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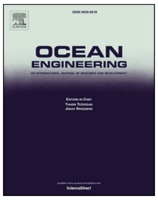

# Integrating fourth–generation reactors into maritime transport

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## ABSTRACT

This study explores the application of fourth–generation (Gen IV) nuclear reactors as propulsion systems for shipping with zero direct emissions of $CO_2$. It evaluates the potential to replace fossil fuels, supporting the United Nations sustainable development goals (SDGs). Gen IV reactors offer high energy efficiency, zero greenhouse gas emissions, and extended operational autonomy without refuelling. Technologies such as very high–temperature reactors (VHTRs), small modular reactors (SMRs), and molten salt reactors (MSRs) are highlighted for their innovative safety features and fuel flexibility. Technical feasibility is assessed alongside economic aspects of nuclear propulsion, including reduced operating costs, potential revenue from carbon credits, and increased cargo capacity. Challenges include high initial costs, public resistance, and regulatory concerns. A comprehensive analysis of Gen IV nuclear reactors addresses these barriers and proposes solutions, including the adoption of advanced passive safety systems. This article demonstrates that the implementation of Gen IV reactors could contribute significantly to maritime decarbonization, ensuring environmental sustainability and economic viability.

## 1. Introduction

Due to the constantly developing international trade, increasing the transport of raw materials or containers by sea is necessary. Currently, around 70 % of all cargo is transported by ship. This results in increased fuel consumption and, therefore, increased $CO_2$, $NO_x$, and $SO_x$ generation, adversely affecting the environment (Dzida et al., 2009; Sui et al., 2019). One major issue in global shipping is the need to reduce greenhouse gas emissions, particularly carbon dioxide (Bryk and Głuch, 2023).

The rising demand for maritime transport can be seen in Fig. 1, which shows the global development of container transport since 2012. Data indicates a steady increase in container throughput, growing from 622 million twenty–foot equivalent units (TEUs) in 2012 to 863 million TEUs in 2021. This growth underscores the trend of increased global trade and the corresponding increase in the needs for maritime transport.

This growth highlights a critical issue: Without implementing changes such as the adoption of environmentally friendly propulsion systems, greenhouse gas emissions, particularly $CO_2$, will continue to increase. The maritime industry must consider sustainable practices and technological advances to mitigate the environmental impact associated with the growing demand for shipping.

Currently, one of the main problems in ship technology is cutting carbon dioxide emissions (Abu Bakar et al., 2023). Its higher atmospheric concentration leads to an ever–increasing greenhouse effect (Papadis and Tsatsaronis, 2020), potentially causing disastrous consequences for humanity in the future (Ziółkowski et al., 2021; Szewczuk-Krypa et al., 2018a, 2018b). Achieving climate neutrality (Klatzer et al., 2022) by 2050 (Ziółkowski et al., 2022a) is essential to obtaining (Drosińska-Komor et al., 2023) the Paris Agreement of 2015 (Cloete et al., 2020; Cownden et al., 2023). The shipping sector accounted for 2.9 % of total atmospheric greenhouse gas emissions in 2018; therefore, some measures must also be taken.

A solution to legal problems resulting from limiting or even

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## Abbreviations

| | |
|---|---|
| ABS | American Bureau of Shipping |
| Art | article |
| ATLAS | Atomic Technologies Licensed for Applications at Sea |
| BWR | boiling water reactor |
| BV | Bureau Veritas |
| CANDU | canadian deuterium uranium |
| CapEx | capital expenditure |
| $CH_4$ | methane |
| ClassNK | Nippon Kaiji Kyokai |
| $CO_2$ | carbon dioxide |
| DNV | Det Norske Veritas |
| EGD | European Green Deal |
| Electra | European Lead Cooled Training Reactor |
| EU | European Union |
| FBR | fast breeder reactor |
| FPSO | floating production storage and offloading |
| Gen IV | fourth–generation reactors |
| GFR | gas–cooled fast reactor |
| GHG | greenhouse gas |
| HFO | heavy fuel oil |
| HTGR | high–temperature gas–cooled reactor |
| IAEA | International Atomic Energy Agency |
| IMO | International Maritime Organization |
| IPWR | integral pressurized water reactor |
| IPyC | inner pyrolytic carbon |
| l | liquid |
| LR | Lloyd’s Register |
| LFR | lead–cooled fast reactor |
| LFTR | Liquid Fluoride Thorium Reactor |
| LMCFN | Liquid metal–cooled–fast–neutron |
| LMFR | liquid metal fast reactor |
| LNG | liquefied natural gas |
| LWR | light–water–cooled reactor |
| MCFR | molten chloride fast reactor |
| MOX | mixed oxide fuel |
| MSR | molten salt reactor |
| MSRE | molten–salt reactor experiment |
| MWt | Mega Watt thermal |
| $N_2O$ | nitrous oxide |
| $NO_x$ | oxides of nitrogen |
| OCR | organic liquid–cooled nuclear reactor |
| OpEx | operating expense |
| OPyC | outer pyrolytic carbon |
| PRISM | power reactor innovative small module |
| PWR | pressurized water reactor |
| RES | renewable energy sources |
| S | solid |
| SCWR | supercritical water–cooled reactor |
| SDG | sustainable development goal |
| SFR | sodium–cooled fast reactor |
| SiC | silicon carbide |
| SMR | small modular reactor |
| $SO_x$ | sulfur oxide |
| SWOT | strengths, weaknesses, opportunities, and threats |
| TEU | twenty–foot equivalent unit |
| TRISO | tri–structural isotropic particle fuel |
| U235 | uranium 235 |
| UNFCCC | United Nations Framework Convention on Climate Change |
| USA | United States of America |
| V | vapor |
| VHTR | very high–temperature reactor |

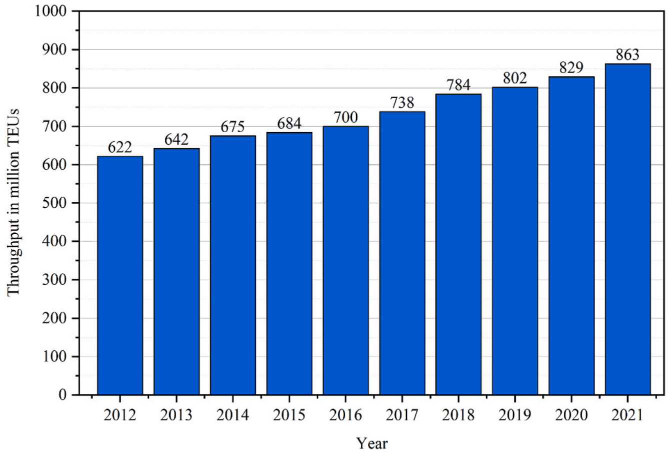

**Fig. 1.** Global Container Throughput from 2012 to 2021 (in Million TEUs). The data for the diagram are based on (Statista). TEU – twenty–foot equivalent unit.

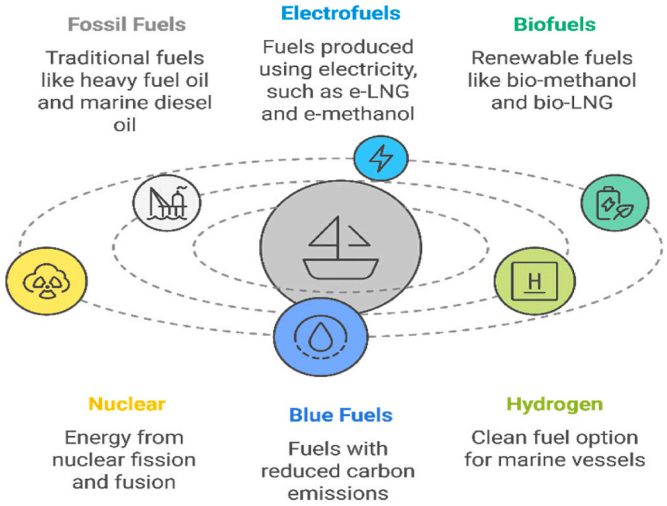

**Fig. 2.** Division of used and tested fuels for ships. The data for the diagram are based on (Mahía Prados et al., 2024; Korberg et al., 2021).

achieving zero $CO_2$ emissions is using zero–emission energy technologies like renewable energy sources (RES), hydrogen (Sánchez et al., 2023), or nuclear power for ship propulsion (Drosińska-Komor et al., 2022). The various types of fuel currently in use or under development for shipping vessels are shown in Fig. 2. These include alternative fuels, such as nuclear and hydrogen, although their use remains marginal compared to traditional fuels.

This work focuses on the use of nuclear fuel as a potential, emission–free propulsion system for vessels, particularly in maritime transport. Generation IV (Gen IV) reactors (Fig. 2) were selected for propulsion due to their high level of innovation and potential to shape the future of nuclear energy. These reactors, such as high–temperature gas reactors (HTGRs) and molten salt reactors (MSRs), can operate continuously with high energy efficiency. They offer a long operational lifespan without the need for frequent fuel replacement, and they produce relatively low amounts of radioactive waste. They can contribute not only to the effective decarbonization of maritime transport but also to technological advancements and the creation of new jobs in ports and vessel operations. Additionally, their passive safety systems allow them to operate safely without human intervention in the event of a malfunction.

The analysis conducted in this paper focuses on Gen IV reactors as modern, zero–emission marine propulsion systems that could contribute to achieving the United Nations sustainable development goals (SDGs). A strengths, weaknesses, opportunities, and threats (SWOT) analysis of the feasibility of using Gen IV reactors for ship propulsion is presented in APPENDIX A, along with an analysis of the economic benefits. Additionally, the appendix includes a detailed SWOT analysis of selected ship types equipped with nuclear propulsion aiming to illustrate the strengths and weaknesses of this technology in practical maritime applications.

Traditional ship propulsion emits greenhouse gases and other pollutants (Inal et al., 2022) such as oil leaks, which harm the environment. According to data from the International Maritime Organization (IMO), ships were responsible for producing 457,000 tons of pollution in 2020.

## 2. Motivation for reduction of greenhouse gas emissions

The need to protect the environment, including reducing greenhouse gas emissions, has been discussed worldwide for many years (Ertesvåg et al., 2023). The most important milestones will be presented in this paper to understand why it is so essential for the authors to try to find optimal solutions for greenhouse gas emissions by replacing traditional ship fuel with nuclear fuel.

### 2.1. *Greenhouse gas emissions by shipping under international law*

As early as 1972, the Declaration of the United Nations Conference on the Human Environment was adopted (Handl et al., 1972). At that time, the problem of global technical, industrial and civilizational progress and thus the need to protect (and implicitly even defend) the environment was highlighted and recognized (Baste and Watson, 2022). In the preamble, the 'principles' of the said declaration, it is stated that 'Man has the fundamental right to (…) adequate conditions of life in an environment of quality that makes it possible to live in dignity and well–being.' Man is responsible for protecting and improving the environment for present and future generations (Kocot and Wolfke, 1976).

The first World Climate Conference occurred in 1979 in Geneva (Montoro-Ramírez et al., 2022; Cifuentes-Faura, 2022). At that time, $CO_2$ emission into the atmosphere became the focus of interest of numerous scientists and was an essential point of the above Conference (Guihenneuc et al., 2023). The potential consequences of the increase in the content of $CO_2$ in the atmosphere resulting from the burning of fossil fuels were said to be recognized and that this increase was already a serious global problem (Li et al., 2023). Furthermore, it was realized that deforestation, as well as emissions of other gases, have the impact of increasing the effects of $CO_2$ (Füssel, 2009). It was discovered that the $CO_2$ content in the atmosphere had increased by up to 10 % in 50 years, which is predicted to result in a global increase in temperature and global warming (including the melting of glaciers). In the last century, the concentration has reached a higher level of 15 % and is increasing by a third to 1 % each year (World Meteorological Organization).

The issue of the effects of the increased emission of $CO_2$ still requires further research, as it is not known what fossil fuels can be replaced with: 1) in particular: coal, whose combustion produces a high level of $CO_2$ emission, 2) what the actual consequences of the increased emission of $CO_2$ into the atmosphere are, 3) how rapidly the economy and industry will develop and what the implications of this will be, and 4) what other factors contribute to the increase in $CO_2$ emissions.

The legislative bodies of the countries of the world at the international level have addressed and regulated the following issues first: ozone layer (Cifuentes-Faura, 2022; Grevsmühl and Briday, 2023), followed by an increase in sea level in islands and coastal areas (especially low–lying areas (Possible adverse effects of sea, 1989) and desertification (Vasseur, 1973; Resolution adopted by the General Assembly 44/172)), which are related to greenhouse gas emissions, although this has not been fully explored. The world economy has been developing, and greenhouse gas emissions have been increasing, while specific visible impacts have been vital to address, i.e., depletion of the ozone layer, desertification, rising sea levels, and melting glaciers. These have been tangible burning problems, the effects of which had to be stopped immediately.

The International Panel on Climate Change, established in December 1988, compiled and then presented a report in July 1990 (Brulle, 2023), in which the most prominent scientists – climatologists – extensively reported their research, in which they addressed the issue of greenhouse gas emissions into the environment and their disturbing effects, and presented the results of their study (Zommers et al., 2020). It was emphasized that the global temperature has increased from 0.3 °C to 0.6 °C within the last century (Villalba et al., 2003). The authors urge an immediate 60 % reduction in greenhouse gas emissions compared to 1990 (Consilium (Paris Agreement)).

The report above has given an impetus to greenhouse gas emissions at the Second International Conference on Climate Change, which took place in 1990 in Geneva (Wen et al., 2023). At that time, it was decided that an international convention and guidelines for cooperation to reduce greenhouse gas emissions were necessary (Jin and Kim, 2018) and would be developed. In pursuit of this, the UN Framework Convention on Climate Change text was prepared, which was drawn up in its final form on May 9, 1992, in New York at the UN headquarters.

This convention was adopted at the second Earth Summit held in Rio de Janeiro in 1992 (Gu et al., 2021), and its full name is *the United Nations Framework Convention on Climate Change* (UNFCCC) (Quandt et al., 2023), the main objective of which is set out in Art. 2: 'stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system'. Therefore, it is intended to protect people and the environment and reduce greenhouse gas emissions (Knez et al., 2022). This is a legal act ratified (The Journal of Laws, 1994, 1994) by Poland on June 16, 1994, which is to be complied with.

The convention set an ambitious objective, to bring emissions of greenhouse gases not covered by the Montreal Convention to 1990 levels (Art. 4 item 2(b)). A body with broad enforcement and monitoring powers was established, the 'Conference of the Parties' (Art. 7 of the UNFCCC) and subsidiary bodies in the following articles were to oversee progress and monitor the situation.

While the UNFCCC is only an incentive, a recommendation, a typical plan, and an idea to improve the climate situation, the Kyoto Protocol is the first binding legal act of international nature (He et al., 2022; Depledge, 2022). It was signed on December 11, 1997 and is commonly called the 'Kyoto Protocol' (He et al., 2022; Kamani and Ardehali, 2023). It focused on climate change and developed strategies for 2008–2012 and 2013–2020 (EUR-Lex (LEGISSUM: kyoto_protoc)).

Its successor was the Paris Agreement (Li et al., 2023), one of whose signatories was the European Union (Dmochowska-Dudek and Wójcik, 2022). The legal text was adopted by the UNFCCC at the Paris Conference (Subramanian and Madejski, 2023), then ratified by the EU on October 5, 2016 and entered into force on November 4, 2016. The agreement addresses climate change issues (Sobolewski et al., 2022), and the main objective was that the increase in global warming (Guzović et al., 2023) should not exceed 2 °C compared to the preindustrial era (Subramanian and Madejski, 2023; Ziółkowski et al., 2022b), and, ideally, the temperature growth should be a maximum of 1.5 °C (Millar et al., 2017; Hansen et al., 2001) compared to the preindustrial age (Bergman-Fonte et al., 2023). This requires excellent efforts since the global temperature rose by 0.85 °C (from 0.3 °C to 0.6 °C in 1988), so the increase is rapid and must be stopped as quickly as possible (Klatzer et al., 2022).

The EU has set itself the goal of becoming climate–neutral by 2050 by implementing the obligations imposed on it (Duwe et al., 2023). On December 11, 2019, the European Commission presented the European Green Deal Communication (hereafter referred to as the Green Deal; COM, 2019, 640 final) (Szpilko and Ejdys, 2022), which is part of the implementation of the 2030 Agenda for Sustainable Development and the Sustainable Development Goals (Relva et al., 2021). Its main objective is to reduce net greenhouse gas emissions to zero by 2050 and achieve a sustainable economy while maintaining respect for humanity (Costa et al., 2022). According to the declarations and promises in the EGD, one of the tools to achieve this goal is to create a European climate law (Mentes, 2023). In the implementation of this commitment, Regulation (EU) 2021/1119 of the European Parliament and the Council of June 30, 2021, on establishing a framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 (referred to as European Climate Law) was issued (EUR-Lex (CELEX 32021R1119)). The 20th preamble of the said regulation summarizes what has been achieved so far to protect the climate. This chapter includes existing regulations, communications and packages that the EU has implemented and developed in order to reduce greenhouse gas emissions, achieve climate neutrality or even achieve a more ambitious goal: achieving negative greenhouse gas emissions (EUR-Lex (CELEX 32021R1119)).

Indeed, more legislation has emerged over time, but this paper focuses only on those with the most significant impact on the reduction of greenhouse gas emissions through the use of nuclear propulsion on cargo ships.

### *2.2. Greenhouse gas emissions by shipping as motivation for using Gen IV reactors*

Ship greenhouse gas emissions account for only 4 % of total $CO_2$ emissions in the European Union, which is more than 144 million tons of $CO_2$ per year (EC PDF SWD (2021) 228). The share of domestic shipping in greenhouse gas emissions is approximately 0.4 % of total gas emissions, while international shipping produces approximately 3.6 % of total greenhouse gas emissions (EC Reducing emissions from the shipping sector). In terms of the global economy, shipping in 2018 represented 2.9 % (Aakko-Saksa et al., 2023), that is, 1076 million tons of $CO_2$ (Sumin, 2023), emissions; therefore, in the EU, shipping is a more important means of transport than in the rest of the world.

One might call 2.9 % of global $CO_2$ emissions marginal and argue to focus on the remaining 97.1 %. However, shipping—along with aviation—is among the fastest–growing sectors, with the highest increase in $CO_2$ generation.

Shipping and the International Maritime Organization, in particular, is not in a hurry to meet the expectations of becoming climate–neutral by 2050 and is targeting a 50 % reduction by then (Grzelakowski et al., 2022; Dong et al., 2022). In the literature, information can be found that the reduction level may be around 85 % (Fan et al., 2023).

In terms of shipping itself, the total emission of greenhouse gases is made up of all shipping branches (Deng et al., 2022), including tourism and passenger transport, freight and transit (Barone et al., 2023). The subject is even more crucial because up to 80 % of goods are carried by sea, by ships powered by fuels that cause $CO_2$, $CH_4$, and $N_2O$ to enter the atmosphere (Karatuğ and Durmuşoğlu, 2020).

The EU has prepared a *package 'fit for 55'* to reduce greenhouse gas emissions by at least 55 % in 2030 compared to 1990 (Deng et al., 2022). In 2005, an EU tool to reduce greenhouse gas emissions called the EU Emissions Trading Scheme (hereafter referred to as the EU ETS) was introduced, consisting of limits on greenhouse gas emissions and the trading of emission allowances for the above (Bäckstrand, 2022). In the *'fit for 55'* package, it was assumed that the EU ETS would also cover maritime transport (Consilium (Fit for 55, 25.04.2023)).

Maritime transport, in addition to emitting $CO_2$ also produces $CH_4$ (Ushakov et al., 2019) and $N_xO$ (Zincir, 2023). Therefore, it was considered reasonable to include general cargo vessels of more than 400 gross units but less than 5000 gross units in the monitoring from 2050. Even modern ships are a source of pollution during fuel bunkering operations, regardless of whether it is liquid or gaseous fuel. Liquid fuels pollute water and gaseous fuels are a source of atmospheric pollution, mainly through $CH_4$ leaks (Błaszczyk et al., 2011). In addition, liquid fuels leak into the aquatic environment in various quantities during the voyage.

The information mentioned in this subsection regarding the efficiency requirements imposed on the transport industry is necessary to reduce the generation of greenhouse gases. This aspect has led the authors of this paper to conduct research aimed at replacing traditional propulsion with nuclear–powered propulsion, which reduces greenhouse gas emissions and supports the transition toward sustainable maritime transport. UAV structural studies likewise emphasize the need for accurate computational models, as simplifications like ignoring control surfaces or material homogeneity can cause discrepancies between simulations and experimental results (Milewski et al., 2025; Kierzkowski et al., 2025).

## 3. Purpose of the research

The aim of this study is to assess the feasibility of using Gen IV nuclear reactors in maritime transport as an alternative to conventional propulsion systems, with a focus on reducing greenhouse gas emissions and supporting the achievement of the Sustainable Development Goals (SDGs). Specifically, the study explores the potential for achieving climate neutrality in shipbuilding and maritime transport.

To achieve climate neutrality in shipbuilding, many changes must be made to existing systems (Breńkacz and Żywica, 2017; Głuch and Krzyżanowski, 1999), among other things, to optimize (Dominiczak et al., 2020) their operation by improving their parameters (Breńkacz et al., 2017, 2018). The appropriate diagnostic methods should allow the equipment to operate efficiently (Ziółkowski et al., 2023; Butterweck and Głuch, 2014). Furthermore, the introduction of power supplies should be done using new technologies and renewable energy sources, for example, wind (Chou et al., 2021; Nyanya et al., 2021), solar (Zhang and Liang, 2022), electric batteries (Zhang et al., 2023) and fuel cells (Gómez and Hotza, 2016). Replacing traditional hydrocarbon fuels with new fuel types, such as ammonia (Wu et al., 2023a), hydrogen, or synthetic fuels (Bąk et al., 2023; Godinho et al., 2023). Advanced diagnostic systems are already widely used in railway transport, where failures are systematically classified into infrastructure and rolling stock categories, enabling effective detection and analysis of faults and supporting the development of modern monitoring methods for both infrastructure and vehicles (Wróbel et al., 2024).

Nuclear propulsion may well be the future propulsion system for vessels, with its low cost compared to other fuels for ship propulsion. Nuclear ship propulsion can be found in icebreakers (Drosińska-Komor et al., 2022; Freire and De Andrade, 2015). Currently, nuclear fuel is used in Russian icebreakers Taimyr and Arctica (Skripnuk et al., 2020). Additionally, examples of ships from the United States of America where the reactor was used were shown. Examples of other nuclear–powered ships are the NS Otto Hahn (Freire and De Andrade, 2015), NS Savannah (Mcreynolds, 2022), NS Mutsu (Black, 2022) and NS Sevmorput (Islam Rony et al., 2023; Alam et al., 2019). Over the years, five leading countries have emerged in nuclear submarine construction: USA, Russia, The United Kingdom, France, and China (Bayraktar and Yüksel, 2023). Table 1 shows examples of commercial ships.

The examples of ships mentioned in the article, together with Table 1, demonstrate that the use of reactors for propulsion on floating vessels is not a new concept. However, challenges arise when attempting to implement such propulsion systems on different types of ship, e.g. cargo or passenger vessels. These challenges stem primarily from the need to ensure the safety of crew and passengers, which is further complicated by social concerns surrounding nuclear technology.

**Table 1**
Examples of civilian ships powered by pressurized water reactors (PWRs) (Black, 2022; Fialkoff et al., 2022; Wróbel, 2022; Stevens et al., 2024).

| Name ship | Type | Years in service | Installed power [MW] |
|---|---|---|---|
| Lenin | Icebreaker | 1959–1989 | 3 reactors 90 = 270 for 1970 year, after 2 reactors 171 = 342 |
| NS Savanah | Cargo and passenger | 1962–1972 | 74 |
| NS Otto Hahn | Cargo | 1968–1979 | 38 |
| NS Mutsu | Cargo | 1974–1992 | 36 |
| Arktika | Icebreaker | 1975–2008 | 2 reactors 171 = 342 |
| Sibir | Icebreaker | 1978–1992 | 2 reactors 171 = 342 |
| Rossiya | Icebreaker | 1985–2013 | 2 reactors 17 = 342 |
| NS Sevmorput | Cargo | 1988–2007<br>2016–present | 135 |
| Taimyr | Icebreaker | 1989–present | 171 |
| Sovetskiy Soyuz | Icebreaker | 1989–2014 | 2 reactors 171 = 342 |
| Vaygach | Icebreaker | 1990–present | 171 MW |
| Yamal | Icebreaker | 1992–present | 2 reactors 171 = 342 |
| 50 Let Pobedy | Icebreaker | 2007–present | 2 reactors 171 = 342 |
| NS Yakutia | Icebreaker | 2022–present | 2 reactors 175 = 350 |
| NS Chukotka | Icebreaker | Expected 2024 | 2 reactors 175 = 350 |

Protecting sea and ocean waters is crucial to avoid potential climate catastrophes. To address public safety concerns, Gen IV reactors with advanced passive safety systems are recommended. These reactors support the decarbonization of water transport, which is essential for environmental protection. An additional incentive is the fluctuating price of oil (Fig. 3) (EIA Petroleum and Other Liquids), which has risen since 2000, increasing transportation costs. In contrast, nuclear fuel maintains stable pricing, helps budget planning, and improves profitability. Although the initial cost of building or retrofitting ships with reactors is higher, it remains a more profitable long–term investment. The fuel market analysis is in line (Fig. 3), with the sustainable development goals (SDGs).

The most commonly used types of reactors on ships are pressurized water reactors (PWR) and boiling water reactors (BWR) (Alam, 2016). PWRs are preferred for their reliability and efficiency, using water as both a neutron moderator and a coolant (Yamaji and Sako, 1994). The water circulates in a primary loop under high pressure, preventing it from boiling. The heat is then transferred to a secondary loop, where water turns into steam to drive the turbines. BWRs also use water as a coolant and moderator, but the water boils directly in the reactor vessel, producing steam that drives the turbines, simplifying the design and improving efficiency in some cases.

In addition to nuclear reactors, alternative methods for generating energy are being extensively studied to reduce greenhouse gas (GHG) emissions in the various sectors and maybe also in the future in maritime transport. A promising technology is the organic Rankine cycle (ORC), which uses low–boiling working fluids to generate electricity from low–temperature heat sources (Breńkacz et al., 2019a; Żywica et al., 2018). During the 1950s and 1960s, intensive research was conducted on organic liquid–cooled nuclear reactors (OCRs), including the OMRE, Piqua (USA) and WR–1 (Canada) (Mooradian et al., 1967). Organic coolants have been credited with advantages such as lower corrosivity and no risk of rapid boiling. However, their low heat capacity, susceptibility to radiolysis and flammability and toxicity generated serious operational and safety problems. As a result, OCRs have not found commercial application. The modern ORC uses similar liquids, but only as working fluids in heat recovery systems – not as reactor coolants. The relationship of ORCs to historic OCRs is therefore limited, and technological and safety barriers remain significant (Colonna et al., 2015).

Nuclear reactor designs for maritime use must be significantly smaller and lighter than those used in land–based power plants. They must fit within the confined spaces of the hull of a ship, necessitating advanced engineering solutions and component miniaturization. For example, reactors in aircraft carriers of the American Nimitz class have an output mechanical power of approximately 190 MW each but are much smaller than land–based reactors of similar capacity. Furthermore, the reactor and its systems must be resistant to shocks and vibrations caused by the movements of the ship and potential collisions.

Safety is another critical aspect. Maritime reactors are equipped with advanced safety systems, such as passive emergency cooling systems that can operate for extended periods without external power. Furthermore, these reactors must be able to operate at extremely low temperatures, as seen with icebreakers operating in the Arctic, as well as other harsh environmental conditions (Kok, 2009). Maritime reactors

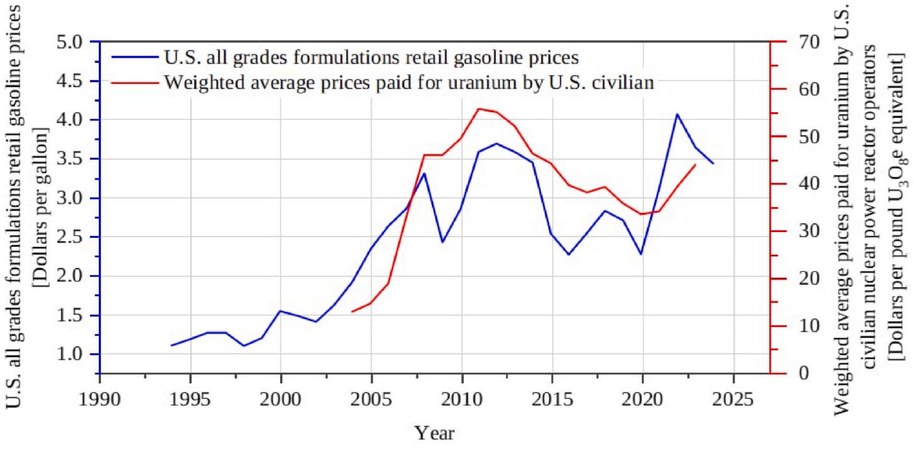

**Fig. 3.** Retail gasoline price in dollars per gallon (based on (EIA Petroleum and Other Liquids), and weighted average prices paid for uranium in dollars per pound (based on (EIA).

must also provide long operational autonomy without the need for refuelling, which is crucial for submarines and icebreakers operating in remote areas. For example, reactors in aircraft carriers of the American Nimitz class can operate for 20–25 years with a single fuel load, significantly reducing the need for frequent refuelling and associated emissions.

## 4. Methodology

### 4.1. Literature search strategy

This study employed a targeted literature review to collect relevant information on Generation IV reactors in maritime transportation. Relevant peer–reviewed articles were identified through searches in scientific databases (Scopus, Web of Science, and Google Scholar), institutional portals (e.g. International Atomic Energy Agency [IAEA], IMO, EU law database), and official technical reports of regulatory/industry portals, supplemented by citation chasing. Search strings included terms such as "generation IV reactors", "small modular reactor", “nuclear propulsion ", or “nuclear reactors”. Search strings were combined using Boolean operators (AND/OR) and adapted to the syntax of each database. The search was complemented by backward and forward citation chasing to identify additional relevant studies.

### 4.2. Inclusion and exclusion criteria

The temporal scope covered 1967–2025. Early publications (1967–2002) were used only to provide historical background and are not part of the quantitative analysis. The main analysis focused on studies from 2003 to 2025. While formally covers this full period, a particular emphasis was given on studies published in the past decade. Priority was given to peer–reviewed journal articles, technical reports, classification society or regulatory documents, and recognized industry publications.

The reviewed sources are predominantly in English, reflecting the international scope of research and regulatory discussion on nuclear propulsion in shipping. A small number of Polish–language sources, mainly industry portals and EU legal documents available in official Polish versions. These materials were used only as supportive background, while the core analysis relied on English–language, peer–reviewed publications. While the majority of scientific and technical data were drawn from peer–reviewed and official institutional publications, industry news portals and company websites were included to capture ongoing developments in nuclear reactors developments and were treated as lower–confidence evidence unless corroborated by independent reports or peer–reviewed literature.

Inclusion criteria prioritized peer–reviewed articles, official institutional reports, and authoritative regulatory or industry publications, as these offer the highest level of methodological transparency. Industry news portals and company websites were used selectively, primarily to capture recent developments not yet covered in the academic literature. Exclusion criteria were: (1) lack of methodological detail, (2) duplicated information already contained in more authoritative publications, and (3) languages other than English or Polish.

### 4.3. Data extraction and validation

The study draws on a diverse body of references, combining peer–reviewed journal articles, official institutional reports, regulatory texts, and industry publications. The core analytical material was obtained from peer–reviewed research and authoritative reports of international organizations such as the IAEA and the EU (e.g., Fit for 55 package, EU Climate Law, and Paris Agreement documentation). Supplementary information was sourced from recognized classification societies’ (DNV, Lloyd’s Register, ABS, Bureau Veritas, and ClassNK), statistical databases (e.g., Statista), industry trade press (e.g., SWZ Maritime, Baird Maritime), and selected company or research group websites (e.g., TerraPower, Politecnico di Milano – SMR Research, Newcleo).

Cost and performance data were extracted from a combination of publicly available statistical databases, energy market reports, and industry publications. Global container throughput statistics were obtained from Statista (Statista), retail gasoline prices and uranium prices were sourced from the U.S. Energy Information Administration (EIA Petroleum and Other Liquids; No Titlei n), and lifecycle cost estimates for nuclear–powered vessels were derived from industry analyses and expert assessments (e.g., Fennelly in Seatrade Maritime) (Seatrade-Maritime News).

Reported values were cross–checked across multiple independent sources when available. Values corroborated by two or more independent sources were considered robust; single–source estimates were flagged and used only qualitatively. Outliers or uncorroborated estimates were either validated against benchmarks or excluded.

### 4.4. Framework and tools

The analytical and comparative framework was based on organizing diverse data into tables and figures, allowing cost, performance, regulatory, and technical aspects to be compared on a common basis. This ensured that heterogeneous sources were evaluated consistently and transparently across propulsion technologies and ship types. Within this framework, the following analytical tools were applied: (1) a scenario–based techno–economic analysis, (2) lifecycle cost assessment for a reference vessel (25-year operation) across three propulsion options (HFO + carbon tax, SMR, green fuels), (3) multi–criteria qualitative assessment of Gen IV reactor concepts (e.g. size/mass, fuel type, refuelling interval, operational lifetime, safety systems), and (4) SWOT analysis of implementation strategies. These tools allowed consistent comparison of cost, performance, emissions, safety, and regulatory aspects across propulsion options.

The comparative analysis of Gen IV reactor technologies for marine applications used a combination of quantitative and qualitative analytical tools. The quantitative approach included a scenario-based technoeconomic analysis comparing different propulsion options. A ship life cycle cost analysis (total CapEx + OpEx) was performed for a commercial vessel (approximately 25 years of operation) in three scenarios: conventional propulsion (HFO fuel including $CO_2$ tax), nuclear propulsion (SMR reactor) and alternative propulsion with green fuel (e.g. ammonia/methanol). This analysis, based on data from the literature (including (Seatrade-Maritime News)), is illustrated in Fig. 5 and takes into account initial investments, fuel costs, and greenhouse gas emission fees. In the emission assessment, it was assumed that nuclear propulsion does not generate direct $CO_2$ emissions, while in the conventional scenario, the financial impact of the emissions was calculated by imposing $CO_2$ charges (e.g., ~$100 per ton of CO2, according to the proposed regulations). In addition, a qualitative multicriteria assessment of individual reactor concepts was carried out in terms of their suitability for different types of ships. Key evaluation criteria included, among others, the reactor’s thermal power range, its physical dimensions and weight, fuel type and refuelling frequency, expected service life, and advanced safety systems used (especially passive systems). These factors were used to determine which types of Gen IV reactors can be integrated into specific classes of ships, as shown in Table 6. Furthermore, a SWOT analysis (Appendix A) was used to assess the overall conditions of the implementation strategy, identifying key strengths and weaknesses, as well as opportunities and threats associated with the implementation of nuclear propulsion. The use of the described approaches and analytical tools ensures that the assessment of the potential of Gen IV reactors in maritime transport is comprehensive, taking into account both technical and economic aspects, as well as issues of emissions, safety, and the regulatory framework.

### *4.5. Limitations*

A limitation of the present study is the absence of a formal sensitivity analysis. While the cost and performance assessments are based on the available data for key parameters, the robustness of the results to variations in these parameters has not been systematically tested. Consequently, the outcomes reported should be interpreted as indicative under the chosen assumptions. Future work could extend the analysis by performing sensitivity tests to assess how changes in critical variables affect the comparative performance, costs, and environmental impact of alternative propulsion options.

Another limitation stems from the intended design as a review article, which makes parts of the manuscript largely descriptive. Nonetheless, the study incorporates several original analyses to complement the literature review. Specifically, reactors were categorized according to power output (Table 4) and physical size (Table 5), providing a systematic comparative perspective. In addition, a SWOT analysis was conducted for each reactor type, offering an original assessment of the strengths, weaknesses, opportunities, and threats associated with the implementation of Gen IV reactors in maritime applications. These analyses add interpretative value beyond the descriptive overview, while still aligning with the review–oriented scope of the article.

## 5. Comparison of the regulatory framework and classification requirements of selected classification societies for nuclear propulsion in shipping

Today's shipping industry faces growing pressure to adopt new propulsion technologies that improve environmental performance and energy efficiency. In this transition, classification societies play a crucial role. They not only certify and oversee the technical integrity of vessels but also develop and update safety standards for emerging technologies. By doing so, they ensure that innovative propulsion systems meet demanding technical, operational, and environmental requirements (Voroniuk, 2024). Currently, there are no uniform international standards governing the use of nuclear propulsion in civil shipping. To facilitate the safe introduction of nuclear technologies in the maritime sector, the International Atomic Energy Agency (IAEA) will initiate the Atomic Technologies Licensed for Applications at Sea (ATLAS) project in 2025. The initiative aims to establish a comprehensive international framework for civil nuclear applications in shipping, in close collaboration with the International Maritime Organization (IMO). Each of the leading classification societies develops its own guidelines and procedures, often in close cooperation with national nuclear regulators and the flag administration (Kim et al., 2024a). This situation leads to discrepancies in requirements for safety, crew certification, waste management or emergency procedures, which is a significant barrier to the widespread implementation of nuclear propulsion in commercial shipping (Wang et al., 2023a). Classification societies play a pivotal role in the certification of nuclear–powered vessels, ensuring compliance with technical, safety and environmental requirements (Nersesian and Mahmood, 2010). Each of the leading societies has its own history, specialisation and approach to implementing innovative propulsion technologies.

**Det Norske Veritas (DNV)** is a Norwegian classification society and one of the largest and most recognized in the world. It specializes in developing technical standards for shipping, energy, and offshore industries. DNV is actively involved in research projects on alternative propulsion, including nuclear, and promotes international cooperation in developing new regulations.

**Lloyd's Register (LR)** is a UK–based global society with a long–standing tradition in the classification of ships and marine infrastructure. LR is known for its rigorous assessments of regulatory compliance and for conducting risk analyses for nuclear–powered vessels. It also takes part in initiatives aimed at adapting existing standards to new technologies.

**American Bureau of Shipping (ABS)** is a U.S. classification society that leads in developing detailed requirements for floating nuclear power plants and nuclear–powered vessels. ABS publishes its own standards covering safety, nuclear system design, and radiological protection, and works closely with nuclear regulators to support new developments.

**Bureau Veritas (BV)** is a French classification society active in qualifying new reactor technologies and analyzing their applications in shipping. BV participates in international research projects, assesses the adequacy of existing standards, and supports the development of guidelines for innovative propulsion systems.

**ClassNK (Nippon Kaiji Kyokai)** is a Japanese classification society and one of the largest in Asia. ClassNK monitors the development of alternative propulsion systems, including nuclear, and publishes guidelines for new technologies. It places particular emphasis on aligning national regulations with the specific requirements of nuclear propulsion and maintains close cooperation with state administrations and regulators.

The cooperation of these societies with state authorities and nuclear regulatory bodies is essential to ensure regulatory consistency, a high level of safety, and public acceptance of nuclear propulsion in civil shipping (Schøyen and Steger-Jensen, 2017).

Table 2 provides a comparison of the activities of selected classification societies with regard to regulations and standards for ship nuclear propulsion. It considers the regulatory framework in place or under development, the special guidelines and standards available, the degree of cooperation with government authorities, as well as the specific challenges and considerations related to the development of this technology.

The implementation of nuclear propulsion in civil shipping requires not only advanced technology, but above all a consistent and precise regulatory framework. An analysis of the approach of selected classification societies (DNV, LR, ABS, BV, ClassNK) reveals significant differences and gaps in key areas (Sims and Dowling, 2025). In terms of safety, the societies define requirements for reactor safety systems, the degree of safety redundancy and passive emergency systems differently. ABS has the most detailed guidelines, for example for Floating Nuclear Power Plants, while DNV and ClassNK focus mainly on case studies and general guidelines, emphasising the need for further regulatory development. Differences also include the approach to risk assessment and the integration of safety systems into ship design (Adumene et al., 2022).

Regarding waste management, there are currently no uniform standards for the storage and transport of radioactive waste on ships. ABS and BV include detailed procedures for this in their documents, while DNV and ClassNK indicate the need to develop such guidelines in the future. Differences in waste reporting and monitoring requirements are also apparent. In the area of radiological protection, the requirements of the various societies for crew and environmental protection are divergent. Some, like ABS, introduce detailed standards, others limit themselves to general recommendations. Requirements for radiation monitoring systems and emergency procedures in case of contamination also vary. There is currently no uniform system for the training and certification of crews operating nuclear–powered vessels. Requirements for qualification, training and emergency response vary from company to company and from flag state to flag state. An additional problem remains the lack of international recognition of certificates. In the case of emergency procedures, there are noticeable differences in their detail, including evacuation plans, crisis management and communication with port and state authorities. ABS and LR are developing detailed scenarios in this area, while DNV and ClassNK highlight the need for further development and harmonization of these arrangements.

Based on the analysis of sources (Voroniuk, 2024; Kim et al., 2024a; Wang et al., 2023a; Nersesian and Mahmood, 2010; Schøyen and Steger-Jensen, 2017; Sims and Dowling, 2025; Adumene et al., 2022) it is evident that there are significant shortcomings in the comprehensive international regulation of nuclear propulsion in civil shipping.

**Table 2**
Comparison of the classification societies' approach to nuclear propulsion. ABS – American Bureau of Shipping, ClassNK – Nippon Kaiji Kyokai, DNV **–** Det Norske Veritas.

| Classification society | Regulatory framework for nuclear propulsion | Specific guidelines/standards | Cooperation with state authorities | Specific challenges/remarks |
|---|---|---|---|---|
| DNV | No dedicated framework, work on guidelines in progress | Case studies, reports, forecasts | Yes | Need for new international regulations and harmonization of rules |
| Lloyd's Register | Assessment of existing regulations, studies | Regulatory Assessment Studies, Nuclear Code | Yes | Legal changes required, adaptation to new technologies, close cooperation with flag administration and regulatory bodies |
| ABS | Detailed requirements for Floating Nuclear Power Plant and offshore units | ABS Rules for Floating Nuclear Power Plants | Yes | Cooperation with nuclear regulators, need to integrate classification requirements with national and international regulations |
| Bureau Veritas | Technology analysis, participation in pilot projects | Guidelines for new technologies, innovation qualification | Yes | Qualification of new solutions, assessment of compliance with international and local standards |
| ClassNK | Monitoring developments, general guidelines | Guidelines for alternative fuels, Energy Efficiency Design Index | Yes | Adaptation of national regulations, need to update guidelines for nuclear propulsion |

Significant fragmentation and lack of harmonization of requirements in key areas such as operational safety, radioactive waste management and radiological protection of crew and the environment were identified. The unregulated system of crew training and certification, as well as the mutual recognition of qualifications at international level, also remains a major challenge. Differences in the approach of the various classification societies to emergency procedures and crisis management further highlight the need for consistent global guidelines. It therefore appears necessary to take coordinated action at an international level to establish uniform standards covering both technical and organisational aspects, including rules of cooperation with the nuclear regulators and the flag administration.

International rules set by organizations like the IMO, IAEA, and the European Union provide the overarching legal and policy frameworks guiding decarbonization and the safe use of nuclear propulsion at sea. However, these high–level regulations must be translated into detailed technical and operational standards before they can be applied to specific vessels. This is where classification societies become essential: they serve as the operational link between global regulatory goals and the practical design, certification, and operation of ships.

The main classification societies, such as ABS, DNV, Lloyd's Register, BV, and ClassNK, interpret international rules and adapt them into class–specific requirements. These organizations provide shipowners, designers, and regulatory authorities with practical procedures covering safety systems, waste handling, radiological protection, and crew training—ensuring thorough operational readiness for nuclear propulsion.

By harmonizing global policy with class–based standards, classification societies make it possible to move from regulatory intentions to concrete implementation within the shipping industry. This integration is crucial for gradual adoption of Gen IV nuclear propulsion, enabling practical progress while maintaining compliance and safety. Fig. 4 illustrates the roadmap for implementing Gen IV nuclear propulsion, moving from international legal frameworks through classification society standards and harmonization initiatives to practical deployment on vessels.

The roadmap (Fig. 4) provides a clear direction for adopting Gen IV nuclear propulsion in shipping, but it also highlights several important challenges that need to be solved for successful rollout. Among the most pressing issues are the lack of unified standards for handling radioactive waste, inconsistent rules for radiological safety, and the absence of widely accepted systems for crew training and certification.

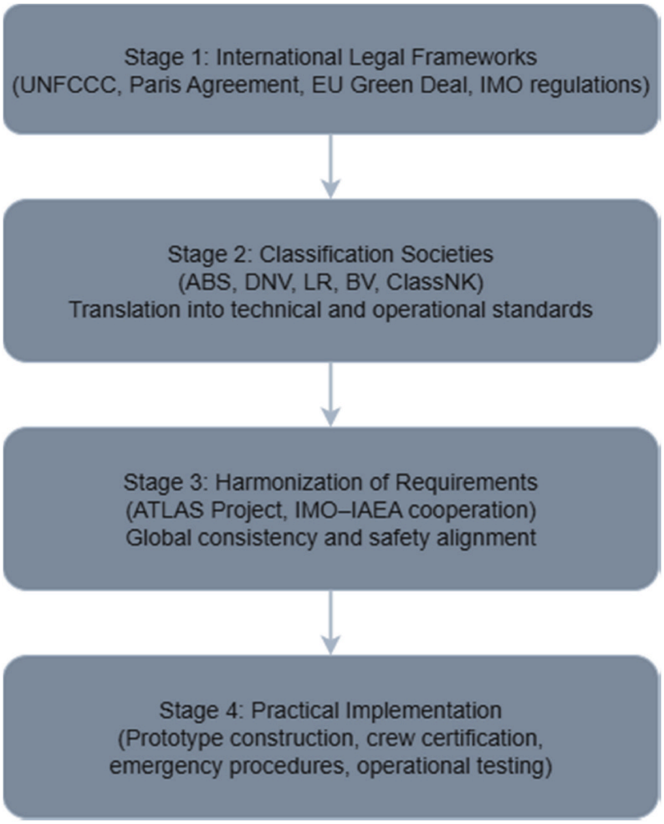

**Fig. 4.** Roadmap for the implementation of Gen IV nuclear propulsion in maritime transport, illustrating the transition from international legal frameworks through classification societies and harmonization initiatives to practical shipowner–level deployment. UNFCCC – United Nations Framework Convention on Climate Change, EU – European Union, IMO – International Maritime Organization, ABS – American Bureau of Shipping, ClassNK – Nippon Kaiji Kyokai, DNV **–** Det Norske Veritas, ATLAS – Atomic Technologies Licensed for Applications at Sea, IAEA – International Atomic Energy Agency.

## 6. Design and safety considerations for nuclear–powered ships

Designing nuclear–powered ships requires a distinct approach that accounts for both the technical complexity of nuclear systems and the unique constraints of the maritime environment. Safety remains a central concern, influencing decisions at every stage of design, construction, and operation. This chapter examines two critical aspects: the feasibility of adapting existing vessels for nuclear propulsion versus building new, dedicated designs, and the role of passive safety mechanisms in ensuring reliable operation under marine conditions.

### 6.1. *Evaluation of retrofitting existing ships with nuclear systems versus purpose–built new designs*

The use of nuclear reactors to power ships has a history, primarily in

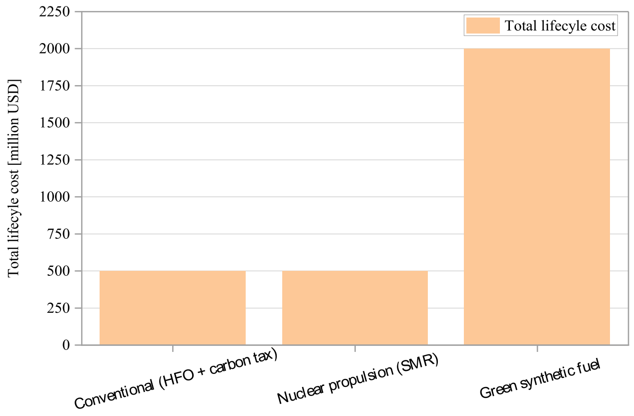

**Fig. 5.** Comparison of indicative life–cycle costs (CapEx + OpEx, ∼25-year horizon) for a Newcastlemax–class vessel: conventional propulsion (HFO + carbon tax), nuclear propulsion (SMR), and a variant using green synthetic fuels. Data: Seatrade Maritime, after W. Fennelly/Core Power. Independently, the IEA indicates that synthetic fuels are currently 4–6 × more expensive than fossil fuels, which explains the differences shown (Seatrade-Maritime News; Projected Costs of Generating Electricity, 2020). CapEx - capital expenditure, HFO – heavy fuel oil, SMR - small modular reactor, OpEx - operating expense.

specialized vessels such as icebreakers. The first nuclear–powered vessels, introduced in the 1950s, were specifically designed from the outset to integrate nuclear reactors. It is estimated that several hundred marine reactors are still in operation at present. It is noteworthy that all of these vessels were constructed as nuclear prototypes from the outset, frequently for research purposes rather than purely commercial ones. None of these vessels were built through the conversion of an existing vessel, thereby indicating that the practice of retrofitting conventional vessels to nuclear power has not been conducted to date.

However, in light of the ongoing efforts to decarbonize shipping, there has been a renewed focus on next–generation nuclear reactors, such as small modular reactors (SMRs), as a zero direct emission source of energy for maritime vessels. The question that must be addressed is whether it is preferable to convert existing ships to nuclear propulsion or to construct new vessels from the ground up with a reactor. The following section outlines a hypothetical course of action concerning the conversion of existing vessels.

The design of a reactor vessel from the ground up facilitates optimal nuclear system layout and integration. The vessel's hull, propulsion system, and safety systems can be designed specifically for the reactor, e.g., the design can ensure adequate space for biological shielding, cooling, and emergency systems. Consequently, a new ship can be designed so that the heavy reactor is in the optimal position (e.g., centrally or below the waterline) for stability. Additionally, double bulkheads and safety shields can be utilized around the reactor.

Retrofitting an existing vessel (i.e., installing a reactor in an already built vessel) poses substantial engineering challenges. First of all, it is necessary to fit the reactor into the engine room space originally designed for internal combustion engines. This involves rebuilding the hull structure – such as cutting out sections to accommodate the reactor and auxiliary systems – and reinforcing the structure to support the weight of the reactor and its shielding. Mass distribution is a significant problem: a reactor with shields can weigh significantly more than a conventional engine with fuel, potentially compromising the vessel's stability and maneuverability. Furthermore, the reactor would most likely need to be installed where the original engines were located (usually the aft part of the hull), leading to a concentration of substantial mass at the stern.

The nuclear safety industry has issued a series of additional demands. The converted ship must undergo retrofitting to incorporate all the requisite safety systems for a nuclear unit. These systems include, but are not limited to, emergency reactor cooling mechanisms, radiation detection systems, and biological shielding for the crew. The integration of nuclear power into shipping can face significant challenges related to safety, regulation, and public acceptance. Retrofitted ships are likely to encounter difficulties in meeting the rigorous safety and environmental standards required for nuclear systems, particularly if the original design did not account for such integration. Conversely, purpose–built nuclear vessels can be designed to better align with current regulatory requirements; however, progress in these standards is essential to enable a more efficient and transparent licensing process. To support safe deployment, the International Atomic Energy Agency (IAEA) will launch the Atomic Technologies Licensed for Applications at Sea (ATLAS) project in 2025 (Lloyd's Register). Its objective is to develop a global framework for civil maritime nuclear applications, in cooperation with IMO. Notably, concerns regarding safety and public acceptance present significant challenges for passenger ships, particularly in the context of adopting nuclear propulsion. Achieving public trust in the reliability of protective systems is of pivotal importance. Therefore, the utilization of Gen IV reactors equipped with self–protection systems is recommended to mitigate public concerns.

It is important to note that the durability and life cycle of a nuclear reactor differ significantly from those of typical marine engines. Modern reactors have been demonstrated to operate for up to 20–30 years without replacing fuel, whereas the lifespan of a standard commercial ship is approximately 25–30 years. Lloyd's Register (Nuclear Engineering International) predicts that if nuclear propulsion becomes widespread, the design life of hulls could extend up to ∼50 years. This means, however, that refitting an older vessel may not be economically viable for technical reasons – a 10-year–old vessel, for example, has ∼15 years of service ahead of it, and an installed reactor could operate longer. In that case, either the reactor would be used below potential (ending its life along with the hull), or it would have to be removed later and transferred to a new ship, an extremely complex and expensive operation. Consequently, numerous experts have emphasized that it is more rational to construct new vessels equipped with reactors rather than to retrofit existing vessels with these systems. As Giulio Gennaro of Core Power observes, the cost of the reactor itself is so substantial that the cost of the hull becomes secondary. Utilizing an existing unit with a low residual value does not result in significant savings, and it carries inherent risks and technical limitations (Seatrade-Maritime News).

While retrofitting is technically feasible, as are other major structural modifications, such as ship lengthening, it may prove impractical in real–world applications due to limited economic justification. It appears that the initial commercial nuclear–powered ships will be newly constructed vessels. The feasibility of converting existing vessels depends on the technological efficacy of the solution. Candidate ships for such conversions include power–intensive offshore vessels, such as specialized cable, service, and deep–sea fishing vessels, which already demand high power and extended operational autonomy. These types of vessels are particularly well–suited for the implementation of small modular reactors (SMRs), as they could operate for prolonged periods without the need for frequent refuelling or port calls (IEEE Spectrum).

The cost of the initial investment is the biggest barrier to nuclear propulsion, regardless of whether the context is the retrofitting of an existing vessel or the construction of a new one. The construction of a nuclear reactor, including the installation of nuclear fuel, is an investment that can reach hundreds of millions of dollars. Analyses indicate that for a large commercial vessel (e.g., a Newcastlemax bulk carrier or a 14,000 TEU container ship), the total capital and operating expenditure over the life cycle (∼25 years) for the nuclear option could be around $500 million (Seatrade-Maritime News). It is noteworthy that a comparable conventional vessel would consume a similar sum, approximately $500 million, over this period, if the following factors are considered: the construction cost (∼$60 million), fuel costs, and emission fees (with a bunker price of about $600/t and a carbon tax of $100/t). Conversely, the utilization of environmentally sustainable fuels, such as ammonia and methanol derived from synthesis, has the potential to escalate total expenditures up to fourfold, with estimated costs reaching approximately $2 billion per vessel. Consequently, from the perspective of a shipowner, the implementation of nuclear propulsion has the potential to achieve cost–effectiveness in comparison to conventional propulsion, particularly in the context of the forthcoming implementation of stringent $CO_2$ emission fees.

Fig. 5 compares life–cycle costs (capital expenditure [CapEx] + operating expense [OpEx]) for a Newcastlemax over about 25 years across three propulsion options. In the Core Power estimate (reported by Seatrade Maritime), a conventional ship totals around USD 500 million: roughly USD 60 million for the hull, fuel priced at about USD 600/t, and a carbon charge near USD 100/t $CO_2$. The nuclear SMR case lands in a similar range—about USD 100 million for the hull, USD 150 million for the reactor, and USD 250 million for the fuel inventory, again close to USD 500 million in total. Switching to green synthetic fuels drives the bill to roughly USD 2 billion ($\approx 4\times$ higher). That order–of–magnitude gap is consistent with independent IEA reviews that put synthetic–fuel production costs at roughly 4–6 × those of conventional fuels, which translates into markedly higher operating costs for ships that use them.

From an economic perspective, the retrofitting of an existing ship with nuclear propulsion systems offers minimal financial benefits. The only major potential saving lies in avoiding the cost of a new hull, which is estimated to range from $60 to $100 million. This is due to the fact that the hull, engine room, and ship systems must undergo comprehensive upgrades, and the entire certification process, equivalent to that of a newly constructed ship, must be undertaken. Furthermore, the value of a vessel diminishes over time, and by the end of its operational life, the ship's residual value is often negligible. Consequently, it is difficult to justify an investment potentially amounting to hundreds of millions of dollars in the retrofitting of aging vessels. As highlighted in the research (Peakman et al., 2019), the financial expense associated with the construction of the hull in the context of nuclear–powered ship design is comparatively minimal when viewed in relation to the overall cost of the vessel. This observation prompts a critical examination of the economic viability of adapting conventional ships to accommodate SMR reactor vessels. It may be more financially beneficial to initiate the design and construction of a new vessel from the ground up.

Considering these economic factors, the construction of a new nuclear–powered vessel entails a higher initial cost but enables the effective utilization of the reactor's full capabilities over the vessel's lifespan. The retrofitting of an existing vessel does not eliminate the financial expenditure required for the reactor; rather, it merely reduces the cost of the hull, which constitutes a negligible portion of the overall budget and seldom justifies the benefits offered by a new design. In light of the expected increase in alternative fuel prices and emissions–related charges, nuclear propulsion has the potential to emerge as the most cost–effective zero direct emission solution for shipping, provided that regulatory and social barriers can be overcome. The logical starting point appears to be the construction of a prototype nuclear–powered vessel. Further development could follow as technological advances and standardization of shipboard reactors allow for a gradual fleet expansion, potentially including the conversion of select modern vessels. Although conversion is technically feasible, retrofitting is clearly outperformed by new designs in terms of both engineering (e.g., enhanced integration and safety) and economic aspects (e.g., optimal investment efficiency).

### 6.2. *Passive safety strategies from a marine engineering perspective*

Gen IV reactors inherently feature passive safety systems; however, when these reactors are installed on various types of vessels, additional passive safety measures can be implemented during the design phase, particularly through marine engineering approaches. In such cases, these systems may address failure risks resulting from, for instance, collisions with other ships, explosions, or groundings (HDIAC). To effectively employ passive safety systems, the design process must begin with the ship's hull structure. Since reactors are typically located in the part that has double walls, it is crucial to reinforce the double hull structure, which is designed to absorb impact energy in the event of a collision (Jurewicz et al., 2014). Furthermore, the construction process should incorporate high–strength steels with enhanced resistance to cracking and deformation. Ideally, the reactor should be positioned in the central and most protected part of the hull to minimize the effects of side damage (SWZ|Maritime).

The next step involves ensuring the structural integrity of the entire vessel. The next step involves ensuring the structural integrity of the entire vessel. This includes designing the space surrounding the reactor in a way that enables controlled deformation under impact, thereby absorbing the energy of the incident and minimizing, or ideally eliminating, the amount that reaches the reactor (Lee et al., 2013). Additionally, anti–shock systems may be employed due to the vessel's potential operation in varying weather conditions. The use of shock absorbers and similar devices helps reduce vibrations.

When designing the vessel, it is important to consider the reactor's passive safety systems. This includes, among other things, passive cooling mechanisms that do not rely on electricity to power pumps. Automatic reactor shutdown can be achieved through the use of materials with a positive temperature coefficient of reactivity, meaning that as temperature increases, the reactor power decreases. The incorporation of passive safety systems into reactors and vessels design is crucial for ensuring safety during emergency scenarios such as collisions, onboard fires, or groundings. Therefore, the integration of knowledge from both nuclear and marine engineering is essential for the safe and reliable operation of nuclear reactors as marine propulsion systems.

## 7. Gen IV reactors as ship propulsion

Gen IV reactors represent the most advanced nuclear technology, offering enhanced electricity production with superior safety measures (Şahin and Şahin, 2021). Gen IV reactors are divided into several types. Most Gen IV reactors are highly efficient, generating more energy from the same amount of fuel compared to earlier solutions (Adumene et al., 2022), which reduces the need for frequent fuel replacement, which is critical for ship propulsion. Equipped with innovative active and passive safety systems, Gen IV reactors ensure safer operation (Kowalczyk et al., 2016). Passive systems, which are based on natural processes such as convection or gravity, function automatically without electrical power or human intervention, minimizing the risk of human error. These features are particularly valuable for ships operating far from land, where reliable and long–lasting safety systems are essential.

Some Gen IV reactors produce less radioactive waste than earlier generation reactors, reducing storage costs and boosting shipowners' profits. Although the installation of nuclear reactors is initially expensive, the costs decrease over time. Shipowners can also profit from selling green certificates by meeting $CO_2$ reduction targets, making nuclear powered ships zero–emission and key to sustainable maritime transport. Nuclear reactors also take up less space in the engine room of ships (Fig. 6), which generates more space for transported goods, increasing the potential profit of the shipowner. This is particularly visible in small modular reactors (SMRs) (Houtkoop et al., 2022). Examples of commercial solutions for reactors in the ship industry are presented in Table 3.

In addition to the classification by technology type presented in Table 3, Gen IV reactors can also be categorized based on criteria such as thermal power output or physical size. When classified according to thermal power, reactors are divided into three categories: small, medium, and large units, as illustrated in Table 4. Another classification system is presented in Tables 5 and 6. This system is based on physical dimensions and is further subdivided into categories of small, medium, and large reactors. It is important to acknowledge that reactors with equivalent power output can vary considerably in size, attributable to

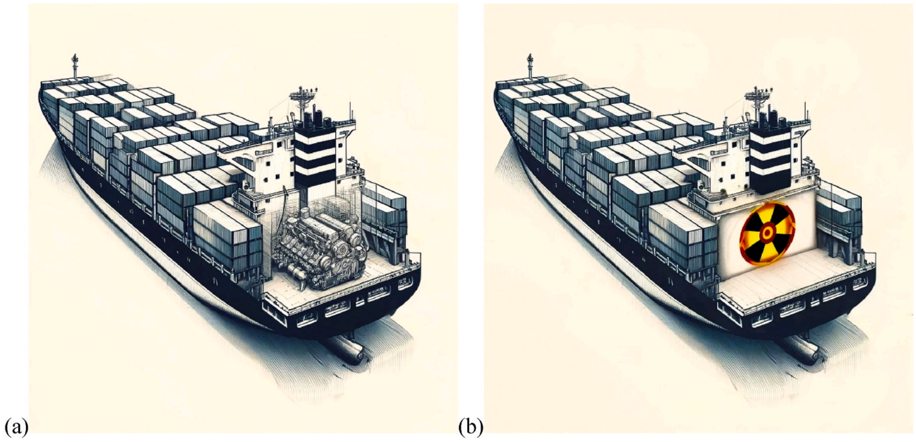

**Fig. 6.** Schematic view with two different sources of energy on the ship a) classical diesel engine and b) using reactor.

factors such as the type of coolant employed and the safety systems. A significant feature of many Generation IV reactor designs is their emphasis on modularity, a characteristic that enables the customization of power output to suit particular operational requirements. In the context of maritime applications, small and compact Gen IV reactors appear to be the most promising, while larger reactors may be suitable for deployment on floating platforms or as stationary power sources for coastal infrastructure. Examples of different types of ships on which it is proposed to use reactors are shown Fig. 7.

Gen IV reactors can use TRISO nuclear fuel (Forsberg, 2024), composed of 6 cm diameter balls (Wang et al., 2023b) with a core surrounded by four protective layers (Fang and Di Fulvio, 2023). This fuel is known for its stability and safety (Recuero et al., 2024) remaining resilient even at temperatures exceeding 1600 °C, making it suitable for VHTR and High Temperature Gas cooled Reactors (HTGR) (Gulden et al., 2017). The layered structure ensures mechanical and chemical stability, preventing radioactive leakage (Powers and Wirth, 2010). Even in the event of a reactor failure, TRISO fuel maintains its integrity, minimizing environmental risks.

In addition to TRISO fuel, some types of reactors can use thorium as fuel, which is found in mixed oxide (MOX) fuel (Crawford et al., 2007), as an alternative to the commonly used uranium (Jie et al., 2024). Thorium offers advantages such as shorter–lived waste and greater availability worldwide. These reactors demonstrate that thorium can be a viable alternative to traditional fuels for ships.

The Gen–IV Forum has set eight technological goals in four areas: sustainability, economics, safety, and proliferation resistance. In the context of maritime reactors, long–term operation without fuel reloading and a closed fuel cycle, which reduces waste but leads to actinide accumulation requiring long cooling, are important. A key challenge is the implementation of MOX fuel, as its onboard processing requires sophisticated systems, increasing the weight of the vessel and complicating logistics. LFR–type reactors, burning actinides during operation, may be a solution, but their implementation depends on advances in research into corrosion–resistant materials (Driscoll and Hejzlar, 2005). The cost–effectiveness of Generation IV systems is expected to come from standardisation and the use of passive safety systems, with safety provided by new materials resistant to extreme conditions. Proliferation is countered by denatured fuels and systems that prevent the recovery of fissile materials (Salvatores and Knebel, 2009).

### 7.1. *Very high temperature reactor*

Very high temperature reactors (VHTRs) are advanced Gen IV reactors (Kim et al., 2008), designed to replace the HTGRs (Kowalczyk et al., 2016). HTRG are graphite–moderated, helium–cooled systems developed primarily in the 20th century as precursors to VHTRs (Li et al., 2025). They typically achieve outlet temperatures between 750 °C and 950 °C (Qin and Strydom, 2025). It is lower than the temperature envisioned for VHTRs, yet still considerably higher than in conventional nuclear reactors. By employing TRISO fuel and graphite moderation, HTGRs serve as a base technology toward the more advanced VHTR designs.

VHTR can operate at very high temperatures, ranging from 700 °C to 1000 °C, allowing greater thermal efficiency (up to 50 %) in electricity production (Hoffelner, 2005). In VHTR systems, graphite is used as a moderator (Takamatsu and Hu, 2015), which slows fast neutrons, making it possible to maintain the chain reaction necessary to generate energy. In this case, graphite must be stable at high temperatures (Gutowska et al., 2023). The reactor core can be a prismatic block or a piled bed, with TRISO fuel used in the latter (Ji and Martin, 2007).

VHTRs use helium as a coolant (Halsted and Gutowska, 2023), which is chemically inert, nonflammable (Gutowska et al., 2019), and noncorrosive, extending the useful life of materials (Zhou et al., 2024). Most importantly, helium does not become radioactive under radiation, ensuring greater safety for those onboard ships. VHTRs also feature passive safety systems, which allow cooling in emergencies without external power or human intervention (Wang et al., 2023b).

Considering financial aspects, these reactors have a great advantage in the form of efficient use of nuclear fuel for energy production, which results in lower purchase costs. Furthermore, the high temperature that allows the purchase of this reactor can allow the process of desalination of seawater, which can be used effectively in floating facilities. The VHTR has a higher fuel burn–up than previous–generation reactors (Ion et al., 2004).

VHTRs can operate with either a direct cycle using a gas turbine or an indirect cycle with a steam or gas turbine (Głuch et al., 2024). The direct cycle offers a simple design that enhances reliability and is commonly used because of its high efficiency at elevated temperatures. However, it has the drawback of potential contamination of the non–nuclear components by radionuclides carried with helium (Klisińska). To address the radioactivity of helium in the direct cycle, a purification system is installed to remove undesirable elements (Kugeler et al., 2017). The direct cycle is also more efficient than the indirect cycle as a result of the higher temperature of the medium at the turbine inlet. In contrast, the indirect cycle is more complex and requires additional components (Dostal et al., 2004). Furthermore, nuclear reactors are more energy efficient than traditional internal combustion engines, leading to lower energy consumption per unit of distance travelled (Patel, 2024). Examples of VHTRs in development are shown in Table 3.

### 7.2. *Small modular reactor*

Another example of a Gen IV reactor is the small modular reactor

**Table 3**

Examples of current reactors under development. GFR – gas–cooled fast reactor; HTGR – high–temperature gas–cooled reactor; IPWR – integral pressurized water reactor; LFR – lead–cooled fast reactor; LMCFN– Liquid metal–cooled–fast–neutron; LMFR – liquid metal fast reactor; MCFR – molten chloride fast reactor; MSR – molten salt reactor; SCWR – supercritical water–cooled reactor; SFR – sodium–cooled fast reactor; SMR – small modular reactor; VHTR – very high–temperature reactor.

| Type Gen IV | | Coolant | Project | Company | Number of modules | Power [MWe] | Operating status |
|---|---|---|---|---|---|---|---|
| HTGR and VHTR (Wu et al., 2023b; Berens et al., 2024; Fütterer et al., 2014; Demick, 2011; Gauthier et al., 2006) | | Helium | Xe –100 | X –Energy | 1 | 80 | Current |
| | | Helium | HTR –PM | CNNC, Tsinghua University | 2 | 210 (1 module 105) | Current |
| | | Helium | GT –MHR | General Atomics, Rosatom | 1 | 285 | Closed |
| | | Helium | ANTARES | Framatome | 1 | 300 | Closed |
| | | Helium | NGNP | Idaho National Laboratory, DOE | 1 | 600 | Closed |
| | | Helium | GTHTR300/ GTHTR300C | Japan Atomic Energy Agency | 1 | 274–300 | Conception |
| SMR (Rzymkowski, 2022; Politecnico di Milano, Nuclear Reactors Group; Baird Maritime; Hoque et al., 2018; Rowinski et al., 2015; Black et al., 2019; Ghandour and Francis, 2025; Shirvan et al., 2016; Toshinsky and Petrochenko, 2012; Silva et al., 2023; Boyarinov and Fomichenko, 2011) | *IPWR* | Water | CAREM–25 | CNEA Argentina | 1 | 27 | Suspended |
| | *IPWR* | Water | IRIS | Westinghouse Electric | 1 | 125 | Closed |
| | *HTGR* | Helium | PBMR | Eskom | 1 | 165 | Suspended |
| | *HTGR* | Helium | HTR–PM | INET Tsinghua University | 2 | 210 | Current |
| | *HTGR* | Helium | GT–MHR | General Atomic US. | 1 | 285 | Closed |
| | *LMFR* | Lead | Newcleo SMR | Newcleo | Modular (varies) | 120–129 | Suspended |
| | *LMFR* | Metal | SVBR–100 | AKME–Engineering Co. | 1 | 101 | Closed |
| | *LMFR* | Metal | PRISM | GE Nuclear Energy US. | 4 | 1244 | Closed |
| | *PWR* | Water | ACP100 | China National Nuclear Corporation | 1 | 125 | Current |
| SFR (Alrammah, 2022; Eliseev et al., 2016; Yamamoto et al., 2020; Panizo et al., 2024; Loewen et al., 2018; Kato et al., 2022; IAEA ARIS) | | Sodium | MBIR (experimental SFR) | Rosatom | 1 | 150 | Current |
| | | Sodium | S–PRISM | GE Hitachi | Modular (varies) | 311 | Conception non realize |
| | | Sodium | PFBR | Indira Gandhi Centre for Atomic Research | 1 | 500 | Current |
| | | Sodium | JSFR | Japan Atomic Energy Agency | 1 | 600 | Closed |
| | | Sodium | ASTRID | CEA (France) | 1 | 600 | Closed |
| | | Sodium | BN –1200 | Rosenergoatom | 1 | 1200 | Current |
| | | Sodium | Natrium | TerraPower and GE Hitachi | 1 | 345 | Currently under construction |
| | | Sodium | ARC–100 | ARC Clean Technology and GE Hitachi | 1 | 100–200 | Current |
| | | Sodium | 4S | Toshiba and Central Research Institute of Electric Power Industry | 1 | 10 or 50 | Current– new concept |
| MCFR (TerraPower; Mausolff et al., 2021) | | Molten chloride | Future | TerraPower | 1 | 500 | Current |
| MSR (IAEA ARIS; Deol and Gabbar, 2015; Ma et al., 2019; Krepel and Kramer, 2024; Dana et al., 2024; Zhu and Yan, 2024; Liu et al., 2020; Dunn, 2024; Mishra et al., 2024) | | Molten salt | MSRE (research project) | US. (ORNL–Oak Ridge National Laboratory) | 1 | 7 | Closed |
| | | Molten salt | TMSR–LF1 | CNNC (China National Nuclear Corporation) | 1 | 373 | Current |
| | | Molten salt | Flibe Energy LFTR (Liquid Fluoride Thorium Reactor) | Flibe Energy | 1 | 100–200 | Current |
| | | Molten salt | Seaborg | Seaborg Technologies | Modular | 200 | Current |
| | | Molten salt | IMSR | Terrestrial Energy | Modular | 80–400 | Current |
| | | Molten salt | CorePower | CorePower | Modular | ~50–200 | Current |
| | | Molten salt | Copenhagen Atomics | Copenhagen Atomics | Modular | ~20–100 (est.) | Current |
| | | Molten salt | FLEX Reactor | MoltexFLEX | Modular | 24 | Current |
| | | Molten salt | ThorCon | ThorCon Power | Modular | 250 | Current |
| LFR (IAEA ARIS; Alemberti et al., 2020; Gol'din and Pestryakova, 2014; Alemberti et al., 2011; Grasso et al., 2014; Fedorovich et al., 2022) | | Lead | ALFRED (Advanced Lead–cooled Fast Reactor European Demonstrator) | Ansaldo Nucleare in collaboration with SCK CEN, ENEA (Italy) and RATEN–ICN | 1 | 300 | Current |
| | | Lead | BREST–OD–300 | Rosatom | 1 | 300 | Current |
| | | Lead | European Lead Fast Reactor | EURATOM, FZJ (Forschungszentrum Jülich), SCK–CEN | 1 | 600 | Current – new concept |
| | | Lead | Gen4 Module | Gen4 Energy Inc. | Modular | 25 | Current |
| | | Lead–bismuth | Electra (European Lead Cooled Training Reactor) | Kungliga Tekniska Högskolan | 1 | 0 | Non active |
| GFR (van Rooijen and Kloosterman, 2009; Moses, 2010) | | Helium | GFR –600 | French Alternative Energies, Atomic Energy Commission and EURATOM | 1 | 600 | Non active |

(*continued on next page*)

**Table 3** (*continued*)

| Type Gen IV | Coolant | Project | Company | Number of modules | Power [MWe] | Operating status |
|---|---|---|---|---|---|---|
| | Helium | Fast Modular Reactor | General Atomics | Modular | 50 | Current |
| | Carbon dioxide | Supercritical CO2 cooled Fast Reactor (SCO2–FR) | Westinghouse | 1 | 300 | Non active |
| SCWR (Wu et al., 2022; Muritala et al., 2013; Kryková et al., 2021; Edwards and Leung, 2022) | Supercritical water | EU SCWR | European Union Collaborators (Various) | 1 | 1200 | Non active |
| | Supercritical Light Water | HP–LWR (High Performance LWR) | KIT and partners | Modular | 25 | Closed |
| | Supercritical water | Nuclear Innovation South | General Electric, Westinghouse, DOE | 1 | 1000–1500 | Non active |

**Table 4**
Gen IV reactor power classification. LFR – lead–cooled fast reactor; MSR – molten salt reactor; SCWR – supercritical water–cooled reactor; SFR – sodium–cooled fast reactor; SMR – small modular reactor; VHTR – very high–temperature reactor.

| Reactor type | Power range [MWt] | Example of a Gen IV reactor | Key features |
|---|---|---|---|
| Low thermal power reactor (Umezu, 2023; Omar et al., 2022; Zheng et al., 2018) | <1000 | – **LFR (small)** – SEALER<br>– **NuScale** SMR<br>– **MSR (small)**<br>–ThorCon Mini | – Compact, often modular<br>– Easier to transport and install<br>– Less space required<br>– Very long fuel cycles<br>– Can be used on submarines |
| Medium thermal power reactor (Bushnag et al., 2024; Ma et al., 2021) | from 1000 to 2000 | **– VHTR**<br>– **SFR (medium)** – BN–600<br>– **MSR (medium)** – Moltex SSR–W | – Use on research vessels where there is a high demand for power |
| High thermal power reactor (Bertrand et al., 2021; Guenadou et al., 2024; Alnassar and Galahom, 2024; Tassone et al., 2024; Syarifah et al., 2024) | >2000 | – **SFR (high)** – ASTRID<br>– **SCWR** – Project Canadian SCWR<br>– **LFR (high)** – ELFR<br>– **MSR (high)** – Fuji MSR | – High energy efficiency<br>– Can be used to produce energy on ships as floating power plants<br>– Greater technical requirements and cooling<br>– Can be used offshore |

**Table 5**
Comparison Gen IV reactors by size. GFR – gas–cooled fast reactor; LFR – lead–cooled fast reactor; MSR – molten salt reactor; SCWR – supercritical water–cooled reactor; SFR – sodium–cooled fast reactor; SMR – small modular reactor; VHTR – very high–temperature reactor.

| Reactor size | Example of Gen IV | Characteristic | Type of ship with the possibility of using a reactor |
|---|---|---|---|
| Small (compact) (Dong et al., 2025; Susyadi et al., 2024) | – HTR–PM (modular)<br>– NuScale<br>– LFR SEALER | – Due to their dimensions of up to several meters, they are suitable for modular transport | – Icebreakers – Special vessels, e.g. research vessels<br>– Floating power plants |
| Medium (scale) (Afsharipour et al., 2024) | – MSR (medium)<br>– VHTR<br>– Moltex SSR–W | – Larger than compact but still some allow for modular construction<br>– Balanced installation requirements | – Large cargo ships<br>– Offshore platforms |
| High (full scale) (Blanc et al., 2014; Serp et al., 2014) | – SFR ASTRID<br>– GFR<br>– SCWR<br>– MSR Fuji | – Highly complex systems<br>– Difficult to transport<br>– Due to their dimensions, they are not suitable for conventional ships | – Port floating power plants<br>– Mega offshore platforms |

(SMR) (Ingale et al., 2025; Epiney et al., 2022). As defined by the IAEA, SMRs have an electrical power output of less than 300 MW (Mignacca and Locatelli, 2020; IAEA), thus the different solutions (types) of reactors are summarized in Table 3.

This design is intended to be a smaller and safer alternative to larger reactors (Memorandum and Zohuri, 2023). Due to its smaller dimensions, it is cheaper to produce (Adumene et al., 2022), allowing for serial production of components and shorter production time, which is more economical (Black et al., 2015). Their compact design allows for more efficient use of space, making them suitable for smaller vessels.

The SMR is equipped with passive cooling systems, which improves its level of safety (Liu and Fan, 2014). Its smaller size reduces the risk of core overheating and failure compared to larger reactors (Carless et al., 2016). This makes SMRs suitable for most ships, including smaller ones. An important advantage is zero direct emissions of carbon dioxide and greenhouse gas emissions (Michaelson and Jiang, 2021), helping meet the legal requirements to reduce emissions in transport. Furthermore, due to their lower power, SMRs generate less radioactive waste compared to larger reactors (Locatelli et al., 2018).

SMRs can be cooled by water, gas, or salts, depending on the type (Locatelli et al., 2015). Currently, countries like the USA, Argentina, and Italy are developing SMRs for commercial purposes (Kim et al., 2024b), bringing the possibility of using them for ship propulsion closer to reality. Due to their small size and efficient characteristics, SMRs could be the first Gen IV reactors used for energy production on various ships. Most nuclear–powered vessels, capable of operating for up to 20 years without the need for refuelling, are equipped with pressurized water reactors (PWRs) with highly enriched uranium fuel (Park et al., 2024), which enables such long operating times and is well documented in icebreakers. In contrast, Generation IV reactor concepts, such as molten salt reactors (MSRs), require a different operational approach: fuel is supplied continuously in liquid form, and fission products – especially volatile and gaseous – must be regularly removed and safely managed on board. This requires advanced chemical fuel purification and waste handling systems, which presents significant technical and logistical challenges in offshore applications (Park et al., 2024).

The only small modular reactors that operate commercially are a set of two 35 MW reactors, which since 2020 have been part of the Russian power plant floating in Arctic waters. China plans to launch SMRs in 2026 and has chosen Hainan Island as its location, where a power plant is already operating (GLOBEnergia).

One of the disadvantages of SMR reactors is the possibility of disseminating nuclear materials for criminal purposes. The control of the nonproliferation of nuclear materials is carried out by the IAEA. This control also applies to other reactors. The SMR reactor security system must consider the variety of reactor designs used (e.g., core structure, type of fuel), the way of handling spent fuel, radioactive waste, and transport.

**Table 6**
Comparison of Gen IV reactor types by suitability for different ship types. GFR – gas–cooled fast reactor; LFR – lead–cooled fast reactor; MSR – molten salt reactor; SCWR – supercritical water–cooled reactor; SFR – sodium–cooled fast reactor; SMR – small modular reactor; VHTR – very high–temperature reactor.

| Ship type | Reactor type | Advantages | Performance criterion |
|---|---|---|---|
| Container ship (Fig. 7 (a)) | VHTR, MSR, SCWR | Simple operation, high thermal efficiency | High thermal efficiency, compatible with turbines, and capable of long–haul operation without the need for port calls |
| Passenger cruise ship (Fig. 7 (b)) | VHTR/SCWR | High efficiency, low noise | High efficiency |
| Tanker (Fig. 7 (c)) | MSR | Possibility of using energy to process LNG | Continuous operation. Chemical safety, heat recovery capability |
| Specialized ship (Fig. 7 (d)) | SFR/LFR | Resistance to damage, high power | Variable load, operation in extreme conditions |
| Bulk carrier (Fig. 7 (e)) | SCWR/MSR | Simple design, high thermal efficiency, long fuel cycle | A medium level of automation results in limited staff |
| Car carrier (Fig. 7 (f)) | LFR/MSR/GFR | High efficiency, passive safety systems | Long operating cycle without the need to refuel |
| Offshore and floating production storage and offloading (FPSO) (Fig. 7 (g)) | LFR/MSR | High reliability and passive safety systems, fault tolerance, high power density | Long fuel cycle, corrosion resistance. High energy consumption. Infrequent servicing |

### 7.3. *Sodium–cooled fast reactor*

Another Gen IV reactor considered for ship propulsion is the sodium–cooled fast reactor (SFR), also known as a fast neutron reactor (Liu et al., 2024). In SFRs, fast neutrons are used to sustain the chain reaction within the reactor, unlike traditional water reactors, which rely on a moderator such as water or graphite. These reactors are cooled with liquid sodium (Şahin and Şahin, 2021) which has excellent thermal properties so that heat can be removed from the reactor more efficiently. Additionally, sodium does not absorb neutrons, and, at relatively low pressure and high temperature, it remains in the liquid state, which has excellent thermal properties, enabling more efficient heat removal. This also reduces the risk of failure associated with high–pressure systems, which is particularly important for floating objects like ships. However, the high reactivity of chemicals, especially with water and air, poses significant challenges, requiring additional safety systems to prevent accidents (Imaizumi et al., 2023).

The use of advanced reactors on ships, particularly icebreakers, holds promise for the future, offering several advantages but also posing challenges. One major advantage is fuel efficiency, as these reactors can use uranium–238, which is more abundant than uranium–235 (Vaidyanathan, 2024). Fast neutron reactors can also use by–products from other reactors, such as plutonium or actinides, such as neptunium, americium, and curium, which reduces operating costs and enables longer voyages. Furthermore, operating costs are lower compared to traditional propulsion, as the reactor uses a closed fuel cycle and MOX fuel (Crawford et al., 2007), (a mixture of uranium oxide and plutonium), derived primarily from plutonium recycling. This reduces nuclear fuel costs, which benefits shipowners. The use of MOX fuel also reduces radioactive waste and the space needed to store spent fuel. However, operating at higher temperatures with fast neutrons presents challenges in material selection, as conventional materials degrade more rapidly (Konomura and Ichimiya, 2007).

Currently, no ships are using fast neutrons as propulsion, but these reactors are used as experimental reactors and commercial ones (Table 3). In Russia, there is the BN–600 reactor based on fast reactor technology (fast breeder reactor – FBR), which is one of the most advanced reactors of this type operating commercially, its thermal power is 1470 MW and its electrical power is 600 MWe. In Russia, there is also a newer version of the BN–600 reactor, BN–800, launched in 2015 (Ivanov et al., 2012). Another example can be found in Japan, that is, the experimental Monju reactor (Kamide et al., 2024) launched in 1994, but due to technical problems, including a sodium leak in 1995, which caused the reactor to stop working in 2016, it was decided to close it (Takubo, 2017). France also had the experimental reactors Phénix and Superphénix, which are also not operational now (Aoto et al., 2014). Korea also presented a conceptual model of the SFR KALIMER–600, which is a medium–sized pool–type reactor with improved passive safety systems (Hahn et al., 2007).

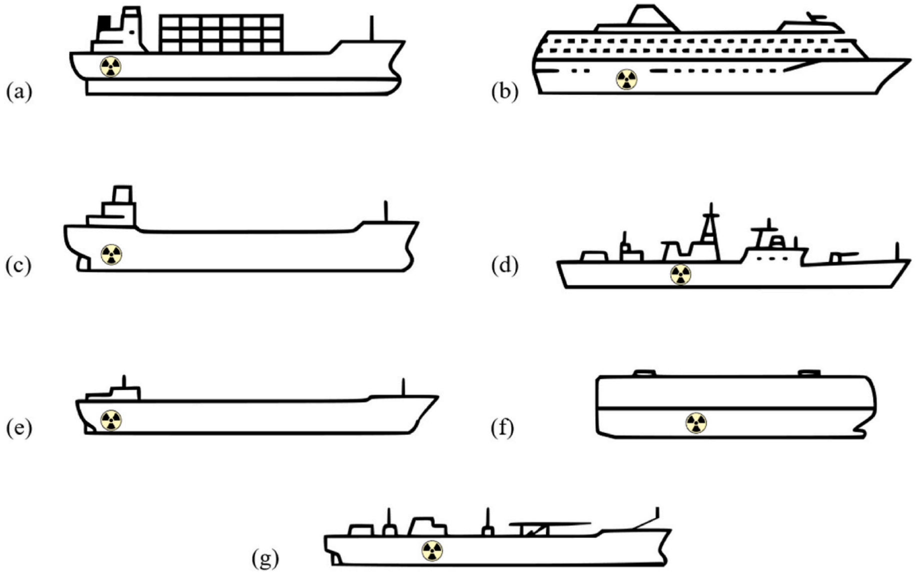

**Fig. 7.** Types of ships proposed to be powered by a reactor: (a) Container ship, (b) passenger cruise ship, (c) tanker, (d) specialized ship, (e) bulk carrier, (f) car carrier, (g) offshore and floating production storage and offloading (FPSO).

### *7.4. Molten salt reactor*

The molten salt reactor (MSR) is one of the newest reactor types, classified as Gen IV (Besmann et al., 2024). The advantages of MSR have been known for many years (Skutnik et al., 2024) because its prototype, the molten–salt reactor experiment (MSRE) (Kedl, 1970), operated from 1966 to 1969 as a research reactor and was located at Oak Ridge National Laboratory (Kedl, 1970; Lee et al., 2024). This experimental reactor had a power of 8 MWth (LeBlanc, 2010). After the successful experiment, a continuation of this reactor was proposed as a 1000 MWe denatured molten salt reactor, but it was never built (Houtkoop, 2022). Examples of the MSR reactors are shown in Table 3.

The MSR reactor stands out from other reactors because it has liquid fuel created by dissolving nuclear fuel in liquid salts (Lee et al., 2023). In this case, nuclear fuel can be commonly used in reactors of uranium, but also thorium and plutonium (Ladkany et al., 2018) because of different types of fuel (Dwijayanto and Harto, 2024). In the case of thorium, it is more widely available than uranium, which makes it very attractive. MSR operates at low pressure (atmospheric) (Emblemsvåg, 2021), which is important because it eliminates the possibility of explosion. In the event of failure, the liquid fuel can be cooled or transported to safety (Freitas Neto et al., 2021). This minimizes the potential threat and therefore catastrophe to the population and the environment.

In molten salt reactors, the coolant is typically a salt mixture formed by combining fluoride compounds with nuclear fuel. As a result, the fuel and the coolant circulate through the reactor core and the heat exchanger, allowing them to be removed or replaced without shutting down the reactor. This continuous operation is particularly advantageous for applications such as marine propulsion, where uninterrupted power is critical (IAEA, 2020).

These reactors can operate at higher temperatures and the average operating temperature range in the core is 650 °C–800 °C (Lee et al., 2023), which makes them operate with greater thermodynamic efficiency (Hasibuan et al., 2024). Due to the operating temperature range, the MSR reactor is characterized by high synergy with the supercritical Brayton cycle (Lee et al., 2023). Another advantage is the possibility of processing and using nuclear waste from PWR reactors as fuel in the MSR reactor. One of the disadvantages of this reactor is the use of appropriate materials for its construction due to the high temperatures in the system and corrosion caused by salts. These reactors can be used to propel cargo ships, which will reduce greenhouse gas emissions, icebreakers, especially where high output power is needed to carry out operations in Arctic conditions, allowing for long–term autonomy without the need for refuelling. In the case of use on submarines, the reactor size should be taken into account to ensure low power; in article (Hasibuan et al., 2024) a small modular MSR was presented which was designed to produce 100 MWe.

There have been previous attempts to design a ship whose propulsion system was based on MSR reactors. In 2012, in the work (Hill et al., 2012) they presented a conceptual design of a propulsion system based on the SMR reactor. This design was created in the MSRE and molten salt demonstration reactor. Another work in 2021 described the use of MSR as propulsion for merchant ships, showing their superiority over PWR reactors (Freitas Neto et al., 2021).

### *7.5. Molten chloride fast reactor*

The molten chloride fast reactor (MCFR) (Mausolff et al., 2021) is an advanced reactor concept classified within Gen IV technologies. The MCFR builds on the general principles of molten salt reactors (MSRs) but distinguishes itself by using molten chloride salts as both fuel solvent and coolant, enabling fast neutron spectrum operation (Krepel et al., 2022). This reactor type has attracted growing interest in recent years due to its potential for efficient fuel utilization and waste minimization.

Unlike traditional molten fluoride salt reactors, the MCFR employs chloride salts, which allow the reactor to sustain a fast neutron spectrum essential for breeding and burning actinides, including minor actinides and plutonium. This characteristic supports enhanced fuel recycling and closed fuel cycles, contributing to improved sustainability and reduced long–term radiotoxicity.

The MCFR operates at low to moderate pressures, typically near atmospheric, which enhances operational safety by lowering the risk of high–pressure accidents. The liquid fuel and coolant mixture enables passive safety features such as drain tanks for emergency cooling and simplified heat removal systems. Additionally, the reactor design facilitates online fuel processing, allowing continuous removal of fission products and replenishment of fuel, which optimizes reactor performance and reduces downtime.

### *7.6. Lead–cooled fast reactor*

The lead–bismuth fast neutron reactor (LFR) is one of the most promising Gen IV nuclear reactor designs, offering improved safety, sustainability, and economic competitiveness (Loewen and Tokuhiro, 2003). LFR uses liquid lead or lead–bismuth eutecticum as coolant, providing advantages such as low operating pressure, chemical inertness, and favourable thermodynamic properties (Cinotti et al., 2009). These reactors were originally developed in Russia for submarine propulsion and are now being studied worldwide for applications in power generation and actinic nuclear waste disposal. Despite its many advantages, LFRs face challenges, such as corrosion caused by liquid metals (Loewen and Tokuhiro, 2003). Research by organizations such as ENEA focuses on core design, safety assessment, and research on coolant and material properties (Tarantino et al., 2021).

LFR reactors are distinguished by increased safety and efficiency due to the use of lead or Pb–Bi eutecticum as coolant, which has a high boiling point and natural circulation. Compared to sodium–cooled reactors, LFR provides better temperature control and coolant circulation, which is beneficial in the event of an accident. The LFR can make efficient use of nuclear waste and operate in a closed fuel cycle. However, the compatibility of structural materials with liquid lead remains a challenge due to corrosion and embrittlement (Mascari et al., 2024). Nitride fuels are preferred in LFR reactors because of their good coolant compatibility and favourable thermal properties. Ferritic–martensitic steels, ceramics, and refractory metals may be required for reactor designs that operate at higher temperatures (Allen and Crawford, 2007).

Table 3 shows examples of reactor designs that may be suitable for marine propulsion applications. LeadCold SEALER, developed by LeadCold in collaboration with KTH, is a 3–10 MWe molten salt–cooled modular reactor that allows safe low–pressure operation. LeadCold SEALER, developed by LeadCold in collaboration with KTH, is a 3–10 MWe lead–cooled fast modular reactor designed for safe, low–pressure operation.

### *7.7. Gas–cooled fast reactor*

The gas–cooled fast neutron reactor (GFR) is one of the Gen IV designs, characterized by high thermodynamic efficiency and the ability to operate in a closed fuel cycle. The GFR uses a gas (usually helium) as a coolant, which provides low operating pressure and excellent heat transfer properties (Farmer et al., 2006). This design was developed in response to the need to increase safety and reduce nuclear waste while allowing efficient use of fuel such as plutonium and transuranic waste (Stainsby et al., 2009).

Unlike classical aqueous reactors, the GFR features gas–based cooling, which allows operation at higher operating temperatures of up to 850–950 °C. This allows these reactors to operate with the supercritical Brayton cycle, achieving high thermodynamic efficiencies of up to 48 %. High temperature operation also allows the production of hydrogen as a supplementary energy source, increasing the potential for the use of GFR in the energy industry (Weaver et al., 2004).

GFR reactors also offer flexibility in fuel selection, allowing the use of nitride fuels, which have high thermal stability and compatibility with gaseous coolant. However, high operating temperatures and intense neutron radiation pose challenges for structural materials. Advanced materials such as ceramics, refractory metal alloys, and special protective coatings are currently being investigated to provide adequate resistance to corrosion and embrittlement (Hatala, 2021).

### *7.8. Supercritical water–cooled reactor*

The supercritical water–cooled reactor (SCWR) operation is based on two technologies: light–water–cooled reactors (LWR) and supercritical coal–fired boilers. These systems can operate with a thermal or fast neutron spectrum, depending on the core design (Ishraq et al., 2024). In the thermal neutron case, the reactor uses a once–through uranium fuel cycle (open fuel cycle). In the fast neutron case, a closed fuel cycle is used with advanced water processing for recycling spent fuel. Fuels can include mixtures of uranium, plutonium, or thorium. Enrichment ranges from 5 to 20 %, with increased enrichment increasing costs. SCWRs can also be designed as converter reactors (Alnassar and Galahom, 2024), converting non–fissile isotopes like uranium–238 into fissile isotopes like uranium–239 for later use as fuel.

This reactor uses supercritical water (APPENDIX B), which acts as a coolant and moderator. The supercritical state is obtained by heating it above the critical point of 374 °C and 22.06 MPa (Valujerdi and Talebi, 2020). The reactor has a simplified system due to the use of a single–phase coolant flow, that is, a moderator (Chaudri et al., 2012). Due to the high thermal energy density in SCWR, moderated (water is used to slow down neutrons) and unmoderated (water is used only as a coolant) designs are considered.

Thanks to the high steam parameters of 25 MPa and 510 °C (APPENDIX B) (Wu et al., 2022), it is possible to achieve high efficiency of the power plant at the level of 45 %, and even theoretically reach the value of 50 % (Boungiorno et al., 2003). This efficiency means lower fuel consumption for shipowners and thus lower operating costs related to the cost of fuel and storage of radioactive waste. Additionally, there is no boiling crisis during normal reactor operation as a result of the lack of phase change. The SCWR design is characterized by simplicity resulting from the lack of additional heat exchangers and the reduction of elements in the system, which also generates economic profit. The smaller dimensions favor the future use of SCWR as ship propulsion.

Due to the high temperatures, it is necessary to use appropriate materials here (Rahman et al., 2020). Currently, there is no commercially available SCWR reactor, but this reactor is under research and development (Table 3). Depending on the research center or country, the designs differ. An example of such a project is CANDU–SCWR created in Canada by Atomic Energy of Canada Limited and uses existing CANDU (CANadian deuterium uranium) (Shan et al., 2009). In this case, low–enriched uranium is used and the system is to be equipped with passive safety systems. Another example of a reactor project is being developed in the European Union and is called EU–SCWR. It is being implemented by a consortium of European companies and research institutes.

## 8. Discussion

Nuclear reactors are used on icebreakers, but commercial and passenger ships with nuclear propulsion remain a novelty. Shipping based on nuclear fuel may prove to be an attractive option due to legal regulations on limiting greenhouse gas emissions. A nuclear ship could operate for decades without producing greenhouse gases. The use of nuclear fuel allows for the reduction of $CO_2$ production; for instance, 12500 TEU container vessels, 4850 tons of $CO_2$ reduction can be achieved on a route of 3500 nautical miles (Bayraktar and Yüksel, 2023).

To show the benefits of using nuclear fuel, a comparison of the classic fuel for ship propulsion with nuclear fuel is shown in Table 7. One of the limitations related to the operation of nuclear ships is public concern about the possibility of a failure that could cause environmental contamination. For the same reason, marinas or ports could prohibit these units from entering their territory. Therefore, it is important to introduce clear regulations governing the production of nuclear–powered ships. The use of Gen IV reactors is supported by the fact that different types of fuel: uranium, thorium, or plutonium (Humphrey and Khandaker, 2018), can also contribute to reducing fuel costs, and this generation of reactors is characterized by a high degree of burnout, resulting in a small amount of radioactive waste.

**Table 7**
Comparison of nuclear fuel with classic ship fuel (Seatrade-Maritime News; Salvatores and Knebel, 2009; Kim et al., 2008).

| | Traditional fuel for ships | Nuclear fuel | |
|---|---|---|---|
| Equivalent $CO_2$ | Well–to–tank<br>95 g $CO_2$eq/kWh<br>Tank–to–wake<br>568 g $CO_2$eq/kWh | Production process 12 g $CO_2$eq/kWh | |
| Solid waste | No solid waste | Fuel spent: high–level waste | Equal to the fuel usage in a once–through cycle, or as low as one–third of the fuel usage in a closed cycle |
| | | Waste at the low and intermediate levels | 0.05–0.1 $m^3$ attributable to MWe installed per year |
| | | By–product of fuel extraction and fuel factor | Between 8 and 38 times the fuel consumption in weight for low–enriched uranium of 5 % and 20 % U235 |
| | | Decommissioning waste | Depends on reactor size |
| Air pollution | $NO_x$, $SO_x$, $CO_2$, greenhouse gases | No air pollution | |
| Influence on ship design | Reduced construction requirements | Requires special construction to protect the reactor | |
| Operation time | Shorter (requiring more frequent refuelling) | Long (the reactor can operate for several decades without a fuel supply) | |
| Ship range | Limited | Very large | |
| Energy efficiency | Average (depending on fuel type) | Very high (significantly higher energy density) | |
| Fuel cost | Lower initial cost, higher operating cost | High initial cost, low operating cost | |

To summarize the information about Gen IV reactors, Table 8 was created. Furthermore, the advantages and disadvantages of each type of reactor are also collected in Table 9.

In order to provide an even better safety system, diagnostic methods should be used not only for the reactor but also for devices in the engine room, including thermal flow machines. For this purpose, artificial intelligence–based diagnostic methods can be used (Błaszczyk et al., 2011). Genetic algorithms can be used to detect multiple degradations in steam turbines (Drosińska-Komor et al., 2023). The work (Drosińska-Komor et al., 2025) describes a diagnostic model that, after refining the model to a specific system on a ship, can help operators observe damage and plan repairs for the time spent in port and order the necessary equipment in advance. Quite important are also diagnostic processes of the bearing, especially in respect to fluid–flow machinery (Breńkacz et al., 2016, 2019b).

One of the main disadvantages of Gen IV reactors is their high initial cost, as most are still in the research phase and require permits and trained staff. However, according to DNV's Maritime Impact 17 analysis,

**Table 8**

Comparison of Gen IV reactors (Wróbel, 2022; Ma et al., 2021; Serp et al., 2014). GFR – gas–cooled fast reactor; LFR – lead–cooled fast reactor; MSR – molten salt reactor; SCWR – supercritical water–cooled reactor; SFR – sodium–cooled fast reactor; VHTR – very high–temperature reactor.

| Reactor type | VHTR | SFR | LFR | GFR | MSR | SCWR |
|---|---|---|---|---|---|---|
| Neutron spectrum | thermal | fast | fast | fast | fast & thermal | fast & thermal |
| Fuel cycle | open | open/closed | open/closed | open/closed | open/closed | open/closed |
| Reactor coolant | helium | sodium | lead or bismuth | helium | molten salt | water in supercritical state |
| Operating temperature [°C] | 700–1000 | 500–550 | <600 | <850 | <800 | <510 |
| Burnup [GWd/tHM] | 90–200+ | 130+ | 130+ | 130+ | 90+ | 50–70 or 100 |
| Energy efficiency [%] | 50 | 42 | 45 | 50 | 45 | 45–50 |
| Fuel type | Uranium, Thorium, Plutonium | Uranium, Thorium, Plutonium<br>MOX | Uranium, Thorium, Plutonium | Uranium, Thor, Plutonium | Uranium, Thorium, Plutonium | Uranium, Thorium, Plutonium |
| Type | converter | converter | converter | converter | converter | converter |
| Thorium capable | breeding | breeding | breeding | breeding | breeding/continuous cycle | breeding |
| Refuelling cycle low end [years] | 1.5–2 | 1.5–2 | 1.5–2 | 1.5–2 | 1.5–2 | 1–2 |
| Passive safety | yes | Yes | yes | passive safety only lower density or small size | yes | yes |

**Table 9**

Advantages and disadvantages of Gen IV reactors. GFR – gas–cooled fast reactor; LFR – lead–cooled fast reactor; MSR – molten salt reactor; SCWR – supercritical water–cooled reactor; SFR – sodium–cooled fast reactor; VHTR – very high–temperature reactor.

| Reactor type | VHTR | SFR | LFR | GFR | MSR | SMR | SCWR |
|---|---|---|---|---|---|---|---|
| Advantage | – Operation at temperatures of 700 °C–1000 °C<br>– Increased efficiency<br>– Possibility of using TRISO fuel<br>– Helium as a coolant<br>– Potential for hydrogen production<br>– Passive safety systems | – The use of fast neutrons results in more efficient use of fuel<br>– Reduction of nuclear waste<br>– Efficient cooling | – High cooling efficiency<br>– Operation at temperatures up to 800 °C<br>– Passive safety systems<br>– Chemical stability of lead<br>– Closed fuel cycle<br>– Resistance to neutron poisoning | – High efficiency<br>– Use and conversion of transuranium elements<br>– Passive systems<br>– Possibility of using different fuels | – Increased safety through the use of liquid salts<br>– Burning of radioactive waste<br>– Using thorium as fuel<br>– Passive safety systems | –Modularity<br>– Small dimensions<br>– Possibility of using different types of reactors<br>– Use of passive safety systems<br>– Speed of construction<br>– Low initial costs<br>– Flexible in the fuel cycle | – High thermodynamic efficiency<br>– Simple design<br>– Use of MOX fuel<br>– Availability of water as coolant |
| Disadvantage | – Necessity to use appropriate construction materials due to the high temperature<br>– Cost of construction – Need for high pressure – Corrosion | – Reactivity of sodium with water and air<br>– Adequate infrastructure for sodium storage | – Liquid lead is responsible for corrosion<br>– Lead's high weight<br>– Lead toxicity | – Difficulties in emergency cooling<br>– Use of appropriate materials due to high temperature | – Salt corrosivity<br>– Management of radioactive waste including salt fusion products<br>– Continuous monitoring of fuel and reactor status<br>– Higher initial costs | – Provide protection against theft of fissile material<br>– High unit costs<br>– Small–scale economic uncertainty | – High material requirements<br>– Risk of failure due to high pressure |

nuclear propulsion could be financially viable if reactor prices fall to the lower end of estimates (around US $35–40 million annually). Despite the high upfront costs compared to other fuels, nuclear propulsion offers the advantage of stable operating costs, unaffected by price fluctuations, as nuclear–powered ships can operate for years without refuelling.

Table 10 presents a detailed analysis of how the proposed application of Gen IV reactors in maritime transport supports the sustainable development goals (SDGs) established by the United Nations. For each of the 17 goals, the connection to the solution was classified as direct, indirect, or unrelated. Specific tasks for each goal were identified, along with their potential achievement through the implementation of nuclear technology in maritime transport.

Gen IV reactors directly impact the implementation of several key SDGs. In protecting water resources (Goal 6), their use reduces marine contamination from fossil fuel spills and enables efficient seawater desalination technology for ships. In energy (Goal 7), reactors significantly increase energy efficiency, promoting zero–emission technologies that reduce the impact of maritime transport on the environment. The development of reactor infrastructure generates jobs, supporting economic growth and sustainable development (Goal 8). The most visible benefits can be found in climate action (Goal 13), where reactors contribute to a significant reduction in greenhouse gas emissions, which is in line with international regulations like the Paris Agreement. Finally, reactors protect life underwater (Goal 14), eliminating the risk of contamination of oceans and marine waters with classic fuels, safeguarding marine ecosystems and their biodiversity.

Gen IV reactors also have a significant, but indirect, impact on the implementation of selected SDGs, improving quality of life globally. Technological and infrastructure development creates new jobs, both in the reactor production sector and in their operation, which supports poverty reduction (Goal 1). Cheaper maritime transport improves goods delivery, reducing distribution costs and enhancing food security, especially in remote areas (Goal 2, Task 2). Additionally, ships equipped with nuclear reactors can function as floating power plants after their operation, providing cheap and stable energy to poor regions, improving living conditions in developing countries, and reducing social inequalities (Goal 10).

Table 10 emphasizes that the use of Gen IV reactors is consistent with

**Table 10**
Comparison of the 17 sustainable development goals (SDGs) met with Gen IV reactors.

| SDG | Affiliation (directly, not applicable, indirectly applicable) | SDG description |
|---|---|---|
| 1. No poverty | Indirectly applicable | Possibility of reducing poverty through new jobs and access to cheap transport. Fulfilment of the task 1.4. |
| 2. No hungry | Indirectly applicable | Reducing the cost of transporting food. Fulfilment of the task 2.C. |
| 3. Good health and well–being | Indirectly applicable | Research on the decarbonization and reduction of greenhouse gases in maritime transport using nuclear propulsion. In this way, the number of people suffering from diseases caused by pollution will be reduced. Improving air quality in ports and coastal cities. Fulfilment of the task 3.9. |
| 4. Quality education | Indirectly applicable | The need for technical and specialized education in training in nuclear engineering and maritime systems and new technologies for sustainable development. Fulfilment of the task 4.4 4.7. |
| 5. Gender equality | Not applicable | |
| 6. Clean water and sanitation | Directly | Using reactors for ship propulsion does not cause water contamination. Additionally, ships can use water from the desalination of seawater. Radioactive waste and spills need to be controlled. Fulfilment of tasks 6.3, 6.A. |
| 7. Affordable and clean energy | Directly | Increasing energy efficiency through the use of new reactors in transport. In addition, environmental awareness is enhanced by publishing scientific papers on the benefits for the environment from the use of nuclear reactors, in particular the availability of SMRs. Fulfilment of tasks 7.A, 7.3. |
| 8. Decent work and economic growth | Directly | Economic growth through increased employment in the production and operation of innovative reactors. The need for training and courses for maritime workers to prepare those without experience with nuclear reactors. Fulfilment of tasks 8.2, 8.4. |
| 9. Industry, innovation, and infrastructure | Directly | Developing maritime transport to minimize classic fuel use through clean technologies. The development of port infrastructure, new ports, and modern marine engineering. Cheaper transport will result in greater accessibility for people. Publishing research on new technologies, i.e. Gen IV reactors to use them in maritime transport. Fulfilment of tasks 9.1, 9.4. |
| 10. Reduced inequality | Indirectly applicable | Presentation of the risk analysis related to the safety of using reactors as propulsion on ships. Because of this, environmental and human protection is better understood. In the future, when ships finish their use, they can act as floating power plants in less developed and poor regions, providing cheap energy that will raise the standard of living of people. Fulfilment of the task 10. B. |
| 11. Sustainable cities and communities | Indirectly applicable | Development of maritime transport to minimize classic fuel use through clean technologies. Supports cleaner air in ports and development of maritime tourism. Constructing ports where nuclear ships can enter. Fulfilment of the task 11.2. |
| 12. Responsible consumption and production | Directly | Presentation of research on sustainable energy production for ship propulsion. The entire life cycle is more ecological than other types of nuclear reactors. Fulfilment of tasks 12.2, 12.4, 12.5. |
| 13. Climate action | Directly | Reducing the carbon footprint by reducing the production of greenhouse gases. Meeting legal requirements concerning, among others, the United Nations Framework Convention on Climate Change. Fulfilment of tasks 13.2, 13.A. |
| 14. Life below water | Directly | Protection of sea and ocean waters against contamination with classic fuels. Fulfilment of the task 14.1. |
| 15. Life on land | Directly | Protecting the environment by not producing greenhouse gases and also reducing the extraction of fossil fuels. Fulfilment of the task 15.6. |
| 16. Peace, justice, and strong institutions | Indirectly applicable | Strengthening national and global governance structures is essential to ensure the safe, peaceful, and equitable implementation of advanced nuclear technologies. There is a need for international control mechanisms to regulate security and counter cyberattacks and sabotage acts. Fulfilment of tasks 16.6, 16.a. |
| 17. Partnerships for the goals | Directly | Cooperation within consortia, e.g. work on creating reactors. At the time of using reactors on ships, also with an analysis of the operating costs of such a unit. Fulfilment of tasks 17.7, 17.6. |

the idea of sustainable development, both in the environmental and socio–economic context. Although it requires high initial costs, this technology allows long–term improvements in the fields of environmental protection, energy availability, and emission reduction.

## 9. Summary

This article examines the application of Generation IV (Gen IV) nuclear reactors as modern propulsion systems for maritime transport with zero direct carbon dioxide emissions. The development of nuclear technologies for the maritime sector is a response to the growing need for decarbonization and reduction of GHG emissions, especially in the context of international commitments such as the Paris Agreement.

Comprehensive analysis shows that Gen IV reactors, such as VHTR, SMR, or MSR, can contribute significantly to reducing the carbon footprint of maritime transport. The use of nuclear fuel eliminates $CO_2$, NOx, and SOx emissions and also reduces the risk of water contamination associated with fossil fuel leaks.

In addition, the article discusses passive safety strategies from a marine engineering perspective, with emphasis on hull strength, structural integrity, and survivability in scenarios involving collisions, explosions, or groundings. The use of passive safety systems and innovative technological solutions, such as TRISO fuels or closed fuel cycles, increases the safety and operational efficiency of these technologies.

A critical evaluation is provided on the tradeoffs between retrofitting existing vessels with nuclear systems and designing purpose–built nuclear ships. Technical feasibility, cost implications, and lifecycle efficiency are analyzed to inform strategic investment decisions in the maritime sector.

The article further offers a comparative overview of the regulatory and classification requirements for nuclear–powered vessels across five major classification societies. This regulatory landscape is examined with respect to safety, environmental compliance, and reactor integration standards.

The article also presents the economic benefits of using Gen IV reactors, including the stability of nuclear fuel prices, the increased cargo space of ships, and the possibility of selling green certificates. At the same time, it identifies challenges related to the implementation of this technology, such as high initial costs, lack of full social acceptance, and complexity of legal regulations. To respond to these challenges, it proposes actions that include the development of policies that support the transformation of the maritime sector, educational campaigns, and international cooperation for research and implementation.

Finally, the article emphasizes that Gen IV reactors are consistent with the UN Sustainable Development Goals (SDGs), in particular, SDG 7 and SDG 13. Their use in maritime transport allows the reduction of emissions, the protection of aquatic and terrestrial ecosystems, and the promotion of sustainable socioeconomic development. The article argues that the inclusion of this technology in the global maritime transport system can become a key element of the transformation towards climate neutrality and environmental protection.

## CRediT authorship contribution statement

**M. Drosińska–Komor:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **J. Głuch:** Writing – review & editing, Supervision, Investigation, Conceptualization. **N. Ziółkowska:** Writing – review & editing, Investigation, Formal analysis. **Ł. Breńkacz:** Writing – original draft, Visualization, Software. **K. Brzezińska–Gołębiewska:** Writing – original draft, Methodology, Formal analysis. **J. Blaut:** Writing – review & editing, Visualization, Formal analysis. **P. Ziółkowski:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## APPENDIX A

This appendix provides strengths, weaknesses, opportunities, and threats (SWOT) analysis (Table A. 1) for the use of Gen IV reactors for propulsion on the ship analysis to show the possibility of using Gen IV reactors as ship propulsion. In addition, a more detailed SWOT analysis was carried out for individual ship types and is show from Table A. 1 to Table A. 7.

Additionally, the economic criteria considering the possibility of using Gen IV reactors applications for ship propulsion is assessed in (Table A. 8)

**Table A. 1**

A strengths, weaknesses, opportunities, and threats (SWOT) analysis for the use of Gen IV reactors for propulsion on the ship.

| Internal factors | Strengths: | Weaknesses: |
|---|---|---|
| | • Zero direct emission of greenhouse gases<br>• Independence from fossil fuels<br>• No oil contamination<br>• High energy efficiency<br>• Having to arrive at the port<br>• Cargo space<br>• Long–term exploitation<br>• Passive safety<br>• Less radioactive residue | • Non–acceptance with society<br>• Possibility of failure<br>• High starting cost<br>• Problem with radioactive waste management<br>• No fully industrial application<br>• Safety and regulatory concerns<br>• Material and technical challenges |
| **External factors** | **Opportunities:** | **Threats:** |
| | • New power propulsion for ships<br>• Greater ship capacity and increased competitiveness<br>• Lower transportation costs<br>• Higher protection against failure than previous nuclear reactors<br>• Innovative technologies<br>• Interest in the civilian markets | • Risk of failure<br>• No common working solutions with Gen IV reactors<br>• Lack of public approval<br>• Low resistance of the material to extreme temperatures and pressures |

**Table A. 2**
A strengths, weaknesses, opportunities, and threats (SWOT) analysis for the use of Gen IV reactors as a propulsion for a container ship.

| | | |
|---|---|---|
| **Internal factors** | **Strengths:**<br>• Continuous reactor operation required for ship propulsion and onboard energy needs<br>• Reduction of $CO_2$, $NO_x$, and other petroleum–derived emissions<br>• Capability for long–term operation, even for several years without refuelling<br>• New safety systems for reactors | **Weaknesses:**<br>• Lack of port infrastructure<br>• High initial investment costs<br>• Need to employ qualified personnel<br>• Investment risk |
| **External factors** | **Opportunities:**<br>• Potential competitive advantage over other shipowners in the event of mandatory decarbonization<br>• No need to enter port for refuelling, especially important when carrying strategic cargo to ensure its security<br>• Ability to power container ship refrigeration systems without the need for additional equipment, such as energy storage or diesel generators | **Threats:**<br>• Public opposition<br>• Strong competition in the maritime transport market<br>• Lack of legal regulations<br>• Lengthy certification process for new technologies |

**Table A. 3**
A strengths, weaknesses, opportunities, and threats (SWOT) analysis for the use of Gen IV reactors as propulsion for a tanker ship.

| | | |
|---|---|---|
| **Internal factors** | **Strengths:**<br>• Fuel savings, especially on long–distance routes<br>• Reduced transportation costs for goods<br>• Lower greenhouse gas emissions, helping to meet legal and environmental requirements<br>• Greater independence from fuel markets and suppliers<br>• Generation IV reactors are less prone to meltdown and shocks, which increases safety when transporting hazardous cargo | **Weaknesses:**<br>• High initial cost for both ship construction and reactor installation<br>• Lack of port infrastructure to accommodate nuclear–powered ships<br>• Significant risk in the event of an accident, due to the nature of the transported cargo<br>• Potential exclusion from certain trade routes |
| **External factors** | **Opportunities:**<br>• Growth potential for the shipowner<br>• Compliance with legal requirements for green energy<br>• Increasing demands for decarbonization of the maritime fleet<br>• Energy independence | **Threats:**<br>• Public resistance<br>• Legal restrictions<br>• Cyberattacks |

**Table A. 4**
A strengths, weaknesses, opportunities, and threats (SWOT) analysis for the use of Gen IV reactors as propulsion for a bulk carrier ship.

| | | |
|---|---|---|
| **Internal factors** | **Strengths:**<br>• Increased economic potential by transporting large cargo over long distances without the need to call at port<br>• Support for routes with limited fuel and port availability<br>• Use of Generation IV reactors offers higher efficiency and improved safety compared to earlier technologies | **Weaknesses:**<br>• Profits spread over a long period of time<br>• Limited access to ports<br>• Need to build new ships or modernize existing ones |
| **External factors** | **Opportunities:**<br>• Possibility of using bulk carriers on long and difficult routes<br>• Technological development<br>• Potential use as polar–class vessels | **Threats:**<br>• Not cost–effective on short routes<br>• Risk of port or national authorities refusing ship entry<br>• Financial risk |

**Table A. 5**
A strengths, weaknesses, opportunities, and threats (SWOT) analysis for the use of Gen IV reactors as a passenger ship propulsion.

| | | |
|---|---|---|
| | **Strengths:**<br>• Reduced noise resulting from the use of nuclear propulsion<br>• Compliance with the decarbonization process and contribution to achieving strategic development goals<br>• Ability to sail without refuelling | **Weaknesses:**<br>• Potential risk of a nuclear disaster, especially dangerous when carrying a large number of passengers<br>• Increased requirements from ship insurers and legal regulations |
| **External factors** | **Opportunities:**<br>• New technologies<br>• New job opportunities | **Threats:**<br>• Public opposition<br>• Competitiveness of alternative ship propulsion systems |

Table A. 6. A strengths, weaknesses, opportunities, and threats (SWOT) analysis for the use of Gen IV reactors as propulsion for a specialized ship.

| | | |
|---|---|---|
| **Internal factors** | **Strengths:**<br>• No need for refuelling over long periods results in virtually unlimited range<br>• Quiet operation<br>• Ability to operate for extended periods without needing to enter port<br>• Capability to provide constant power required for research systems and onboard laboratories | **Weaknesses:**<br>• High shipbuilding costs<br>• High operational costs<br>• Implementation of safeguards against attack or sabotage |
| **External factors** | **Opportunities:**<br>• The integration of advanced technologies on specialized vessels often requires high energy output, which can be effectively supplied by nuclear reactors<br>• Need to operate in areas without access to ports and fuel | **Threats:**<br>• Nuclear–powered ships can become potential subjects of public concern due to safety and environmental considerations<br>• Possibility of malfunction or failure |

**Table A. 7**

A strengths, weaknesses, opportunities, and threats (SWOT) analysis for the use of Gen IV reactors as propulsion for offshore vessels and FPSO (floating production storage and offloading).

| | | |
|---|---|---|
| **Internal factors** | **Strengths:**<br>• Energy independence<br>• Stable power source for offshore platforms<br>• Potential collaboration with underwater installations, e.g., to power underwater infrastructure | **Weaknesses:**<br>• Need for various types of security measures<br>• Safety requirements for personnel<br>• Potential subjects of public concern due to safety and environmental considerations<br>• Technological risk due to potentially higher costs in initial deployments |
| **External factors** | **Opportunities:**<br>• Development of marine energy and green technologies<br>• Possibility to use the ship as a so–called energy island for areas with limited electricity supply<br>• Support for floating wind farms, especially during their outages | **Threats:**<br>• Problem with social acceptance<br>• Destabilization of offshore systems<br>• Different laws in various territorial waters |

**Table A. 8**

Economic criteria that favor the possibility of using Gen IV reactors for ship propulsion.

| Number | Economic criteria: |
|---|---|
| 1 | Increased cargo capacity with the same ship dimensions compared to a classic drive |
| 2 | Lower fuel consumption, e.g. by using nuclear fuel waste |
| 3 | Relatively high power |
| 4 | Stable prices for nuclear fuels |
| 5 | Possibility of selling energy certificates |
| 6 | Extended cruising time without requiring port stops for refuelling |
| 7 | High energy efficiency |
| 8 | Long–term exploitation |
| 9 | Potential to use thorium as fuel |
| 10 | Lower fuel loading costs than previous generations of reactors |
| 11 | Reduction of greenhouse gas |
| 12 | Possibility of using SMR reactors |
| 13 | Enhanced safety and reduced failure risk with passive safety systems |

## APPENDIX B

This appendix presents a graphical comparison of the operating parameters for three types of nuclear reactors: pressurized water reactor (PWR), boiling water reactor (BWR), and supercritical water–cooled reactor (SCWR). In Fig. B.1, the graphs illustrate key metrics for each reactor type, highlighting differences in their operating characteristics.

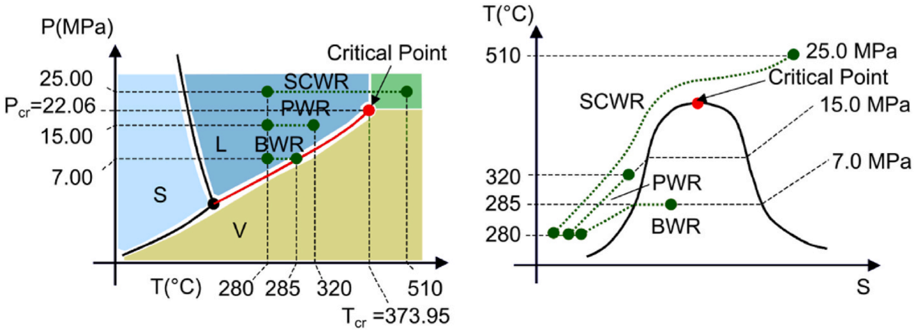

**Fig. B. 1.** Graphs showing operating parameters for comparing a pressurized water reactor (PWR), a boiling water reactor (BWR), and a supercritical water–cooled reactor (SCWR) reactors. S–solid, V–vapor, and L–liquid.

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