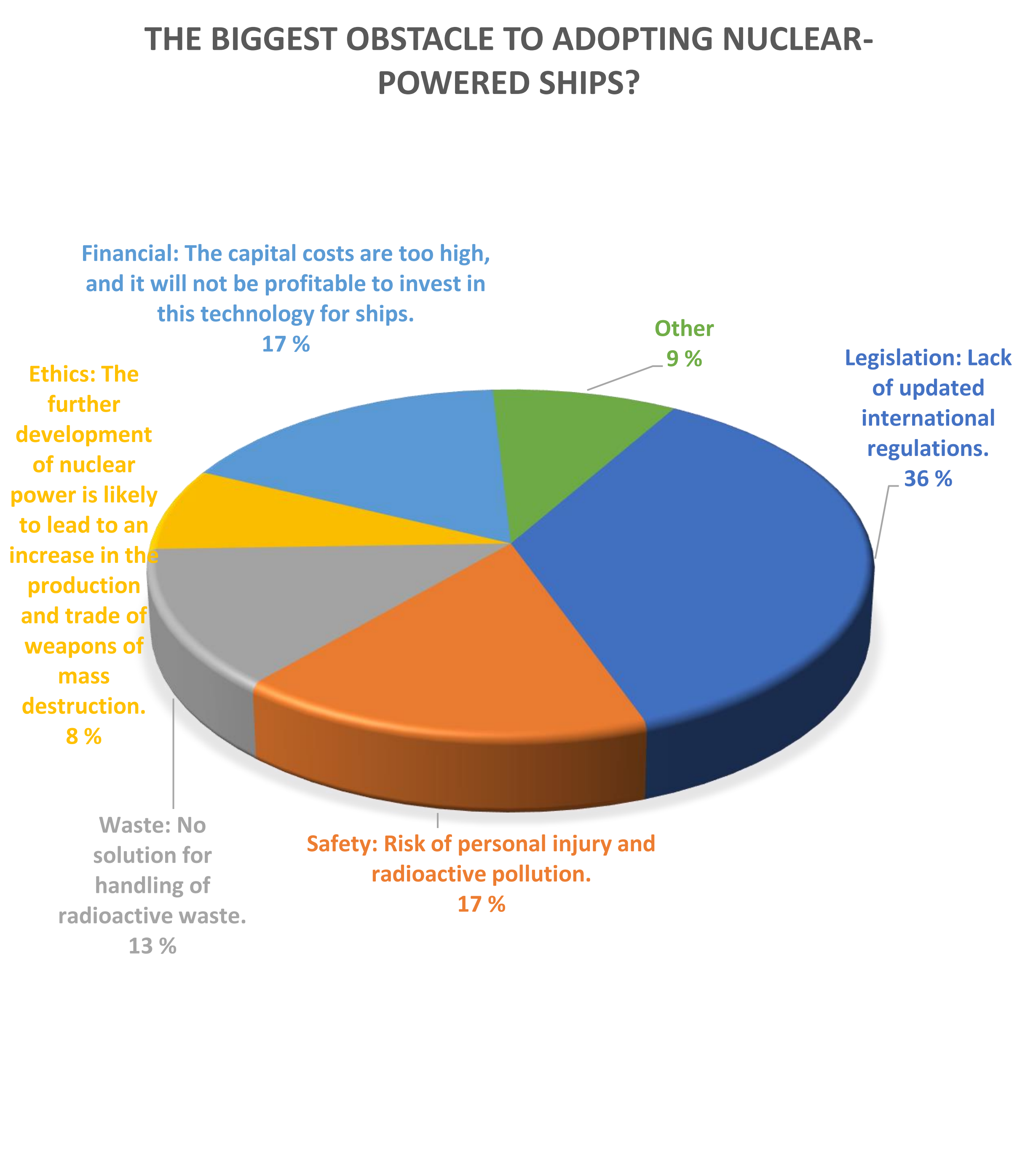

Figure 10 Answers to survey.

When asked which ship types are most suitable for nuclear propulsion, deep-sea cargo vessels were most frequently mentioned. These ships' high energy demands, and long travel distances make them prime candidates for nuclear power. Only a small number of respondents believed nuclear power was unsuitable for any ship type.

Regarding accidents, while some respondents feared serious outcomes in case of grounding or collision, the majority either believed such scenarios were unlikely or that modern designs could contain the risks. Free-text responses highlighted the importance of reactor design, regulation, and risk assessment in mitigating these dangers.

Respondents generally agreed that nuclear-powered ships would be more efficient over their lifespan, with lower fuel costs and the potential for greater cargo capacity or speed. Yet there was less consensus about maintenance costs or whether these ships would earn more.

Choices of fuel

On the topic of nuclear fuel, most respondents believed the choice of fuel matters, though a majority admitted they lacked sufficient knowledge to recommend either thorium or uranium. Nonetheless, thorium was viewed more favourably.

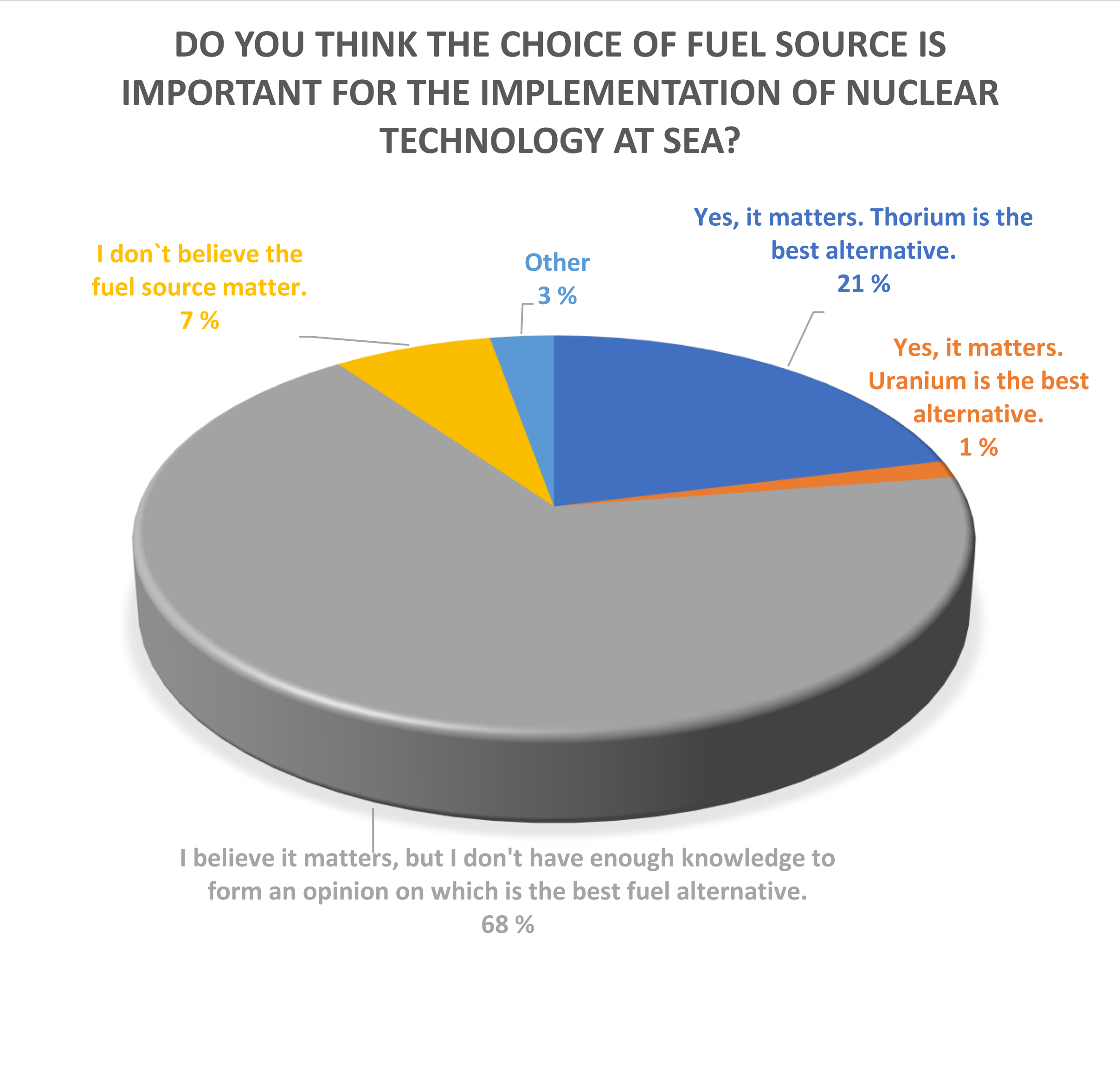

Figure 11 Answers to survey.

Conclusion

In conclusion, the investigation shows a cautiously optimistic stance toward nuclear propulsion in shipping. While there are substantial barriers, regulatory, technical, financial, and perceptual, most stakeholders see the potential in nuclear power, particularly for large, long-distance vessels. The key to broader acceptance lies in public education, international regulatory frameworks, demonstration projects, and continued technological development.

Work Process 2, Advanced Nuclear Technology

In this chapter the GSP pilot partners have investigated relevant nuclear technologies, and both challenges and opportunities for using nuclear propulsion in the merchant fleet. We present a case study here for a Maran Shuttle Tankers vessel, where we have considered the viability of a nuclear retrofit, finding that in terms of area and space, we see that it should be feasible to convert the engine room to nuclear power.

In sections WP 2.1-2.3 selection criteria for the advanced reactor designs that have been considered are described. In section WP 2.4 we discuss the need for radioactive waste management, while in section WP 2.5 the potential benefits of using nuclear power are explored. The need for training of crew is explored in section WP 2.6, and finally in section WP 2.7 we describe our case study ship, Altera Wave, that has been considered for a nuclear propulsion retrofit.

WP 2.1) Existing and emerging nuclear technologies

According to the World Nuclear Association[9] we can sum up the Nuclear Power in the world today as follows:

- The first commercial nuclear power stations commenced operations in the 1950s.
- Nuclear energy currently provides approximately 9% of the world's electricity, generated from roughly 440 power reactors.
- Nuclear power contributes about one-quarter of the world’s low-carbon electricity.
- Nuclear energy is the world's second largest source of low-carbon power.
- Over 50 countries utilize nuclear energy in around 220 research reactors, which are employed not only for research purposes but also to produce medical and industrial isotopes, as well as for training.

Nuclear technology harnesses the energy released by splitting the atoms of certain elements. Initially developed in the 1940s, research during the Second World War was primarily directed towards producing bombs. However, in the 1950s, the focus shifted to the peaceful application of nuclear fission, particularly for power generation and marine propulsion.

Civil nuclear power has accumulated approximately 20,000 reactor years of operating experience, with nuclear power plants functioning in 31 countries globally. Through regional transmission grids, many additional countries partly rely on nuclear-generated power, particularly in Europe.

When the commercial nuclear industry started in the 1960s, there were distinct boundaries between the industries of the East and West. Currently, the nuclear industry features international commerce. A reactor being built in Asia today may have components sourced from South Korea, Canada, Japan, France, Germany, Russia, and other nations. Similarly, uranium from Australia or Namibia may be used in a reactor in the UAE after undergoing conversion in France, enrichment in the Netherlands, deconversion in the UK, and fabrication in South Korea.

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[9] www.world-nuclear.org

The applications of nuclear technology go beyond providing low-carbon energy. It aids in controlling disease spread, assists medical professionals in diagnosing and treating patients, and supports space exploration missions. These diverse applications place nuclear technologies at the core of global efforts toward sustainable development.

In 2023, nuclear plants generated 2,602 TWh of electricity, an increase from 2,545 TWh in 2022. Fourteen countries produced over a quarter of their electricity from nuclear power. France gets about 70% of its electricity from nuclear, while Ukraine, Slovakia, and Hungary get roughly half. Japan, previously dependent on nuclear for over a quarter of its power, is expected to return to similar levels. Nuclear reactor performance has significantly improved over the past 40 years, with more reactors achieving high-capacity factors.

Globally, new generating capacity is needed to replace old fossil fuel units, especially coal-fired ones, and to meet rising electricity demand. In 2022, 61% of electricity came from fossil fuels. Despite growth in renewable sources, fossil fuel's contribution has remained steady (66.5% in 2005).

The OECD International Energy Agency publishes annual scenarios related to energy. In its World Energy Outlook 2023[10] the Net Zero Emissions by 2050 Scenario (NZE) *"maps out a way to achieve a 1.5°C stabilization in the rise in global average temperatures, alongside universal access to modern energy by 2030"*.

Other nuclear reactors

About 220 research reactors operate in over 50 countries, with more being built. These are used for research, training, and producing medical and industrial isotopes.

Marine propulsion reactors are mainly used by major navies, powering submarines and large ships for the past five decades. Over 160 ships, mostly submarines, are powered by around 200 reactors, providing over 13,000 reactor years of experience. Russia and the USA have decommissioned many Cold War-era submarines. Russia also operates nuclear-powered icebreakers and has several under construction. It has connected a floating nuclear power plant with two 32 MWe reactors to the grid in Pevek, an arctic region. These reactors are adapted from those used in icebreakers.

Small modular reactors (SMRs) are defined as nuclear reactors typically 300 MWe equivalent or smaller, designed with modular technology using factory fabrication of modules, aiming for economies of scale in production and reduced construction times. This definition, provided by the World Nuclear Association, aligns closely with those from the IAEA and the US Nuclear Energy Institute. While some small reactors currently in operation do not meet this definition, most described here do. PWR types may include integral steam generators, requiring a larger reactor pressure vessel, which limits the portability from factory to site.

Modern small reactors, particularly SMRs, are anticipated to feature simpler designs, economical factory production, shorter construction times, and lower siting costs. They often include high levels of passive or inherent safety and are designed to be placed underground for added security against terrorism. A 2010 American Nuclear Society report indicated that many safety measures required in large reactors are

[10] https://www.iea.org/reports/world-energy-outlook-2023?wpappninja_v=o5bj1zhuo

unnecessary for small designs due to their higher surface area to volume ratio, which simplifies heat removal and other engineering requirements.

SMR development is advancing in Western countries with significant private investment, including from smaller companies. The involvement of these new investors suggests a shift from government-led and funded nuclear research and development to initiatives led by the private sector and individuals with entrepreneurial goals, often associated with deploying affordable clean energy without carbon dioxide emissions.

Small Modular Reactors (SMRs) are gaining recognition among policymakers and industry players as a promising nuclear technology. Reactor types here are.

- Light water reactors
- High-temperature gas-cooled reactors
- Liquid metal-cooled fast reactors
- Molten salt reactors

WP 2.2) Selection of nuclear reactors

The content of WP2 has largely been extracted from the NTNU report "Nuclear Propulsion for Merchant Ships I" (NuProShip I)[11] In this feasibility study we're only focusing on Gen IV reactors onboard commercial ships.

The objective of NuProShip I, was to perform a concept and feasibility study of marine propulsion for merchant shipping by identifying the reactor designs that will fulfil all criteria considering technical, regulatory, competitiveness towards HFO, impact on ship design and other issues.

A complete list of future work is also developed in NuProShip I. The future work identified in NuProShip I will be addressed in NuProShip II (the Design and Development Phase).

The final three steps (Development Engineering, Production Engineering, and Scaling & Commercialization) will be addressed in separate demonstration projects born out of the Centre for Research-Based Innovation (SFI) SAINT (application pending), and possible several other NuProShip projects in years to come with specific research objectives necessary to address before the demonstration projects can be launched.

Starting in 2022, the timeframe is 10 – 12 years largely depending on the licensing process and funding. There is also considerable uncertainty concerning how the International Maritime Organisation (IMO) will handle a commercial nuclear ship in terms of rules on the high seas as well as local jurisdictions where these carriers will operate. To increase the likelihood of a successful licensing process, the project will position itself towards the United States Nuclear Regulatory Commission (US NRC) because most countries in the world have requirements that are either identical or very similar. Following stringent qualification and commissioning tests (fulfilling all relevant requirements from authorities and regulatory bodies) of the prototype system, nuclear propulsion systems will be installed into newbuilt ships and into ships currently running on HFO. Similarly, close cooperation with IMO and class society is important, and

[11] https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/3174539

both DNV and Sjøfartsdirektoratet (Norwegian Maritime Authority) are members of the project consortium.

Generation IV reactors represent a significant shift from earlier generations of nuclear technology, which various navies around the world have used for decades. The NuProShip project is considered "new to the world" due to its combination of novel technology and applications that have not been previously combined. Consequently, the project is ambitious, original, and novel. Structured in phases, the first phase of NuProShip I served as an extensive fact-finding mission to address the novelty and ambition of the project.

The project, and this GSP pilot project, operated on a new-to-the-world level of novelty regarding:

- Generation IV, particularly the application at sea, has never been implemented before, even in a naval context. This will enhance knowledge in nuclear engineering, ship design, regulations, and class approval of nuclear ships.
- The detailed implications for merchant shipping. While there have been a few nuclear merchant ships historically, they were discontinued due to costs, regulatory complexity, or failed stakeholder involvement.
- The operational impact of this technology on crew, safety, and large-scale operations.

The scientific impact is significant because the technology is 'new to the world,' and with the deep-sea fleet being a substantial part of marine emissions, the societal impact could be considerable, potentially eliminating 2% of global climate emissions. This aligns directly with Sustainability Development Goals (SDG) no. 7 (Affordable and Clean Energy) and no. 13 (Climate Action).

Regarding industrial impact, the project has begun assisting nuclear reactor designers in testing their designs, promoting innovations in nuclear technology. This contributes to SDG nos. 7, 11 (Sustainable Cities and Communities), and 13.

Criteria for evaluation of reactor designs

The first step in the selection process was to develop a set of criteria for the evaluation of each of the reactor designs. The challenge lies in the diversity of the criteria, leading to a classic multi-objective selection process involving both quantitative and qualitative objectives or criteria. Therefore, the selection process will be subjective with such a variety of criteria.

One of the best qualitative methods for providing decision-support in multi-objective situations, is the Analytic Hierarchy Process (AHP) developed in the late 1960s, see Figure 12. The AHP has been used in a wide array of situations, including resource allocation, scheduling, project evaluation, military strategy, forecasting, conflict resolution, political strategy, safety, financial risks, and strategic planning. AHP has also been used in supplier selection, business performance measurement, quantitative construction risk management and selection of maintenance strategy and organization.

However, given the high number of alternatives, the direct application of the AHP can be challenging. This issue was resolved by performing an initial screening using basic exclusion criteria with the purpose of bringing the complexity down to a manageable size. The full exclusion and selection processes can be found in the full NuProShip I report[11].

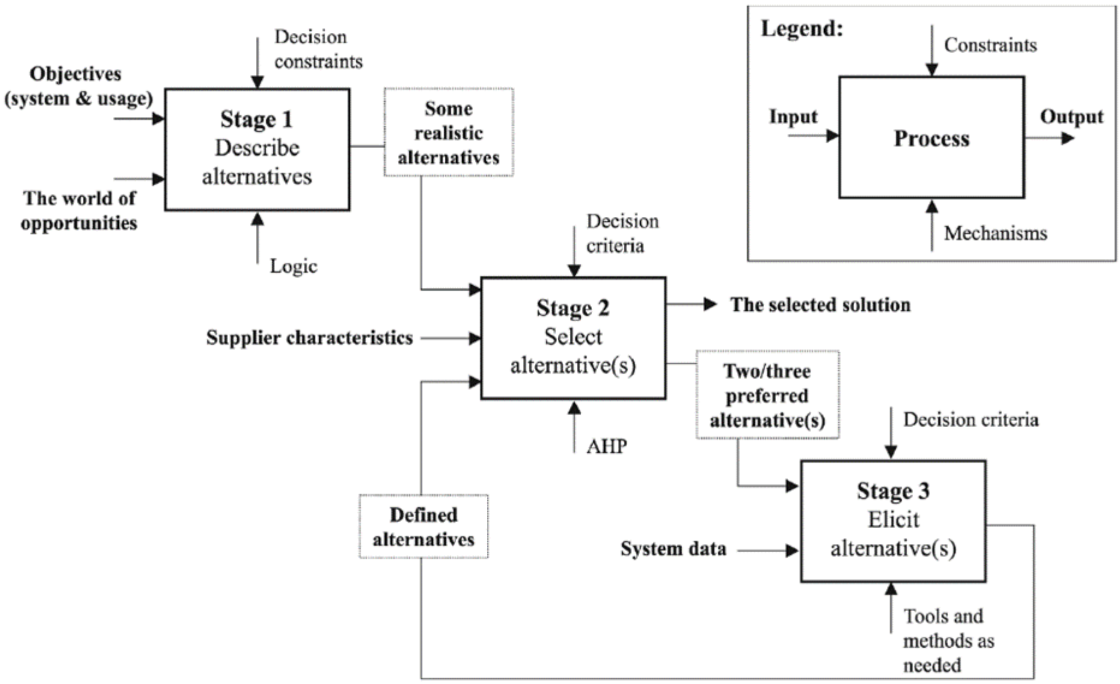


Figure 12 Overall selection process, using the Analytical Hierarchy Process

Stage 1 consists of the screening of over 80 reactor designs to a reduced number of feasible alternatives. To do so, a set of exclusion criteria were defined, which are essentially hard constraints defined as criteria whereby reactor concepts having this specific feature or characteristic are by default excluded from the overall decision process. As a result, the feasible reactor designs that pass these exclusion criteria are obtained. However, instead of focusing on specific designs, the different reactor technologies that are possible for ship propulsion are introduced in below.

Exclusion Criteria

To screen the 80 reactor designs a set of exclusion criteria has been defined. The set is based on the guidelines of the Gen IV Forum as well as the applicability for marine propulsion. The exclusion criteria are:

1. Using water as coolant: Some of the reactors use water as a coolant, but all water based SMRs (Small Modular Reactor) are excluded from the analysis. The reason for this is that water-based reactors may face strong public opposition, regardless of their safety performance. This is based on the observation that many people cannot differentiate between Generation III reactors and Generation III+ reactors, which have advanced safety features and impeccable records, and Generation II reactors, which were involved in major accidents such as Chernobyl and Fukushima (both accidents were greatly miscommunicated by media). It is expected that this negative belief will also affect water-based Generation IV SMRs. Water-based reactors will also struggle to meet the 5-year continuous operation requirement, discussed later, with the enrichment-level civilian operators will be allowed to use. Therefore, the analysis focuses on Generation IV SMRs that use alternative coolants, such as helium, molten salt, or liquid metal, which offer higher efficiency, lower waste, and enhanced safety.
2. Reliance on active safety systems: One of the main characteristics of Generation IV reactors is their dependence on passive safety systems or passive shutdown systems, which require no human action

and aim to prevent any release of radioactivity to the environment by air or water. Reactor concepts that lack this feature or do not specifically establish their safety systems are discarded.

3. Limited proliferation resistance: Reactor concepts that do not enhance barriers that reduce to a minimum the extraction and use for military purposes of fissile material were excluded from further consideration. This is obviously important for ships crossing in and out of jurisdictions on frequent basis. However, it must be noted that fast reactor designs that are fuelled only once in their lifetime are not excluded by this criterion, since the fissile material can't be easily extracted from the reactor. Annex I contains additional discussions pertinent to certain types of MSR.
4. Fuel enrichment and highly toxic bi-products: Reactor concepts must require fuel enrichment below 20% of uranium-235 and no significant highly radioactive bi-products. The limit in uranium enrichment is set by international agencies, such as the IAEA, and enhances safety, security and non-proliferation goals. Examples of highly radioactive bi-products are Polonium-210 that is generated in lead-bismuth reactors or Chlorine-36 produced in chlorine-based molten salt reactors.
5. Too large power output: The thermal- and electric-output should be in line with the needs for marine propulsion. For the largest Oil/LNG tankers and container ships, the need for power could be more than 50 MWe while for the smallest ships the requirements may go down to less than 5 MWe. Reactors of higher power output should be able to scale down with minor design changes (for example reducing the volume of fissile material in the reactor vessel), otherwise they are excluded.
6. Technology is not mature enough: Among the over 80 SMR concepts analysed, only a handful are at a noteworthy Technology Readiness Level (TRL) and most of them are in an early stage of development and not in a licensing preparedness process. On the other hand, new concepts are continuously being introduced and some of these concepts could be developed and be at a demonstration stage (prototype or licensing) before several of those listed. This selection is limited to those that are at a high Technology Readiness Level for being commissioned.
7. Less than 5 years of continuous operation: There are several prerequisites that must be met to introduce nuclear reactors on a ship, and one of these are the 5-years intervals where ships are brought to a dry dock for inspection and maintenance according to classification society rules. This means a minimum of 5-years continuous operation before maintenance and ideally an interval for refuelling over 5 years. However, some reactors have continuous or short period refuelling which means that they are refuelled onboard, such as some molten salt reactors.
8. Using classic pebble bed technology: In a challenging marine environment, there are certain limitations on structures that cannot withstand sudden movements or disturbances of ocean waves. That could be the case for High Temperature Gas-cooled Reactors (HTGR) based on pebble bed technology, being the main reason why these are excluded from the list.
9. High pressure in the reactor primary system: Similarly, it is also important to limit the pressure allowed in the reactor vessel, so that it is guaranteed that the pressure limit in accidental conditions is below the limit of what the ship structures can sustain. Reactor concepts that cannot guarantee this, are excluded.
10. Violent reaction of coolant with water: In a marine environment, the chemical reactivity of coolants and salts is an issue. This excludes molten salt reactors based on highly soluble compounds such as NaCl due to the violent reaction of high temperature molten salt interacting with water. Based on the same criteria, Sodium-cooled Fast Reactor (SFR) technology is excluded.
11. Violation of export control: Export control issues (and trade embargos) with some countries must also be considered. These embargoes condition the import of either reactor designs or constructive materials such as graphite from restricted countries.

Feasible reactor technologies

Based on the discussion of exclusion criteria, only three categories of reactors were considered for marine applications in this study and will be briefly described in this chapter. Only seven reactor concepts of these technologies survived the exclusion process.

Molten Salt Reactor (MSR)

In a molten salt reactor, the primary coolant and/or the fuel is a mixture of molten salt with a fissionable material. An MSR could also be a combination of Tri-structural Isotropic (TRISO) particle fuel in pebble form coupled with molten fluoride salt as coolant. There are several reactor concepts of Molten Salt Reactors (MSRs), and it would be beyond the scope of this report to describe the different concepts in detail. Altogether 13 reactor concepts were reviewed, and only a few of these reactor concepts survived the evaluation by exclusion criteria.

One of the main advantages of MSRs for marine applications is that they can operate at or close to atmospheric pressure and can be refuelled while in operation. However, this can also face problems related to proliferation and crossing of different jurisdictions. Another advantage is the retention of fissile material in the salt, or intrinsic retention in TRISO fuel, and the complete unit decommissioning. Depending on the reactor concept, refuelling could take place onboard continuously (online refuelling or during certain periods (months/years)), or in other cases during the 5-year maintenance intervals of ships. Note that the refuelling operations in the MSRs considered involve only the addition of tiny amounts of fresh makeup fuel salt to maintain power and no extraction of spent fuel salt is performed, which would pose serious challenges from the proliferation point of view. MSRs are expected to need extensive qualification of materials to address possible corrosion issues.

High Temperature Gas-Cooled Reactors (HTGR)

High-Temperature Gas-cooled Reactors use uranium fuel and helium coolant to produce very high temperatures. The fuel in the reactor core can be either in the form of prismatic blocks or a pebble-bed. In the first, TRISO particles are embedded in a solid prismatic block of structural material (typically graphite) that are arranged in an array inside the reactor vessel. In the last, TRISO particles are embedded on spherical fuel elements (pebbles) and the reactor vessel is filled with thousands of these pebbles, which are continuously cycled through the reactor. This last design is rejected due to the 8th exclusion criterion (Pebble bed technology).

The main advantages of HTGR are the use of an inert and non-corrosive gas (helium) as the coolant, the intrinsic retention of fission products in TRISO particles and its high proliferation resistance despite high fuel enrichment (between 9.99% and 19.75%). However, the coolant requires the use of a pressurized vessel. Another advantage for marine applications is that the reactor has no moving parts and can be placed horizontally, thus limiting the space occupied.

Lead-Cooled Fast Reactors (LFR)

Lead-cooled reactors use liquid lead or lead-bismuth eutectic as the primary coolant. This type of reactors has several advantages such as high operating efficiency at atmospheric pressure, inherent safety, no need of refuelling, and closed unit decommissioning. The main drawback is the production of Po-210, which, in case of coolant leakage, constitutes a radiological hazard, requiring methods based on alkaline extraction to safeguard both personnel and the environment. Lead is considered a more attractive coolant option than lead-bismuth, mainly due to its higher availability, lower price, and lower amount of induced polonium activity (by a factor of 104 compared with lead-bismuth), which is why lead-bismuth reactors are strongly penalized during the selection process.

The pure liquid-lead cooled reactors have potential problems of clogging during operation and will need external heating while reducing/increasing the power. However, the use of lead as a coolant has advantages as it is a radiation shielding and makes it possible to achieve passive safety systems. Liquid-lead reactors are also known to have experienced corrosion issues in the past which new reactor designs promise to solve.

The Stage 2 selection process follows the mentioned AHP approach for identification of selection criteria.

Following the discussion of 11 exclusion criteria, a total of 8 selection criteria and 22 sub-criteria were identified through a series of workshops and discussions of the NuProShip I project throughout 2023. These criteria and sub-criteria stand for those aspects that get more relevance for the final selection goal. This task has been performed by the participants in the NuProShip I project, which includes staff with extensive experience in a wide variety of relevant fields, including nuclear engineering, ship design and ship building. In Figure 13 below, the set of evaluation criteria and sub-criteria are hierarchically displayed.

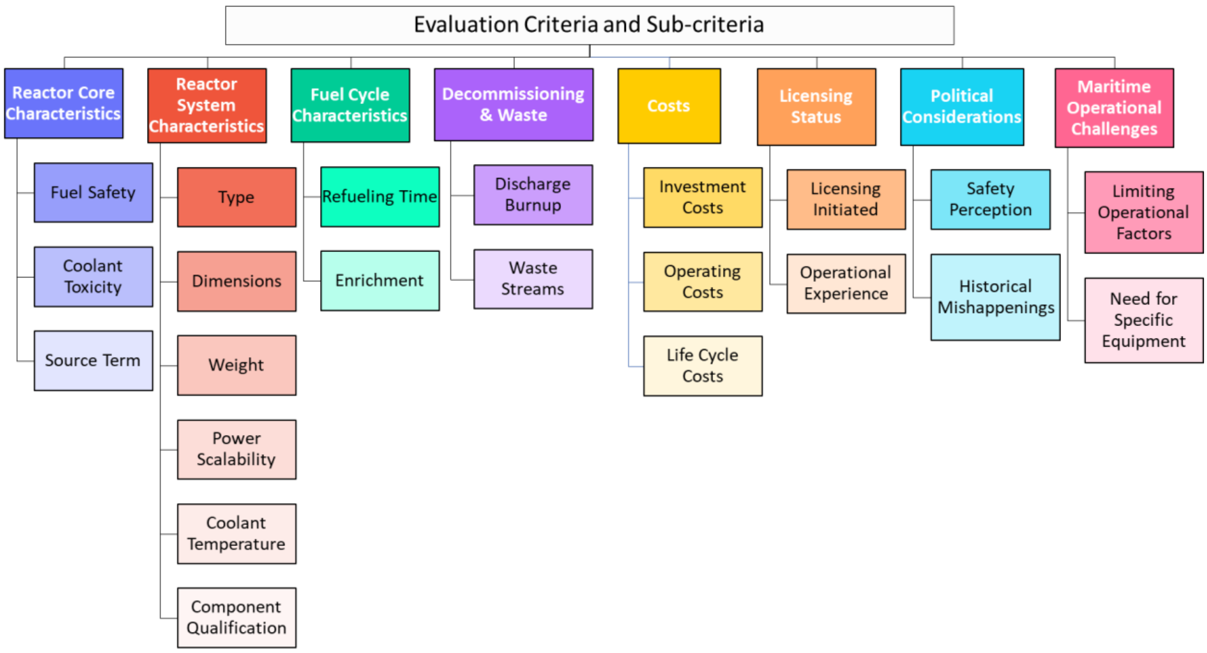


Figure 13 The criteria for selecting nuclear reactor concepts for propulsion of merchant ships

These criteria and sub-criteria are explained hereafter, starting from the left to the right:

1. Reactor Core Characteristics: The core of the reactor will decide its behaviour, and it is therefore an important criterion to consider. It is refined into 3 sub-criteria:
   a. Fuel Safety: Behaviour of the fuel in an accident and its environmental impact is a key factor. Different reactor concepts make use of nuclear fuel in different forms with a different degree of safety. For example, TRISO fuel is considered the most robust nuclear fuel ever engineered given its capability to retain fission products and to withstand

extreme temperatures. In contrast, conventional oxide pellets organized in fuel assemblies have shown potential safety issues, such as swelling, cracking or mechanical interaction with cladding, that could lead to fission product release when operating at abnormal temperatures.

   b. Coolant Toxicity: This sub-criterion is related to the harmful effect of the coolant. While the safety shall be excellent, there can always be a small possibility of coolant leakage or spillage during maintenance operations, and therefore, minimizing the toxicity of the coolant is important for workers and the environment.
   c. Source Term: The types and amounts of radioactive or hazardous substances that could be released to the environment following an accident – reflecting the potential radiological consequences – are also important safety parameters. Different reactor concepts may have different source terms, depending on the fuel type, coolant type, operating conditions, etc.

2. Reactor System Characteristics: This criterion is important as it is key for the interaction with the ship, and it is refined into 6 sub-criteria:
   a. Type: Whether the secondary system consists of one or more loops (with natural or forced convection) or the design is integral, with the secondary system held inside the reactor vessel, will have consequences for the overall system complexity and performance.
   b. Dimensions: This criterion measures the size of the propulsion unit, which relates to the fact that space is scarce on ships.
   c. Weight: Weight of the propulsion unit is another physical aspect that must be considered, not because of its magnitude per se, but because the location of this weight may affect the stability of the ship.
   d. Power Scalability: Considers the different ways the propulsion unit can increase/decrease its power, whether by adding more reactor units, by increasing/decreasing the enrichment or size, etc. This criterion rewards those reactor designs with higher adaptability to ship power requirements.
   e. Coolant Temperature: Outlet temperature of the reactor coolant is an important sub-criterion since it will affect the heat insulation needs of many subsystems.
   f. Component Qualification: This sub-criterion considers the often-time-consuming qualification processes needed for development of new components and materials.
3. Fuel Cycle Characteristics: There are particularly two aspects of the fuel cycle that are considered important, leading to the following sub-criteria:
   a. Refuelling Time: Refuelling may constitute one of the most critical operations to be performed. On the one hand, spent nuclear fuel and fresh fuel are manipulated, and on the other hand it usually requires the shutdown of the reactor and the opening of the reactor vessel, with the corresponding need of specialized structures for the shielding of the radiation (i.e., a hot cell). Thus, reactors without refuelling are considered advantageous. Nevertheless, since most reactors at some point need to be refuelled, this should ideally take place when the ship docks for inspection. This docking takes place every 5 years, being the expected life of the ship 30 years.
   b. Enrichment: This factor considers the increased percentage of U-235 needed for the operation of the reactor. Enrichment is primarily a cost issue as well as, potentially, a political issue. This is why Natural Uranium and Low Enriched Uranium are favoured.

4. Decommissioning and Waste: Both decommissioning and waste are important criteria because they can be a challenge in certain political and economic scenarios. This criterion is broken down into two sub-criteria:
    a. Discharge Burnup: This sub-criterion is a measure of how much energy has been extracted from the nuclear fuel. This is why higher levels of discharge burnup are favoured.
    b. Waste Streams: This sub-criterion accounts for the estimated types and amounts of radioactive waste generated in operation of each reactor design.
5. Costs: The sub-criteria related to costs are omitted in the first selection because the information is not mature enough to provide reasonable accurate cost estimates. Furthermore, the cost estimates provided by the vendors themselves vary too much to be consistent as some vendors provide costs for the First Of A Kind (FOAK) and others provide them for the Nth Of A Kind (NOAK), some provide estimates for the of LCOE, a metric often used to compare technologies and policymaking worldwide, etc. The following sub-criteria will therefore be reviewed at a later stage, once more mature information is available, to primarily ensure that double counting is avoided, and correct estimates of individual costs are used:
    a. Investment Costs: The costs of the fabrication, construction, commissioning, and licensing of the propulsion unit compose an important economic sub-criterion because of the strong focus on investment costs in the shipping industry. Note that the propulsion unit includes the reactor as well as any auxiliary systems such as heat exchangers, turbines and load management system needed for its safe operation to propel ships.
    b. Operating Costs: It refers to the costs of the operation of the propulsion unit, which considers among others cost of the fuel, maintenance.
    c. Life Cycle Costs: Costs of the decommissioning of the propulsion unit as well as waste handling will ultimately impact the total economics of the reactor concept.
6. Licensing Status: The purpose of this criterion is to avoid selecting reactor concepts that face many difficulties in terms of approval or are far into the future. This criterion has been divided into 2 sub-criteria:
    a. Licensing Initiated: This sub-criterion refers to the status of the reactor considering its phase in the licensing process.
    b. Operational Experience: Describes whether the technology of the nuclear reactor is completely new, or some previous experience already exists.
7. Political Considerations: Nuclear power is highly influenced by politics. To this, the fact that ships cross several jurisdictions on their voyages must be added, increasing this influence and the political issues that reactor concepts will meet. This criterion has been divided into 2 sub-criteria:
    a. Safety Perception: This sub-criterion refers to the public and political awareness and understanding of potential hazards and risks of the specific reactor concept, which is a main factor for the public acceptance of nuclear reactors for shipping.
    b. Historical incidents and accidents: This sub-criterion accounts for events that occurred in the past, related to the technology with negative or unintended consequences, which could jeopardize the deployment of that technology in a reactor concept for shipping.
8. Maritime Operational Challenges: Ships undergo various operational modes through their life cycle, so choosing a reactor that can satisfy these modes is crucial. This criterion has been divided into 2 sub-criteria:

a. Limiting Operational Factors: This sub-criterion refers to the aspects of each reactor design that can limit its application towards nuclear propulsion. Examples of these challenges are, the effect of the sea movement on reactors relying on natural circulation, the potential clogging problems on Lead-Cooled Reactors due to load variations, etc.
b. Need for Specific Equipment: This sub-criterion essentially focuses on the need for development or implementation of specific equipment for the optimal performance of the reactor in maritime environment.

For weighting of the Selection sub-criteria, the Selection criteria, Global weights of selection criteria and sub-criteria, Rating scales of selection sub-criteria, and Scoring of reactors, we refer to the full NuProShip I report[11].

Results and Discussion

Out of the seven reactor designs belonging to feasible technologies, the three most ranked designs are selected for Stage 3 of the project. The result obtained for these three reactors (MMR, SEALER-55 and KP-FHR) is shown in Figure 14.

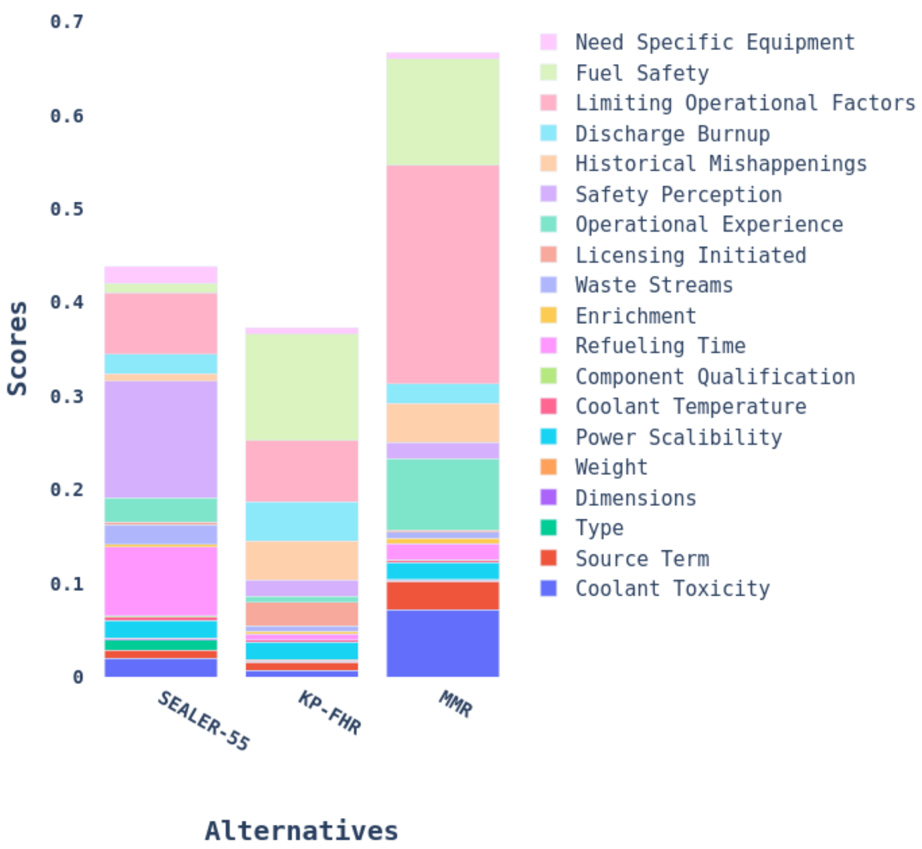


Figure 14 Score for the top 3 reactors: MMR, SEALER-55 and KP-FHR

The reactor with the highest score is the Micro Modular Reactor (MMR), a High Temperature Gas-cooled Reactor (HTGR) developed by Ultra Safe Nuclear Corporation. This reactor has a thermal power ranging from 15 to 45 MWth (5 to 15 MWe), depending on the enrichment of the fuel (which can vary from 9.99% to 19.75%). The fuel consists of Fully Ceramic Micro-Encapsulated (FCM) pellets that are stacked in columns in solid hexagonal graphite blocks and incorporate fuel formed of TRi-structural ISOtropic (TRISO) particles embedded in silicon carbide (SiC). The reactor is pressurized at 6 MPa, as the responsible for cooling down the TRISO prismatic array is Helium gas. This design, stands out with respect to the others since the configuration with no moving parts minimizes the effect of sea dynamics during reactor operation, being one of the main reasons of its high score in the sub-criterion Limiting Operational Factors. Furthermore, by using fuel in TRISO form, excellent fission product confinement is ensured giving its high score in the Fuel Safety sub-criterion. In addition, gas-cooled reactors, including High Temperature Helium-cooled Reactors, have been in operation for more than 60 years in several countries, providing sufficient Operational Experience. Finally, the use of an inert gas as coolant provides an excellent Coolant Toxicity score.

SEALER-55, which is in second place, is a Lead Fast-Cooled Reactor (LFR) developed by the Swedish company Blykalla. This reactor has a thermal power of 140 MWth and an electric power of 55 MWe. The reactor operates at atmospheric pressure and has a lead-cooled hexagonal core composed of Uranium Nitride pellets. Its cradle-to-grave approach, meaning that the reactor is fuelled only once and can be dismantled as a whole unit, provides excellent scores on the sub-criteria Safety Perception and Refuelling Time. However, given the potential problems in the marinization of the reactor (sub-criterion Limiting Operational Factors), such as the possible coolant solidification during power ramp-downs below a certain level (30-40% of the nominal power), and the fact the reactor uses conventional oxide pellets as fuels (sub-criterion Fuel Safety) lower the overall score.

Finally, the third design in the top 3 is the Kairos Power Fluoride salt-cooled High temperature Reactor (KP-FHR), a high temperature Molten Salt Reactor (MSR) developed by Kairos Power. The commercial reactor has a thermal power of 180 MWth and an electric power of 75 MWe. The fuel consists of spherical pebbles filled with TRISO fuel particles. The reactor coolant is a chemically stable molten fluoride salt mixture $2LiF{:}BeF_2$ (FLiBe). Buoyancy makes the pebbles circulate through the reactor core from the bottom to the top. A fuel handling system extracts the pebbles from the active core and based on burn-up measurement, either inserts them back into the active core or directs them to spent fuel storage. The reactor operates at near atmospheric pressure and an intermediate salt loop transfers the heat to the power conversion system through a steam generator.

Kairos Power has also developed a smaller version, KP-Hermes, initially for demonstration purposes, but with potential commercial deployment for ship propulsion purposes. It has a thermal power of 35 MWth and an electric power of 14 MWe. Apart from power and size, the characteristics of this reactor are expected to be like the KP-FHR. Kairos Power obtained the construction permit for the KP-Hermestrit at the end of 2023 and is planning to start its operation as early as 2026.

As in the MMR, the excellent fission product confinement provided by the TRISO particles first, and, in this case, the molten salt coolant next, gives a high score on Fuel Safety sub-criterion. The fact that TRISO particles cycle through the core several times allows achieving a higher Discharge Burnup. Finally, its advanced status in licensing, with approved license for the construction of the Hermes test reactor, provides a high score in the Licensing Initiated sub-criterion. However, the potential problems in the marinization of the reactor (sub-criterion Limiting Operational Factors), such as the challenges that online refuelling (sub-criterion Refuelling Time) can face from the security viewpoint, and the lack of operational experience with such designs (sub-criterion Operational Experience) punish the global score.

Later discussions and full-scale fuel recirculation testing in an Engineering Test Unit indicate that the refuelling issue is better than first anticipated, and the ability to extract additional energy from the fuel if transferred to a larger land-based reactor, therefore make the final score of the reactor better than suggested here.

Conclusions and future work in NuProShip

Due to the innovative nature of the project, there is still lot of work to perform and issues to solve to make nuclear reactors a real and viable alternative to today's propulsion technologies. This is why the analysis captured in this document needs to be completed and developed in various aspects for a safe and effective deployment of the technology, leading to new process stages to be performed in the future. For example, given that, unlike land-based reactors, the reactors for ship propulsion will move through different jurisdictions, a crucial step, which is currently ongoing, is the engagement with national and international regulatory bodies and public stakeholders to begin discussions on the proper regulatory framework to facilitate the implementation of nuclear ship propulsion.

The next stage in the process involves engaging with various vendors of the selected reactor concepts, to discuss their technology in more detail as well as monitor new concepts. This process is key to verify that the publicly available information is still valid. If it is not valid due to design changes, updated information will be requested. These discussions may lead to the introduction of more selection criteria for Stage 2. Once the initial information gathering is performed, a new AHP can be executed, and a smaller set of reactor concepts can be chosen. This work is expected to be completed by year-end 2025.

Following this, the project will move into a detailed design analysis and cost study of the chosen reactors. As all three candidates are land-based technologies currently under design, the objectives will be to identify any design criteria that may need modification for the maritime version and to obtain a relatively reliable cost estimate after industrialization, which may take longer to gather, but is likely to be significantly lower than for the first prototypes. Then, these reactor concepts will be mapped onto various ship designs and operational modes identifying which will fit each ship type the best, considering technical and regulatory issues, competitiveness towards HFO and other fuels, impact on ship design, and other issues relevant for marine propulsion of merchant ships. This work will be performed in the next project, NuProShip II.

WP 2.3) Selection of adequate systems

For existing vessels, propulsion and other power requirements are typically met by various types of engines. Historically, these engines have primarily operated on different grades of fossil fuels.

Traditionally, most commercial vessels are equipped with either 2-stroke or 4-stroke diesel engines to operate the propellers. System configurations can vary from simple single screw propulsion systems to complex arrangements with numerous operational modes. A hybrid propulsion system enables energy sources and propellers to operate optimally over a broad power range, thereby harnessing the advantages of both systems.

Similarly, as in the case of a diesel-electric hybrid propulsion system, a nuclear-electric propulsion system can also achieve reduced energy demand (i.e., less installed power). For a diesel-electric system, this translates to fuel savings. For a nuclear-electric propulsion system, the primary benefit might not be the need for reducing fuel consumption but rather improved response time and a reduction in the need for frequent adjustments to reactor output. This enhances manoeuvrability by providing quicker response times.

In general, propulsion requirements within the shipping industry can be categorized as follows:

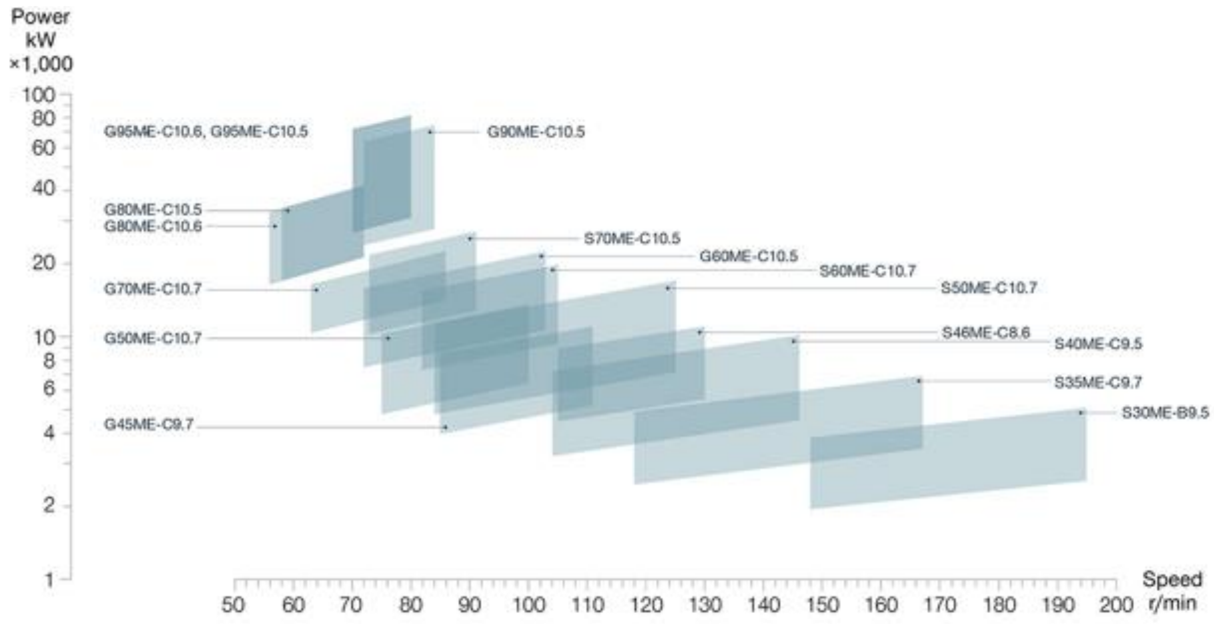
Table 3 Propulsion requirements within the shipping industry

TRADE	VESSEL TYPE	INSTALLATION SIZE	PORT CALLS	HYBRID (& power)
Deep sea	Container vessels Tankers Bulkers Car carriers Seismic vessels	15 – 50+ MW	Monthly	Some vessels installed shaft generators. Limited fuel flexibility
Short sea	Container feeders Tankers & bulkers Shuttle tankers (DP) Car carriers Cruise Offshore vessels (DP) Fishing	5 – 30 MW	Weekly	Hybrid and battery solutions beneficial for most vessels. Shore power. Limited fuel flexibility for vessels in "tramp trade"
Coastal	Small tankers & bulkers Fishing vessels Cruise & ferries Tugs	< 15MW	Daily	Hybrid and battery solutions beneficial for most vessels. Shore power. Fuel flexibility
Local	Small tankers & bulkers Ferries Harbour tugs Fish farming	< 5MW	Daily	Hybrid and battery solutions beneficial, full electrification for some vessels. Fuel flexibility

The deep-sea market constitutes the largest consumers of fuel, thereby contributing significantly to GHG emissions. This sector is primarily dominated by large 2-stroke engines used for vessel propulsion. Additionally, vessels are equipped with 4-stroke engines for auxiliary power. Some vessels also incorporate shaft generators to enhance fuel efficiency during voyages. Furthermore, the deployment of nuclear propulsion in the deep-sea segment could potentially have a substantial impact.

Hybrid propulsion systems in marine applications integrate combustion engines with battery power to optimize engine performance and reduce emissions. These systems are particularly suitable for vessels that require flexible operation profiles and varying power demands throughout their running hours. Hybrid propulsion involves the use of two or more distinct power sources to efficiently drive the propellers. By integrating these power sources with electric motors, a hybrid propulsion system is created. Additional energy carriers/converters can include battery packs, permanent magnet motors, among others.

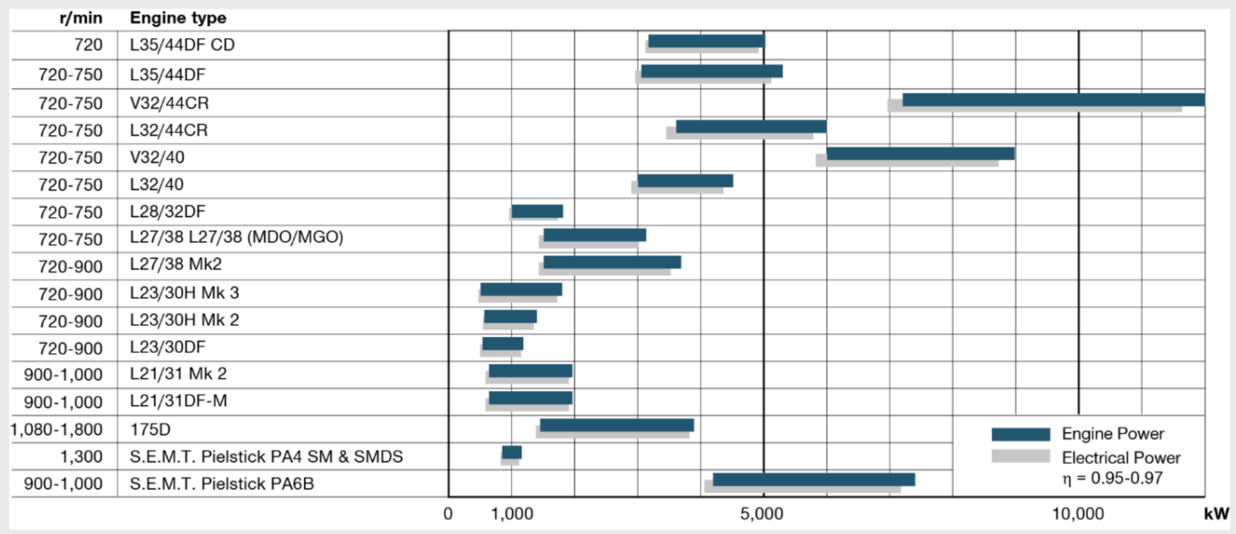
Combining various power sources with an optimized propulsion line can further enhance vessel performance, whether through the installation of a fixed pitch propeller (FPP) or a controllable pitch propeller (CPP) system. The choice of systems will depend significantly on the vessel type and size, trading patterns, and requirements for manoeuvrability and redundancy.



Typical 2-stroke engine sizes

Courtesy: MAN Energy Solutions

Figure 15 Typical 2-stroke engines, courtesy MAN Energy Solutions



Courtesy: MAN Energy Solutions

Figure 16 Typical 4-stroke engines, courtesy MAN Energy Solutions

Considering the trading patterns and power requirements as shown in **Error! Reference source not found.**, it can be anticipated that Deep Sea vessels operating over long distances with infrequent port calls may benefit from a direct drive system. This means that the reactor and turbine would be directly connected to the propulsion line. For larger vessels with more frequent port calls or other operational dependencies, a hybrid installation should be considered. In cases requiring redundancy or safe return to port capabilities, an evaluation of either a single or double reactor installation is advisable.

For Short Sea operations, hybrid systems are increasingly relevant due to the higher number of ports calls and opens for a nuclear electric system, meaning that the reactor and turbine would drive an electric motor, or motors in case of redundancy requirement. The power demand for these vessels is generally lower than that for larger vessels, thus limiting the types of reactors suitable for this trading pattern. Most vessels require less power during port stays, which might also promote the use of battery systems. A future scenario worth considering is that during port stays, ships could deliver power from ship-to-shore, thereby contributing to the global power needs.

Under section 2.7 we have done a pilot study on a Shuttle Tanker where most of these challenges come into play, and how it is possible to deal with these.

In Coastal operations, there is an increasing variety of vessel types, sizes, and operational differences. Nuclear installations below 5 MW have not yet been considered for the maritime industry. This is partly due to lower emissions from this fleet and the potential role of other renewable fuels in decarbonisation, as it is easier to control both production and logistics of these fuels in this market. Vessels with installation requirements between 5 to 15 MW are being considered, with nuclear electric and hybrid systems being relevant for these cases.

WP 2.4) Spent fuel storage and disposal

A primary concern associated with nuclear energy is the generation of radioactive waste. This waste is produced in various types of facilities and can exhibit a broad range of radionuclide concentrations, as well as diverse physical and chemical forms. These variations necessitate a diverse array of management strategies, contingent upon the duration of storage required prior to disposal (short-term or long-term). Additionally, factors such as radioactive activity and heat dissipation requirements influence the selection of the final disposal site, which may range from near-surface repositories to deep geological formations.

The implementation of nuclear reactors in merchant ships poses new challenges on how these wastes are handled. While it can be expected that all reactor designs will produce small amounts of Low- and Mid-Level Waste during the operation, for example, coming from the coolant purification systems that would collect activated impurities found in the coolant, that will have to be securely stored onboard until it is offloaded in harbour during maintenance/load-unload stops; the differences on refuelling needs of different reactor designs will lead to different management scenarios for the spent fuel:

- In Harbor Refuelling: In this case, Spent Nuclear Fuel is generated each time the reactor concludes a refuelling cycle. The stops for refuelling will have to match the stops of the ship for maintenance, which will require specialized harbours including new areas where refuelling following IAEA standards can be performed. Independently of the form of the Spent Nuclear Fuel (conventional fuel assemblies, molten salt, TRISO), the Spent Nuclear Fuel may be extracted from the reactor is expected to be reprocessed to generate new nuclear fuel, in line with sustainability objectives; although this is not done with most fuel today, and in whatever case, storage is necessary. This will, however, also depend on issues like risk of proliferation and availability of facilities, as very few countries presently reprocess spent nuclear fuel. Certain fuels, like TRISO, has not been designed to facilitate reprocessing.
- Online Refuelling: Reactor designs with online refuelling belong to this case. In this case, depleted fuel will be generated, burnt, collected and encapsulated in sealed canisters during the operation of the reactor. These canisters are later transferred to a reprocessing facility or a land-based reactor with the objective of achieving full burnup, to extract the remaining energy. This is a consequence of the load profile of the reactor working as a propulsion system with constant load changes to adapt the speed of the ship, in contrast to land-based reactors working at full load for electricity production. The transfer of this partially burnt fuel must ensure its compliance with the highest safety standards. As online refuelling may be performed in high seas, fresh fuel should also be present on the ship with the objective of replacing the outcoming fuel. Inconveniencies due to the fact that both fresh and Spent Fuel need to be stored and managed in the ship come as a safety and security related issue.
- No Refuelling: Some reactor designs can operate their whole lifetime without the need for refuelling. This involves having all Spent Fuel and most radiological waste just at the end of the life of the reactor, which makes this the most convenient and safe scenario from the waste management point of view. These reactors are designed so that the spent fuel can be directly disposed in canisters after decommissioning.

A challenge regarding waste management in new generation reactors is the uncertainty in the type of Spent Fuel and radioactive waste that will be generated as well as in the quantity, time and place of this generation. As these new concepts remain in a preliminary design status, the amounts and specific characteristics of the waste must be thoroughly simulated and verified through measurements on experimental test units.

However, observing the proportions in waste inventories, a similar proportion might be expected for Gen IV reactor designs, with small inventory variations due to concept differences. For example, impurities in irradiated molten salt from MSR will likely be classified as Low-Level Waste (LLW), while part of the fuel, regardless of its form (TRISO, solid pellets, molten salt fuel) will be High Level Waste (HLW) and consequently vitrified and disposed in a deep geological repository.

While for land-based reactors it is easier to establish the responsibility for the spent fuel and radioactive waste management and disposal (assumed by both public and private entities depending on the agreements), in the case of reactors moving all over the world, lines of responsibility become blurred. The question is whether it will be the reactor operator, the shipping company, the country owning the ship, or the shipping company country that will be responsible of this management.

Several international bodies have established that the prime responsibility for ensuring the safety of Spent Fuel and radioactive waste management relies on the license holder as a basic prerequisite. However, agreements between new nuclear reactor design development companies, shipping companies and regulatory bodies must be ensured for cooperation and responsibility distribution.

IAEA encourages cooperation between countries in nuclear waste management. It facilitates the exchange of information, collaboration in research, and joint development of technologies.

Besides, due to the long-time frame of waste disposal, in certain cases it is practical to establish Waste Management Organizations (WMOs) owned and operated by private/public waste generators. This could be an interesting approach for maritime reactor operators to enable the management of the waste in a more international approach with facilities located across the most active countries. To this extent, organizations such as the International Maritime Organization (IMO) could emerge as candidates for the regulation and standardization of nuclear-powered ships and the management of the generated waste and spent fuel.

In the context of maritime propulsion, the management of radioactive waste must be considered due to environmental concerns associated with heat release and potential discharges of radioactive materials into the sea. Factors such as operational security and efficient logistics play a significant role. Consequently, specialized facilities are necessary for the temporary storage of these wastes, considering their indoor capacity.

WP 2.5) Opportunities by installing “unlimited power”

Nuclear powered ships offer several advantages to the maritime industry, potentially revolutionizing ship design, energy consumption and environmental impact.

The presence of a virtually infinite energy supply allows for more innovative and ambitious designs. Ships could be larger, faster, and equipped with advanced technology, all while maintaining high levels of efficiency. This innovation in design could lead to fewer ships being needed to carry out the same amount of work, streamlining operations and reducing costs.

Nuclear powered ships produce no direct greenhouse gas emissions, making them an attractive option for meeting the International Maritime Organization’s (IMO) net-zero demand by 2050. This aligns with global efforts to combat climate change and reduce the carbon footprint of the shipping industry.

By eliminating the need for conventional fuel bunkering processes and the transport of fossil fuels to ships, the risk of spills and related environmental hazards is significantly reduced. This not only protects marine ecosystems but also enhances the safety and reliability of shipping operations. A nuclear-powered cargo ship can operate for years without the need for refuelling, providing significant advantages for long-distance routes. This extended operational capability ensures that ships can maintain their schedules and deliver goods more efficiently, without the interruptions and delays associated with conventional refuelling processes. Global fuel prices are subject to fluctuation, and shipping companies could face fuel shortages or sanctions that can disrupt operations. Nuclear propulsion offers a more predictable and stable operational cost structure, insulating companies from the volatility of traditional fuel markets.

Despite the high initial investment required for nuclear propulsion systems, the operational costs over time are significantly lower. The stability and predictability of nuclear fuel costs contribute to more consistent budgeting and financial planning for shipping companies.

Nuclear powered ships, if the supporting infrastructure is developed, could serve a dual function by delivering excess power onshore to meet the growing demand for energy on land. This capability could be especially beneficial in remote areas or during emergency situations where traditional power sources are inadequate or unavailable.

Nuclear powered ships present a compelling case for the future of maritime transportation. From their environmental benefits to their operational efficiencies and potential for innovative ship design, the advantages are clear. As infrastructure and technology continue to develop, the adoption of nuclear propulsion in the shipping industry could become a transformative force, aligning with global sustainability goals and enhancing the efficiency and reliability of maritime operations.

WP 2.6) Need and scale of training

This section presents summary recommendations, based on task analysis, concerning training and other qualification requirements appropriate for personnel to serve on future new commercial nuclear ships. Training content and type (classroom, shoreside practical/simulation, onboard) are recommended for 12 personnel functional areas. The study described in this section is seen as an initial step in the process of developing marine nuclear personnel requirements.

Pertinent existing standards and legal requirements are considered in the recommendations; however, the need for regulatory guidelines specific to the Merchant Marine environment is identified. The task data presented offer a basis for specific training curriculum development once the regulatory guidelines are defined. In addition to the task data and summary recommendations, the report is a compendium of reference materials including description of the design proposals for new nuclear commercial ships; discussion of nuclear hazards; description of existing standards and legal requirements; and summaries of nuclear personnel requirements for the utilities, the U.S. Navy, and on the prototype ship NS Savannha.

Maritime education and training for nuclear powered ships

All maritime education must follow the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers 78 as Amended (STCW) and additional national requirements. In Norway, the regulation FOR2011-12-22 nr. 1523 *Forskrift om kvalifikasjoner og sertifikater for sjøfolk* applies. National requirements cover STCW requirements and additional national requirements beyond the international requirements from STCW.

The International Maritime Organization, IMO, sets the regulatory framework through STCW. The STCW Convention and Code defines the international regulatory framework for education of seafarers in all positions across the world.

Standard competencies are covered by the educational programs, while specialized competencies must be achieved as an addition to the educational program.

Requirements on extended competencies for specialized vessels such as e.g. tankers, passenger vessels, etc. are defined through own regulations and competency tables within the STCW Convention and Code. These regulations and tables define the required competence for e.g. tankerman certificates.

Requirements from STCW Convention for officers:

- Deck officer, operational level – STCW regulation A-II/1, section A-II/1 and table A-II/1.
- Deck officer, management level – STCW regulation A-II/2, section A-II/2 and table A-II/2.
- Engine officer, operational level – STCW regulation A-III/1, section A-III/1 and table A-III/1.
- Engine officer, management level – STCW regulation A-III/2, section A-III/2 and table A-III/2.
- Electrotechnical officer (ETO), operational level – STCW regulation A-III/6, section A-III/6 and table A-III/6.

Norwegian maritime education framework

In Norway, there are several ways of completing maritime education and becoming a deck or engine officer:

- High school (maritime) + apprentice on board + vocational college + cadet on board (2 years + 2 years + 2 years + 6 months) – most deck and engine officers in Norway have completed this educational path.
- High school (maritime) + apprentice on board + vocational Bachelor of Nautical Science or vocational Bachelor of Marine Engineering + cadet on board (2 years + 2 years + 3 years + 6 months).
- High school (study specialization) + Bachelor of Nautical Science or Bachelor of Marine Engineering + cadet on board (3 years + 3 years + 12 months).

In addition to completing the educational program for the relevant position, it is necessary to complete tankerman training when working onboard specialized vessels, such as a tanker.

Tankerman training is divided into two different levels, where personnel participating in operations must complete the basic training or have 90 days sea time and personnel leading operations must complete the advanced training (basic training is a prerequisite for the advanced training). In addition, it is necessary to have 90 days sea time on tankers to apply for the tankerman certificate.

Tankerman advanced training + 90 days sea time = Certificate of Competence (CoP) tankerman highest grade.

The existing complete list of certificates for familiarization and specialization for the three types of tankers (oil, chemical and gas tankers), are the following:

Familiarization training according STCW Convention:

- BASIC TRAINING FOR OIL AND CHEMICAL TANKERS, in compliance with the contents of paragraph 1 in section A-V/1-1 (table A-V/1-1-1);
- BASIC TRAINING FOR LIQUEFIED GAS TANKERS, in compliance with the contents of paragraph 1 in section A-V/1-2 (table A-V/1-2-1).

Specialization training according STCW Convention:

- ADVANCED TRAINING FOR OIL TANKERS, in compliance with the contents in section A-V/1-1 (table A-V/1-1-2);
- ADVANCED TRAINING FOR CHEMICAL TANKERS, in compliance with the contents of section A-V/1-1 (table A-V/1-1-3);
- ADVANCED TRAINING FOR LIQUEFIED GAS TANKERS, in compliance with the contents of section A-V/1-2 (table A-V/1-2-2).

Norwegian vessels for which the INTERNATIONAL CODE OF SAFETY FOR SHIP USING GASES OR OTHER LOW-FLASHPOINT FUELS (IGF CODE) applies

IGF basic training or CoP tankerman for Gas Tankers + valid health declaration and CoP safety training (basic or advanced) = CoP IGF Basic.

There are several alternatives to qualify for IGF advanced. All alternatives require valid health declaration and CoP safety training (basic or advanced), training (several alternatives) and practical experience/sea time (several alternatives).

The complete list of certificates for familiarization and specialization for vessels for which the IGF Code applies, are the following:

- Familiarization training according STCW Convention:

BASIC TRAINING FOR SHIPS SUBJECT TO THE INTERNATIONAL CODE OF SAFETY FOR SHIP USING GASES OR OTHER LOW-FLASHPOINT FUELS (IGF CODE), in compliance with the contents in table A-V/3-1.

- Specialization training according STCW Convention:

ADVANCED TRAINING FOR SHIPS SUBJECT TO THE INTERNATIONAL CODE OF SAFETY FOR SHIP USING GASES OR OTHER LOW-FLASHPOINT FUELS (IGF CODE), in compliance with the contents in table A-V/3-2.

Certificates and documentation

In shipping industry, there are several types of documentation which is included in a seafarer's total documentation:

1. Certificate of Competency (CoC) – the CoC is a certificate issued and endorsed for masters, officers and GMDSS radio operators in accordance with the provisions of Chapters II, III, IV or VII of the STCW which entitles the lawful holder of the certificate to serve in the capacity and perform functions involved at the level of responsibility specified therein (STCW 78 as Amended).
2. Certificate of Proficiency (CoP) – the CoP is a certificate, other than a certificate of competency issued to a seafarer, stating that the relevant requirements of training, competencies or seagoing service in the Convention have been met (STCW 78 as Amended).
3. Documentary evidence - documentary evidence is documentation, other than a certificate of competency or certificate of proficiency, used to establish that the relevant requirements of the Convention have been met (STCW 78 as Amended). Documentary evidence can e.g. be a course certificate, course diploma, etc.

Nuclear powered vessels

In the tanker trade today, the regulatory framework is fixed. In addition, there are several other requirements which also come into force, from industry, charterers, makers and own company. This means that the certificate and course matrixes in the tanker trade are quite complex. In addition to the already existing requirements, it will be necessary to include vessel specific training for nuclear powered vessels.

In order to find the correct level for vessel specific training, it is important to secure a regulatory framework for Nuclear Powered Vessels. This regulatory framework can be included in STCW Chapter V which contains the standards regarding special training requirements for personnel on certain types of ships or be developed as a separate code (based on a highly necessary revision of the existing nuclear code). As followed by IMO for tankers and vessels for which the IGF Code applies, the regulatory framework must encompass two training levels: basic and advanced training, and two certification levels: lowest and highest grade.

Based on the regulatory framework, training needs to be developed. In order to be in line with the hierarchy of the STCW, we suggest the following:

- CoP for Nuclear Powered Vessels – highest grade and lowest grade – maritime education in collaboration with maker provide advanced training for personnel on nuclear powered vessels, and maritime education institutions provide basic training for personnel on nuclear powered vessels.
    - CoP Nuclear Powered Vessels – highest grade – advanced technical and operational understanding and competence on nuclear powered vessels.
    - CoP Nuclear Powered Vessels – lowest grade – basic technical and operational understanding and competence on nuclear powered vessels.
- CoP for Safety Training in Nuclear Powered Vessels – highest and lowest grade.
    - CoP for Safety Training in Nuclear Powered Vessels – highest grade – advanced safety knowledge, skills and understanding relevant for nuclear powered vessels.
    - CoP Safety Training Nuclear Powered Vessels – lowest grade – basic safety knowledge, skills and understanding relevant for nuclear powered vessels.

In the certificate matrix of a given nuclear-powered vessel, such requirements can look like the one found in Table 4. Please note that one engine officer position and one engine rating position is removed compared to ordinary LNG tanker manning, as per info discussed in the subsequent paragraph.

Table 4 Certificate matrix that can be applicable

		POSITIONS																				
Certificates	Validity	Master	Chief officer	2nd Officer	3rd Officer	Senior Deck cadet	Deck cadet	Chief engineer	Cargo engineer	2.engineer	3.engineer	Engine cadet	Electrician ETO	Electrician cadet	Bosun	Pumpman	AB	OS	Fitter	Motorman	Ch. Steward/Cook	Messman/Boy
CoP Nuclear powered vessels highest grade	5y							M		M	M	M	M	M								
CoP Nuclear powered vessels lowest grade	5y	M	M	M	M				M						M	M	M	M	M	M		
CoP Safety training nuclear powered vessels highest grade	5y	M	M	M	M			M	M	M	M		M		M	M						
CoP Safety training nuclear powered vessels lowest grade	5y					M	M					M		M			M	M	M	M	M	M

When established, the regulatory framework for personnel working on nuclear powered vessels, it will be important to look into the manning requirements for such vessels. From our point of view, it may be possible to reduce manning in the engine department by at least one engineer and one rating, as the equipment on board a nuclear-powered vessel will require less maintenance than the equipment found on board vessels today.

Nuclear powered vessels – Emergency Response Management Team

In addition to establishing requirements for the on-board personnel, competency requirements for the shore organization's Emergency Response Management Team (ERMT) must be developed. We suggest that the shore organization ERMT must have at least two members with competence on CoP Nuclear Powered Vessels highest grade and CoP in Safety Training for Nuclear Powered Vessels highest grade or similar. It would be beneficial if own courses for the ERMT is developed for the whole team to be well prepared in case of emergency situations.

WP 2.7) Pilot Ship study, Maran Shuttle Tankers

The pilot study is summarised by Maran Shuttle Tankers (MST), NTNU, ABB, Brevik Engineering, and OSM Thome.

Maran Shuttle Tankers offered one of their modern shuttle tankers as a study object to assess the feasibility of a nuclear installation. These vessels are ideal due to their busy regional trade patterns, need for variable power, quick power ramp-up, and stringent safety requirements.

In the Shuttle Tanker segment, the conventional design has traditionally relied on an engine configuration that combines 2-stroke engines with direct drive for propulsion and 4-stroke engines to provide power to energy consumers such as thrusters, pumps, and other equipment. In 2015, Teekay (now Maran Shuttle Tankers) initiated a project called "Teekay E-shuttle," which introduced an innovative shuttle concept aimed at benefiting all stakeholders within the industry. The primary objective of this initiative was to achieve a significant improvement in fuel efficiency, with expectations set between 15-30% compared to existing shuttle tankers at that time, by introduction of Gas/Diesel Electric Propulsion with hybrid battery power and dual fuel LNG/MGO capability.

Based on the experience gained from this new concept, see Figure 17, the feasibility study introduced the idea of considering nuclear as an option for this type of vessel.

Figure 17 Our pilot vessel Altera Wave (Courtesy: Maran Shuttle Tankers)

Reactor selection

The proposed installation is a nuclear-electric propulsion system. Its main benefit is improved response time, reducing the need for frequent reactor output adjustments. This enhances manoeuvrability with quicker response times.

The selected reactor, the Micro Modular Reactor (MMR) by Ultra Safe Nuclear Corporation, is a High Temperature Gas-cooled Reactor (HTGR) with a thermal power of 15-45 MWth (5-15 MWe), ideal for this installation. It uses TRISO fuel and is pressurized at 6 MPa, with Helium gas cooling the TRISO prismatic array. This design minimizes sea dynamics effects due to its no-moving-parts configuration and ensures excellent fission product confinement. Gas-cooled reactors have also a good track record with over 60 years of operational experience in various countries.

Energy conversion

New supercritical CO_2 (sCO2) conversion technology enables next-generation micro modular (MMRs) and very small modular nuclear reactors (VSMRs) to be safe, clean, and cost-effective. Peregrine Turbine's proprietary sCO2 energy conversion technology offers solutions not available in earlier nuclear systems:

- 1.5x the efficiency of steam with benefits like no water cooling, black start capability, compact size, and low maintenance.
- 3x the efficiency of air Brayton systems with similar critical advantages.

Peregrine's technology improves VSMRs[12] and MMRs in cost, efficiency, and reliability. Over the past decade, these reactors have become a high priority for the US DoD and industrial decarbonization sectors like data centres, steel, and cement.

Peregrine's sCO2 turbines are 30% – 50% more efficient than equivalent steam plants, air-cooled, needing no high-level licensed operators, and designed for easy field maintenance. The sCO2 system tackles the challenges of large, inefficient steam turbines that need substantial water sources and high costs. PTT's heat engine achieves a thermal to electric conversion efficiency of 45%, compared to 30-33% for steam systems, enhancing reactor output and reducing costs per MWe.

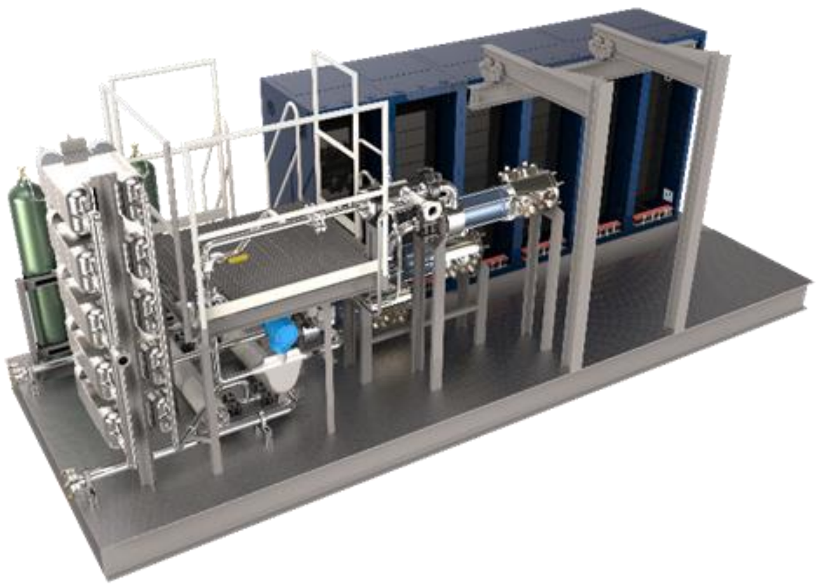


Figure 18 Peregrine Turbine's sCO2 energy conversion unit (Courtesy: Peregrine Turbine Technologies)

Class demand

Due to the sensitive operational nature of shuttle tankers, stringent safety and environmental regulations are enforced. Dynamic positioning (DP) systems are a crucial element in contemporary shuttle tanker technology and must be capable of maintaining the tanker's position even under severe weather conditions. Currently, the majority of cargo owners mandate that new shuttle tankers meet IMO dynamic positioning Class 2 requirements.

In hybrid DP operations, batteries can provide power for approximately one-third of the operational duration, thereby reducing generator cycles and offering a faster response time compared to generator sets. Batteries can be optimized either for fuel efficiency or as backup power, contingent upon the specific application. For nuclear installations, back-up generator sets must be installed, operating on biofuel in this case.

[12] Very small modular reactors

For our pilot vessel this gives a "4-split installation", fulfilling requirements in the IMO dynamic positioning Class 2.

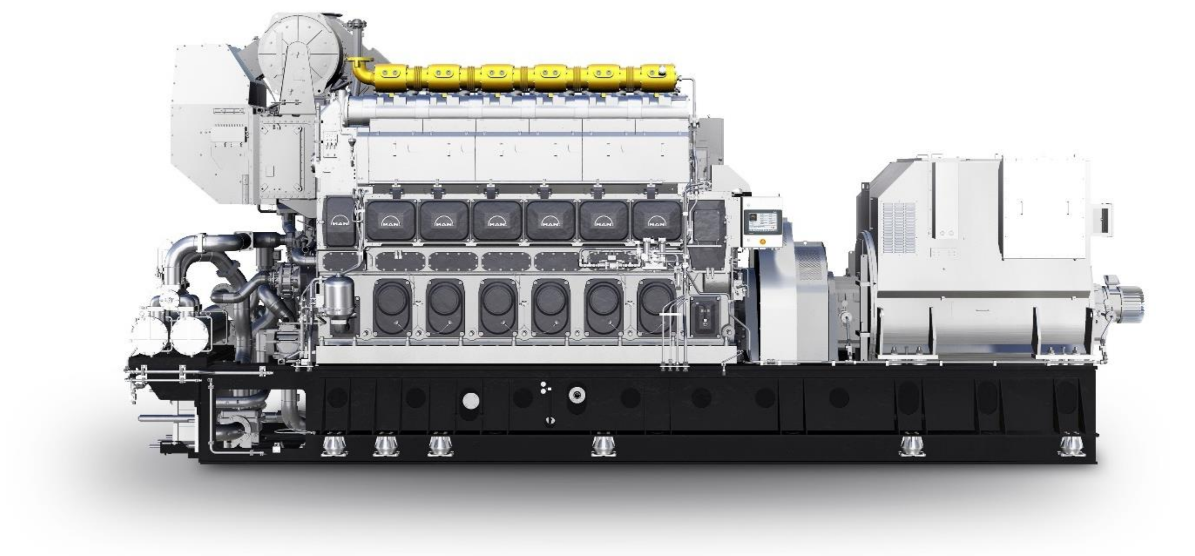


Figure 19 Generator set 9L 35/44DF (Courtesy: MAN Energy Solutions)

Operation

If the vessel operates 365 days per year this give 3.760 running hours in total with an operational profile as described in Figure 20.

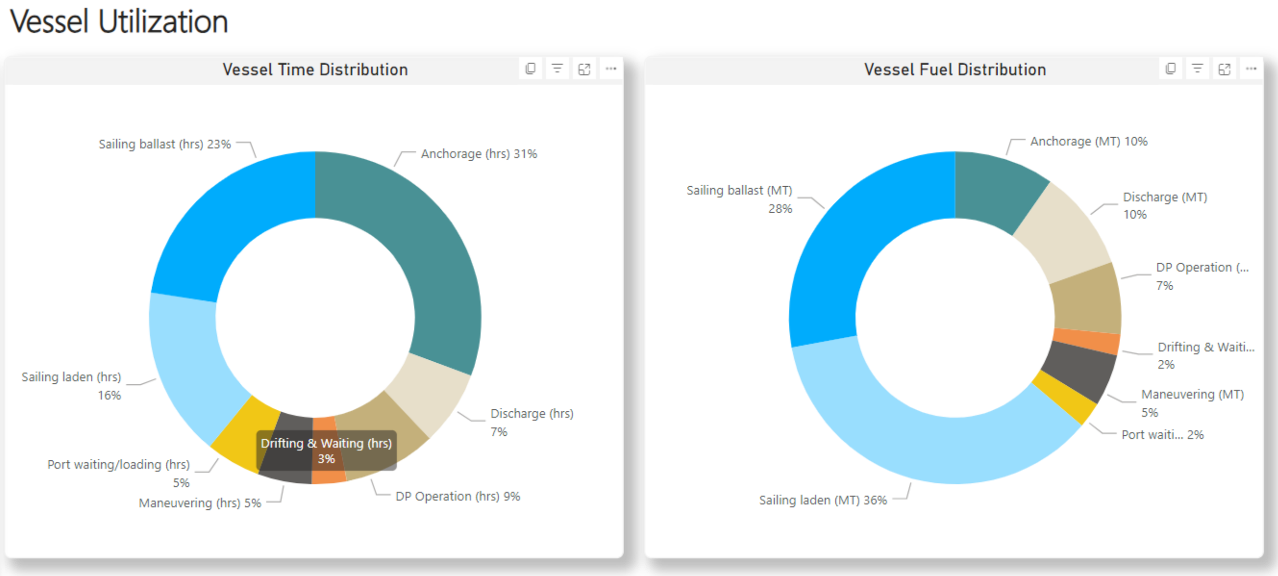


Figure 20 Operational mode of pilot study ship (Source: Maran Shuttle Tankers)

The vessel is capable of sailing at 14.5 knots under laden conditions with a power utilization of 15.9 MW, though this scenario occurs for only 0.1% of the year. Typically, the vessel sails at less than 12 knots in laden conditions, which accounts for 16% of the time, with a power demand of 9.6 MW. This allows the vessel to operate solely on its nuclear installation. In ballast conditions, the maximum speed is typically 13 knots, requiring up to 10 MW of power; this situation represents 23% of the time and can also be managed using the reactors. The power demand during discharge while in port is slightly lower.

Typically, during dynamic positioning (DP) operations, the maximum power demand is 5 MW, which can be met by operating one reactor and using the hybrid system for peak shaving. However, for redundancy requirements in accordance with the DP classification, much more power must be available. The battery installation ensures fast response time when in DP mode, hence improves safety during loading cargo at sea. The chosen installation demonstrates that the nuclear electric set-up is sufficient to cover all operational scenarios, optimizing the use of the hybrid system effectively.

Design and engineering aspects

A group of GSP Partners have explored converting the gas-electric power production of the shuttle tanker Altera Wave to nuclear power.

- Feasibility Study: In cooperation with Maran Shuttle Tankers, NTNU, ABB and OSM Thome, Brevik Engineering conducted a preliminary feasibility study, evaluating the potential for converting the Altera Wave to nuclear power. Initial weight and stability assessments indicate that the conversion is feasible.
- Machine Room Arrangement: The conversion involves removing two generator sets and relocating some equipment to make space for two nuclear reactors, turbines, and heat exchanger. Existing generator sets will be integrated with the nuclear setup.
- Weight and Stability: The removal of two generator sets and the addition of new nuclear equipment result in a net lightship weight change of -1100 tons, minimally affecting the ship's centre of gravity and stability. Additional studies are needed to address local strength and thermal battery placement.

Summary of findings

Brevik Engineering has together with MST looked at a possible conversion of the shuttle tanker Altera Wave from diesel-electric power generation to nuclear power-driven power generation.

Based on the received documentation, Brevik Engineering has outlined a possible arrangement in the engine room, as well as assessed the weight and stability impact on the hull.

Both sketch and weight calculations give positive results, and it is considered possible to convert the shuttle tanker based on these calculations.

The study is to be regarded as a light feasibility study, and it is pointed out that preliminary and rough calculations have been made. Further studies may increase the level of knowledge.

Engine room arrangement

By removing two of the four gensets, as well as moving some equipment, it will free up space for the nuclear power reactor, turbine and heat exchanger. The two gensets that are retained are part of the nuclear power setup. The existing genset is the same size as the proposal in the new set-up.

The next two figures show the existing, and new arrangement. In addition to the equipment that is placed in the engine room itself, two of the MGO tanks are used for thermal batteries.

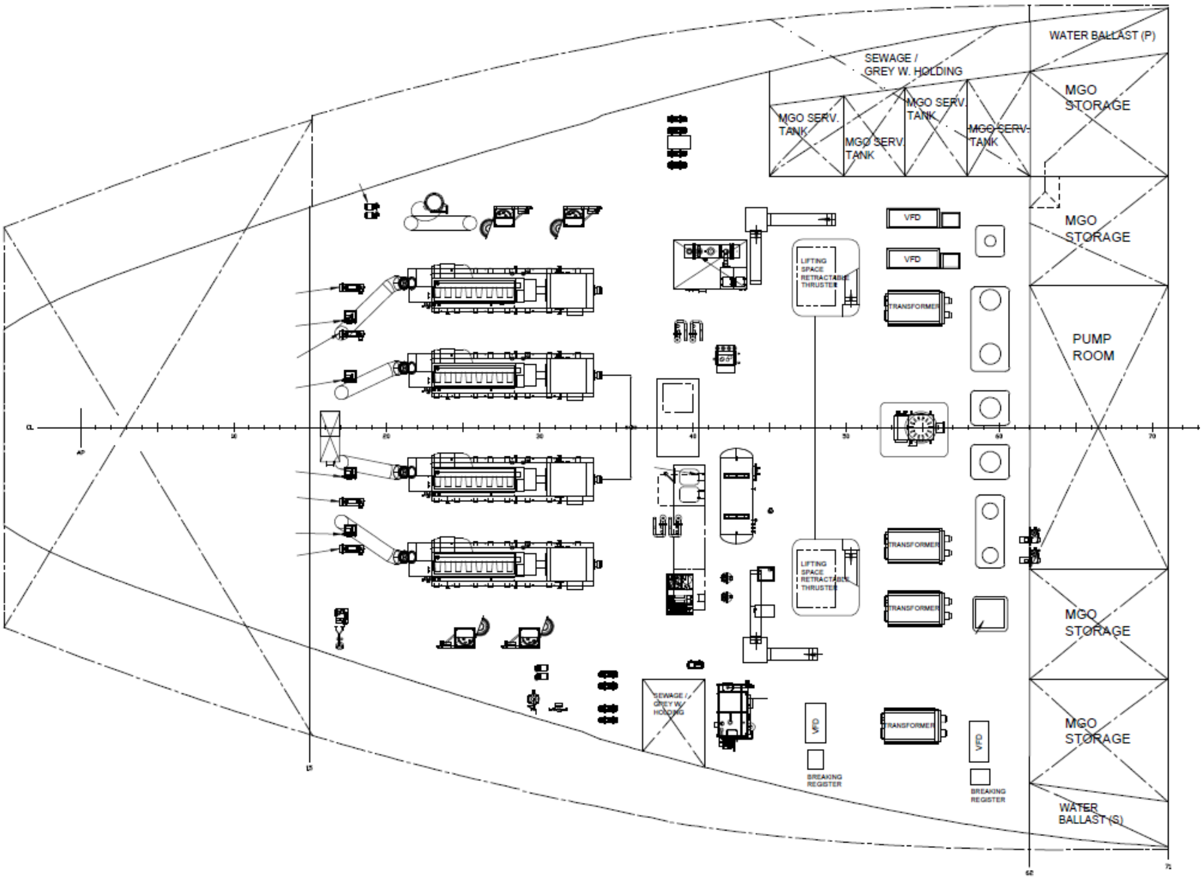


Figure 21 Existing engine room installation of pilot study ship (Courtesy: Brevik Engineering)

Figure 22 Existing engine room onboard Altera Wave (Courtesy: Maran Shuttle Tankers)

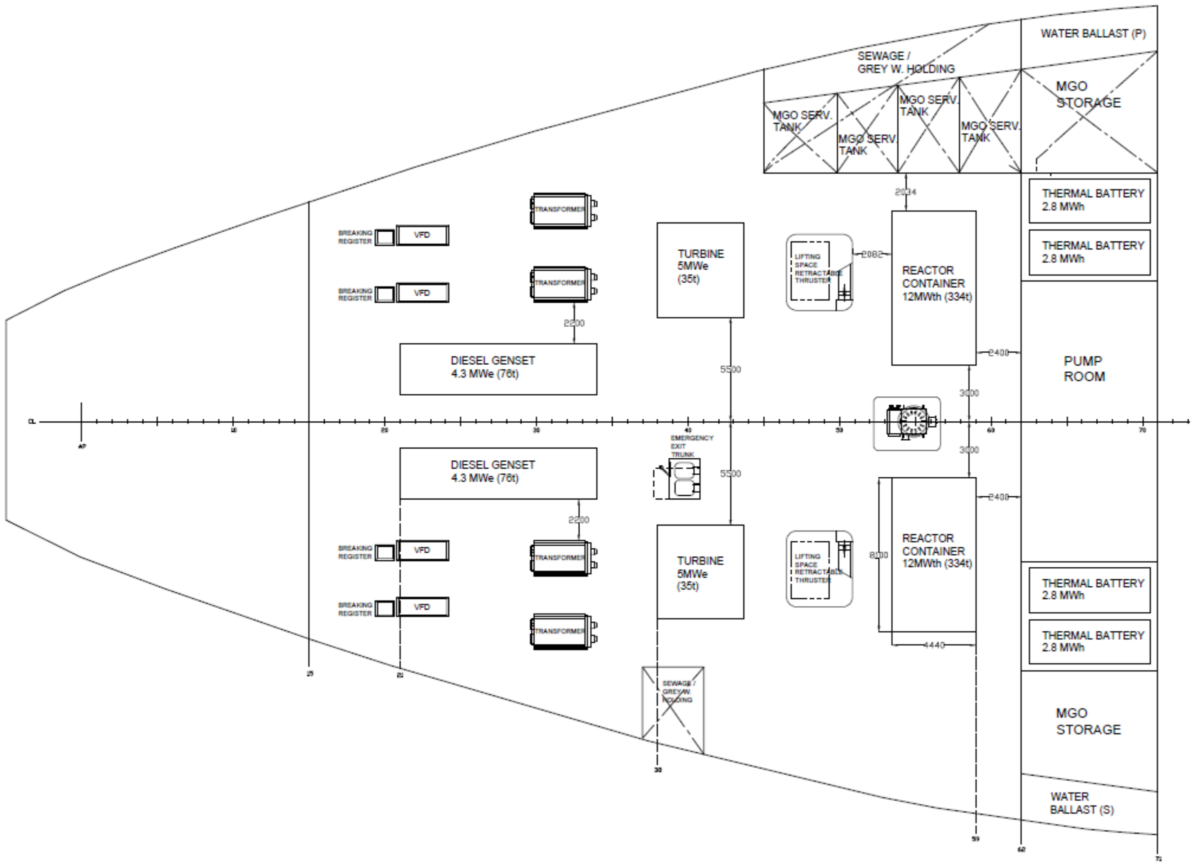


Figure 23 Engine room nuclear conversion for pilot study ship (Courtesy: Brevik Engineering)

There are many details in the engine room that will not be correct, but the main point is to visualize that two equally large sets of reactors have enough space.

The next figure shows the stern from the side. Battery compartments 1 and 2 are also visible here, these house the battery packs that can be used to take the peaks in the event of a short-term higher power requirement.

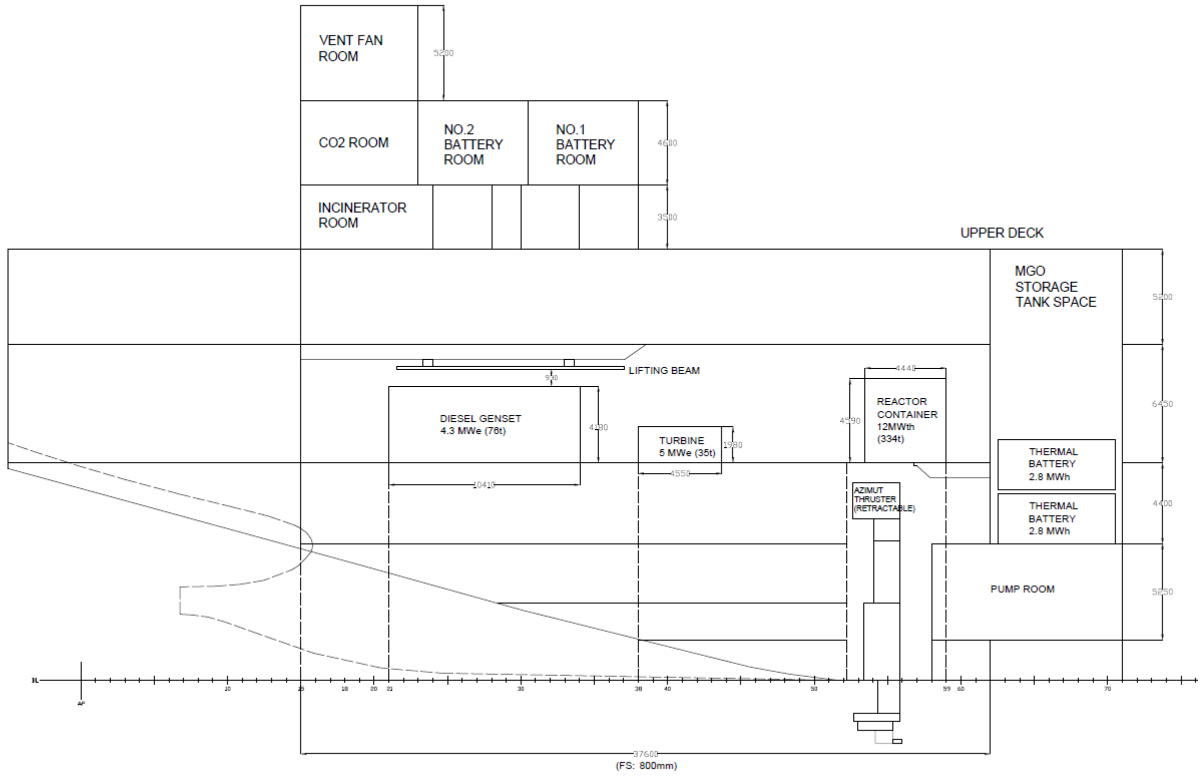


Figure 24 Aft Ship side view of pilot study ship

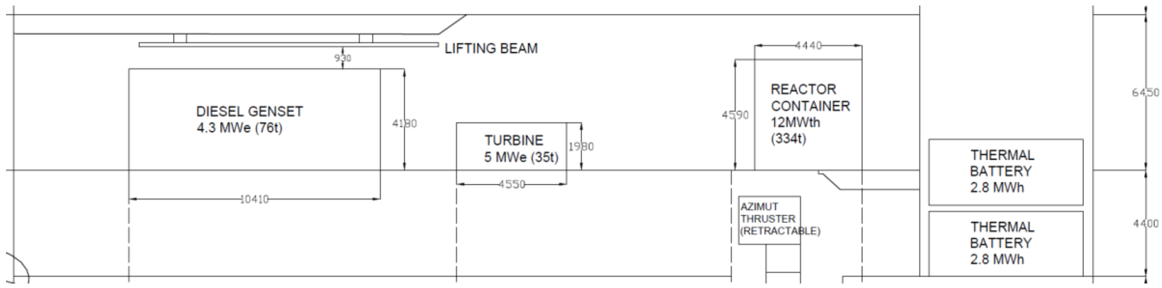


Figure 25 Focus on deck 2 and 3, side view for pilot study ship (Courtesy: Brevik Engineering)

Weight and stability

The table below shows changes in lightship weight. Two gensets amount to about 300 tons, new equipment in connection with the nuclear power installation amounts to approximately 1400 tons. Difference -1100 tons, this has the effect on the centre of gravity that the longship COG (LCG) is pulled 2.87 meters aft, vertical COG (VCG) only 16 mm higher while it has a negligible effect on the transverse COG (TCG).

Table 5 Light-ship weights of pilot study ship (Courtesy: Brevik Engineering)

Lightship	**W**	**LCG**	**TCG**	**VCG**
	t	m	m	m
Ship (as is)	25,022	108.419	0.022	14.164
Removals	-300	30.000	0.000	12.000
Installations	1,400	38.000	0.000	14.000
Ship (nucl.)	**26,122**	**105.545**	**0.021**	**14.180**
Diff.	*1,100*	*-2.874*	*-0.001*	*0.016*

The table below shows cargo condition 12, which is fully loaded ship for design draft. Here, the new light vessel weight is used, and the change in MGO fuel is deducted. This gives a minor difference on the longship COG (0.1 meters stern), as well as a negligible change in the transverse and vertical COG.

Table 6 Cargo condition 12 (fully loaded design draft) of pilot study ship (Courtesy: Brevik Engineering)

Cond no.12	W	LCG	TCG	VCG
	t	m	m	m
Fully loaded (as is)	120,580	122.910	0.028	12.719
Ship (as is)	-25,022	108.419	0.022	14.164
Ship (nucl.)	26,122	106	0	14
Consumables (MGO)	-1,200	53.0	0.0	14.0
Final	**120,480**	**122.851**	**0.028**	**12.723**
Diff.	*-100*	*-0.059*	*0.000*	*0.004*

Conclusion

In terms of area and space, we see that it should be feasible to convert the engine room to nuclear power. Further engineering is needed to look at how smaller equipment can be relocated, and whether equipment can be removed in connection with the removal of two diesel gensets.

For a possible newbuild ship, it would be an even better starting point to adapt the engine room to nuclear power.

The ship's total weight and stability will change negligible. The payload is reduced by around 100 t. LCG is shifted a few millimetres aft, which increases aft trim minimally. A slight increase in VCG of the order of a few millimetres has only a minimal effect on the stability of the ship.

The reason for the relatively small changes lies in the reduction of the MGO fuel requirement. This was reduced in the assessment by about half, 1200 tonnes.

It is assumed that local strength must be improved where the reactor is to be placed. This requires further analysis. Furthermore, it is likely that double bulkheads will be required to be installed in the engine room or where the reactor is located.

There is some uncertainty associated with the size and location of thermal batteries. It is not a given that MGO storage tanks will be appropriate for such installations, but these should be able to fit either in the stern or on deck during further investigations. Here, weight, stability and strength analyses will be important to look at.

The purpose of keeping two diesel gensets is to be able to able to contain the same power generation configuration as of today and keep DP functionality. It will also provide a ”take me home” function. The amount of diesel that will be available for these gensets will need to be further analysed in any next phases of studies.

Received documentation

In addition to a selection of documents from Altera Wave, Brevik Engineering's assessments have been made based on the following documentation:

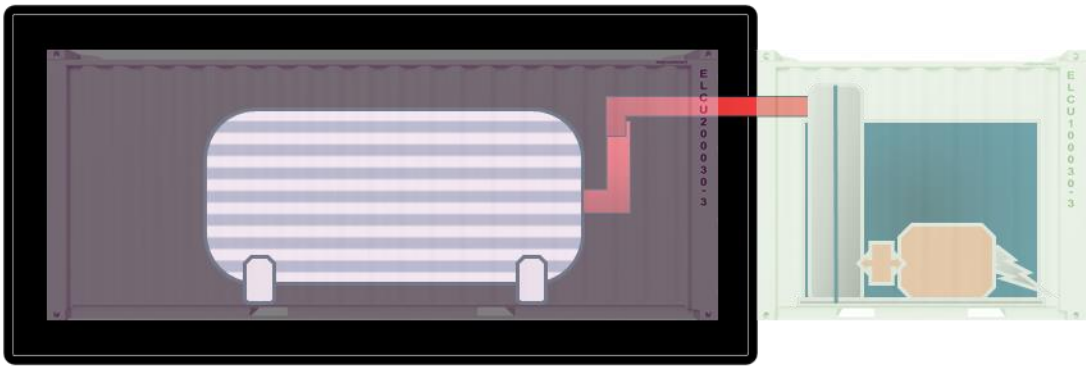


Figure 26 Illustration of reactor and turbine system (including sarcophagus)

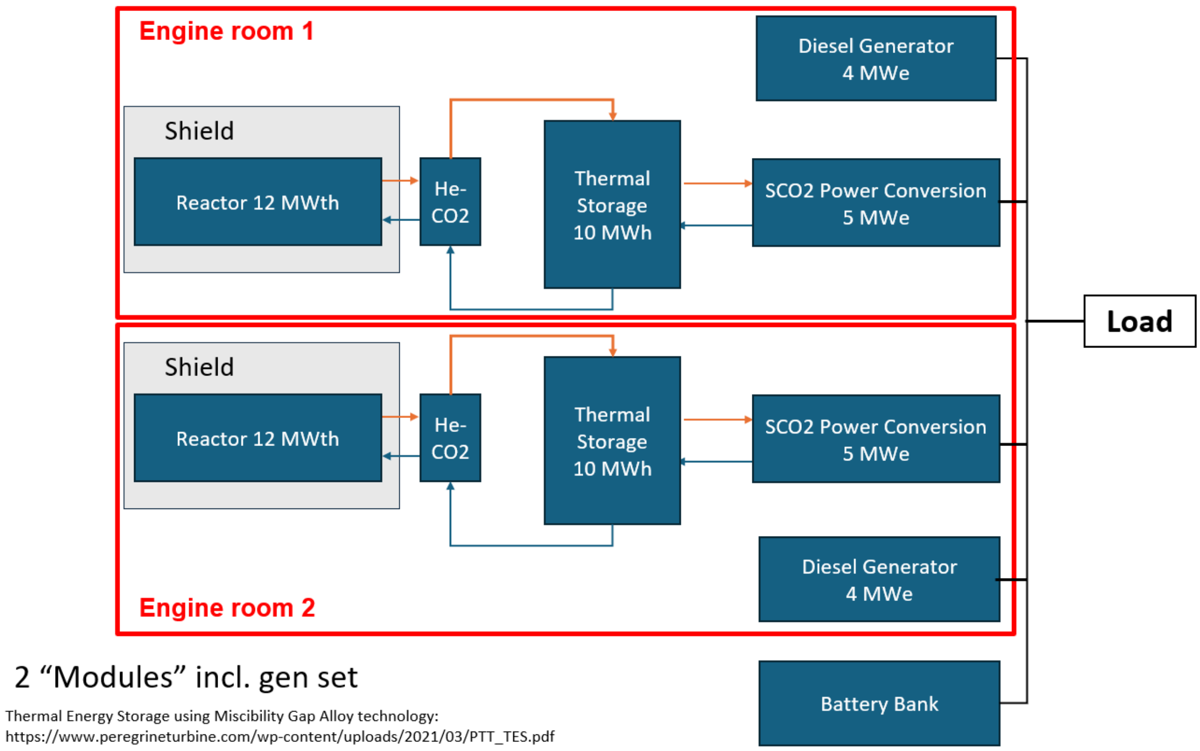


Figure 27 Suggested turbine configuration (Courtesy: NTNU)

Table 7 Dimensions and weight of reactor containers, turbines, thermal battery (Courtesy: NTNU)

Total system mass								
1 Reactor system unit					**2 Reactor system units**			
Containment structure	334	tonnes	33.4 %		Containment structure	668	tonnes	46.9 %
Reactor vessel	30	tonnes	3.0 %		Reactor vessel	60	tonnes	4.2 %
Thermal battery (22.4 MWh, th)	350	tonnes	35.0 %		Thermal battery (22.4 MWh, th)	350	tonnes	24.6 %
Turbine (5 MWe)	35	tonnes	3.5 %		Turbine (5 MWe)	70	tonnes	4.9 %
Electrical battery (1.5 MWh, el)	25	tonnes	2.5 %		Electrical battery (1.5 MWh, el)	50	tonnes	3.5 %
Diesel Gen Set (4.3 MWe)	76	tonnes	7.6 %		Diesel Gen Set (4.3 MWe)	76	tonnes	5.3 %
Diesel	150	tonnes	15.0 %		Diesel	150	tonnes	10.5 %
TOTAL incl. containment structure	**1000**	**tonnes**			**TOTAL incl. containment structure**	**1424**	**tonnes**	
Dimensions per system unit [m]	**Length**	**Width**	**Height**			**Length**	**Width**	**Height**
Containment structure	8.10	4.44	4.59			16.20	8.88	9.18
Diesel Gen Set (4.3 MWe)	10.41	2.69	3.98			20.82	5.38	7.96
Turbine (5 MWe)	4.55	4.95	1.98			9.11	9.90	3.96
Thermal battery (22.4 MWh, th)	51.22	18.74	21.65	8	modules	51.22	18.74	21.65
Thernal battery module (2,8 MWh, th	6.40	2.34	2.71					

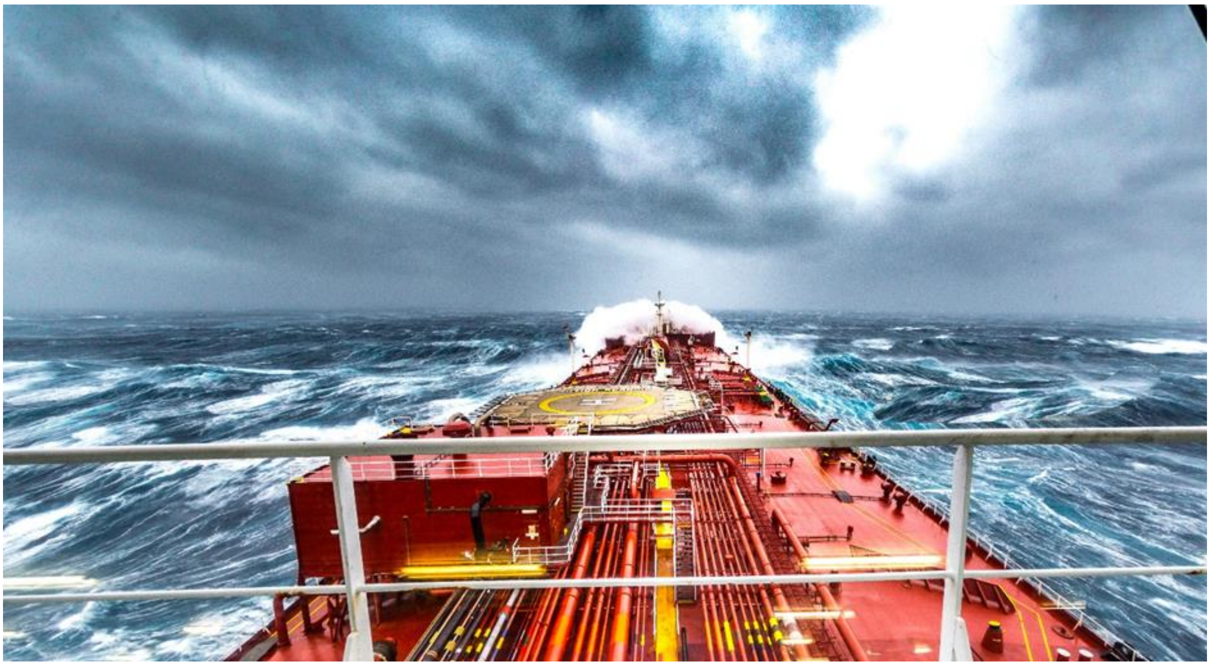


Figure 28 Altera Wave in rough seas (Courtesy: Maran Shuttle Tankers)

Work Process 3, Environmental and health impact

This work process provides an examination of the environmental and health impacts of nuclear energy. It covers conventional nuclear power operations, the life cycle and greenhouse gas emissions of nuclear-powered vessels, and the health consequences of emissions from energy production.

In sections WP 3.1-3.2 we give an overview of nuclear technology in use and in development today, and the historical environmental and safety impact of nuclear power. In section WP 3.3 we review the emissions from nuclear power and compare them with the total WTW GHG emissions from other marine fuels, both in use and proposed for decarbonization. In sections WP 3.4-3.5 we look at the health impact of local pollution from marine fuels and the energy densities of non-nuclear marine fuels.

WP 3.1) What are the known safety risks using nuclear and how to handle

There are different opinions on use of nuclear, spanning from deep scepticism to being "the silver bullet". This chapter contains information from "UNECE Integrated Life-cycle Assessment of Electricity Sources"[13], in this report with focus on nuclear.

Conventional nuclear power

The term "conventional" nuclear power includes most of the fleet in operation today, i.e. pressurized water reactors, pressurized heavy-water reactors, boiling water reactors, and light water graphite-moderated reactors. As of early 2021, 443 of these nuclear power plants are in operation, providing 393 TW of power capacity. The installed fleet delivered 2.6 PWh of electricity to the global grid in 2019, almost exactly 10% of the total that year. The IPCC characterizes nuclear power as able to deliver long-term low-carbon electricity at scale. However, nuclear power faces perceived obstacles to its further deployment in some countries, among which are public acceptance, high upfront costs, and challenges to the disposal of radioactive waste.

Nuclear power reactors come in various designs, commonly classified into generational categories, based on maturity, technology-readiness level, and more generally, the history of nuclear power development. **Generation I** reactors include the first prototypes operational in the 1950s and 1960s, which are no longer in use today. **Generation II** includes most reactors in operation in 2021, mainly light water reactors, with their two main variants, pressurised water reactors (PWR) and boiling water reactors (BWR), which dominate the market. Generation II also includes some heavy water reactors (such as the Canadian CANDU), fast neutron reactors (FNRs) or light water graphite reactors reactor (LWGR) and advanced gas-cooled reactors (AGR designs).

Some **Generation III** reactors are advanced versions of Generation II reactors, but do not include the passive safety features of the later **Generation III+** reactors. The newest European, US and Chinese PWR reactors are Generation III+, with significantly improved safety features to most operational nuclear reactors (that historically have had very high levels of safety).

[13] https://unece.org/documents/2022/08/integrated-life-cycle-assessment-electricity-sources

The **Generation IV** category normally includes six main technologies under development, which offer various operational and environmental improvements over existing technologies – the very-high-temperature reactor (VHTR), molten salt reactor (MSR), lead-cooled fast reactor (LFR), supercritical-water-cooled reactor (SCWR), sodium-cooled fast reactor (SFR) and the gas-cooled fast reactor (GFR). The last two of these designs are fast neutron reactors (FNRs) which have a common objective of "closing" the fuel cycle, thereby allowing the reuse of nuclear fuel for power generation, by reprocessing spent fuel. Several FNRs have operated historically and two are currently operating. These have all essentially been prototype units. The UNECE study aims at modelling the average conventional reactor in use as of 2020, in its two main variants, BWR and PWR. Some elements from Generation III reactors are considered in the life cycle inventory (e.g. the number of bulk materials in construction), mainly for information and comparative purposes.

The nuclear power fuel cycle involves the following steps:

- **Uranium mining and milling**, extracting ore and then separating out the uranium for transport as a uranium oxide
- **Uranium conversion and enrichment**, converting the solid uranium oxide into gaseous UF6 for enrichment, which increases the concentration of the useful isotope 235U 5
- **Fuel fabrication**, converting the enriched uranium into a highly stable compound before loading into manufactured assemblies
- **Power generation** at nuclear power plant
- **Used fuel management**
- High-level radioactive **waste management and disposal**

The first steps, from mining to fuel fabrication, are commonly called "front end", while "back end" refers to the retreatment of the used fuel. It is also possible to "reprocess" used fuel to recover useful isotopes and recycle uranium and plutonium as new fuel.

WP 3.2) Environmental impact of nuclear power compared with other energy sources

From an environmental life cycle perspective, nuclear power has been shown to be low carbon but also presents several co-benefits. It causes low land occupation and transformation over the life cycle, and due to the high energy density of fuel elements, which minimizes mining area per kWh, and to the relatively low occupation of power plant sites. Human health and biodiversity impacts are overall low for the PWR and BWR technologies.

Conclusions from the 2021 "EU JRC report on nuclear energy assessment" (Said, et al., 2021) shows the following:

- The average annual exposure to a member of the public, due to effects attributable to nuclear energy-based electricity production is four orders of magnitude less than the average annual dose due to the natural background radiation.

- The total impact on human health of both the radiological and non-radiological emissions from the nuclear energy chain are comparable with the human health impact from offshore wind energy.
- If health impacts due to normal operation of the various electricity generation technologies are compared, then nuclear energy has the lowest values, both for premature fatalities (caused e.g. by air pollution) and for accident fatalities (e.g. workplace accidents).
- If severe accident fatality rates are compared (see Figure 3.5-1), then the current Western Gen II NPPs have a very low fatality rate (≈5·10-7 fatalities/GWh). This value is much smaller than that characterizing any form of fossil fuel-based electricity production technology and comparable with hydropower in OECD countries and wind power (only solar power has significantly lower fatality rate).
- These latest technology developments are reflected in the very low fatality rate for the Gen III EPR design (≈8·10-10 fatalities/GWh, see Figure 3.5-1). The fatality rates characterizing state-of-the art Gen III NPPs are the lowest of all the electricity generation technologies.

It can therefore be concluded that all potentially harmful impacts of the various nuclear energy lifecycle phases on human health and the environment can be duly prevented or avoided. The nuclear energy-based electricity production and the associated activities in the whole nuclear fuel cycle (e.g. uranium mining, nuclear fuel fabrication, etc.) do not represent significant harm to any of the TEG objectives, provided that all specific industrial activities involved fulfil the related Technical Screening Criteria.

WP 3.3) GHG emissions for nuclear powered vessels

This chapter gives a rough approximation of the GHG emission factor for nuclear powered vessels based on LCA literature for conventional nuclear power plants. In line with current thinking and system boundaries for analysis of maritime fuels, we include all emissions from the fuel's life cycle but exclude emissions from the construction and dismantling of the vessel itself, including machinery and systems.

Note that the emission factors are based on conventional nuclear reactors because nuclear reactors for vessels are not yet fully developed and tested and therefore factors pertaining to maritime applications of nuclear are lacking.

The memo then compares the emission factor for nuclear powered ships with other alternative fuels based on SINTEF Ocean data.

While nuclear energy can offer very significant reductions in GHG emissions, there are other environmental, health, security and societal issues that must be addressed and resolved for nuclear energy to become an environmentally and socially acceptable energy source, on land and at sea.

Nuclear energy has been used in naval vessels since 1955 and in arctic icebreakers since 1975. Only a handful of cargo vessels have been built with nuclear power. Three of these (the American NS Savannah, the German Otto Hahn and the Japanese Mutsu) must be considered technology demonstration vessels and only one has been useful in normal service, the Russian vessel Sevmorput.

Nuclear energy is appreciated by naval vessels and ice breakers because of the high energy content and energy density that limit the need for bunkering and space onboard. In commercial applications, however, nuclear energy is attracting interest as a way to eliminate greenhouse gas emissions.

This chapter explains the GHG emissions – and only the GHG emissions – of nuclear energy in maritime applications.

While nuclear energy can offer very significant reductions in GHG emissions, there are other environmental, health, security and societal issues that must be addressed and resolved for nuclear energy to become an environmentally and socially acceptable energy source, on land and at sea.

Relevance of existing life cycle analysis of nuclear energy

In lack of environmental life cycle analyses of nuclear energy for ships, we turn to studies of nuclear power plants for electricity production. But how relevant are these for shipping?

System borders and scope for life cycle analysis

Traditionally, ship owners and maritime regulators have focused on emissions from the vessels' funnel only so-called tank to wake emissions (part of shipowner's scope 1). These emissions are reported in sustainability reports and to the EU under the MRV-scheme and counted in IMO's GHG reports.

The advent of alternative fuels with significant emissions in the production phase (well to tank and part of shipowner's/-operator's scope 3) and low or zero emissions in the combustion phase changed this. It is now recommended practice to address the emissions along the fuels' life cycle. This is important for a meaningful evaluation of hydrogen and ammonia, methanol, biofuels and synthetic fuel versions.

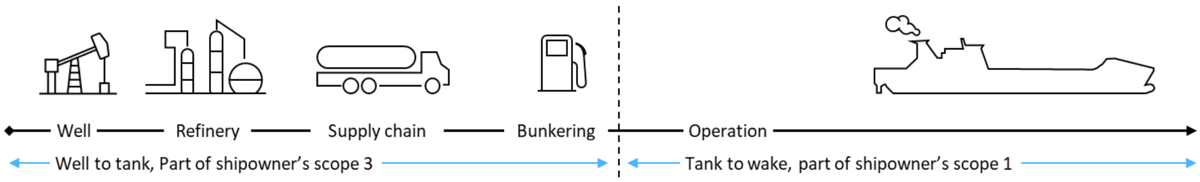


Figure 29 The fuel's life cycle

However, it is not yet customary to address emissions over the vessels' life cycle by including emissions arising from the production and dismantling of the vessel in addition to the operation phase. In an evaluation of fuels, this omittance means very little because most of the alternative fuels utilize more or less the same type of machinery, storage tanks and systems, broadly speaking, so the impact of a switch from one fuel to another does not make much of a difference.

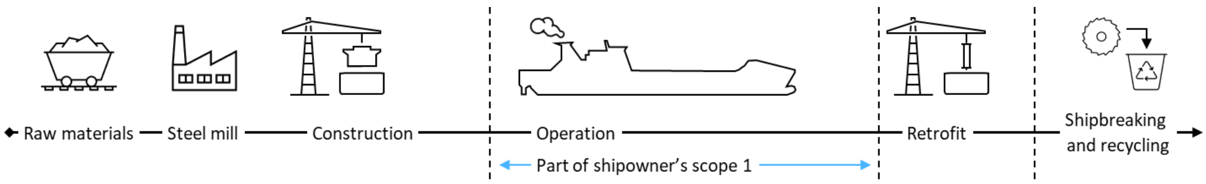


Figure 30 The vessel's life cycle

Most life cycle emissions conducted for nuclear energy, however, have been undertaken for large nuclear power generation plants built to generate electricity. In this sector, it is customary to include the construction of the power plant itself in the analysis. When we take emission factors for nuclear energy from studies done on nuclear power plants, this difference in system borders and scope introduces an error that must be accounted for or at least acknowledged.

Reactor type and size

Most life cycle analysis for nuclear energy is based on very large reactor sizes; typically 1,000 MW. These are 10-100 times larger than the reactor size foreseen in commercial shipping.

Also, most studies of nuclear energy analyses pressurized water reactors, which is the most common reactor type in nuclear power plants.

Tank to wake emissions (TTW)

Using nuclear energy in a reactor onboard gives zero greenhouse gas emissions. There is no combustion and exhaust.

A vessel powered by nuclear energy will likely need back-up generators and ancillary power systems to cover power peaks and troughs, much like fuel cells which also prefer relatively stable load factor.

This can be conventional rotating machinery, fuel cells or batteries. Thus, a portion of the energy must be produced from other fuels, and this will give some emissions depending on the load curve and load fluctuations.

Well to wake emissions (WTW)

The footprint of nuclear energy in power plants from various sources is summarized in Table 8. Note that this is a non-exhaustive overview provided to give an indication of the magnitude and range of the footprint.

Table 8 GHG footprint of nuclear power plants.

Source	*Comments: Assumptions, system boundaries, etc*	*gram CO_2-eq./kWh$_e$*
(UNECE, 2022)	Global average 2020, large pressure water reactor	5.1-6.4
↑	SMR, estimated. Reactor included.	4.8-8.4
World Nuclear Association, 2011[14]		2-130, mean 29
LSE, Dec 2022[15]		5-50
(Sovacool, 2008)	Review of 103 LCA-studies of nuclear energy	1.4-288, mean 66
(Beerten, 2009)	European context	32

Based on the above, we can conclude that the most recent report[13] put GHG emissions for nuclear power plants to 5-10 CO_2-eq./kWh$_e$. Other sources of interest include the World Nuclear Association (29 g/kWh) and (Sovacool, 2008) (66 g CO_2-eq./kWh$_e$). We conclude with a low estimate (10 CO_2-eq./kWh$_e$), medium (30) and high (70).

Emissions for nuclear power plants can be attributed to at least five stages, according to (Sovacool, 2008). Not all of these are relevant for nuclear power in maritime applications, and we have indicated this in the last column in Table 9.

Table 9 Breakdown of footprint of life cycle GHG emissions, (Sovacool, 2008)

	Stage	*g CO2-eq./kWh$_e$*		*Notes*	*Relevance*
1	Frontend	25.1	38%	Mining, milling, conversion, fuel fabrication and transportation	Yes
2	Construction	8.2	12%	Materials and energy for building the facility	No
3	Operation	11.6	18%	Energy for maintenance, cooling and fuel cycles, backup generators.	Yes, but accounted for otherwise
4	Backend	9.2	14%	Fuel processing, conditioning, reprocessing, interim and permanent storage.	Yes
5	Decom.	12	18%	Deconstruction of facility and land reclamation.	Partly
	Σ	66.1			

14 https://world-nuclear.org/our-association/publications/working-group-reports/lifecycle-ghg-emissions-of-electricity-generation

15 https://www.lse.ac.uk/granthaminstitute/explainers/role-nuclear-power-energy-mix-reducing-greenhouse-gas-emissions/

Stage 1 and 4 apply in full to nuclear energy in maritime applications. Stage 5 considers deconstruction and reclamation of land used both for the power plant and the uranium mine and only the latter applies to nuclear energy in maritime applications. Emissions from operation, stage 3, apply but will be different on a vessel and accounted for otherwise based on the vessel's machinery configuration and operation profile.

To conclude and sum up, we assume that at least emission from stage 1 and 4 are relevant, and parts of stage 5. Emissions in stage 3 shall be estimated specifically based on the vessel's machinery configuration. We sum this up to 52% - 70% and suggest that 60% of the emission factor for nuclear power plants apply to nuclear powered vessels.

Subtracting emissions from irrelevant stages, ref. table 2 above, we can estimate the footprint for nuclear powered vessels to low 6, medium 20 and high 45 g/kWh$_e$.

Emission factors for nuclear vs. other alternative fuels

To put the emission factors for nuclear into perspective, we compare them with those for other alternative fuels.

Fossil fuels: Emission factors for MGO, LSFO, HFO, LPG and LNG come from numerous studies by Lindstad et al. The values for LNG reflect best and worst-case LNG with low and high production emissions (4-18.5 g CO_2-eq./MJ respectively (Lindstad, Gamlem, Rialland, & Valland, 2021) (Lindstad, Lagemann, Rialland, Gamlem, & Valland, 2021) (Equinor, 2021)) and low and high methane slip (1-7 g methane/kWh respectively (Stenersen & Thonstad, 2017) (Ushakov, 2019)). There are less significant variations for the other fossil fuels and therefore only a single value is given.

Methanol: Emission factors for fossil methanol, bio-methanol and synthetic methanol are taken from IRENA's Innovation Outlook Renewable Methanol (2021)[16], page 59-64 and studies by (Lindstad, Gamlem, Rialland, & Valland, 2021).

Biofuels: For liquid biofuels (biodiesel and HVO) and gaseous biomethane, we use standard values from EU RED II. The values for biofuels vary significantly and depend on a number of factors and assumptions.

Hydrogen fuels: Emission factors for grey hydrogen and ammonia come from (Lindstad, Gamlem, Rialland, & Valland, 2021)while factors for blue hydrogen and ammonia are taken from (Gilbert, 2018) and (LR/UMAS, 2020). The emission factors for green hydrogen and ammonia are estimated based on the electricity consumption and the electricity footprint in Norway (low: 15 g CO_2-eq./kWh$_e$) and EU (mid: 210 CO_2-eq./kWh$_e$).

WTT emissions are converted from g CO_2-eq./MJ to g CO_2-eq./kWh by assuming a machinery efficiency $\eta = 0.425$ which is realistic for medium speed engines. Slow speed engines can achieve better, up to 0.50 while high speed machinery performs a bit below at around 0.40.

[16] https://www.irena.org/publications/2021/Jan/Innovation-Outlook-Renewable-Methanol

WTT emission factors for fuels produced from electricity depend significantly on the electricity footprint. A good overview is provided by Ember Climate reproduced by Our World in Data[17].

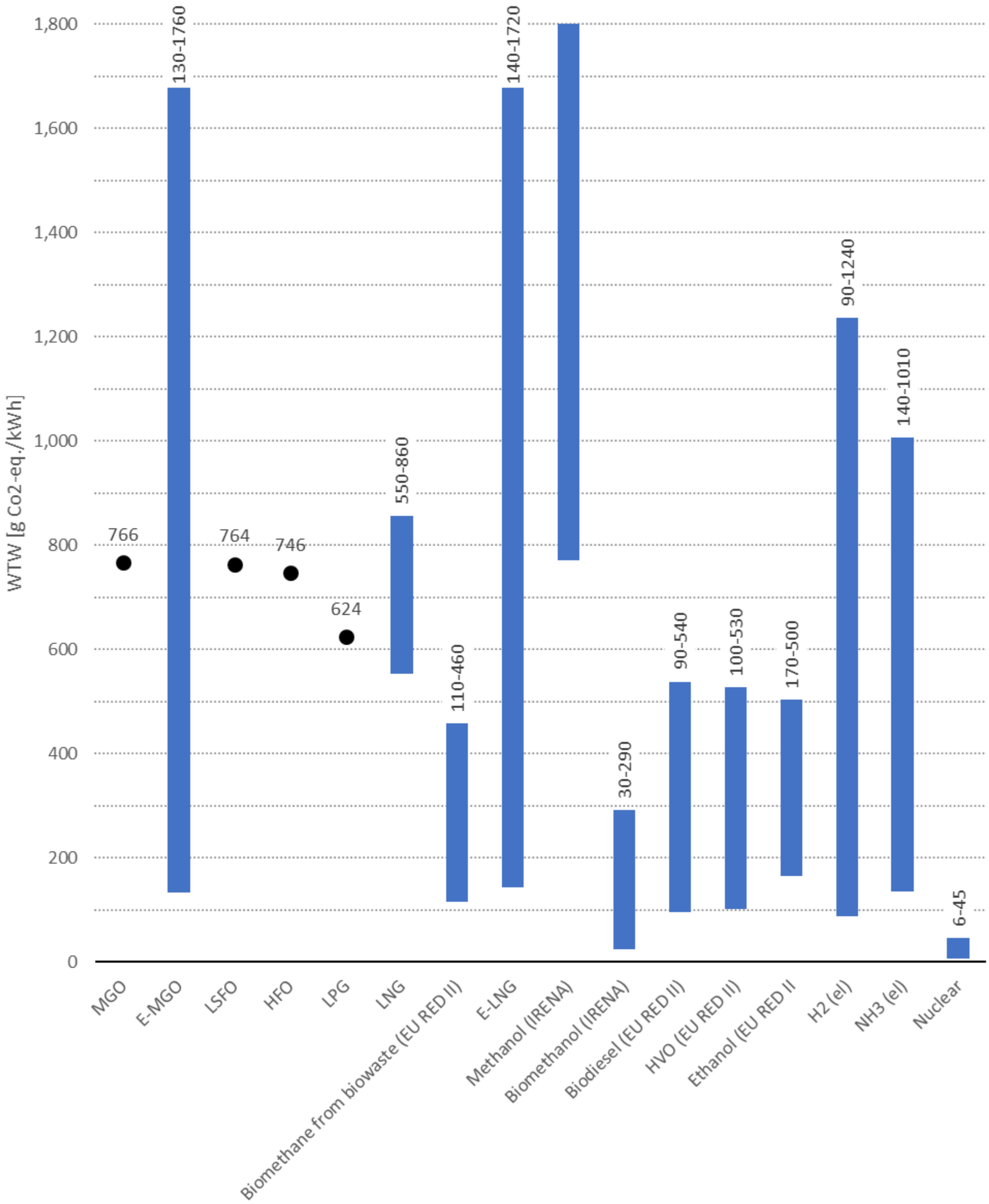


Figure 31 Emission factors for alternative fuels assuming machinery efficiency η = 0.425.

Conclusion

17 https://ourworldindata.org/grapher/carbon-intensity-electricity, https://ourworldindata.org/explorers/impacts-of-energy-sources

First, we note the significant range in GHG emission factors for most fuels. While most of the estimates are somewhat uncertain, the range is explained by variations in primary energy, production process and supply chain.

Secondly, the diagram indicates that the GHG well to wake emissions for nuclear power (5-45 gCO2-eq./kWh) is less than the emissions for other maritime alternative fuels and a lot less than most of them.

Nuclear energy will certainly give lower GHG emissions than the most polluting variants of alternative fuels, but the advantage compared to the least polluting variation of alternative fuels is less pronounced. Let us take bio-methanol, with a footprint of 30-290 g CO2-eq./kWh, as an example: Today, almost all methanol is produced from unabated fossil sources (natural gas and coal) with very high emissions (up to abt. 290 g CO2-eq./kWh). Compared to this, nuclear (5-45 g CO2-eq./kWh) will emit 40-80% less. But when we compare nuclear with the most advantageous biomethanol with a footprint of abt. 30 g CO2-eq./kWh, nuclear will emit from 80% less to 40% more.

Compared to the best hydrogen and ammonia available, produced by electrolysis with low carbon electricity and an emission factor of 90 and 135 g CO2-eq./kWh respectively, nuclear power can reduce the GHG emission factor by 50-95%. Note that this variant of hydrogen and ammonia is very scarcely available and that the fossil variants of hydrogen and ammonia cover >99% of current production.

Noting from Figure 31 that most fuels have emission factors stretching from 100 g CO2-eq./kWh to 300, 500 or 800 and even 1100 and 1300, we must conclude that in terms of GHG, nuclear energy can offer very significant GHG emissions reductions in the order of 80% to near 100%.

While nuclear energy can offer very significant reductions in GHG emissions, there are other environmental, health, security and societal issues that must be addressed and resolved for nuclear energy to become an environmentally and socially acceptable energy source, on land and at sea.

WP 3.4) Health impact of other emissions (NOx, SOx, PM)

Emissions from engines can be divided into two categories:

Local emissions - health & environment related

- Contributes to deterioration of human health, loss of wellbeing
- Mainly NOx, SOx and particulates
- Also impact the natural environment (flora & fauna) on short term
- Impact depends very much on location of emission. Focus on densely populated areas and sensitive ecosystems

GHG emissions - climate related

- Contributes to global warming / climate change
- Mainly CO2 and CH4 (methane)
- Low to no impact on human health or the natural environment on short term
- Impact is not dependent on location of emission, as climate change is a global problem

Health Impact of Emissions - NOx, SOx, PM

NOx (Nitrogen Oxides), SOx (Sulfur Oxides), and PM (Particulate Matter) are significant pollutants emitted through various energy production processes and transportation activities. These emissions can have profound adverse effects on human health.

Nitrogen Oxides (NOx)

NOx emissions primarily result from combustion processes such as those occurring in power plants, vehicles, and industrial facilities. These gases contribute to the formation of ground-level ozone and particulate matter, both of which are harmful to respiratory health. Exposure to NOx can lead to an increase in respiratory infections, asthma, and reduced lung function. Long-term exposure may also contribute to cardiovascular diseases.

Sulphur Oxides (SOx)

SOx emissions mainly stem from the burning of fossil fuels, particularly coal and oil. Sulfur dioxide (SO2) can react in the atmosphere to form fine particulate matter, which poses health risks when inhaled. Short-term exposure to high levels of SO2 may result in throat and eye irritation, coughing, and shortness of breath. Long-term exposure can aggravate existing lung conditions, such as asthma and bronchitis, and has been associated with increased hospital admissions for respiratory and cardiovascular diseases.

Particulate Matter (PM)

Particulate matter consists of tiny particles that can be inhaled into the lungs. PM is categorized by its size, with PM2.5 and PM10 being the most concerning for health impacts. Sources of PM include vehicle emissions, industrial processes, and the burning of fossil fuels. Health impacts from PM exposure include respiratory and cardiovascular issues, such as heart attacks, aggravated asthma, and decreased lung function. Chronic exposure may lead to more severe conditions, including lung cancer and premature death.

The mitigation of emissions from these pollutants is crucial for protecting public health and improving air quality. Strategies such as adopting cleaner energy technologies, enhancing emission controls, and implementing stricter regulations can significantly reduce the adverse health impacts associated with NOx, SOx, and PM emissions.

WP 3.5) Fuel types and energy density in relation to cargo capacity

A good understanding of comparative pricing, vessel performance, and procurement of marine fuels is necessary to efficiently plan for decarbonisation efforts.

It is essential to examine the specific capabilities and requirements of low emissions fuels, including their energy density's impact on newbuild and retrofit investment decisions. This examination should also consider the implications for the size and cost of fuel storage systems, available cargo and passenger space, vessel design, deadweight tonnage, and fuel purchasing for operators and owners.

Fuel energy density, both volumetric and gravimetric, is often ignored due to outdated comparison methods. Comparing fuels solely by volume or weight overlooks true energy value. With new fuels entering the market, evaluating performance and price by metric tonnes needs context, as energy density varies by fuel type and properties.

Considering volumetric energy density is crucial in vessel investment decisions to maximize cargo space. As hydrogen-based fuels like synthetic LNG, green methanol, and ammonia become available from renewable sources, they will impact vessel design, deadweight tonnage, cargo capacity, and passenger accommodation due to their lower energy density. Storage system size and cost are influenced by insulation, containment pressure, and safety requirements, potentially reducing cargo capacity and requiring careful planning for design implications.

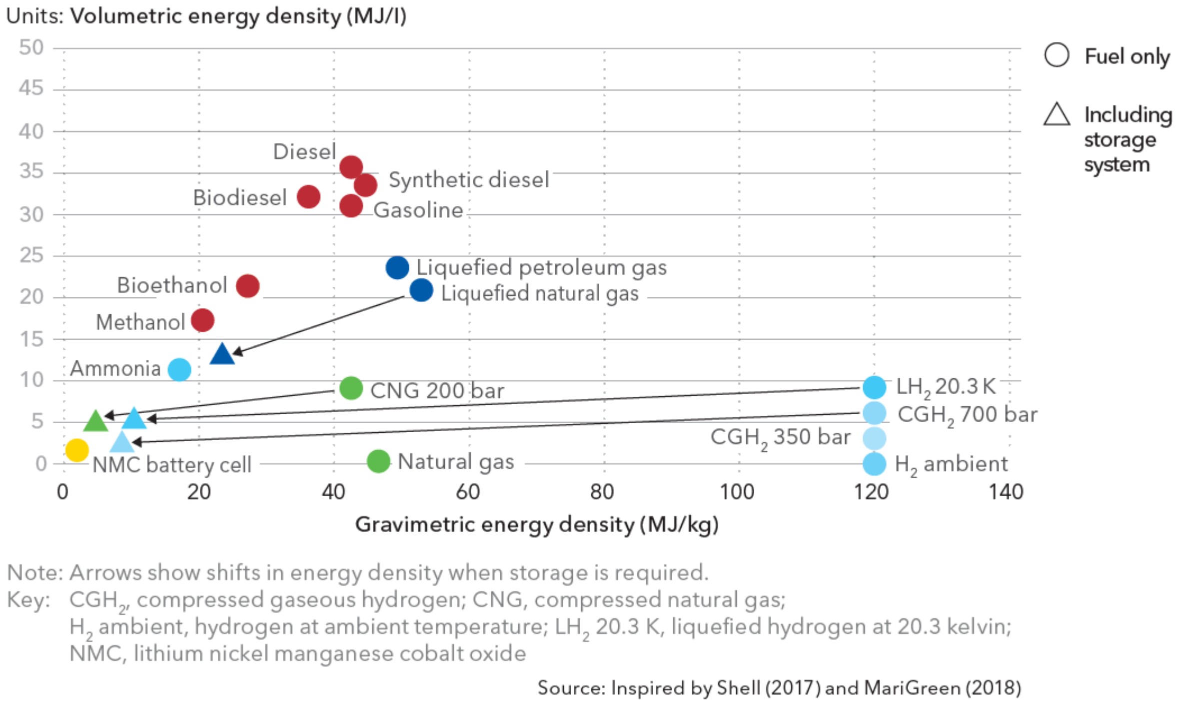


Figure 32 Fuel energy density (DNV, 2019)

Gravimetric energy density measures the energy content of a fuel relative to its mass. This is crucial for comparing energy costs of fuels. When purchasing fuel, you are essentially buying energy to power the ship and its operations, so knowing the energy content is vital for bunker transactions.

It is essential for the industry to comprehend the various physical properties of both current and future marine fuels to make informed investment and fuel procurement decisions. Errors in this process can be costly. Establishing a standardised methodology is necessary so that the industry can make fuel comparisons based on a consistent baseline. A thorough understanding of fuel performance is crucial, as it will allow operators to make informed decisions regarding pricing, value, and their low-carbon fuel procurement opportunities.

Work Process 4, Class and regulatory

In this chapter the pilot partners have investigated the international maritime framework, the role of class and the role international and national nuclear regulations (sections WP 4.1-4.7), as well as providing a list of important aspects of nuclear shipping (WP 4.8) and finding that today, nuclear shipping is explicitly excluded from the largest commercial shipping insuring organization (WP 4.9).

Nuclear shipping

The feasibility of nuclear-powered shipping and private ship-owner decisions are shaped by the contextual environment where political and regulatory factors influence the "rules of the game". There are safety and security standards impacting the design phase, and regulations on design and structural requirements and nuclear fuel choice. In the operational phase there are several requirements, for example on security personnel, on specialized facilities such as nuclear reactor maintenance and nuclear refuelling yards. Additionally, governments are settings restrictions on operation, e.g. no-go / nuclear-free zones or other NIMSY restrictions[18].

Civil nuclear activities undertaken within the jurisdiction of States are, like any other activities, subject to the general principles and customary rules of international law, in addition to conventional obligations to which States may subscribe. Accordingly, States are expected to adopt regulations and measures relevant to nuclear shipping, as may be necessary to fulfil their international obligations.

There are two distinct systems that needs to be considered, the maritime and the nuclear – international and national – regimes. The detailed regulations are not yet fully developed, given the broad variety of nuclear technologies that may be applied for SBNPP (sea-based nuclear power plant), from conventional water-water technology[19] with high pressure and high temperature circuits, to unproven molten salt technology in a low-pressure system.

Nuclear shipping regulations will, as with other aspects of nuclear shipping, vary with the phase of the activity, see Table 10. The regulations, moreover, need not only to cover traditional shipping requirements, but also any national atomic legislation and regulations, and international conventions as well as occupational health practices. In effect, the regulatory side of nuclear shipping is likely to go beyond that to which the shipping industry is accustomed.

Table 10 An overview of the regulatory basis during different phases of the ship.

	GOVERNMENT	FLAG/IMO	CLASS	PORT AUTHORITY	LEGAL ENTITY

[18] NIMBY is an acronym for not in my back yard, a term used to describe opposition from communities and/ or residents to proposed development close to them. The term NIMSY as an acronym for not in my shipyard is merely an attempt to apply the NIMBY term to the shipping sector.

[19] Water as coolant within the reactor vessel, and also water driving the turbine for power generation. A standard PWR reactor has water within the reactor, and heat is extracted from that circuit in a heat exchanger/steam generator, where another circuit of water is used to generate steam to drive the turbine.

	National nuclear	International nuclear	SOLAS		ISPS	Rules, regulations
Design & Construction	x	x	x	x		
Operation		x	x	x	x	
Decommission	x	x				
Disposal	x	x				

This is not only true for the operational phase, in which SOLAS Chapter VIII requires a safety assessment that is much more comprehensive than that required in other shipping-related matters. Just as important are the national and international nuclear- and radiation-related regulations that apply during building of the reactor, the storage and handling of the reactor at the yard, and during decommissioning of the ship and handling of radioactive waste.

WP 4.1) International maritime framework

Regarding licensing of ships, the International Maritime Organization, made up of representatives from the various flag administrations, administers the relevant conventions (UN Convention on the Law of the Sea (UNCLOS), the IMO Safety of Life at Sea (SOLAS) Convention and the IMO Convention on the Liability of Operators of Nuclear-Powered Ships and the Nuclear Ship Safety Code).

Flag Authority requirements

The Flag Authority requirements are stated in SOLAS Chapter VIII ”Nuclear Ships”. The concise, clear requirements stated therein (3 pages only) are, in fact, quite comprehensive. The following requirements apply: a Flag Authority shall issue a ”Nuclear Passenger Ship Safety Certificate” or ”Nuclear Cargo Ship Safety Certificate” respectively. The certificate shall always be updated, and in no case older than 12 months. As a basis for the certificate, an approved Operating Manual and an approved Safety Assessment shall be in place.

The operating manual shall be fully detailed to ”serve as information and guidance for the operating personnel in their duties on all safety related matters related to the operation of the nuclear power plant”. The safety assessment shall be prepared ”to permit evaluation of the nuclear power plant and safety of the ship to ensure that there are no unreasonable radiation or other hazards, at sea or in port, to the crew, passengers or public, or to the waterways or food or water resources”. The operating manual and safety assessment shall always be kept updated and be available onboard.

It shall also serve as basis for information to “Contracting Governments of the countries which the nuclear ship intends to visit, so that they may evaluate the safety of the ship”. Thus, the safety assessment shall also provide the information needed for Port authorities to decide whether they can accept the ship calling their port.

The expected level of the safety assessment is further detailed in Annex A491 (written in 1984), a document of more than one hundred pages, expressing expectations and recommendations for the amount, detailing level, content, and analyses to be covered in the safety assessment. It defines a safety assessment level comparable to that required for nuclear power plants but adapted to shipborne conditions. Basically, all risks to which a ship may be subjected shall be analysed in light of the fact that there is a nuclear reactor onboard. Some examples of topics that need to be covered are:

- *Protection against damage due to collision and grounding*. The reactor area must be equipped with extra structural strength, to protect the reactor from damage / release of radiation in the case of collision and grounding.
- *Preparation for rescue after sinking.* The possibility of retrieving a reactor from a wreck if the ship is sunk shall be considered and, if feasible, included in the design.
- *Alarms and control system.* The reactor installation and all related systems shall be equipped with alarm and control systems compliant with maritime regulations. All interaction effects between this control system and the remaining power systems / control systems of the ship shall be analysed, and it shall be demonstrated that all reasonable risk mitigating actions are installed, and that no unacceptable risks are present.
- *Additional means of propulsion and power supply.* Events that require emergency shutdown of the reactor shall be anticipated, and it is not acceptable that such a situation leads to the loss of any of the ship's main functions. That means it must be possible to operate the ship in an acceptable and safe manner even in the case of reactor shutdown.
- *Sabotage.* Annex A491 clearly states that sabotage is a risk factor that shall be considered. In modern terms, this means that all related risks, i.e. terrorism, piracy etc. shall be included in the assessment.
- *Information to Port Authorities.* It is required in SOLAS Chapter VIII that the safety assessment is made available "sufficiently in advance to the Contracting Governments of the countries which the nuclear ship intends to visit".

Accident /event reporting. SOLAS Chapter VIII requires that any accident or event having a potential impact on safety, shall immediately be reported to the Flag Authority and port Contracting Government.

Thus, the SOLAS requirements comprise consideration of relevant parts of other national and international regulations and provide a large part of the technical basis for other approvals, including class and port state approvals.

Flag States are the only parties required to issue a dedicated "nuclear safety certificate" for a ship. This certificate is the key element for the legislative approval of the nuclear ship, as it (along with its underlying documents) will form the basis for class approval and Port State approval. The choice of Flag State, therefore, is a crucial decision in a project for building a nuclear-powered ship. Choice of Flag State should be based on technical as well as political considerations. The chosen Flag State must be

- Willing to issue a nuclear ship safety certificate as per SOLAS Chapter VIII
- Competent to perform, or at least manage and audit, the safety assessment.
- Fully recognised by all major class societies
- Recognised as a serious and trustworthy statutory authority by all relevant Port States

Obviously, this set of requirements limits the number of eligible Flag States. The need for domestic expertise, both of a technical as well as a legislative character, could point in the direction of significant domestic nuclear activities as an informal prerequisite for becoming a credible Flag State for nuclear shipping. As of today, some forty-four states may qualify in a formal sense[20]. In practise, the number is likely to be lower.

[20] These are the states with "nuclear capabilities" and that are required to sign and ratify the Comprehensive Test Ban Treaty in order for the Treaty to come into force: Algeria, Argentina, Australia, Austria, Bangladesh, Belgium, Brazil, Bulgaria, Canada, Chile, China, Colombia, Democratic People's Republic of Korea, Egypt, Finland, France, Germany, Hungary, India, Indonesia, Iran (Islamic Republic of), Israel, Italy, Japan, Mexico, Netherlands, Norway, Pakistan, Peru, Poland, Romania, Republic of Korea, Russian Federation, Slovakia, South Africa, Spain, Sweden, Switzerland, Turkey, Ukraine, United Kingdom of Great Britain and Northern Ireland, United States of America, Vietnam, Zaire.

Code of nuclear safety for merchant ships

The SOLAS convention contains provisions for civil nuclear shipping (Chapter VIII), which include basic requirements for nuclear-powered ships and deal with radiation hazards, through the detailed and comprehensive Code of Safety for Nuclear Merchant Ships adopted in 1981. This international framework can serve as a starting point for the consideration of basic requirements for the construction and operation of nuclear ships. The requirements of the flag states are laid down in Chapter VIII of the SOLAS Convention: the issue of a "Nuclear Passenger Ship Safety Certificate" or a "Nuclear Cargo Ship Safety Certificate". An approved operating manual and an approved safety assessment must therefore be in place.

Although the safety code has rarely been applied, the documents mentioned above - an approved operating manual and an approved safety assessment – are similar in principle to those required by the basis for a license application required by the nuclear regulatory body for land-based facilities. As with onshore reactors, the license serves as a basis of information for all countries that the nuclear ship intends to call at so that they can assess the safety of the ship. The license covers the relevant elements of the maritime nuclear fuel cycle as described above for the fuel – including qualification and production, storage, handling and after-use – the reactor(s) and the ship.

WP 4.2) Class Societies

The classification societies/recognized organizations (class rules/flag administration rules) play an important role, originating in the conventions. When a classification society is assigned tasks by the administration of the flag state, which is ultimately responsible for certifying the safety of the ships it registers, it is referred to as a recognized organisation (RO). Due to the international nature of shipping and the historical context in which it is necessary to systematically address the issue of safety, classification societies fulfil the role of an independent third-party organisation in relation to, among other things, hull and stability, mechanical and electrical systems and fire safety both towards the yard, in the design and construction of the ship.

Currently there are no DNV rules for nuclear powered ships. Thus, class approval of such ships would have to use the approach for qualification of novel technologies, as is stated in, for example, RP A203, "Qualification Procedures for New Technology".

The procedure prescribes a risk-based approach, which will generally include the following steps:

- A hazard/threat Identification exercise, defining all the potential hazards and threats that need to be considered for the installation. Usually, this is done in a workshop comprising personnel with different types of experiences with nuclear installation, for example: designers, operators, maintenance staff, safety officers, and class officers. In a "brainstorming" session, the workshop participants list all those risk elements that they can identify and subsequently rank them according to the extent of further consideration required.
- Next, risk control options (RCO) are identified. An RCO is a means or routine that can be established to control a risk element. Examples are redundancy/duplication of critical equipment, monitoring/alarm devices, or structural design measures to reduce or eliminate the risk. Another "brainstorming" exercise mapping all possible RCOs is followed by a phase in which the best RCOs are selected. The final step is usually a failure mode and effect analysis (FMEA), in which the different failure modes are considered, their effects (given the available RCOs) are studied, and it

is demonstrated that no ”reasonable” likelihood exists that a failure has unacceptable consequences.

Together, these measures are relatively similar to the requirements for the ”safety assessment” demanded by SOLAS. However, although the principles and approach to the analyses are generally the same, some differences should be noted.

The SOLAS safety assessment requires that all risks to crew, passengers, public, waterways, food, and water sources are considered, whilst DNV rules consider risks to crew, passengers, and ship. DNV rules additionally consider availability of the ship’s main functions, of which propulsion, steering, and power generation are the most relevant regarding the nuclear installation. The requirement is that a single failure (defined as a single failure event along with its immediate consequent damages) must not make any of the main functions unavailable. In general, FMEA is a feasible tool to demonstrate compliance to this requirement for new technologies.

WP 4.3) National nuclear and radiation safety regulations

The national regulations around nuclear installations and radiation safety will apply for civilian merchant ships. The nuclear domain gradually grew after the second world war, with first only military, later also with civilian facilities. As the activities associated with these facilities have been considered to represent significant societal risk, the societal control – the regulation – has been anchored in regulatory agencies with regional or – most commonly – national responsibilities.

A licencing authority normally commissions a technical support organisation (TSO) to carry out the detailed technical analysis required to ensure safe design, operation and all related activities. There are certain aspects of nuclear activities that is truly multi-national and multinational harmonised, for example safeguards, e.g. the oversight of nuclear material, however, on the other hand, fundamental and complex issues like nuclear security and safety are assessed, decided upon and enforced on a national basis.

Nuclear and radiation protection requirements

Nuclear-specific regulations aim at ensuring the protection of man and the environment against radiation. While being based on the same international standards and recommendations, no uniform set of domestic nuclear regulations exist.

The elements of the Norwegian regulatory basis may be as indicative as any and is therefore presented in the following as an example. Norwegian nuclear legislation that might be applicable (not exhaustive) to nuclear shipping entails:

- Regulations on environmental impact assessment (1 April 2005 No. 27)
- Act concerning nuclear energy activities (12 May 1972)
- Regulations on the Physical Protection of Nuclear Material (2 November 198
- Regulations on Possession, Transfer and Transportation of Nuclear Material and Dual-use Equipment (12 May 2000)
- Act relating to the generation, conversion, transmission, trading, distribution and use of energy etc. (Energy Act)
- Act on Radiation Protection and use of Radiation (Radiation Protection Act) (12 May 2000 No. 36)
- Regulations on Radiation Protection and use of Radiation (Radiation Protection Regulations) (21 November 2003 No. 1362)

- Act relating to protection against pollution and relating to waste [The Pollution Control Act] (13 March 1981 No. 6) with regulations.
- Act relating to working environment, working hours and employment protection, etc. (Working Environment Act) (17 June 2005 No. 62)
- Regulation relating to work with ionising radiation (14 June 19XX)
- Regulations relating to systematic health, environmental and safety activities in enterprises [Internal control regulations] (6 December 1996 No. 1127)

Export and import controls

Export and import of nuclear materials are regulated by national regulation and arrangements. Laws and decisions on export applications are normally rooted in international guidelines and recommendations like those of the Nuclear Suppliers Group. The NSG is a group of nuclear supplier countries which seeks to contribute to the non-proliferation of nuclear weapons through the implementation of Guidelines for nuclear exports and nuclear-related exports. The NSG Guidelines are implemented by each Participating Government in accordance with its national laws and practices. The NSG Guidelines aim to ensure that nuclear trade for peaceful purposes does not contribute to the proliferation of nuclear weapons or other nuclear explosive devices but does not hinder international trade and cooperation in the nuclear field. The NSG Guidelines facilitate the development of trade in this area by providing the means whereby obligations to facilitate peaceful nuclear cooperation can be implemented in a manner consistent with international nuclear non-proliferation norms.

The first set of NSG Guidelines governs the export of items that are specially designed or prepared for nuclear use (IAEA, 2006):

- nuclear material.
- nuclear reactors and equipment.
- non-nuclear material for reactors.
- plants and equipment for the reprocessing, enrichment, and conversion of nuclear material and
- for fuel fabrication and heavy water production; and
- technologies associated with each of the above items.

The second set of NSG Guidelines governs the export of nuclear related dual-use items and technologies; that is, items that can make a major contribution to an unsafeguarded nuclear fuel cycle or nuclear explosive activity, but which have non-nuclear uses as well, for example in industry (ICRP, 2007).

WP 4.4) International nuclear framework

As the number of countries involved with nuclear activities grew, the international framework – collecting the national responsibilities together in conventions – evolved to a large system covering nuclear safety, nuclear security, waste management and spent fuel handling and insurance; in some cases specifically limited to land-based facilities, though in most cases covering all types of activities. This international framework, established through the International Atomic Energy Agency (IAEA), a UN organization, describe principles, roles and responsibilities, while the detailed assessments with respect to for example safety rests with the national legislation. This legislation also set up the licensing process.

To ensure peaceful utilisation of nuclear energy, States conclude agreements on international safeguards with the International Atomic Energy Agency: The IAEA is the world's nuclear inspectorate, with more than four decades of verification experience. Inspectors work to verify that safeguarded nuclear material and activities are not used for military purposes. The IAEA inspects nuclear and related facilities under Safeguard agreements with more than 140 States. Most agreements are with States that have internationally committed themselves to refraining from possession of nuclear weapons. They are concluded pursuant to the global Treaty on the Non-Proliferation of Nuclear Weapons (NPT), for which the IAEA is the verification authority, and include:

- The Agreement between State and the Agency for the Application of Safeguards in connection with the Treaty on the Non-Proliferation of Nuclear Weapons (1 March 1972), and
- Protocol additional to the Agreement between the State and the International Atomic Energy Agency for the Application of Safeguards in connection with the Treaty on the Non-Proliferation of Nuclear Weapons (29 September 1999).

The main features of the Protocol are that it:

- extends the reporting required of States beyond nuclear materials accountancy to areas such as nuclear fuel cycle-related R&D, specified manufacturing activities (e.g. centrifuge or heavy water production), and exports and imports of non-nuclear material and equipment (essentially as specified in the Trigger List of the Nuclear Suppliers Group).
- provides for extended access by the IAEA to check this reporting (but not with the same degree of accounting rigour as employed in respect to nuclear material).

Such extended information and access, allied to systematic collection and analysis of a wide range of relevant information from other sources (e.g. from publications both academic and popular media) provides the IAEA with a much more comprehensive picture of a State’s nuclear activities, and means that the IAEA is better placed than previously to spot and pursue indicators of possible undeclared activities.

One exemption to the safeguard's agreement may be of particular interest to the international shipping community. Paragraph 14 reads that nuclear material, for instance in the form of naval fuel, may be defined as material to be used in “non-peaceful activities” other than nuclear explosives. Accordingly, the state may freely use the material for military naval propulsion.

Other international nuclear-related conventions

A range of conventions in the areas of Nuclear, Radiation, Transport and Waste Safety are also applicable to nuclear shipping. These include:

- *Convention on Nuclear Safety* - commits participating States operating land-based nuclear power plants to maintaining a high level of safety by setting international benchmarks to which States subscribe.
- *Convention on Early Notification of a Nuclear Accident or Radiological Emergency* - establishes a notification system for nuclear accidents that have the potential for international transboundary release that could be of radiological safety significance for another State.
- *Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency* - sets out an international framework for co-operation among Parties and with the IAEA to facilitate prompt assistance and support in the event of nuclear accidents or radiological emergencies.
- *Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management* - is the first legally binding international treaty on safety in these areas. It represents a commitment by participating States to achieve and maintain consistently high levels

of safety in the management of spent fuel and of radioactive waste as part of the global safety regime for ensuring the proper protection of people and the environment.

- *Convention on the Physical Protection of Nuclear Material* - obliges Contracting States to ensure the protection of nuclear material within their territory or on board their ships or aircraft during international nuclear transport.
- *Convention Relating to Civil Liability in the Field of Maritime Carriage of Nuclear Materials* (Depositary: International Maritime Organization, London)
- *Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter* (London Dumping Convention)
- *International Convention for the Safety of Life at Sea* (Depositary: International Maritime Organization, London)
- *Convention on Environmental Impact Assessment in a Transboundary Context OSPAR Convention for the Protection of the Marine Environment of the North-East Atlantic*
- *Hong Kong Convention for recycling of Ships*

WP 4.6) Port Authority requirements

The International Ship and Port Facility Security Code (ISPS Code) was adopted by a Conference of Contracting Governments to the International Convention for the Safety of Life at Sea, 1974, convened in London from 9 to 13 December 2002. The Code aims, among other things, to establish an international framework for co-operation between Contracting Governments, Government agencies, local administrations and the shipping and port industries to detect security threats and take preventive measures against security incidents affecting ships or port facilities used in international trade. It also aims at the establishment of relevant roles and responsibilities at the national and international level. These objectives are to be achieved by the designation of appropriate personnel on each ship, in each port facility, and in each ship-owning company to be responsible for assessments and to put into effect the security plans that will be approved for each ship and port facility. The Code is divided into two parts. Part A presents mandatory requirements, and part B provides recommendatory guidance regarding the provisions of chapter XI-2 of the Convention and part A of the Code.

Ownership of Norwegian ports lies mainly with the municipalities, with some elements of private ownership. Private ports operate independently and can decide which activity they want to serve, but there are still laws and regulations that apply in the same way as for public ports.

When it comes to nuclear-powered ships, there are two sections in the *Act relating to ports and navigable waters*[21,22] which are particularly relevant. The first is section 27, which deals with the port's duty to receive vessels: "Owners and operators of ports and port terminals are obliged to receive vessels. […] The obligation does not apply if receiving the vessel may entail a risk to the environment or to safety." In other words, the port has an obligation to receive vessels but has the option of rejecting a vessel if the port has grounds to say that there is a risk to public safety or the environment.

A preliminary draft of a treaty between Germany and Norway was drafted in August 1969 regarding the use of Norwegian territorial waters and ports by Otto Hahn, with 20 articles regulating the various aspects of port access, referring to SOLAS Chapter VIII. The operator should submit the safety assessment as regulated by Regulation 7 of Chapter VIII in SOLAS. Besides sorting out the roles and responsibilities in various stages of the visit, a large part of the draft agreement was designated to insurance and indemnification, limiting the responsibility to "Deutsche Mark 400 Million". The agreement also should undergo ratification, as a treaty. The Norwegian government should be the party to make arrangements with the appropriate local authorities for entrance of the ship into Norwegian ports and the use thereof,

[21]Norwegian: https://lovdata.no/dokument/NL/lov/2019-06-21-70

[22] English: https://www.kystverket.no/en/regulations/

also the one responsible for fire and police protection, crowd control and the general preparation of the harbour area with respect to acceptance of the ship.

It is conceivable that an owner/operator who does not want nuclear-powered vessels in his area may attempt to reject such vessels on the basis of this section. On the other hand, the shipowner can use the port's duty to receive as an argument for being allowed to come to port. In any case, it will be the duty to receive that weighs heaviest, as seen stated by the Ministry of Transport in their letter to the Ministry of Defence in 2020. Here questions had been raised as to whether there was an obligation for the Port of Tromsø to receive reactor-powered submarines from allies[23]: “The fact that a vessel is a reactor-powered underwater vehicle is not in itself a reason to reject the vessel for the sake of "the environment or for safety" in the port.” The assumption is that if the vessel complies with the relevant requirements, there will also be no basis for rejecting the vessel for the sake of the environment or the safety of the port.

IN SHORT

The visits usually take place to established ports of call, either in open waters or to a port.
There has been a significant increase in the number of visits from nuclear-powered naval vessels to Norway in recent years. From 10–15 visits per year a few years ago, to 30–40 visits per year today. The most common visits are from nuclear-powered submarines, but the regulations also cover surface vessels such as nuclear-powered aircraft carriers.

Figure 33 Frequent nuclear-powered visits to Norway, From Norwegian radiation and nuclear safety agency (DSA) website.

Note the following regarding private ports from the section 27 of the *Act relating to ports and navigable waters*: "The obligation to receive vessels pursuant to the first paragraph does not apply to private ports that do not offer calls and services to anyone other than the owners of the port."

The other particularly relevant part of the act is section 30, which deals with the security of ports and port facilities: "Owners and operators of ports and port facilities shall take the measures necessary to prevent terrorist acts and other illegal acts directed against the port, port facilities or vessels in the port." In other words, the owner and operator must take the measures necessary to ensure that any vessel, including nuclear-powered vessels, is safe while in port.

The International Ship and Port Facility Security (ISPS) code is the regulation which covers security of ships and port facilities in relation to international traffic. The purpose of the security measures is to prevent and obstruct security-related incidents that may damage the ports, the port facilities or the ships that call in to such ports. The ISPS Code does not differentiate between vessels based on types of energy carrier or propulsion technology. Thus, there are no direct barriers for nuclear-powered vessels in the ISPS Code.

Any relevant risks related to a port call by any vessel, regardless of energy carrier, shall be included in the port’s risk assessment. The assessment will identify risks, risk reducing barriers and mitigating actions. The

[23]https://www.regjeringen.no/contentassets/3a91ecea46694050bec90edea665ebe1/havne-og-farvannsloven-27-om-mottaksplikt-tromso-havn-l1969368.pdf

current practice is that the risk related to nuclear vessel port calls is assumed to be higher, e.g., this is the assessment done in relation to port calls to Tromsø by naval reactor-powered submarines.

It is the Norwegian Coastal Administration who is responsible for ensuring that the regulations for maritime security (incl. ISPS) are implemented at Norwegian ports and port facilities. The ISPS code also have a section regarding the vessel itself, which the vessel is responsible for fulfilling and which the Norwegian Maritime Authority enforces.

With regards to security in relation to ports, port facilities, and port calls, there are no direct barriers against nuclear-powered vessels. But the functional requirements need to be fulfilled, as for any other vessel and port call.

WP 4.7) Regulation during nuclear shipping phases

Nuclear shipping regulations will, as for other aspects of nuclear shipping, vary with the phase of the activity. The regulations, moreover, need not only to cover traditional shipping requirements, but also any national atomic legislation and regulations, and international conventions as well as occupational health practices. In effect, the regulatory side of nuclear shipping is likely to go beyond that to which the shipping industry is accustomed.

This is not only true for the operational phase, in which SOLAS Chapter VIII requires a safety assessment that is much more comprehensive than that required in other shipping-related matters. Just as important are the national and international nuclear- and radiation-related regulations that apply during building of the reactor, the storage and handling of the reactor at the yard, and during decommissioning of the ship and handling of radioactive waste.

Design and construction.

During building of the reactor, the regulations for nuclear safety and security in the respective country apply. Regarding transportation to the yard, national (and possibly international) regulations for export of nuclear material, along with similar import regulations of the country of the yard, must be observed.

And for the yard, the national regulations in the country of the yard apply. These regulations may vary from country to country, and must be carefully analysed prior to starting the building of a nuclear-powered ship, as some of them may represent ”show stoppers” for such a project. Some national (Norway, taken as an example) and international regulations that must be observed in this respect are described in Section 5.3.1.

Operation

During operation, a nuclear-powered ship, like all other ships in international trade, requires certificates from a Flag State and from a Class Society. The two certificates are mutually dependent on each other. A Flag State certificate refers to SOLAS, and SOLAS states that it is assumed that the rules from one of the international class societies are complied with as a starting point. Similarly, DNV rules state that class certificates can only be issued to ships that have been certified by a Flag Authority. This formal ”chicken and egg” problem is handled routinely in all ship deliveries. However, for approval of a nuclear-powered ship, special procedures must be adopted by both parties in the first cases, and there must be awareness of this potential problem.

Decommissioning and disposal

During refuelling of the reactor, as well as during the final scrapping phase of the ship, the same national regulations of the country of the refuelling yard/scrapping yard apply as for the building yard during the building phase. That is, the reactor compartment and the spent fuel will have to meet domestic requirements and relevant nuclear regulations.

WP 4.8) Highlights, political, societal, and regulatory aspects

- Visibility: the ship is likely to be the subject of particular attention, especially during operation and decommissioning
- Perceptions: to many, nuclear reactors are inescapably linked to Chernobyl and Fukushima (accidents) or Hiroshima (bombs). As humans have no ability to sense radiation[24], sentiments may run strong with "knee jerk" reactions (opposition).
- Discourse: opponents of nuclear shipping will find that expressing their views must commence with the general debate on nuclear power. Existing platforms and structures for public interference may magnify opposing voices.
- Infrastructure: a nuclear infrastructure for fuel production, refuelling, dismantlement, decommissioning, and disposal is essential. Without this, the operator may be subject to supply dependency.
- Engine builder (reactor builder)'s national requirements for nuclear- and radiation-related issues must be observed, including SHE issues, export restrictions, proliferation, and protection of the nuclear device.
- Yards national requirements to nuclear- and radiation-related issues must be observed, including SHE issues, export restrictions, proliferation, and protection of the nuclear device during storage and handing at yard.
- Strong political and technical commitment for Flag State Authorities in connection with statutory approval. The required rigorous safety assessment can, along with time consuming national political clarifications, lead to a long and expensive process before a statutory certificate can be issued.
- Many stakeholders will be "default negative" to the idea of nuclear-powered ships, due to the troubling history of nuclear power. Therefore, in a project promoting use of nuclear-powered ships, a limited number of stakeholders should be invited to join/follow the development project (e.g. port authorities, Flag authorities, class, charterers, owners). In the initial operating phase, only selected stakeholders should be involved. Safeguards: controls by the International Atomic Energy Agency required at least outside nuclear weapon-states
- Errors made in connection with daily inspection / maintenance work are potentially more harmful for nuclear powered ships. Therefore, more comprehensive routines / instructions are called for. SOLAS Chapter VIII requires that these routines are specially approved by the Flag Authority. Therefore, condition monitoring should be used in lieu of conventional inspection wherever feasible. On the other hand, planned and estimated repair / exchange of nuclear reactor components is probably less than for conventional engine components.
- Nuclear powered ships, as all other ships trading internationally, need approval and certification from Flag Authority and Class. Flag Authority rules are stated in SOLAS Chapter VIII. Updated class rules do not exist. For DNV, this means that approval of a nuclear-powered ship must be based on the principles and routines for qualification of new technology. Flag and Class approval will therefore be an extra cost (estimated to 1-2 mill USD) for a nuclear-powered ship.

[24] Except, of course, visible light and radiative heat.

Flag and IMO regulations Nuclear

Below statistical data is collected from Norwegian Shipowners Association annual report 2023 and Paris MOU period 2023-2024:

Table 11 Norwegian Shipowners Association data on Norwegian owned vessels.

IMO White List 01/07/2023 - 30/06/2024		
		Number of Norwegian owned vessels under the Administration
1	Denmark	
2	Italy	
3	Greece	
4	Netherlands	19
5	Norway	873
6	Singapore	26
7	Finland	
8	Cyprus	41
9	Belgium	
10	UK	15
11	Bahamas	127
12	Turkey	
13	Sweden	10
14	Hong Kong	
15	Japan	
16	Cayman Island	
17	France	12
18	Marshall Island	98
19	Gibraltar	20
20	Malta	49
21	Luxenbourg	
22	Lithuenia	
23	Bermuda	
24	Ireland	
25	Liberia	26
26	Portugal	28
27	USA	11
28	China	
29	Russian federation	
30	Faroe island	
31	Antigua & Barbuda	14

32	Barbados	93
33	Isle of man	33
34	Germany	
35	Estonia	
36	Spain	11
37	Lativa	
38	Poland	
39	Thailand	
	Brazil	26 (Unlisted)

TOP 10 largest Flag states (2023)	
1	Panama
2	Liberia
3	Marshall Island
4	Hong Kong
5	Singapore
6	Malta
7	Bahamas
8	China
9	Greece
10	Japan

Largest Shipping Nations (2023)	
1	China
2	Greece
3	Japan
4	Norway
5	USA
6	Singapore
7	South Korea
8	Germany
9	UK
10	Denmark

When reviewing the numbers from Norwegian Shipowners Association published for 2023[25] combined with the SOLAS implementations and National Nuclear Information references published by the different Flag Administrations (see table below) we recognize that further progress is needed in both IMO and the Flag Administrations.

SOLAS Chapter VIII: Nuclear ships

[25] 2024 not yet published at time of writing

Only basic requirements were given, which were supplemented by various recommendations contained in an attachment to the Final Act of the 1974 SOLAS Conference. These recommendations have now been overtaken by the safety code for nuclear merchant ships and recommendations on the use of ports by nuclear merchant ships.

No further updates have been done in later ratifications of the SOLAS, however some of the Flag Administrations have taken steps setting new rules and standards for nuclear vessels and transport as indicated in the below table. SOLAS underwent amendments in 1988 and 1996 (SOLAS 88, SOLAS 96), although the amendments were not directly relevant for nuclear reactors on ships.

Table 12 Norwegian controlled fleet under national and foreign flag, as per Q1-2024.

Norwegian controlled fleet under foreign flag (01- 2024)					
		Number of Vessels	SOLAS 88 Ratified	SOLAS 96 Ratified	Nuclear information
1	Bahamas	127	YES	NO	None
2	Marshall Islands	98	YES	NO	Ref to IMO circular - RESOLUTION MSC.338(91) and SOLAS VIII RESOLUTION MSC.294(87) - IMDG code The Maritime act; ref to Nuclear Damage
3	Barbados	93	YES	NO	None
4	Malta	49	YES	NO	None
5	Kypros	41	YES	NO	Ref to IMO circular
6	Isle of Man	33	YES	YES	UK
7	Madeira	28	YES	NO	(Portugal)
8	Singapore	26	YES	NO	MPA documents found, 6. Resolution MSC.456(101), MSC.496(105) and MSC.497(105) adopted amendments to the certificate forms of the Passenger Ship Safety Certificate, the Cargo Ship Safety Equipment Certificate, the Cargo Ship Safety Radio Certificate, the Nuclear Passenger Ship Safety Certificate and the Nuclear Cargo Ship Safety Certificate, as well as changes to the associated records of equipment for passenger ship safety (Form P), cargo ship safety (Form E), cargo ship safety radio (Form R) and cargo ship safety (Form C).
9	Liberia	26	Yes	NO	
10	Brasil	26	YES	NO	(unlisted IMO white list)
11	Gibraltar	20	YES	NO	
12	Nederland	19	YES	NO	
13	UK	15	YES	YES	MGN 679 Nuclear Ships Guidance on the application of the Merchant Shipping (Nuclear Ships) Regulations 2022 (SI 2022/1169), which regulate UK commercial nuclear-powered ships and foreign commercial nuclear-powered ships visiting UK waters. MGN 679 -Annex 1 - Offences under the Merchant Shipping (Nuclear Ships) Regulations 2022 MGN 679 (M) Nuclear Ships
14	Antigua & Barbuda	14	YES	NO	
15	FIS (Frankrike	12	YES	NO	
16	Spania	11	YES	NO	
17	USA	11	YES	NO	
18	Sverige	10	YES	YES	
19	Others (16)	53			

WP 4.9) Insurance

The nuclear and the maritime sector have similar, though different, systems for insurance, pooling the risk. While the Nordic nuclear installations for decades have had their own insurance pool, one important arrangement in the maritime area is the International Group of P&I Clubs.

Non-life insurance companies worldwide exclude nuclear risk from their insurance coverage due to the complexity, the potential for a large loss and the need for large insurance capacity. A pool is a group of insurance companies which collectively insure a specific risk. The pool solution is ideal for nuclear risks. Consequently, the pool concept has become a popular way of insuring nuclear risks around the world.

For governmental nuclear facilities, such as the Himdalen waste repository in Norway, the self-insurance principle applies, as for all enterprises that are legally part of the state. If the enterprise is organised as an administrative body, including an administrative undertaking or administrative body with special authorisations, self-insurance will apply in full. The same applies to the courts and the parliament and its bodies. The principle may also apply to an enterprise organised as a separate legal entity in a limited liability company, foundation, state-owned enterprise or under special legislation if the enterprise's income and expenses are allocated through the national budget. Budgetary coverage for damage or loss must therefore in principle be submitted to the parliament. For state-owned enterprises, the practice is for the companies to take out their own insurance in the market.

Nordic nuclear facilities

The Swedish and Finnish Atomic Insurance Pools were established in 1956 and 1957 respectively with the purpose to provide insurance for the Swedish and Finnish nuclear industry. The two pools merged in 2002 into Nordic Nuclear Insurers. In addition, NNI provides insurance capacity as reinsurer of nuclear installations around the world in association with foreign nuclear pools. The Norwegian nuclear facilities have been included under the NNI at the initiative of the insurance company *Gjensidige*, which handles the non-nuclear risk associated with the facilities owned and operated by IFE.

Maritime insurance system

The International Group of P&I Clubs is a not-for-profit association of 12 P&I Clubs providing marine liability cover for 90% of the world's ocean-going tonnage. Through the unique Group structure, the member Clubs, whilst individually competitive, share between them their large loss exposures, and also share their respective knowledge and expertise on matters relating to shipowners' liabilities and the insurance and reinsurance of such liabilities.[1]

Claims pooling and Reinsurance

The primary function of the Group is the co-ordination and operation of the Clubs' claims pooling arrangements. Liabilities which exceed the individual Club retention which is currently set at US$10 million are shared between all twelve Clubs in accordance with the terms of the Pooling Agreement. Much of the Group's day to day work involves defining and refining the scope of cover for pool claims, and the rules and guidelines under which claims are shared between the Clubs.

Group functions

The Group has three "core" functions, firstly the operation of the claims sharing ("pooling") arrangements and the collective reinsurance of these arrangements, secondly it operates as a forum for collecting and exchanging views between the Clubs and their shipowner members on matters relating to shipowners' liabilities, and insurance of such liabilities, and thirdly it provides a collective industry voice for the purposes of engaging with external stakeholders including intergovernmental maritime organisations, national governments, marine authorities around the world and the shipping and marine insurance/reinsurance industries.

Nuclear and IG

For any commercial nuclear ship, it would be essential for its operation to get access P&I insurance. Currently, "nuclear risks' liabilities, cost and expenses" are excluded under Skuld's Rule 30.4.2 (see text box below[26]) and which reflects the position in the Pooling Agreement which applies between the Clubs.

Nuclear Risks liabilities, costs and expenses

"Liabilities, costs and expenses directly or indirectly caused by or contributed to by or arising from

> a) Ionising radiations from or contamination by radioactivity from any nuclear fuel or from any nuclear waste or from the combustion of nuclear fuel,
>
> b) the radioactive, toxic, explosive or other hazardous or contaminating properties of any nuclear installation, reactor or other nuclear assembly or nuclear component thereof,
>
> c) any weapon or device employing nuclear fission and/or fusion or other like reaction or radioactive force or matter, or
>
> d) the radioactive, toxic, explosive or other hazardous or contaminating properties of any radioactive matter other than liabilities, losses, costs or expenses arising out of carriage of "excepted matter" (as defined in the Nuclear Installations Act 1965 of the United Kingdom or any regulations made thereunder) as cargo in an entered vessel."

This means that nuclear vessels will not be covered by P&I rules as it stands today.

Possible new arrangements

26 https://www.igpandi.org/

Transport of nuclear material is not regulated by maritime conventions but rather by nuclear liability conventions such as the IAEA Vienna Convention (1997)[27] and the OECD Paris Convention (2004)[28]. Additionally, the Vienna Convention expressly exclude from the definition of nuclear installation any reactor "with which a means of sea or air transport is equipped for use as a source of power, whether for propulsion thereof or for any other purpose"[29].

The 1962 Brussel Convention[30] (Convention on the liability of operators of Nuclear Ships) was intended to be applicable for nuclear powered merchant vessels. However, it was never ratified, and the main reason was the inclusion of warships which meant that both USA and USSR did not ratify the convention. The Scandinavian countries abstained from signing, as did Greece, whilst Panama and Liberia, two of the major modern flag states, signed the convention. Nuclear power countries at the time, such as UK and France, also abstained from signing. The convention never became a reality, but it may be seen as a good starting point for future international agreements.

The Brussel convention Article 1.7 defines "Nuclear damage" as "loss of life or personal injury and loss or damage to property which arises out of or results from the radioactive properties or a combination of radioactive properties with toxic, explosive or other hazardous properties of nuclear fuel or of radioactive products of waste; any other loss, damage of expense so arising or resulting shall be included only if and to the extent that the applicable national law so provides."

It is important to note that this definition of nuclear damage is from 1962 and accidents like Chernobyl (1986) and Fukushima (2011) were obviously not part of the considerations. Damage to the environment is not included in this definition and it is reasonable to believe that if any definition would be written today it would be included.

The Fukushima accident also triggered a ban on fishing operations in the local area and it lasted for a year[31]. For example, the EU did not lift the restrictions on food from the Fukushima area until 2023.[32] When drafting a potential new Convention, it will have to be considered how nuclear damage will affect relevant parties and the extent to which liability would vest in the shipowner.

Additionally, the ship "Ever Given" blocked the Suez Canal for several days in 2021 and questions arising on what would happen if a nuclear-powered vessel would have an accident and blocking trade in canals or other bottlenecks will also be relevant to discuss today. The effect that a casualty involving a nuclear-powered vessel will have, even if there is no immediate release of radiation, will add complexities and costs to the safe handling the incident.

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[27] Article 1 Vienna Convention 1997 definition: 1c. i) Nuclear fuel, excluding natural uranium and depleted uranium, capable of producing energy by a self-sustaining chain process of nuclear fission outside a reactor, either alone or in combination with some other material. ii) Radioactive products or waste, https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1279_web.pdf

[28] https://legalinstruments.oecd.org/public/doc/199/199.en.pdf

[29] Scope of application 1.2 Vienna Convention

[30] https://www.oecd-nea.org/jcms/pl_58579/convention-on-the-liability-of-operators-of-nuclear-ships-and-additional-protocol?details=true

[31] https://www.cnn.com/2023/04/19/asia/japan-fukushima-disaster-wastewater-fishing-concerns-hnk-dst-dg-intl/index.html

[32] https://ec.europa.eu/commission/presscorner/detail/en/ip_23_3781

P&I risks and nuclear

If we are to hypothetically assume that nuclear vessels would have access to P&I cover, then cover for nuclear risks would have an impact on almost all risks covered by P&I, such as people claims, pollution, wreck removal and cargo. This would likely be seen as an increase in risk and from an underwriting perspective and this would affect the premium. Any inclusion of nuclear risk would also have to be approved by the reinsurers as their exposure would increase, and such incidents could easily exceed the Pool retention of the Group cover.

Hull insurance (H&M)

A hull insurance normally covers the assured loss where the vessel is considered a total loss, is damaged or have incurred liability if the insured vessels is involved in a collision. In addition, the insurance will cover the assured's loss if costs are incurred to avert or minimize loss covered by the insurance.

Insurance cover is always subject to the loss being caused by an insured peril. Both an insurance against marine perils as well as an insurance against war perils will always exclude perils covered by the so-called RACE II Clause introduced by the reinsurance market after the terrorist attack 11. September 2001. The RACE II Clause reads:

INSTITUTE RADIOACTIVE CONTAMINATION, CHEMICAL, BIOLOGICAL, BIO-CHEMICAL AND ELECTROMAGNETIC WEAPONS EXCLUSION CLAUSE

This clause shall be paramount and shall override anything contained in this insurance inconsistent therewith

1. In no case shall this insurance cover loss damage liability or expense directly or indirectly caused by or contributed to by or arising from

   1.1 ionising radiations from or contamination by radioactivity from any nuclear fuel or from any nuclear waste or from the combustion of nuclear fuel

   1.2 the radioactive, toxic, explosive or other hazardous or contaminating properties of any nuclear installation, reactor or other nuclear assembly or nuclear component thereof

   1.3 any weapon or device employing atomic or nuclear fission and/or fusion or other like reaction or radioactive force or matter

   1.4 the radioactive, toxic, explosive or other hazardous or contaminating properties of any radioactive matter. The exclusion in this sub-clause does not extend to radioactive isotopes, other than nuclear fuel, when such isotopes are being prepared, carried, stored, or used for commercial, agricultural, medical, scientific or other similar peaceful purposes

   1.5 any chemical, biological, bio-chemical, or electromagnetic weapon.

10/11/03

CL370

In principle a commercial nuclear vessel might be insured under a H&M insurance. However, there will be a significant exclusion for loss, damage or liability caused by "nuclear fuel", cf. Cl. 370 no 1.1 and 1.4.

Reinsurance

The RACE II perils mentioned will always be excluded in all reinsurance contracts. Insuring this risk without back-to-back reinsurance will likely limit the monetary exposure for the individual insurer.

Practical challenges

For hull insurance, the same practical challenges mentioned above under P&I may arise from casualty adding complexities and costs to the handling of a casualty.

Way forward

Nuclear risks, and thereby also use of nuclear fuel, are excluded in marine insurance policies and for it to change, international agreements and conventions needs to be developed. In addition to such developments the insurance industry will independently have to consider whether such risks are something they are prepared to cover and mapping of the risks will be an important step in this process.

For the moment insurance is a showstopper for nuclear propulsion with current rules and regulations. A new debate and discussion around all aspects of nuclear in the maritime value chain are seen as an important step towards the industry maturing on the topic. Insights, like this report are producing, are welcome to increase awareness amongst insurance and reinsurance peers. We already see the nuclear topic become agenda points in IMO and other important regulatory forums .

Work Process 5, Financial aspects

This work package discusses various aspects of nuclear energy, particularly focusing on political risk, investment initiatives, technological advancements, and financial considerations. It highlights the evolving perception of nuclear power and its role in achieving net-zero emissions.

First, in this section we list factors impacting financing decisions and nuclear energy, then

There are several important aspects to finance and nuclear energy:

- **Political Risk in Nuclear Energy** - Investments in nuclear energy face significant political risks, which have contributed to delays and cost overruns. However, the perception of nuclear power is changing due to the current energy situation, improved public knowledge about the sustainability of nuclear energy, and the challenges of alternative renewable energy sources.
- **Factors Influencing Political Risk** - Political risk in nuclear energy is influenced by geopolitics, regulatory risks, and economic factors.
- **Revived Interest in Nuclear Energy** - There has been a renewed interest in nuclear energy, with initiatives like the Triple Nuclear Energy by 2050 aiming to triple global nuclear capacity by 2050 to achieve net-zero emissions.
- **EU JRC Science for Policy Report 2021** - The EU Joint Research Centre's 2021 report concluded that nuclear energy has minimal health impacts compared to other energy sources and highlighted the advancements in Gen III nuclear power plants.
- **Technological Developments in Nuclear Energy** - Generation IV reactors are being considered for use onboard ships, offering greater simplicity of design, reduced costs, and enhanced safety.
- **Key Events in 2024 for Nuclear Power** - 2024 marked significant developments in nuclear power, including the decision to restart Three Mile Island, heavy investments by the US, the passing of the ADVANCE Act, tech-companies deciding to invest in nuclear power, 14 global financial institutions recognising nuclear energy as important for the transition to a low-carbon economy, and the world's first nuclear power summit.
- **Cost of Advanced Nuclear Installation** - The cost of Small Modular Reactors (SMRs) can be evaluated using the Levelized Cost of Electricity (LCOE) metric. SMRs offer operational flexibility and potential cost reductions through modular and standardized production.
- **Financing Opportunities** - Investors can use tools like the Commercial Readiness Index for Renewable Energy Sectors to assess the commercial readiness of renewable energy solutions.
- **Return on Investment** - The payback period for an SMR investment could be 10 to 15 years, half the typical period for conventional nuclear projects, due to shorter pre-project and construction periods.
- **EU Taxonomy and Nuclear Energy** - The EU taxonomy classifies environmentally sustainable economic activities. In 2022, nuclear energy was included in the taxonomy (Said, et al., 2021), on the conditions that international safety standards are followed, that there are operational disposal facilities for low-level waste, and that there is a detailed plan to have in operation by 2050 a disposal facility for high-level waste.

POLITICAL RISK

Investments in nuclear energy projects have often been subject to significant political risk, contributing to both delays and cost overruns. Given the current energy situation and the increasing understanding of the challenges associated with the accelerated development of several alternative renewable energy sources, there are signs that this may be changing, as the general perception of nuclear power among politicians and in society in terms of relevance and risk is changing. In addition, it reflects the fact that other alternative energy projects also are subject to political risks (in addition to cost and scale issues), for example when projects are planned in a market fully dependent on grants and subsidies to function.

Political risk related to nuclear can be influenced by factors such as:

- Geopolitics, particularly the relationship between China and the USA, which can affect value chains and supply security for nuclear power projects, as well as the basis for international agreements on cooperation around nuclear power.
- Regulatory risk, including both the safety aspect (and the perception of it) and the ability of regulations to keep pace with technological development (for example, for SMRs).
- Economic factors and the cost development for nuclear power projects.

Nevertheless, we have in recent years seen a revived interest in nuclear and various initiatives to support increased investments. One example is the Triple Nuclear Energy by 2050 launched at COP28 by over 20 countries from four continents. The goal is to triple global nuclear energy capacity by 2050 to help achieve net-zero greenhouse gas emissions and keep the global temperature rise within 1.5°C. Key elements of the initiative include:

- Recognizing nuclear energy's role in achieving global net-zero emissions.
- Encouraging international financial institutions to include nuclear energy in their lending policies.
- Highlighting nuclear energy as the second-largest source of clean, dispatchable baseload power.

Among the countries supporting the initiative are the USA, United Kingdom, France, Netherlands, Sweden, Finland, Poland, Canada, Japan, South Korea. 14 major global banks have also expressed their support, including Bank of America, Barclays, BNP Paribas, Citi, Credit Agricole, Morgan Stanley and Societe Generale.

This can be seen as a signal of the reducing political risk going forward, at least internationally. Also in Norway, there has been a change in perception among politicians and their parties, and to a (limited) degree also among some environmental organisations. Among the three largest political parties, none rules out nuclear power as part of the solution, but they differ in their view on timeline and relevance for Norway short and medium term.

EU JRC Science for Policy Report 2021

In 2021 the EU Joint Research Centre made a technical assessment of nuclear energy with respect to the "do no significant harm" criteria of Regulation (EU) 2020/852 ("Taxonomy Regulation") (Said, et al., 2021). Some interesting conclusions was made in this report, amongst these:

- The average annual (radiation) exposure to a member of the public, due to effects attributable to nuclear energy-based electricity production is four orders of magnitude less than the average annual dose due to the natural background radiation
- According to the LCIA (Life Cycle Impact Analysis) the total impact on human health of both the radiological and non-radiological emissions from the nuclear energy value chain are comparable with the human health impact from offshore wind energy
- If health impacts due to normal operation of the various electricity generation technologies are compared, then nuclear energy has the lowest values, both for premature fatalities (caused e.g. by air pollution) and for accident fatalities (e.g. workplace accidents)
- If severe accident fatality rates are compared, then the current Western Gen II NPPs have a very low fatality rate (≈5·10-7 fatalities/GWh). This value is much smaller than that characterizing any form of fossil fuel-based electricity production technology and comparable with hydropower in OECD countries and wind power (only solar power has significantly lower fatality rate)
- Severe accidents with core melt have happened in nuclear power plants and the public is aware of the consequences of the three major accidents, namely Three Mile Island (1979, USA), Chernobyl (1986, Soviet Union) and Fukushima (2011, Japan). The NPPs involved in these accidents were of various types (PWR, RBMK127 and BWR) and the circumstances leading to these events were also very different. Severe accidents are events with extremely low probability but with potentially serious consequences and they cannot be ruled out with 100% certainty. After the Chernobyl accident, there were focused international and national efforts to develop Gen III nuclear power plants. These plants were designed according to extended requirements related to severe accident prevention and mitigation, for example they ensure the capability to mitigate the consequences of a severe degradation of the reactor core, if such an event ever happens. The main design objective was to ensure that even in the worst case, the impact of any radioactive releases to the environment would be limited to within a few kilometres of the site boundary.
- These latest technology developments are reflected in the very low fatality rate for the Gen III EPR design (≈8·10-10 fatalities/GWh). The fatality rates characterizing state-of-the art Gen III NPPs are the lowest of all the electricity generation technologies

In our feasibility study, we are only considering Generation IV reactors for use onboard ships. Generally, modern small reactors for power generation, and especially SMRs and MMRs, are expected to have greater simplicity of design, economy of series production largely in factories, short construction times, and reduced siting costs. Most are also designed for a high level of passive or inherent safety in the event of malfunction, ensuring that the technologies are even safer compared to existing land based PWR systems.

International Nuclear Power in 2024

2024 was a very important year for nuclear power internationally, marked by groundbreaking news and a growing enthusiasm for nuclear power, even among people who previously did not follow the energy debate closely. Journalist Angelica Oung, founder of the newsletter "Elemental" has made a nice overview of some of the most important events that shaped the year[33], and here is a short summary:

1. *Restart of Three Mile Island*. Amazon funded a restart of the infamous Three Mile Island power plant in the United States in a $1.6 billion deal to ensure power supply to data centres (not the reactor with an accident – Unit 2, but Unit 1 that operated without accidents until 2019). This marks a shift where technology companies now see nuclear power as a strategic energy source.
2. *The US is investing heavily in nuclear power*. With the completion of Vogtle 3 and 4, Energy Secretary Jennifer Granholm announced an ambitious plan to build 200 new reactors by 2050. A path forward for a tripling of U.S. nuclear power capacity has also been laid, including both large reactors and small modular reactors (SMRs).
3. *The ADVANCE Act passed*. A new law in the United States redefined the regulatory landscape of nuclear power. With broad support, licensing processes were simplified, fees were reduced, and the focus shifted to advancing the development of nuclear energy.
4. *Kairos Power receives license for Hermes 2*. The first power-producing Gen IV reactor in the United States was licensed for construction. This marks an important milestone for the development of next-generation nuclear power.
5. *The world's first nuclear power summit*. In April, world leaders gathered in Brussels to discuss the role of nuclear power in the energy transition. Mark Rutte emphasized the need for nuclear power as an important supplement to solar and wind.
6. *Big banks show support for nuclear power*. During New York Climate Week, 14 leading banks and financial institutions expressed a willingness to invest in nuclear power, a significant change in attitude for a previously "untouchable" technology.
7. *Tech giants such as Google, Microsoft, Amazon and Meta are investing in nuclear power*. Technology companies went from buying electricity from existing nuclear power plants to entering into agreements that can potentially drive new projects. This includes Meta, which is asking for 1.4 GW of nuclear power, and Switch, which signed an agreement for as much as 12 GW.
8. *Flamanville 3 connected to the power grid*. France completed the connection of Flamanville 3 after 17 years, a milestone that could revive confidence in the French nuclear industry.
9. *Molten salt reactor approved in Texas*. In the United States, a molten salt reactor at Abilene Christian University received regulatory approval, one of the first project of its kind in decades. At the same time, China has a similar reactor in operation in the Gobi Desert.

2024 could stand as a turning point for nuclear power globally, with technological advances, political support, and increased interest from private actors paving the way for a new era in energy history.

WP 5.1) Cost of advanced nuclear installation

To understand cost and cost drivers, it is essential to consider the use of land-based SMRs. We have studied IAEAs report “Advances in SMR Developments” from 2024 (IAEA, 2024).

Like other electricity generation technologies, SMRs can be evaluated using the Levelized Cost of Electricity (LCOE) metric (although not all agree that it is suitable for assessing nuclear power[34]), which

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[33] https://elementalenergy.substack.com/p/top-nuclear-news-of-2024

[34] https://www.sciencedirect.com/science/article/pii/S2214629624004882?

represents the cost per megawatt-hour (MWh) of building, financing, and operating a plant over its lifetime. A significant challenge in SMR deployment involves managing the high upfront capital expenditures (CAPEX) associated with construction, which greatly impacts LCOE. However, SMRs are designed for modular and standardized production of components, potentially reducing construction times and costs. By adopting manufacturing practices from industries such as aerospace and shipbuilding, it is expected that SMR developers can achieve cost reductions through learning and scale. A UK study suggests that with sufficient deployment of around 5 GW of SMR capacity LCOE could reach parity with larger nuclear plants, assuming the production of 10 SMR units annually.

Furthermore, some SMR designs offer operational flexibility through cogeneration (e.g., district heating, desalination, or hydrogen production) and load following (adjusting their output based on demand). This allows SMRs to provide valuable services to grids, which are not reflected in the LCOE metric, and they can still maintain a positive net present value irrespective of their LCOEs. The different Generation IV reactor types will come with different auxiliary system demands and consequently, with a different cost picture. We have presented a case study below from (DNV, 2023), and the estimated costs can be found in Figure 35.

The cost of SMR or MMR installations in maritime will of course vary with capacity needs and trade specific demands with regards operational profile, redundancy, etc. These factors will also dictate what type, size and number of reactors to install. Types and experience of reactors are listed below:

Gas cooled SMRs

There are currently 14 high temperature, gas-cooled (GCR or HTGR) type SMRs under development or in operation, providing high-temperature heat (≥ 750°C) for efficient electricity generation, industrial applications and cogeneration. Highlights include the high-temperature reactor–pebble-bed module (HTR-PM), which is in China, was connected to the grid in December 2021 and has operated full power since 2022. Two other HTGR test reactors (one in Japan and one in China) have also been operational for over 20 years.

Liquid metal-cooled, fast-neutron SMRs

10 SMR designs use fast neutrons with liquid metal coolants, including sodium, pure lead, and lead-bismuth eutectic. Significant advances include the BREST-OD-300, a lead-cooled, fast-neutron reactor that is under construction in Seversk, Russian Federation. Other designs under development include a lead-cooled fast reactor by Newcleo, based in France, and a sodium-cooled fast reactor by Oklo in the USA.

Molten salt SMRs

11 SMR designs use molten salt fuel and coolant technologies, one of the six Generation IV designs. Molten salt reactors (MSRs) offer enhanced safety, low-pressure single-phase coolant systems, high efficiency, and flexible fuel cycles. Designs are in design stages in Canada, Denmark, France, the Kingdom of the Netherlands, the UK and the USA. One design has just entered the construction stage in the USA.

Microreactors

These reactors are small SMRs generating typically up to 30 MWt and use various coolants, including light water, helium, molten salt, and liquid metal (heat pipe cooling systems have also been proposed). Several designs are undergoing licensing in Canada and the USA for near-term deployment. Microreactors target niche markets such as microgrids, remote areas, disaster recovery, and critical service restoration. 13 designs are currently under development.

WP 5.2) Responsible ownership of the installation

Land-based nuclear energy is crucial for achieving a clean, reliable, and affordable energy system. Both existing and new nuclear generation are essential for decarbonizing not only the electric sector but also entire economies. Globally, there are a limited number of large licensed operating companies. The operating licenses are granted to companies by national nuclear regulatory bodies, in the US, as an example, the Nuclear Regulatory Commission (NRC) reviews and approves nuclear operators.

The marine industry is once again exploring nuclear propulsion. The advantages, such as zero emissions, elimination of bunkering, low weight, and high design speeds, must be considered alongside the disadvantages related to safety concerns, the need for extended monitoring, non-proliferation issues, social and political risks, and high capital expenditures (CAPEX).

Currently, approximately 200 marine nuclear reactors are in use across around 160 vessels, predominantly state-owned naval aircraft carriers, submarines, icebreakers, and one merchant ship. These vessels are used for strategic purposes, with their superior range enabling autonomous operations.

Unlike other ship propulsion technologies, nuclear propulsion will require approval from national nuclear regulatory bodies in addition to compliance with International Maritime Organization (IMO) rules, flag state regulations, port/coast state rules, and classification society regulations. Before a nuclear reactor can be deployed on ships, it will necessitate a license to operate from at least one nuclear regulatory body. A license is required both for the reactor itself and for the fuel used within it, and includes plans for waste management/storage.

Several questions arise: Can individual shipowners be trusted with the ownership and operation of a reactor? Should ownership be assigned elsewhere, such as to the reactor vendor? Could a third-party licensed owner operating the reactor offer a viable solution? Shipowners might consider purchasing power to operate their vessels, thereby directing their investments elsewhere. Although the concept of "paying for power" has been discussed for conventional installations with limited positive response, the high investment costs associated with a nuclear installation could potentially revive this discussion in boardrooms.

WP 5.3) Financing opportunities

Mature technology and commercial readiness are essential to attract large-scale external capital.

Accessing capital for projects that involve new and unproven technology presents unique challenges compared to conventional ventures. As the application of nuclear technology in commercial shipping is still in early conceptual stages and with any concrete business case still far away, it is challenging to opine full commercial feasibility and future access to external capital or potential financing structures. Key points and considerations to date include:

- While the general sentiment towards nuclear energy is gradually changing and several leading international banks have publicly supported Triple Nuclear Energy by 2050 initiative, more clarity on technical and commercial feasibility and what a realistic business case would look like, would be needed to assess real bankability and attractiveness in the commercial capital markets.
- Bankability requires acceptable credit risks based on a thorough assessment of cashflows, debt service capacity and market value of assets that will serve as collateral, in addition to the counterparty (customer) that owns and operates the financed asset.
- The project should score high or maximum on both Technology Readiness Level (TRL) and Business Readiness Level. From a bankability perspective, accepting variations in BRL would be a discussion around off-taking contracts, as banks are not there to take full risk of innovative technology concepts not yet commercially proven.
- Initial funding for technological development originates from various sources, including government grants, support programs, venture capital, angel investors, and strategic partnerships, until a comprehensive and bankable business case is established.
- Research from Norway suggests that climate technology advancements are financed through equity funding[35].

Backdrop: The financial markets and new climate technology

A report by Menon Economics (2021)[35] shows that innovations in new energy technology seldom are funded by debt but equity. For such developments in offshore wind and maritime transportation, the average debt levels were found to be 15% and 17%, respectively. The report also shows that around half of the respondents (companies investing in new energy-related technology) find financing technology development challenging. For maritime transport 65% of respondents find it challenging.

The main reasons are likely to be the same as often before; uncertainty about technological competitiveness, lack of an existing market and low cashflow visibility will limit the appetite of potential investors and lenders.

Projects come in different shapes with several types and levels of risks. The various levels of risk will require various sources of funding. Looking at capital markets in general, there are few professional investors in initial stages, e.g. seed/pre-seed phases, compared to later stages i.e. when technology is more mature or fully developed. One reason being that climate friendly energy technologies often have long, and capital-intensive development phases combined with uncertain revenues. Furthermore, there may be uncertainties regarding the values and potential stranded asset risk. It is possible that the newly developed technology could become obsolete due to subsequent technological advancements.

However, the general sentiment and interest in nuclear energy solutions is changing. As previously mentioned, the Triple Nuclear Energy by 2050 initiative was launched at COP28, with a goal to triple global nuclear energy capacity by 2050. It was backed by over 20 countries from four continents and supported by 14 major global banks, including Bank of America, Barclays, BNP Paribas, Citi, Credit

35 https://menon.no/prosjekter/klimavennlig-energiteknologi-forsknings-og-innovasjonsdrevet-naeringsutvikling/

Agricole, Morgan Stanley and Societe Generale. They further expressed support for long-term objectives of growing nuclear power generation and expanding the broader nuclear industry to accelerate the generation of clean electrons to support the energy transition. However, cost issue was highlighted during the event, as well as the finance challenge and need for new financial instruments. It was highlighted that traditional commercial funding sources are likely insufficient and potential financing models were discussed including government-backed loans, contracts-for-difference (CfDs) and various risk-sharing mechanisms.

Bank finance and other traditional funding sources need probable cash-flows and values

Equity and bank loans have traditionally been the dominating funding sources for shipping and offshore companies. Bank lending has been dominated by commercial banks (local banks as well as international shipping banks) with additional contributions from export credit agencies and similar (e.g. EksFin in Norway). Some corporate entities have also been able to raise capital in the bond market and some in the private debt market, i.e. private (non-bank) debt investors. Bond issuances have normally been within the High Yield segment ("junk bonds", often secured) as very few entities are regarded as "investment grade" which is a pre-requisite for accessing the larger corporate bond market (often unsecured).

Commercial capital sources, such as banks and equity and debt investors, seek to finance companies and credible business cases with acceptable risk profiles, not single assets based on their value (or future value) alone. Rigorous risk assessments are conducted, focusing on the customer, cash flow, and collateral, typically known as the 3 'C's: Client, Cash-flow, and Collateral. The financier's confidence in the project's viability and potential for success is paramount to unlocking external capital. Any potential financing solution, including loan to value ratio, tenor, pricing, covenants and any additional requirements regarding collateral or contract coverage, will be structured based on this total assessment of the full business case and all the three key elements mentioned that ultimately decide the credit risk.

Banks are commercial entities that 1) are responsible towards their shareholders who require returns on their investments, and 2) are also highly regulated with respect to capital base, reserves and risk management.

Projects involving new technology and innovations should normally be at the highest levels of TRL (Technology Readiness Level) and BRL (Business Readiness Level) to be considered bankable. In certain cases, banks will be able to consider projects with a BRL below maximum score given a project finance structure based on firm contracts mitigating key risks with respect to debt service capacity and residual values (off-take contracts etc.).

Credit evaluation: Analyzing all aspects of the credit, not just value

As mentioned above, banks and other financial institutions make capital allocation and credit decisions on a holistic evaluation of counterparty and cash-flow visibility in addition to asset and collateral value.

a) The Customer – As mentioned, a credit evaluation is about more than just the asset or project in question. Lenders want to know who they are doing business with. Determining whom to finance (the customer) can be just as critical as deciding what to finance (the project or vessel), according to insights gained from various maritime economic cycles of expansion and contraction. Customer assessment will typically include evaluation of the ultimate owners/investors, including their capital base, experience, and record, as well as the company's strategy, management quality, execution ability, governance, ESG profile, general transparency, access to capital and more. Even in a project-focused company, owners and sponsors play a crucial role and are expected to support projects, even when challenges arise.

b) Cash Flow – Lenders want visibility on revenues and debt service capacity, either through firm contracts or based on a positive outlook of an existing, liquid market for the asset and service in question. Firm contracts with a creditworthy counterpart and with a long duration (securing debt service and repayment for majority of debt) will always be regarded as a strong risk mitigant.

c) Collateral value (asset value) – As a second way out (or basis for a successful restructuring) is required and lenders need to be confident about the value of the collateral vessel, also in a distressed situation. This includes evaluating the liquidity of the asset and the ability to generate predictable cashflows in the future, whether it is a somewhat standardized asset or specialized with limited alternative takers or usage.

Investors may use the "Commercial Readiness Index for Renewable Energy Sectors"[36] developed by the Australian Renewable Energy Agency (ARENA), or a similar tool, when deciding to invest in green projects. ARENA has created the Commercial Readiness Index (CRI) as a resource for project proponents to assess the commercial readiness of renewable energy solutions.

Why CRI is required

The Technology Readiness Level (TRL) index is a globally accepted benchmarking tool for tracking progress and supporting development of a specific technology through the early stages of the technology development chain, from blue sky research (TRL1) to actual system demonstration over the full range of expected conditions (TRL9).

The TRL methodology was developed by Stan Sadin with NASA in 1974. Since then, the process has evolved and is used across a wide range of sectors including renewable energy.

While most of the technology risk is retired through the TRL 1–9 framework there is often significant commercial uncertainty and risk remaining in the demonstration and deployment phase. New technology and/or entrants entering a marketplace typically supplied by proven incumbents and financed by capital markets that are often risk adverse, face a multi-faceted range of barriers during the commercialisation

[36] https://arena.gov.au/assets/2014/02/Commercial-Readiness-Index.pdf

process. This is particularly relevant in the context of renewable energy where capital cost and therefore access to capital is a key barrier to accelerating deployment.

There is a wide body of knowledge and literature on the general commercialisation process that has evolved to inform public policy and associated funding tools to enable renewable energy development and deployment. However, there does not appear to be an accepted process to benchmark the commercial readiness of renewable energy technology across the facets of a typical investment due diligence process following successful initial demonstration.

Historically, most of the support for the development of new renewable energy technologies has been through the provision of upfront capital grants. Upfront grants can be useful in assisting companies with acquiring funding for their projects, especially where they are small scale, and the Government funding covers most of the costs. Yet the experience of this traditional funding model is also that rapid change increases risks to projects. Projects that have attempted to go straight from bench or desktop to demonstration at a commercial scale face the greatest challenges, such as raising private sector co-investment commitments, costs exceeding early expectations and the external market context changing over time such that the original goals no longer deliver a sustainable commercial proposition. ARENA was given a broad mandate for assisting renewable energy technologies and projects through to commercialisation; accordingly, ARENA structure its funding support to best reduce risks and barriers at the various stages of the technology development chain.

TRL and CRI Indicators

A pictorial representation of the TRLs and CRI is shown in Figure 34. The figure demonstrates that the CRI begins once the technology is at the stage where there is research to prove that it is feasible in the field (TRL 2). The CRI extends to when the technology or application is being commercially deployed and has become a bankable asset class (i.e. level 6).

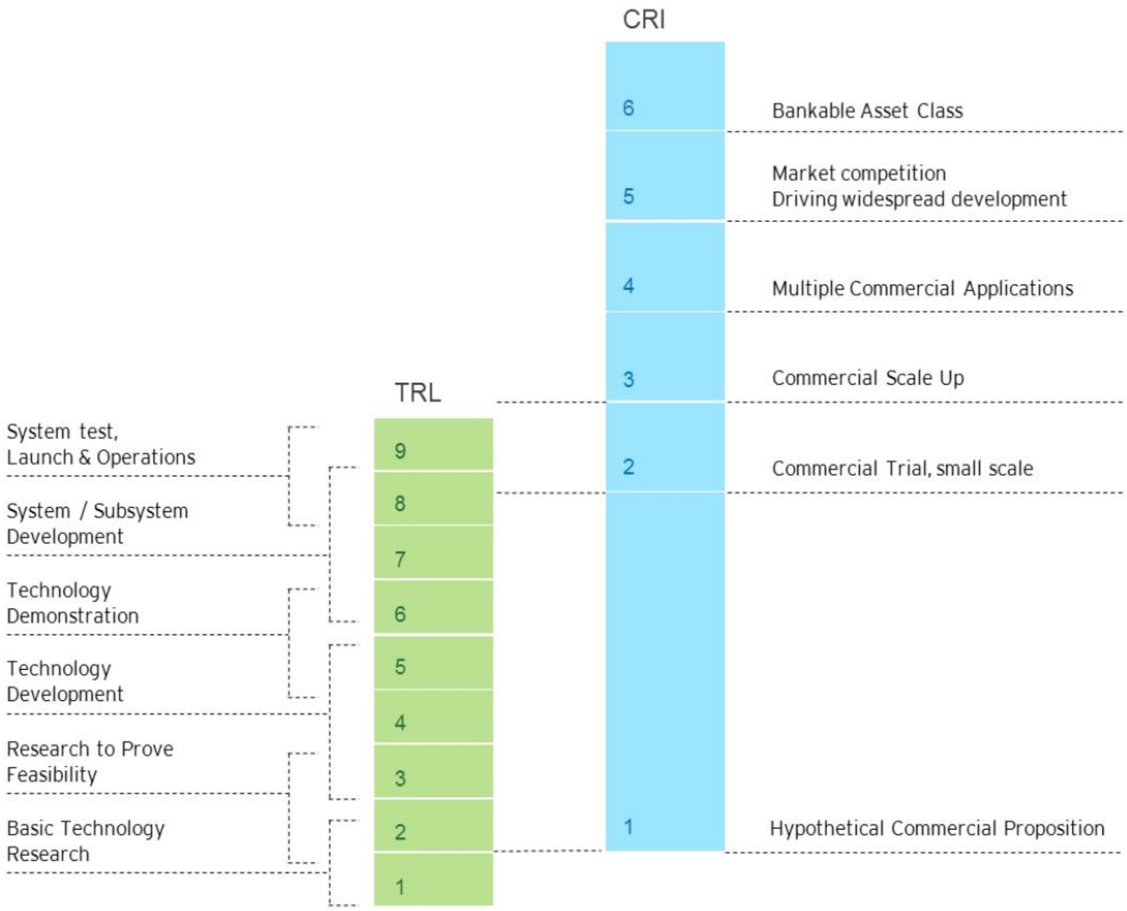

Figure 34 Relation between TRL and CRI

TRL scale

The TRL scale (Technology Readiness Level) ranges from 1 to 9 and is used to assess the technology maturity of the project. TRL 1 is where the research starts, and it is often academia that focuses on TRL 1-4. The business community typically focuses on TRL 7-9, where TRL 8 marks the first time the technology is introduced to the market. TLR 9 thus covers the entire market development of the technology, and at this level the technology is technologically mature. The nine different levels are as follows:

TRL 1: Basic principles of the technology have been observed/identified

TRL 2: The technology concept is formulated

TRL 3: Experimental proof of concept has been established

TRL 4: The technology is validated in a lab environment (typically in academia)

TRL 5: The technology has been tested under relevant operating conditions

TRL 6: The technology has been validated under relevant operating conditions

TRL 7: Full-scale prototype or demonstration plant on a market-relevant scale has been tested under real operating conditions

TRL 8: Truly complete system solution is fully developed, completed and qualified through testing and demonstration

TRL 9: The technology is commercially available and has been in operation over time under commercial frameworks and in all expected operating situations

CRI scale and indicators

The CRI scale (Commercial Readiness Index) distinguishes between degrees of market maturity. The overall scale for assessing market maturity is given below (CRI 1 to 6).

CRI 1: Commercially untested: Technically mature – commercially untested and undocumented. The investment case driven by technology leaders, with little to no verifiable technical or financial data to back up the claims

CRI 2: Early commercial testing: Small-scale, first-of-its-kind project financed with equity and public project support. The investment case backed by verifiable data, but which is typically not available to a larger audience

CRI 3: Commercial scale-up: Driven by targeted policies and opportunities for debt financing. The investment case is being developed by technology providers and other players in the market segment – publicly available data triggers increasing interest from the capital markets and regulatory authorities

CRI 4: Diversified commercial use: Several types of application locally, but still dependent on subsidies. Publicly available verifiable data on technical performance and financial performance generates interest from both equity and debt capital. However, public support is still needed to make the investment profitable. Regulatory challenges are being addressed in several countries

CRI 5: Market competition drives widespread use of the technology based on long-term and predictable political framework conditions. Competition is developing at all stages of the value chain, and there is a productization and standardisation of the main components in the supply chain. The first financial products emerge

CRI 6: "Bankable" asset class with the same type of investment criteria as other mature energy technologies. Considered an attractive and well-established asset class with known standards and clarified expectations for returns

Behind the assessment of CRI, there are several indicators of market maturity. Below shows an overview of the indicators that have been used as a basis for the assessments of CRI, and it is these that market experts have assessed.

Overview of indicators for assessing the commercial maturity of markets Indicator	Summary/brief description of indicator

Regulatory framework	Maturity of regulatory planning processes, permits, and standards related to the technology
Political support	A degree of knowledge and support for the priority area among politicians, including the development of available policy instruments and specified industrial policy ambitions
Critical infrastructure	Level of critical infrastructure required for installation or operation of the technology
Market opportunities	Degree of access to a market, maturity of the market itself and uncertainty related to demand
Technical performance	Degree of availability of information and knowledge of technical performance
Valuation – Costs	Degree of availability of financial information on capital and operating costs
Valuation – Revenue	Degree of availability of financial information about expected revenues
Supply chain (incl. business maturity)	The level of development of the supply chain. Maturity level of the companies commercializing the technology (size, experience and creditworthiness)
Competence	Degree of access to relevant expertise

Advanced Nuclear in Maritime feasibility study overview

To give some clarity related our pilot project, the project Partners have established an overview and comparison of alternative fuels entering the market. The current TRL, and CRI levels are shown in Table 13 and in Table 14. These will of course develop over time, some more rapidly than others.

The findings below give indications on what challenges, and where the focus needs to be to succeed with the alternative fuel solutions in the pipeline today.

Table 13 TRL of alternative fuels (R -renewable, NC – nuclear, PWR – pressurized water reactor)

TRL levels	Brief description of level	Fossil fuel	Biofuels	LNG (R)	Methanol (R)	Ammonia (R)	Hydrogen (R)	NC Gas cooled	NC salt melt	NC lead cooled	NC PWR land/sea
TRL 9	Once a technology has been "*onboard* proven" during a successful sea trial, it can be called TRL 9	☑	☑	☑	☑						☑
TRL 8	Technology has been tested and "*onboard* qualified" and it's ready for implementation into an already existing technology or technology system.										
TRL 7	Technology requires that the working model or prototype be demonstrated in a *onboard* environment									☑	
TRL 6	Technology has a fully functional prototype or representational model					☑	☑				
TRL 5	Continuation of TRL 4, however, a technology that is at 5 is identified as a breadboard technology and must undergo more rigorous testing than technology that is only at TRL 4. Simulations should be run in environments that are as close to realistic as possible.							☑	☑		
TRL 4	Proof-of-concept technology is ready. Multiple component pieces are tested with one another										
TRL 3	Active research and design begin. Generally both analytical and laboratory studies are required at this level to see if a technology is viable and ready to proceed further through the development process. Often during TRL 3, a proof-of-concept model is constructed										
TRL 2	Basic principles have been studied and practical applications can be applied to those initial findings. TRL 2 technology is very speculative, as there is little to no experimental proof of concept for the technology										
TRL 1	Scientific research is beginning and those results are being translated into future research and development.										

Table 14 CRI levels of alternative fuels

Overall Assessment of Commercial Maturity Level (CRI Scale)	Summary/brief description of indicator	Fossil fuel	Biofuels	LNG (R)	Methanol (R)	Ammonia (R)	Hydrogen (R)	NC Gas cooled	NC salt melt	NC lead cooled	NC PWR land/sea
CRI 6: "Bankable" asset	"Bankable" grade asset class driven by same criteria as other mature energy technologies. Considered as a "Bankable" grade asset class with known standards and performance expectations. Market and technology risks not driving investment decisions. Proponent capability, pricing and other typical market forces driving uptake	☑									
CRI 5: Market competition	Market competition driving widespread deployment in context of long-term policy settings. Competition emerging across all areas of supply chain with commoditisation of key components and financial products occurring			☑							
CRI 4: Multiple commercial applications	Multiple commercial applications becoming evident locally although still subsidised. Verifiable data on technical and financial performance in the public domain driving interest from variety of debt and equity sources however still requiring government support. Regulatory challenges being addressed in multiple jurisdictions		☑								
CRI 3: Commercial scale up	Commercial scale up occurring driven by specific policy and emerging debt finance. Commercial proposition being driven by technology proponents and market segment participants – publically discoverable data driving emerging interest from finance and regulatory sectors				☑						
CRI 2: Commercial trial	Small scale, first of a kind project funded by equity and government project support. Commercial proposition backed by evidence of verifiable data typically not in the public domain							☑			☑
CRI 1: Hypothetical commercial proposition	Technically ready – commercially untested and unproven. Commercial proposition driven by technology advocates with little or no evidence of verifiable technical or financial data to substantiate claims					☑	☑		☑	☑	

For land-based energy the smaller scale of SMRs and MMRs makes them potentially more attractive to commercial investors, opening a door to broader private sector participation in nuclear energy.

Based on information from IAEA, SMR vendors plan to use large volumes of serially manufactured items, ranging from systems and equipment to sub-components. This includes a variety of industrial equipment such as commercial turbine sets, cooling equipment, electrical switchgear, pumps, and valves. Proven industrial items, integrated into other high-reliability industrial facilities and with substantial operating experience, are also applicable to SMRs. Serial manufacturing in the nuclear industry offers a way to address some challenges related to stringent procurement requirements on low-volume production orders. Additionally, it can take advantage of the benefits of proven manufactured product designs. By using equipment with a successful track record in industrial settings, nuclear power plant projects can utilize the knowledge and experience gained from their extensive use.

SMR supply chains must prioritize reliable lead times, cost optimization, and consistent adherence to requirements. This is particularly relevant in a near-term market characterized by high-volume demand for equipment. Consequently, the supply chain should be designed to withstand market fluctuations and provide long-term support throughout the plant's operational lifespan. A strategic approach that bases design on proven industrial equipment significantly reduces the risk of bespoke requirements for each jurisdiction or customer and promotes the international standardization of SMR components.

To maximize the use of proven, commercially available products in SMRs, designers should be able to look for such equipment on the market. They can then design systems and subsystems around these products, rather than develop unique specifications for products not readily available in industrial supply chains. This approach allows SMR developers to benefit from industrial products' consistent conformance with established designs, proven operating experience, safety and performance improvements, cost savings, and accelerated deployment timelines. Using existing industrial products supports standardization and offers significant advantages in cost management, access to higher volume manufacture, and time to market. Some SMR vendors have adopted this approach for their near-term deployments by designing SMR systems that can utilize multiple industrial equivalents available on the open market.

WP 5.4) Return of investment

According to IEA, the payback period of an investment in an SMR could be half the typical 20- to 30-year period for conventional nuclear projects, thanks to shorter pre-project and construction periods. In other words, 10 to 15 years.

In the 2023 version of their Maritime Forecast to 2050 report (DNV, 2023) DNV investigated the cost of a nuclear installation onboard a 15 000 TEU container vessel, the installation was larger than the pilot vessel in this pilot project but based on a high cost 6 000 USD/kW and a low cost scenario of 4 000 USD/kW (2023 dollars), which is still relevant today. Leasing of nuclear reactors was discussed to alleviate issues with financing, cash flow, and risk for the shipowner. For the nuclear-powered ship it was assumed a leasing solution for the reactor with related systems and services. Due to the uncertainty in reactor costs for merchant vessels, they constructed High Nuclear and Low Nuclear scenarios for the costs of the case study ship with nuclear propulsion. The reactor costs in these scenarios are based on literature (Houtkoop, Visser, & Sietsma, 2022) (Lovering, Yip, & Nordhaus, 2016) (Eide, Chryssakis, & Endresen, 2013) and discussions with industry actors.

The assumptions for the case-study ship with nuclear propulsion was the following:

- Regulatory and public acceptance: The ship is allowed to trade in enough ports and waters that it can have the same revenue as the other case-study fuel strategies.
- Cargo capacity: The same cargo carrying capacity as the benchmark fuel strategies.

- Energy conversion system: The reactor will cover most of the energy demand. In addition to the reactor, the system will have auxiliary engines for peak loads and take-me-home capabilities, fuel tanks for the same purpose, battery, steam generator, steam turbines and electromotors for electric propulsion.
    - Nuclear reactor: 42 MW, providing 98% of annual energy to the ship. Estimates for volume and weight of the reactor point to decreased installed volume and weight compared with the other fuel strategies.
    - Gensets: 24 MW
    - Batteries: 2 MW
    - Electric motors: 56 MW
- Compatible fuels: MGO, nuclear fuel, carbon-neutral MGO
- CAPEX: 14.5 MUSD additional CAPEX (9% increase), without the reactor, compared with mono-fuel (MF) VLSFO.
- OPEX: Additional OPEX assumed and included in leasing costs.
- Nuclear reactor costs: We construct a High Nuclear and a Low Nuclear scenario, 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, with an additional 2.5 MUSD in OPEX. The OPEX includes refuelling, remote monitoring, decommissioning fund, extra crew costs and more. The annual leasing cost, including both CAPEX and OPEX, is then used in the Fuel Path 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
    - Annual leasing cost 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
    - Annual leasing cost low, 17.3 MUSD

The results for the High Nuclear and Low Nuclear scenarios are shown in Figure 35. The graph on the left side shows the annual costs, including annualized CAPEX, annual OPEX, fuel cost and carbon cost, while the net present value is shown to the right. The figure shows the annual costs for nuclear propulsion compared with the four benchmark fuel strategies based on fuel oil, LNG, methanol or ammonia as the ship is decarbonized. Nuclear propulsion will be increasingly competitive as the GHG limits are tightened, as can be seen from the stable annual costs of nuclear compared with the benchmark cost range that increases from 2030 to decarbonization in 2050. By comparing the total costs of supplied energy of the most discussed carbon-neutral fuels with two scenarios for costs for nuclear propulsion, we see that if nuclear reactors are developed that can reach the lower range of cost levels described here (2023 dollars), there can be an economic case for nuclear propulsion.

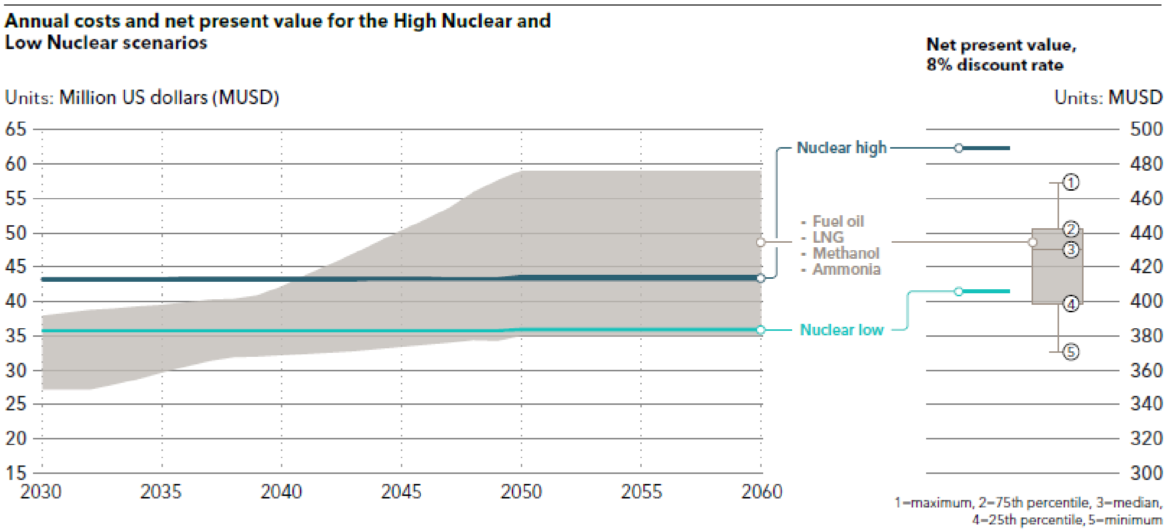

Figure 35 Annual cost and NPV for the High/Low nuclear scenarios. Courtesy DNV, (DNV, 2023).

WP 5.5) Funding/support/subsidies, opportunities

The European Union, with the adoption of the European Green Deal, has signalled its engagement towards becoming a carbon free economy. In this context, EMSA is supporting maritime stakeholders by providing technologically neutral studies on potential alternative fuels and power solutions for shipping[37]. As the last one of a series of studies produced in 2022, 2023 and 2024 covering the Potential use of Biofuels, Potential of Ammonia as fuel and Potential of Hydrogen as fuel, Synthetic fuels, and Potential of Wind-Assisted propulsion for shipping, EMSA published a report on nuclear propulsion[38]. The shipping sector is not the only industry whose goal is to reduce greenhouse gas (GHG) emissions; it faces competition from aviation, road transportation and other industries in the race for carbon-neutral energy. To meet its emission-reduction targets, the production of carbon-neutral fuel alternatives must increase significantly, which may bring about supply uncertainties and price fluctuations. As a result, shipowners need to consider every opportunity, such as fuel flexibility, to navigate these uncertain times. Until now nuclear power has been used for ships mainly for military purposes and for the propulsion of icebreakers in the Arctic. However, at European level, nuclear energy has been identified as a sustainable source of energy able to assist in meeting the zero-emission goal of the EU and therefore is eligible to green sustainable financing. Nuclear power has zero-emission during operation and low carbon during its lifecycle and research is ongoing. New applications are being studied to explore the feasibility of introducing nuclear reactors in shipping. Therefore, nuclear power for shipping seems a pathway that could be explored to contribute to the decarbonization of the sector, but it presents a series of challenges that will need first to be addressed in relation to production, safety, security, training, and the liability/insurance regime.

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37 https://www.emsa.europa.eu/publications/reports.html

38 https://www.emsa.europa.eu/publications/reports/item/5366-potential-use-of-nuclear-power-for-shipping.html

WP 5.6) CO_2 tax regime/taxonomy

EU taxonomy

The EU taxonomy is a classification system, establishing a list of environmentally sustainable economic activities. It could play an important role to help the EU scale up sustainable investment and implement the European green deal. The EU taxonomy would provide companies, investors and policymakers with appropriate definitions for which economic activities can be considered environmentally sustainable. In this way, it should create security for investors, protect private investors from greenwashing, help companies to become more climate-friendly, mitigate market fragmentation and help shift investments where they are most needed.

Rationale for defining nuclear activities as being in line with the EU's climate and environmental objectives

The Technical Expert Group on Sustainable Finance, advising the Commission on Taxonomy, acknowledged that nuclear represents a low-carbon energy source. This is in line with the positions of international organisations such as the Intergovernmental Panel on Climate Change (IPCC), the Organisation for Economic Co-operation and Development (OECD) and the UN Economic Commission for Europe, which consider CO_2 emissions from nuclear power plants over their life-cycle comparable to those from renewable energy sources (as low or even lower). However, expert opinion has been less conclusive on the other environmental impacts of nuclear power and its compatibility with the “do no significant harm (DNSH)” criterion. For this reason, the Commission set up a specific process on nuclear energy, involving a technical assessment by the Joint Research Centre (JRC), the European Commission's science and knowledge service. Their report was published and reviewed by Member States' experts on radiation protection and waste management appointed by the Scientific and Technical Committee under Article 31 of the Euratom Treaty, as well as by experts from the Scientific Committee on Health, Environmental and Emerging Risks (SCHEER). Overall, the report and reviews conclude that compliance with the safety standards and waste management requirements under the regulatory framework in EU Member States ensures a high level of protection for the environment and for people.

For nuclear energy activities to be enlisted under the taxonomy, the screening criteria set requirements beyond the existing regulatory framework; for instance, sunset dates for accelerating transition to advanced technologies, and definite dates for operational disposal facilities to be in place.

Nuclear waste

The Taxonomy Regulation requires that the long-term disposal of waste does not cause significant or long-term harm to the environment.

Nuclear energy generates a relatively low amount of waste in comparison to the large amount of generated heat and/or electricity. It produces mainly low-level radioactive waste, for which there are disposal facilities that have operated for decades, while high-level radioactive waste accounts for 1% of total nuclear waste.

The EU regulatory framework establishes the legal requirement for national policies to keep the generation of radioactive waste to a minimum.

In addition, the technical screening criteria for nuclear energy go beyond requiring mere compliance with legislation regarding radioactive waste management and disposal. Notably, disposal facilities for low-level waste must be operational already, and Member States should have in place a detailed plan to have in operation, by 2050, a disposal facility for high-level radioactive waste. Some Member States have more advanced projects regarding the long-term disposal of nuclear waste. The inclusion of nuclear energy in the EU Taxonomy can accelerate the development of solutions for final waste disposal elsewhere in the EU. In addition, the technical screening criteria for nuclear energy prohibit the export of radioactive waste for disposal in third countries.

Complementary Climate Delegated Act and the energy price discussions

The Taxonomy is not an instrument of EU energy policy. It is a tool to increase transparency in financial markets for private sector sustainable investments. It does not mandate investments and does not prevent any economic sector from receiving investments. Member States remain fully responsible and competent for deciding their own energy mix and for striking the appropriate balance – in terms of energy security, energy price stability and their commitment to decarbonisation and climate neutrality. The Taxonomy is an important element in the sustainable finance toolkit to help fund the Green Deal.

The spike in energy prices that the EU is facing is a major concern for the European Commission. Supporting a clean energy transition would allow us not just to avert the disastrous impacts of climate change but also to reduce the EU's vulnerability to fossil fuel price volatility. In the medium term, our policy response should focus on making the EU more efficient in the use of energy, less dependent on fossil fuels and more resilient to energy price spikes, while providing affordable and clean energy to end-users. The Complementary Delegated Act is part of these efforts and aims to drive the EU towards the required green transition to a decarbonised economy.

Today's Complementary Climate Delegated Act:

- **introduces additional economic activities from the energy sector into the EU Taxonomy.**

The Delegated Act includes certain nuclear energy activities that can play a role, under strict conditions regarding nuclear and environmental safety (also related to waste disposal), in the EU's transition towards climate neutrality. It also covers some gas energy activities as transitional activities, subject to specific conditions which recognise the role gas can play to help some regions transition from the most polluting solid fossil fuel energy sources, such as coal, to renewable energy.

- **introduces specific disclosure requirements for businesses related to their activities in the gas and nuclear energy sectors.**

Those requirements should further enhance the information provided to investors and improve transparency.

Nuclear-related activities:

1. Advanced technologies with closed fuel cycle (“Generation IV”) to incentivise research and innovation into future technologies in terms of safety standards and minimising waste (with no sunset clause);

2. New nuclear power plant projects for energy generation, which will be using best-available existing technologies (“Generation III+”), will be recognised until 2045 (date of approval of construction permit);

3. Modifications and upgrades of existing nuclear installations for the purposes of lifetime extension, will be recognised until 2040 (date of approval by competent authority)

The amendments introduced to the Delegated Act on disclosures under Article 8 of the Taxonomy Regulation

To provide a high degree of market transparency regarding investments in natural gas and nuclear energy activities covered by this Delegated Act, financial and non-financial companies should present specific disclosure requirements that would show to what degree gas and nuclear energy activities, complying with the technical screening criteria, is in the numerator and denominator of the key performance indicators of those undertakings. This should help investors to distinguish among activities they invest in. With the help of this specific disclosure requirement, investors that are not willing to invest in nuclear and gas activities under the conditions in this Delegated Act would be able to identify and invest in activities and financial products that have no exposures to economic activities in the nuclear and gas sectors.

In addition, to provide a high degree of transparency to investors in financial products concerning exposures to fossil gas and nuclear energy activities, the Commission will explore amending further the disclosure framework pertaining to those financial products as appropriate, to provide for full transparency over the whole life of those financial products. To ensure that such information is clearly identified by end-investors, the Commission will consider amending the requirements on the financial and insurance advice given by distributors.

As a result of the feedback, adjustments to the technical screening criteria and disclosure and verification requirements were introduced to reinforce notably their clarity and usability. Some criteria were made more flexible, to reflect commercial availability and technological readiness. Specific adjustments were made to make certain criteria more workable across Member States. Transparency and verification requirements were reinforced to improve information and credibility towards investors.

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