Thesis for the degree of MSc in Maritime Economics and Logistics

Nuclear powered maritime industry: The economic and infrastructural preconditions to acceptance

by

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Abstract

This thesis examines the economic and infrastructural preconditions necessary for integrating nuclear-powered propulsion in the maritime industry. With the backdrop of increasing environmental concerns and regulatory pressures, it critically analyzes the feasibility of adopting nuclear-powered propulsion as a sustainable alternative to traditional fossil fuels.

The study delves into the history and current state of nuclear energy and shipboard applications, comparing it with other alternative fuel sources such as ammonia, hydrogen, methanol, and LNG. Through a comprehensive literature review and empirical analysis, the research addresses key aspects like economic factors, market conditions, and infrastructural requirements for shipboard Floating Nuclear Power Plants (FNPPs). It also explores the challenges of regulatory landscapes, safety standards, and public perception.

The thesis aims to develop a holistic understanding of the potential and constraints of nuclear-powered propulsion in decarbonizing global shipping. It does so by conducting a strengths, weaknesses, opportunities, and threats (SWOT) analysis. It then cross references the most relevant issues in a confrontation matrix to identify opportunities and some of the biggest challenges facing nuclear-powered propulsion's viability. This thesis also offers insights into future research directions and the envisioned path towards a nuclear-powered maritime future.

Preface/thank you

This thesis on economic and infrastructural pre-conditions for the acceptance of nuclear power in marine industry was written as a graduation requirement for the Maritime Economics and Logistics masters program at Erasmus University Rotterdam.

First, I'd like to thank my long-time partner Dave Payne for his unwavering love and patience as I completed this work. His support made this writing process immeasurably easier and less stressful.

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Abbreviations

BOG	Boil off gas
BWR	Boiling water reactor
CAPEX	Capital expense/expenditure
CMNP	Commercial maritime nuclear propulsion
CO2	Carbon dioxide
CSNMS	IMO Code of Safety for Nuclear Merchant Ships
DOE	United States Department of Energy
EDF	Électricité de France
EU	The European Union
EPZ	Emergency Planning Zone
FNPP	Floating nuclear powerplant
GAO	United States Government Accountability Office
GHG	Greenhouse gas
GIF	OECD Generation IV International Forum
HALEU	High-assay, low enriched uranium
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IMO	International Maritime Organization
INL	United States Idaho National Laboratory
KEPCO	Korea Electric Power Corporation
LFR	Lead-cooled fast reactor
LNG	Liquefied natural gas
MARPOL	United Nations International Convention for the Prevention of Pollution from Ships
MGCR	Molten gas cooled reactor
MNAG	INL NRIC Maritime Nuclear Applications Group
MOFA	Japanese Ministry of Foreign Affairs
MSR	Molten salt reactor
MSRE	Molten salt reactor experiment
MWe	Megawatts (electric)
MWt	Megawatts (thermal)
NEIMA	United States Nuclear Energy Innovation and Modernization Act
NIMBY	Not in my backyard
NPP	Nuclear power plant
NRC	United States Nuclear Regulatory Commission
NRIC	INL Nuclear Reactor Innovation Center
OECD	The Organization for Economic Cooperation and Development
OEM	Original equipment manufacturer
OPEX	Operational expense/expenditure
PPP	Public private partnership
PWR	Pressurized water reactor
SCWR	Supercritical-water-cooled reactor
SFR	Sodium-cooled fast reactor
SMR	Small modular reactor
SOLAS	International Convention for the Safety of Life at Sea
SWOT	Strengths, weaknesses, opportunities, and threats
TEU	Twenty foot equivalent units
UF	Uranium fluoride
UNCLOS	United Nations Charter on the Law of the Sea
UO2	Uranium oxide
US	The United States
VHTR/(V)HTR	Very high temperature reactor

1. Introduction

The maritime industry, powered by fossil fuels since 1904, now stands at the precipice of an era that demands drastic reductions in greenhouse gas emissions (GHG). As an industry, the maritime industry contributed around 2.89% of GHG emissions in 2018, increasing from 2012 to around 1.08 billion tons (IMO, 2020), and an estimated 2 percent of which is contributed by port activities (Merk, 2014). To meet Paris Agreement's GHG targets, the International Maritime Organization (IMO) released an initial GHG strategy, known colloquially as "IMO 2023", that seeks to reduce the industry's GHG contributions by 20% by 2030 and 70% by 2050 (IMO, 2023). In response, various entities around the world including governmental institutions, researchers, and members of the energy and maritime industries are evaluating a wide range of low- or no-GHG alternative fuel and alternative energy solutions for the future of maritime propulsion in response to environmental concerns, regulatory pressures, economic considerations, technological advancement, and the need to future-proof against the declining viability of traditional fossil fuels (Chen et al., 2019; Bhattacharyya, El-Emam, and Khalid, 2023; Bilgili, 2021; Laursen et al., 2022; McCormick, n.d.; Taylor et al., 2022; T.U. Eindhoven, 2023; Nike.com, 2023; The Maersk Mc-Kinney Moller Center for Zero Carbon Shipping, 2023; Manich, 2023; Global Maritime Forum, 2022; Paterson, n.d.). Having established the urgency for change as outlined by IMO 2023 (Baraniuk, 2023), it is imperative to explore the potential of alternative fuels, each offering unique benefits and challenges in the quest for sustainable maritime propulsion (Saverys, 2023).

Some of the fuels being evaluated to replace conventional ship fuels include: ammonia, biodiesels, dimethyl ether, ethanol, hydrogen, liquefied natural gas, liquefied petroleum gas, and methanol (Bilgili, 2021). Of these fuels, the most viable alternatives under consideration by the maritime industry for wide-scale use are ammonia, hydrogen, LNG, and methanol (Saverys, 2023). Deployment of each of these fuels will help the industry move towards a more sustainable future and meet the goals set in IMO 2023. However, all four of these fuels come with various issues. Some of these issues are shared, such as the lack of wide-scale infrastructure to support rapid global deployment of one alternative fuel over all others. As we will explore in depth later in this paper, there are other issues unique to each alternative fuel source, such as high GHG emissions in the case of LNG, toxicity in the case of ammonia, and storage issues in the case of methanol and hydrogen that make adoption of these technologies in the long-term untenable. While these alternative fuels present viable pathways, it is crucial to consider nuclear energy, a contender with distinct advantages and complexities, as we delve into a detailed exploration of its role in maritime propulsion.

Nuclear energy provides an interesting alternative energy solution to these four alternative fuel leaders. When examining nuclear-powered propulsion, it's crucial to place it within the broader context of alternative fuel sources. How does nuclear energy stack up against liquefied natural gas, hydrogen, methanol, battery powered propulsion, or even sail power? How does nuclear energy compare to these fuels in terms of efficiency, safety, and environmental impact? Instead of refueling vessels once every couple of weeks, vessels with floating nuclear powerplants onboard would only need to refuel once every couple of years, fuel costs are not subject to high rates of volatility, and the need for fuel storage onboard vessels would disappear to leave more room for cargo. This comparative analysis will provide a clearer picture of nuclear energy's potential role in decarbonizing the shipping sector, as well as how nuclear energy may be used to augment selection of one of these fuels as the primary propellant of the future commercial shipping fleet.

1.1 Problem Statement

Among the various alternative fuel and energy sources, nuclear reactor-based propulsion and power systems have emerged as a potentially exciting and pivotal long-term zero-GHG emitting and economically viable propulsion source. As the world rushes to decarbonize and slow the effects of global climate change, academics and industry seek to evaluate the viability of floating nuclear power plant (FNPP) as an option of truly carbon-neutral power generation for the future.

But what is it that makes nuclear such an attractive future means of power generation and propulsion? Almost all proposed alternative fuels will require updated production and distribution networks on land and require ships to be retrofitted for alternative fuel use on shore, already requiring an industry-wide shift. Many alternative fuel options only offer partial solutions to eliminating GHG emissions as well as a few other challenges which will be explored later. By comparison, “nuclear power at sea has proven to be one of the safest and most efficient ways to power large ships with the benefit of zero emissions” (MNAG, 2022). In fact, the U.S. Navy's nuclear fleet has amassed more than 54,000 safe operational reactor hours, over 2,250 days or 6.16 years (MNAG, 2022). While most published work to date focus on determining what a viable nuclear-propelled ship may look like and its operating parameters, this paper seeks to determine **what support structures are needed to enable nuclear reactor-based propulsion systems for the decarbonization of the maritime industry?**

The bulk of research found for this study evaluated nuclear fissions feasibility as a means of carbon neutral propulsion for the commercial maritime industry. Most discussions related to shipboard FNPPs seek to determine if nuclear fission as a means of propulsion is possible, with most research reviewed determining overwhelmingly that it is. Furthermore, research seeks to determine what type of reactor may best be use for shipboard FNPPs. However, extensive review of published literature does not seem to ascertain how nuclear-powered vessels would be supported while in operation. Therefore, to understand what a nuclear propelled future looks like, it is also essential to evaluate the comprehensive support structures required to facilitate this transition. To better understand this question, we first need to answer:

1. *What historical developments and technological advancements have shaped the current landscape of nuclear power?*
2. *How does the present nuclear industry operate in terms of safety standards, technological advancements, and global reach?*
3. *What economic factors and market conditions must be in place for the widespread adoption of shipboard Floating Nuclear Power Plants (FNPPs)?*
4. *What are the necessary infrastructure requirements, both at sea and in ports, to support the operation and maintenance of shipboard FNPPs?*

1.2 Conceptual Framework for Empirical Analysis

In this essay, we will assess the initial cost of purchasing nuclear-propelled vessels and the long-term operational costs. This involves a detailed analysis of the current state of the nuclear industry, including construction and maintenance costs of nuclear power plants. We will evaluate the necessary infrastructure for the broad adoption of shipboard FNPPs. This includes examining maintenance and fuel support models for conventional maritime propulsion systems and the modifications required for nuclear-powered propulsion. We will outline societal and policy challenges in implementing shipboard FNPPs, which includes qualitative interviews with experts in various related fields to gauge public opinion and legal constraints.

This essay will also investigate potential innovations in nuclear technology that could make shipboard FNPPs more attractive for commercial shipping. This includes analyzing the stability of nuclear fuel prices and technological advancements by leading companies in the field. We will compare those advancements with the current logistics of nuclear power plant production, distribution, and operational demands for shipboard FNPPs, including waste management and international transport logistics. We will also conduct Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis will be used to identify internal and external factors influencing the deployment of shipboard FNPPs in maritime industry.

This conceptual framework will guide the empirical analysis in the subsequent sections of the essay, addressing the research questions with a focus on practicality, feasibility, and sustainability in the implementation of nuclear-powered propulsion for decarbonizing shipping.

1.3 Thesis overview

The nuclear energy industry is currently undergoing a series of transformative changes. While advances in technology, new safety protocols, and an escalating need to combat climate change are just a few factors driving these developments, they grapple with society's slowly evolving perception of nuclear energy over time. The Covid-19 pandemic and geopolitical events like the war in Ukraine have led to a reevaluation of energy policies, breaking "European energy taboos" and pushing for more collective approaches to energy security. The European Green Deal, as part of the REPowerEU plan, underscores the commitment to renewable energies, but also recognizes the need for a diverse energy mix that includes renewables, nuclear, gas, and efficiency measures. This reflects a growing awareness that the end of fossil fuels will not be immediate and that nuclear energy, thanks to discussions on European level green taxonomy, is once again emerging as a credible alternative, seen through the lens of energy security rather than just environmental impact (Brugidou and Bouillet, 2023).

In this context, some private companies are pioneering standardization and miniaturization of nuclear reactors, aiming to make nuclear power more accessible, especially for smaller customers. Companies like TerraPower, in cooperation with Core Power, and NuScale are developing Small Modular Reactors (SMR) that can be produced in a factory and transported to the site for installation. These reactors aim to be simpler and cheaper to manufacture, reducing costs and construction time, and can be deployed incrementally to match energy demand. Core Power's design, which includes active and passive safety features, is expected to be cost-effective for small energy grids, potentially replacing less carbon-efficient sources (Kourasis, 2023). By standardizing these smaller reactors, these companies will be able to drastically reduce the cost of production for nuclear power plants and making these more cost effective solutions for private industry. These private firms are leveraging SMRs to diversify and innovate within the nuclear energy sector by positioning themselves to meet the demands of a market that increasingly values flexibility, safety, and sustainability. By producing smaller, more manageable reactors that can be used in a variety of settings, including remote locations and smaller power grids, these firms are broadening their business scope and potential customer base. This strategic diversification allows these companies to tap into new revenue streams while contributing to the global transition towards cleaner energy solutions. To comprehend the feasibility of nuclear-powered propulsion on commercial ships, one must first understand the nuances and dynamics of shifts in the nuclear sector, which will be covered later in Chapter 5.

To enhance the attractiveness of using nuclear reactors on commercial vessels, manufacturers must undertake groundbreaking innovations in nuclear technology. These innovations are essential to justify the high initial investment and the subsequent long-term cost savings for private customers. A key aspect of this appeal is emphasizing the stability of nuclear fuel prices, which have been less susceptible to fluctuations compared to the highly volatile petroleum market (U.S. Congressional Budget Office, 2011). Companies like TerraPower with help from Core Power, NuScale Power, and Oklo Inc. are at the forefront of this effort (Kourasis, 2023). They aim to refine existing nuclear energy production methods, bolster energy security and reliability, and contribute to addressing global climate challenges. However, deploying nuclear technology on a global scale in the shipboard FNPP sector presents a variety of challenges. It is crucial to engage with all relevant industry and regulatory stakeholders to fully understand their roles and viewpoints, ensuring a comprehensive approach to this complex endeavor.

The pre-conditions that pave the way for nuclear energy's viability in ships extend beyond mere technology. Alternative fuel and energy solutions will require various economic and infrastructural considerations and changes prior to full scale adoption in the maritime industry. These adjustments will need to occur both on ships and on shore. Shoreside updates will necessitate reallocation of port facility space for alternative fuel infrastructure as well as establishment of local or remote fuel or energy production supply chains. They will also need development of inland supply networks designed to minimize energy loss during transport and maximize efficiency. Adoption of alternative fuels at very small scales are already driving logistics chain shifts, as seen in the deployment of LNG onboard cruise and cargo ships and hydrogen on small barges and ferries (Foretich et al., 2021; van den Brink, 2024). Strategic development of alternative energy points will either need to happen with heavy fuel oil (HFO) bunker companies or despite them.

Economic preconditions for acceptance of nuclear-powered propulsion will primarily be related to affordability of new nuclear systems, but also include long term cost projections for refueling and maintenance of shipboard nuclear reactors. These preconditions also include regulatory approvals, capital investments, risk management, and economic viability assessments.

In this thesis, we will conduct a literature review, cover the methodology used to write this essay, provide brief background on the nuclear industry and nuclear vessels, and discuss the current state of the nuclear industry. We will also discuss economic pre-conditions for acceptance of nuclear-powered propulsion, as well as infrastructural preconditions necessary for adoption of shipboard FNPPs in the commercial maritime industry. We will conclude by assessing the viability of shipboard FNPPs in the maritime industry, review areas for further research, and share a vision of path towards a nuclear-powered future.

2. Literature Review

The transition to decarbonized shipping systems has garnered increasing attention in recent years, with nuclear reactor-based propulsion systems in the spotlight as a potential solution. However, their successful implementation hinges on several key considerations, as evidenced by an analysis of pertinent literature in the field.

2.1 Evolution of the Nuclear Energy Industry

The nuclear energy industry has a rich history that dates back to the mid-20th century, marked by significant technological advancements and evolving reactor designs. The development of pressurized water reactors (PWR), one of the first and most common types of nuclear reactors, began in the 1950s, primarily driven by the United States Navy's interest in powering submarines. These PWRs use water under high pressure as a coolant and moderator, a design that has been widely adopted in commercial nuclear power plants around the world (World Nuclear Association, 2018). On the other hand, molten salt reactors (MSR) represent a more recent and innovative approach. The concept of MSRs was first explored in the 1960s at the Oak Ridge National Laboratory in the United States, where researchers developed the Molten-Salt Reactor Experiment (MSRE). MSRs use a fluid fuel in the form of molten salt, which offers several advantages, including higher operating temperatures and improved safety features such as operating at ambient pressures (World Nuclear Association, 2020). Lower pressure operation vastly reduces the risk of wide-spread nuclear disasters as the fissile material is not contained in a system under high pressure that increases during uncontrolled water moderator heating in a nuclear meltdown scenario. These developments reflect the industry's ongoing pursuit of more efficient, safe, and sustainable nuclear energy solutions.

The global nuclear landscape has experienced numerous shifts over the past few decades, shaped in large part by three large scale nuclear disasters. These disasters are commonly known by the locations of the powerplants that suffered failures, Three Mile Island in the USA in 1979, Chernobyl in what is now Ukraine in 1986, and Fukushima in Japan in 2011. These various nuclear accidents inspired the need for development of more modern nuclear reactors with robust safety features, driven by more stringent regulations. Recently, the US Congress passed the Nuclear Energy Innovation and Modernization Act (NEIMA) in

2018 that supports research into advanced reactors. The NEIMA (2018) observed that safety concerns stemming from events like the Fukushima accident have prompted significant advancements in reactor design and safety protocols. Concurrently, the World Nuclear Association highlights the renewed and increasing emphasis on MSRs that promise enhanced safety and flexibility. Their page on Generation IV Nuclear Reactors provides an overview of advanced nuclear reactor designs, including MSRs, highlighting their potential for improved safety, efficiency, and waste management (World Nuclear Association, 2020). It specifically notes that MSRs operate at higher temperatures and lower pressures compared to conventional reactors, offering advantages in thermal efficiency and inherent safety features, such as passive cooling capabilities and resistance to core meltdown. MSRs are especially relevant for maritime applications because of their compact size and modularity. Definitions and details of PWRs and MSRs are provided in Appendix A.

The compelling need to reduce carbon emissions has also positioned nuclear power as a reliable alternative. According to the International Energy Agency (IEA) (2019), nuclear energy remains one of the least carbon-intensive energy sources, with lifecycle emissions comparable to wind and solar. It is the most popular low-carbon source of electricity in many developed countries for the last three decades, though the authors note that industry growth and change will face substantial difficulty following the Three Mile Island, Chernobyl, and Fukushima accidents as public opinion favors continued safe operation of NPPs already in operation than construction of new ones (IEA, 2019).

2.2 Current State of Shipboard Nuclear Energy

The marine application of nuclear energy is far from novel. The history of PWR propulsion in the U.S. Navy began in the mid-20th century, marking a significant advancement in naval propulsion technology. The development was spearheaded by Admiral Hyman G. Rickover, who is often referred to as the "father of the nuclear navy." The first nuclear-powered submarine, USS Nautilus (SSN-571), launched in 1954, was equipped with a PWR, demonstrating the viability and strategic advantage of nuclear-powered propulsion in submarines, leading to its widespread adoption in the U.S. Navy's submarine and aircraft carrier fleets (Polmar et al., 2004). One might say that these vessels were the first proof of concept of the idea of a floating nuclear powerplant (FNPP).

Schmidt (2019) outlines the historical use of nuclear-powered propulsion primarily within naval vessels and presents a vision of a nuclear-propelled US merchant fleet that relies heavily on American naval nuclear-powered propulsion maintenance and training infrastructure. His paper, while novel in its perspective and with an attempt to address infrastructural needs, does not seem to fully comprehend the physical or national security limitations of the U.S. Navy's nuclear training infrastructure.

Research published by Houtkoop (2022), de Freitas Neto et al. (2018), and Hagen (2022) do an excellent job at discussing the viability of various types of nuclear reactors and suggesting the most viable for future industry use. In Houtkoop's (2022) thesis on the application of nuclear reactors for marine propulsion and power generation systems, he identifies very high temperature reactors ((V)HTR) and the MSRs as the most promising Generation IV reactor types for marine application. The (V)HTR is highlighted as a near-term solution due to its higher technology readiness level, while the MSR is seen as a long-term option, offering greater capabilities and the potential for operating on a thorium cycle. Frietas' article also discusses the feasibility of using MSRs for merchant ship propulsion, considering the rising fuel costs, environmental regulations, and potential introduction of carbon taxes in the naval industry. His study highlights the advantages of MSRs, such as their ability to use thorium, which is more abundant than uranium, and the successful use of pressurized water reactors in Russian icebreakers, suggesting that a shift to nuclear-powered propulsion in commercial shipping could be feasible. Hagen (2022) disagrees with adoption of MSRs after a careful evaluation of various nuclear reactor types and asserts that PWR are the reactor types most ready for commercial fleet deployment due to their higher technology readiness level, especially since they are already deployed on naval vessels and icebreakers around the world. Her thesis also acknowledges the potential of the molten gas-cooled reactor (MGCR) as another option, but notes that this technology is not mature enough at the time of her study to fully support. While all three authors agree that nuclear fission power in the commercial industry is possible, they don't necessarily agree on the most feasible means of providing nuclear power to the future commercial fleet.

The Idaho National Laboratory's (INL) document "Introduction to Advanced Commercial Nuclear for Maritime" (2022) similarly concludes that floating nuclear powerplants are viable solutions in the maritime sector, though their work focuses on their environmental, economic, and social justice impacts and emphasizes the opportunities for the U.S. shipbuilding sector to grow and lead globally. This document also addresses the challenges of the regulatory landscape and the need for international collaboration in nuclear maritime demonstration projects is supported by the INL in their nascent maritime use investigation, as highlighted by several documents released by the organization (MNAG, 2022a; Bennett, 2022). Moreover, recent endeavors by companies like Korea Electric Power Corporation (KEPCO) showcase emerging global interest in deployment of small modular molten salt reactors for commercial nuclear-powered propulsion and early stages of deployment in commercial sectors (World Nuclear News, 2023). These companies are showing interest in small modular molten salt reactors for floating power production due to their potential for long-term gains in sustainable energy production and market leadership in advanced technology. This interest reflects a strategic move towards diversifying energy portfolios, capitalizing on technological advancements, and aligning with global market trends and regulatory shifts towards cleaner energy sources.

2.3 Economic Pre-conditions for Shipboard FNPPs

Shifting to nuclear-powered propulsion in the maritime industry entails a multifaceted checklist of requirements. Economically, as Abou Jouade et al. (2023) suggest, the high upfront costs of nuclear-powered propulsion might be offset by lower operational costs and fuel savings over time, though this requires comprehensive economic modeling. Moreover, he suggests that standardization of reactor designs and construction serialization can lead to dramatic cost savings. Regulatory challenges cannot be overstated.

A study published by the IEA (2019) suggested that development of standardized SMRs would best be done through government funding in a mix of research and development funding, public-private partnerships, and grants. The study highlights current efforts in various nuclear nations to employ this funding structure, though they do not discuss potential funding structures for large scale maritime deployment, a subject this paper will discuss in chapter 7.

2.4 Infrastructural Pre-conditions for Shipboard FNPPs

From an infrastructural standpoint, Lohse et al. (2023) argue that producers of nuclear reactors have a few concerns related to increased production of nuclear reactors. Their report highlights that lead time for parts is currently one to two years, depending on the components (Lohse et al., 2023). This would likely shorten if MSR production capacity was increased. They also determined that workforce concerns[1] and uncertainty about the nuclear industry's future are a specific concern related to nuclear component production (Lohse et al., 2023). Their conclusion takes a more sober approach than most MSR proponents, who seem to believe that short-term and large scale production of small modular MSRs is feasible.

As per Wang, Zhang, and Zhu (2023), navigating the intricate maze of international maritime laws, environmental concerns, and nuclear regulations presents a significant challenge, especially given the diverse nature of port state controls. This paper will go into more detail about the update of international regulations in chapter 6.

2.5 Comparison to Other Alternative Fuel Sources

When juxtaposed with other alternative fuel sources, nuclear-powered propulsion exhibits distinct advantages and challenges. Bilgili (2021) conducted a comprehensive review of various alternative energy sources, including: ammonia, biofuels, dimethyl ether, ethanol, hydrogen, liquefied natural gas, liquefied petroleum gas, and methanol. His study determined that, like nuclear energy, worldwide use of alternative fuels is still in the early stages of adoption and plenty of challenges stand in the way of full scale adoption of any one energy source over another. Nuclear energy in the maritime realm exists in a similar state. Nuclear power offers higher energy density and consistent power output compared to sources like wind or solar, though Bhattacharyya, El-Emam and Khalid (2023) highlight that nuclear energy can also be used in alternative fuel production, an assertion supported by other authors.

In the realm of commercial maritime propulsion, the quest for sustainable and efficient fuel alternatives has led to the exploration of hydrogen, methanol, ammonia, and liquefied natural gas (LNG). Each of these fuels presents unique advantages and challenges, as highlighted by recent research in the field.

[1] Concerns regarding availability, experience, turnover, and training, specifically

2.5.1 Hydrogen

Hydrogen, often lauded for its potential as a zero-emission fuel, stands out when produced from renewable sources. The combustion of hydrogen results in water vapor, offering an environmentally friendly option. However, a study by Song et al. (2022) points out significant challenges in its application. Hydrogen has the highest daily boil-off gas (BOG) rate among the fuels considered, leading to more energy wastage. Additionally, the efficient handling of BOG is crucial, indicating significant challenges in storage and transportation.

Hydrogen's primary advantage is its environmental benefit. As a zero-emission fuel when produced from renewable sources, hydrogen's combustion results only in water vapor, aligning perfectly with global efforts to reduce greenhouse gas emissions (Antolini, 2020). This aspect is particularly crucial given the IMO’s ambitious goal to reduce GHG emissions from shipping by 50% by 2050 compared to 2008 levels. Hydrogen-based fuel cells are considered a viable option for decarbonizing maritime transport, provided that renewable energy sources are used in hydrogen production (Antolini, 2020).

However, the application of hydrogen in maritime transport is not without its challenges. A significant issue is the energy efficiency and storage of hydrogen. The high daily BOG rate of hydrogen leads to more energy wastage compared to other fuels like LNG, ammonia, and methanol (Song et al., 2022). Efficient handling of BOG is crucial, indicating significant challenges in storage and transportation.

Moreover, the feasibility of onboard hydrogen production and storage is a critical area of research. Elrhoul, Romero Gómez and Naveiro (2023) review various shipboard methods for green hydrogen production, storage, and consumption. They note that while solar and wind-based hydrogen production methods on ships are limited by their availability, recovery energy requires only a modification of the propulsion system to benefit from the energy excess and produce green hydrogen. The use of ammonia as a hydrogen medium storage and hydrogen solid storage are promising options due to their matching characteristics to hydrogen properties.

Additionally, the technical analysis and prospective of hydrogen-based technologies in the maritime sector are being actively explored. The replacement of conventional diesel gensets with systems based on proton exchange membrane fuel cell technology in vessels like ferries is under investigation. This involves determining the hydrogen consumption for daily operation and comparing different storage technologies involving both compressed and liquefied hydrogen (Minutillo et al., 2022).

Furthermore, the United States Department of Energy (DOE) has been exploring hydrogen as part of a comprehensive energy strategy, focusing extensively on maritime transportation applications. The switch from fossil fuel systems to clean energy systems like hydrogen fuel cells is projected to achieve a 70% reduction in carbon emission by 2030 and carbon neutrality by 2050 (Chavan, Knollmeyer and Khan, 2023). This research evaluates the feasibility of hydrogen fuel cells for various ferry routes, including the current rules, regulations, and standards required for their implementation.

Though hydrogen presents a promising path towards a sustainable maritime sector with its zero-emission potential, the challenges related to its energy efficiency, storage, and the feasibility of onboard production and storage solutions remain significant areas of research and development.

2.5.2 Methanol

Methanol emerges as a strong contender in terms of energy efficiency. Song et al. (2022) note that when produced from renewable sources, methanol shows the highest energy efficiency among the fuels studied, with a remarkable efficiency of 98.02%. This, coupled with its lower emissions compared to traditional marine fuels, makes methanol an attractive option. However, the production cost of green methanol can be high, impacting its economic feasibility. Additionally, methanol is toxic, posing risks in handling and storage.

Methanol's potential as a competitive marine fuel is increasingly recognized, especially in the context of stringent environmental regulations. Lundgren and Wachsmann's (2014) study highlights that methanol can significantly reduce sulphur content in ship exhaust, complying with the MARPOL regulations that demand a maximum sulphur content of 0.1% in marine fuels within Sulphur Emission Control Areas. The study also notes that engine manufacturers are already offering methanol-powered engines and that the IMO is working on a regulatory framework for the use of methanol on merchant vessels. However, the current price of methanol is relatively high, though it is expected to fall in the near future (Lundgren and Wachsmann, 2014).

Anderssen and Lewin (2016) discuss the impact of emission legislations on the adoption of methanol in marine propulsion. They point out that methanol's higher compatibility with existing infrastructure and engine concepts, due to its liquid state at ambient conditions, makes it a viable alternative to LNG. However, the properties of methanol also impose technical challenges and safety concerns. The current low oil price creates a competitive disadvantage for alternative fuels like methanol, which impedes its widespread introduction. Anderssen and Lewin (2016) assert that for methanol to be a feasible long-term fuel alternative, it must comply with future regulations and be available at a cost-competitive price.

Moroianu and Postolache's (2018) research on marine propulsion engine behavior using fossil fuel and methanol indicates that methanol is an attractive alternative due to its potential to reduce polluting emissions and expected lower future costs. Their study analyzes maritime engine performance with both fossil fuels and methanol, highlighting the environmental and economic benefits of switching to methanol (Moroianu and Postolache, 2018).

Bertagna et al. (2023) examine the impact of switching to methanol on the design of an all-electric cruise ship. They argue that methanol has several advantages over other fuels, providing a feasible near-term solution for more sustainable maritime transport. However, the onboard integration of methanol requires careful evaluation to determine the technical and economic feasibility of transitioning the onboard power production to this fuel (Bertagna et al., 2023).

This technical evaluation of methanol underscores the complexity of transitioning to alternative fuels, highlighting the need for comprehensive solutions that balance technical feasibility with environmental and economic considerations.

2.5.3 Ammonia

Ammonia, another alternative, shows promise in terms of reliability in marine applications. Popp and Müller (2021) highlight that ammonia exhibits a very promising overall failure rate. Its combustion does not produce CO2, making it an attractive option for reducing GHG emissions. According to Cheliotis et al. (2021), ammonia's high energy density, low flammability, easy storage, and low production cost are all advantages. However, ammonia's toxicity poses significant safety risks, and its energy efficiency, while better than hydrogen, is lower than that of methanol. Additionally, high production costs, limited availability for bunkering, challenges in ramping up production, and development of specific regulations addressing toxicity, safety, and storage as major barriers all present hurdles to adoption of this alternative fuel (Mallouppas, Ioannou and Yfantis, 2022).

That is not the only problem associated with adoption of ammonia fuels. A technical feasibility analysis was conducted by Di Miccio et al. (2022) analyzing conventional diesel engine replacement on board a commercial vessel using an ammonia-fueled fuel cell system. They found that while the proposed system increases weight in the engine and fuel rooms, it represents a viable solution for zero-emission maritime power. However, a cargo reduction of about 2.88% is necessary to accommodate the system compared to a diesel-fueled ship (Di Micco et al., 2022).

While ammonia could potentially be a promising solution to a carbon-free future, its adoption faces challenges related to production costs, availability, safety, and regulations. Ongoing research is crucial to overcome these challenges and facilitate wider adoption.

2.5.4 LNG

Liquefied natural gas (LNG) offers lower sulfur oxide and particulate matter emissions compared to heavy fuel oil. It is increasingly being adopted as an alternative to conventional marine fuels in maritime transport due to its environmental benefits and cost-effectiveness. Burel, Taccani, and Zuliani (2013) found that using LNG leads to a reduction of 35% in operational costs and 25% in CO2 emissions compared to conventional fuels. Additionally, the study suggests that combustion gases produced by LNG are cleaner, simplifying introduction of exhaust gas heat recovery and potentially reducing fuel consumption by up to 15% (Burel, Taccani, and Zuliani, 2013). It still emits GHGs, albeit less than traditional marine fuels, but methane slip during LNG combustion can negate some of the environmental benefits. While the technology is more mature compared to other alternative fuels it is not free from drawbacks.

The challenge with all alternative fuels is that shore infrastructure will need updates to facilitate the energy transition. Wang and Notteboom (2014) performed a systematic review of studies on the use of LNG as a ship fuel. Their study highlighted the role of ports in facilitating the large-scale adoption of LNG and presents a decision-making framework for shipowners considering a fuel switch from conventional oils to LNG. The study underscores the importance of complying with IMO's MARPOL Annex VI regulations, which drive the consideration of LNG as a marine fuel (Wang & Notteboom, 2014).

LNG presents itself as a viable alternative to traditional marine fuels, offering significant reductions in operational costs and greenhouse gas emissions. However, its adoption is not without challenges, including safety concerns, the need for infrastructure development at ports, and the inherent limitations and GHG emissions this fossil-based fuel. Wider adoption of LNG as a sustainable marine fuel will require further research and testing before it is established as the industry's alternative fuel of choice.

The selection of an appropriate fuel for commercial maritime propulsion requires a careful balance between environmental impact, economic feasibility, and technological maturity. Methanol stands out for its high energy efficiency, while ammonia is notable for its reliability. Hydrogen, despite its zero-emission potential, faces significant challenges in energy efficiency and storage. LNG, while being a cleaner alternative to conventional fuels, still contributes to GHG emissions. A few of the benefits and drawbacks of various alternative fuel sources as discussed above can be found summarized in Table 1 below.

PROS AND CONS OF A FEW ALTERNATIVE FUELS

Fuel Type	Pros	Cons
Hydrogen	• Zero emissions when produced from renewable sources. • Sustainable production.	• High daily boil-off gas rate, leading to energy wastage. • Storage and transportation challenges.
Methanol	• Highest energy efficiency (98.02%) when produced renewably. • Lower emissions.	• High production cost. • Toxic, posing risks in handling and storage.
Ammonia	• Very promising overall failure rate, indicating high reliability. • Zero CO_2 emissions.	• Highly toxic, posing significant safety risks. • Lower energy efficiency than methanol.
LNG	• Lower sulfur oxide and particulate matter emissions. • More mature technology.	• Still emits greenhouse gases.

Fuel Type	Pros	Cons
		• Methane slip during combustion.

Table 1: Benefits and drawbacks of a few alternative fuels (Source: various from text)

2.5.5 Quay-side Greening

Regardless of what alternative fuel or energy source is selected, something can be done in the short term to green ports and ships while moored to the quay. Chen et al. (2019) highlight that "cold ironing", the process by which ships shut down all power generating systems and accept power from a local grid through cables running from an onshore power connection to the ship's power system, could be conducted to help "green" the ports of the future by accepting electricity that could be generated from 100 percent renewable sources. A reverse of this idea, known as "reverse cold ironing", is imagined by proponents of nuclear energy. In this process, vessels with shipboard FNPPs are an essential piece to decarbonization as they would leave shipboard FNPPs running and sell fuel to the port through its shore power connection, an especially advantageous practice while the ship's own power needs are lower. This energy source could also be used to produce alternative fuels, such as hydrogen or ammonia.

2.6 Port Logistics and Commercial Use Challenges

Integrating nuclear-powered ships into the existing maritime framework is fraught with logistical challenges. Chen et al. (2019) highlight that current port infrastructures are ill-equipped to manage vessel cold-ironing. Various international regulations make nuclear waste disposal, emergency response, and safety checks also quite difficult, especially for shipboard reactors which would be defined as "mobile reactors" and treated differently from their stationary terrestrial counterparts. Emblemsvåg (2022) suggests that the challenge of nuclear waste disposal, one of the biggest problems with use of nuclear energy, might be made easier by switching from uranium fuel to thorium fuel, which has a noteworthily shorter half-life. However, adoption of thorium as a fuel source still has many unanswered questions.

Furthermore, the United Nations Convention on the Law of the Sea (1982) (UNCLOS) allows coastal states to freely restrict operations of foreign nuclear powered ships or foreign ships carrying nuclear materials for any or no reason at all (Wang, Zhang, and Zhu, 2023). Gibbs et al. (2014) also notes that ports might be hesitant to accommodate nuclear ships not only due to potential backlash from local communities and stakeholders for accommodating vessels that they may perceive as being “dangerous”, but also because those ports may require infrastructural changes that are hard to plan for due to lack of fidelity in energy consumption data.

2.7 Conclusion

In 50 years, developments in nuclear energy have substantially improved safety and efficiency, especially in the wake of large nuclear incidents. Despite the initial deployment of PWRs on ships, advanced reactors include passive and active safety features that will likely turn the tide of public opinion in their favor. As we saw, several alternative fuels are being considered and developed along with investigations into nuclear-powered propulsion. There is no one alternative fuel or energy that rises above the rest, though nuclear power is the only truly zero carbon option. By courting public opinion, national and international regulators will be able to update nuclear regulations more easily, paving the way for a nuclear-powered future.

3 Methodology, Analytical Framework, and Materials

3.1 Methodology, Data Limitations, and Analytical Framework

In this research, feasibility of nuclear-powered propulsion is evaluated by determining the economic and infrastructural pre-conditions needed to enable broad adoption of shipboard FNPP. To evaluate economic pre-conditions[2], this study seeks to understand the current state of the nuclear industry, to include the cost of construction for terrestrial nuclear power plants (NPP) and NPP long-term maintenance needs and associated costs. A review of the current state of nuclear shipping is conducted to better understand historical examples of nuclear propelled vessels and provide context for historical issues with nuclear propelled vessels and the future state of shipboard nuclear energy. This information will be supplemented by conducting interviews with experts in the fields of nuclear engineering, shipping, port management, maritime economics, and vessel classification. These interviews seek to validate information previously found in literature, provide contrasting expert opinions where they may conflict with literature (thereby inspiring further research), and filling in knowledge gaps. While some interviewees could not directly answer questions central to this thesis, they provided descriptions of industry processes and procedures currently being employed to help determine what must happen for acceptance of shipboard FNPP to occur. Results were triangulated with the established conceptual framework following review of primary sources. Selection bias was addressed by selecting interviewees with diverse professional and socioeconomic backgrounds. In some cases, interviewees engaged in reflective practice and openly stated the limitations of their own knowledge. Other data limitations included temporal limitations and accessibility issues. These limitations were difficult to overcome as broad shipboard FNPP use in maritime industry is quite new and requires more research and pilot studies to best determine viability. Moreover, information related to current operation of nuclear vessels exists at the state level as it relates to nuclear navies and is largely inaccessible for public viewing.

To determine the infrastructural pre-conditions[3] needed for broad adoption of shipboard FNPPs, maintenance and fuel support models for modern conventional maritime propulsion systems will be assessed. A review of prevailing public and legal sentiments

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[2] What this study defines as “economic pre-conditions” can be found in Appendix A
[3] What this study defines as “infrastructural pre-conditions” can be found in Appendix A

toward nuclear energy will be conducted, as not all infrastructural change will be physical and some will be social and legal. Once these infrastructural pre-conditions are determined, the economic and infrastructural pre-conditions will be analyzed to guide development of an imaginary future support system for nuclear-powered propulsion systems. A SWOT analysis will be conducted to determine internal factors that may affect deployment of FNPPs to the shipping industries and assess external factors that may affect FNPP growth.

3.2 Materials Consulted

The materials reviewed for this study encompassed a wide range of sources, meticulously selected to ensure credibility and relevance to the study's overarching theme. Primary among these were peer-reviewed articles from academic and professional journals that offered in-depth insights, empirical findings, and comprehensive analyses on nuclear-powered propulsion and the green energy transition in the commercial maritime industry. The journals provided a balanced perspective by including studies that spanned diverse methodologies, populations, and geographies. In addition to academic journals, the review incorporated several seminal books authored by leading experts in the field. These texts served as foundational pillars, helping to frame the research within historical, theoretical, and conceptual contexts. Their comprehensive nature also provided a broader understanding of the topic, complementing the more specific findings from journal articles. Government reports and white papers were consulted to understand the practical implications and real-world applications of the research. These documents lent a grounded element that ensured the study remained pertinent to current societal and policy challenges. Lastly, the review process was enriched with expert interviews, news articles, and opinion pieces, which provided a nuanced understanding of the topic and highlighted gaps in the current literature and pointed toward future research directions. These dialogues offered a more personalized touch, giving voice to practitioners, stakeholders, and researchers deeply entrenched in the field. In summary, the materials for this study were sourced with an emphasis on breadth, depth, and credibility, ensuring a comprehensive, multidimensional, and up-to-date understanding of the topic under investigation, especially as no direct analysis has been conducted on this particular topic until this point.

4. Nuclear Background

4.1 Nuclear Power Generation Essentials

As a power source, nuclear power wasn't harnessed successfully until the early 1940's (Monaghan, 2016). The discovery of nuclear fission by Enrico Fermi enabled a team of scientists in Chicago to develop the world's first nuclear fission reactor, which was successfully tested and run at the University of Chicago (Monaghan, 2016). Though most early research on nuclear fission was directed towards development of nuclear weaponry during the Second World War, nuclear governments broadened their research focus towards nuclear energy towards the later years of the 1940's and into the 1950's (Monaghan, 2016). After the formation of the Atomic Energy Commission in the United States, an experimental nuclear fission reactor known as a "breeder reactor" was established in the American state of Idaho and first produced electricity from nuclear energy on the 20th of December, 1951 (Monaghan, 2016). In 1956, the UK government opened a commercial reactor in Cumberland and claimed that this reactor was "the first station anywhere in the world to produce electricity from atomic energy on a full industrial scale" (Monaghan, 2016).

Nuclear power can be harnessed in two distinct ways, nuclear fusion and nuclear fission. Both methods produce energy by forcing atoms to interact at the atomic level. Nuclear fusion harnesses the resulting energy from fusing two different atoms together. Nuclear fission occurs when the nucleus of a heavy fissile element like Uranium 235 absorbs a neutron, which provides the nucleus with additional energy that exceeds the nucleus' binding energy and causes it to split (Houtkoop, 2022). This split generates two smaller atoms, several free neutrons, and kinetic energy in the form of heat. The free neutrons can then be absorbed by another nucleus of more fissile material, causing a chain fission reaction to occur, which is the essential principle of nuclear power from fission (Houtkoop, 2022). This chain reaction is known as criticality. Nuclear fission reactors require a comparatively smaller amount of energy to reach criticality. This lower barrier for energy production is the primary reason that fission is the only form of nuclear power generation in commercial use today. Though nuclear fusion generates way more energy, it also requires an incredible amount of energy to reach criticality and, for that reason, has remained largely theoretical until recently (Temple, 2023).

Nuclear fission power generation can be achieved using different processes. The most common nuclear fission reactor type is a PWR, which is a generation II nuclear reactor. Generation II reactors can be broken up into two different types of light water reactors (LWR): PWRs and boiling water reactors (BWR) (radioactivity.eu.com, n.d.). Both reactor types use enriched uranium (which is saturated with extra neutrons) as fuel and rely on water both for cooling and neutron moderation (radioactivity.eu.com, n.d.). The superheated water is then converted to energy by use of a heat exchanger, which generates steam and subsequently spins turbines, generating electricity. Currently, around 85 percent of electricity produced around the world by means of nuclear power comes from generation II reactors, representing a majority of the 439 units in operation today (radioactivity.eu.com, n.d.).

4.2 Maritime Application of Nuclear Power

On the maritime front, the utilization of shipboard nuclear energy in the private sector is still in its infancy. Nuclear-powered propulsion on ships is not a new concept. Nuclear-powered propulsion has been used successfully on military vessels since the 1950's. On commercial vessels, nuclear-powered propulsion was used as a test of concept by the American, German, Japanese, and Russian governments. These tests were largely unsuccessful for various reasons, though the Russian vessel Sevmorput is still in operation today. To appreciate the full scope of nuclear-powered propulsion in the maritime sector, a historical overview of its application, demonstrated in notable vessels such as the Lenin and Savannah, provides essential context. Specific vessel characteristics can be found in Table 2:

CHARACTERISTICS OF EARLY NUCLEAR POWERED VESSELS

Ship	Type of ship	Length overall (m)	Beam (m)	Gross Tonnage	Deadweight Tonnage	Type of reactor	Power generation (MWt)	Years in service
Lenin	Icebreaker	134	27.6	11,62	3073	PWR	270	1959-1989
Savannah	General cargo	181.6	23.8	15,858	9570	PWR	74	1962-1972
Otto Hahn	General cargo	172	23.4	16,87	14,079	PWR	38	1968-1979
Mutsu	General cargo	130	19	8240	2400	PWR	36	1974-1992

Sevmorput	Cargo (LASH/container)	260.3	32.2	38,226	26,48	PWR	135	1988-2007, 2016-present

Table 2: Characteristics of early nuclear powered vessels (Wang et al., 2023)

Nuclear-powered propulsion is used more widely around the world to power large naval vessels, including aircraft carriers and submarines in six countries including: the United States, United Kingdom, China, Russia, France, and India (MNAG, 2022). To date, nuclear-powered propulsion on board maritime vessels has been a state sponsored activity because of the strategic advantage reduced refueling provides and because of the inherently highly risky nature of operating a mobile pressurized water reactor (Naval History and Heritage Command, 2023; Saul, 2023). Vessel purchase, staffing, staff training, fueling, and disposal of all vessels have been done by national governments. In the US, staff training alone for 3000 sailors was estimated to cost between 19.7 – 28.5 million USD annually in 1996, costs which certainly are much higher in modern dollars (U.S. GAO, 2016). The US Navy pays its nuclear-trained personnel is around 90,000 USD, which equates to around 243 million USD annually for each class of approximately 2700 students that completes US Navy Nuclear Power School, the US Navy's floating nuclear reactor training program (Chan, 2023; Zip Recruiter, n.d.). This model is not viable for private commercial industry. Indeed, the US Congressional Budget Office (2011) estimated in 2011 that the cost of 59 nuclear powered vessels would be roughly 20 billion USD more than their conventionally fueled variants over their entire "cradle-to-grave" lifecycle.

Implementation of nuclear-powered ships is not without its challenges. Vessels currently using nuclear energy production means are sponsored by state governments. This comes with state provided maintenance and support infrastructure which is funded by taxpayer money. For shipboard FNPPs to be viable, shipping companies, ship owners, ports, reactor production companies, and nations will need to invest in sensible reactor support infrastructure. This infrastructure will need to be able to provide scheduled and emergent services to vessels all over the world as they deliver commercial goods from port to port. While experts have sang praises of the 20 year lifespan of a single batch of fuel in a nuclear reactor, questions persist about disposal of spent reactor fuel as well as supply of new reactor fuel. Infrastructural issues like the international transport, enrichment, or long-term storage of nuclear waste will be discussed in depth further in this essay. Addressing these logistical questions is paramount to the successful integration of nuclear energy into the maritime industry.

Pressurized water reactors are also the most common type of reactors in naval use by some of the largest navies in the world (Houtkoop, 2022). These PWRs are used on both large surface ships and submarines alike, using highly enriched uranium as their primary fuel. In the U.S. Navy, these reactors have propelled ships for over 50 years without issue (MOFA, 2016). America's 83 nuclear-powered warships have collectively visited over 150 ports in over 50 countries, operating more than 134 million miles with 5700 years of safe reactor operation (MOFA, 2016).[4] Alongside naval vessel propulsion, nuclear power has also been investigated for commercial maritime use. The very first vessel propelled by a nuclear reactor was the Soviet icebreaker Lenin, which entered service in 1959 (Houtkoop, 2022). Since then, the Soviet Union/Russia have commissioned ten nuclear powered icebreakers with one, the Sevmorput, capable of carrying general cargo or containers (Houtkoop, 2022). Additionally, the U.S., Germany, and Japan each constructed a nuclear propelled commercial cargo vessel, though these trials were short-lived and not without issues (as discussed in the next section). An overview of commercial nuclear vessels previously or currently in service can be found in the following table:

NUCLEAR VESSELS PREVIOUSLY OR CURRENTLY IN SERVICE

Ship	Type of ship	Reactor type	Years in service
Lenin	Icebreaker		1959-1989
Savannah	General cargo		1962-1972
Otto Hahn	General cargo		1968-1979
Mutsu	General cargo		1974-1992
Arktika			1975-2008
Sibir	Icebreaker	PWR	1978-1992
Rossiya			1985-2013
Sevmorput	Cargo (LASH/container)		1988-2007, 2016-present
Taimyr	Icebreaker		1989-present

[4] It is difficult to determine how much of this success is owed to inherently safe reactor design and operation and how much is attributed to the fact that no private nuclear powered vessels have ever operated outside of a state-supported construct since the Lenin first sailed in 1959.

Sovetskiy Soyuz			1989-2014
Vaygach			1990-present
Yamal			1992-present
50 Let Pobedy			2007-present
Arktika			2020-present

Table 3: An overview of commercial nuclear vessels previously or currently in service. Source: (Houtkoop, 2022)

4.3 The Nuclear Problem

Nuclear is a source of clean and plentiful energy, capable of providing way more power than fossil fuel and renewable energy. While potential advantages are significant, several critical issues associated with nuclear power often overshadow wide-scale global adoption. Safety is the biggest issue, shared by the public and regulators, alike. Their concerns are driven by three major nuclear incidents: the Three Mile Island incident in 1979, the explosion at the Chernobyl Powerplant in 1986, and most recently the Fukushima powerplant accident in 2011 (IEA, 2019). These accidents resulted in loss of life, long-term environmental contamination, and/or massive economic costs. Another major issue is that LWRs use significant amounts of water for steam production and cooling. This water is taken from large and moving sources to ensure that cooling water temperature remains low enough to reliably cool the reactor. Not only can this lead to energy stability concerns in drought-prone regions (Macknick et al., 2012), but elevated water temperatures from reactor cooling discharge can also adversely affect local aquatic ecosystems (U.S. Geological Survey, 2018). Since Fukushima, modern fourth generation reactor designs (such as molten salt reactors) seek to incorporate reactor safety, efficiency, and sustainability features by using advanced designs and materials to make future reactors both scalable and economical (Rapier, 2023).

As mentioned earlier, the track record for naval nuclear reactors is quite good. Unfortunately, the same cannot be said of commercial reactors used on experimental cargo vessels. During the American vessel NS Savannah's operation, the ship dumped 115,000 gallons of radioactive waste into the ocean, the German vessel Otto Hahn was not allowed to enter some ports and the Suez Canal because of safety concerns, and the Japanese ship Mutsu suffered a minor failure in its radiation shielding in 1974, which lead to public outcry and the ship being blocked from returning to port for several weeks (Baraniuk, 2023). Additionally, the NS Sevmorput, the only operational nuclear powered cargo vessel today, struggles with breakdowns (Baraniuk, 2023) that Russia finds difficult to manage due to the vessels inability to enter ports around the world for repair (Dowling, 2023; MNAG, 2022). Russia's other operational nuclear assets are restricted to Arctic operations, as they are fully dependent on cold Arctic water to keep their reactors cool (Dowling, 2023).

The challenges faced by nuclear maritime shipping are not solely rooted in the technical difficulties or operational mishaps of the vessels themselves. Historically, public perception and regulatory hurdles have played a significant role in stymying the growth of nuclear-powered commercial shipping. The maritime industry is dependent on vessels docking in ports in different nations around the world. Each of these nations has its own set of regulations, safety standards, and public sentiments regarding nuclear energy. The shadow of past terrestrial nuclear incidents coupled with hesitance about the safety of shipboard "mobile" nuclear reactors has led to heightened scrutiny and often outright resistance to nuclear-powered vessels entering certain ports, especially as reactor design and operation standards adopted by one nation may not be the same in use by another nation. This has resulted in logistical nightmares for operators, as they must navigate a complex web of international regulations and treaties. For instance, the Treaty of Tlatelolco prohibits nuclear weapons in Latin America and the Caribbean (OPANAL, 2018), and while it doesn't directly address nuclear-powered propulsion, the sentiment behind such treaties can influence port access decisions.

As the world grapples with climate change and seeks cleaner energy sources, the maritime industry is under pressure from the International Maritime Organization (IMO) to reduce its carbon footprint (2023 IMO Strategy on Reduction of GHG Emissions from Ships). While nuclear-powered propulsion offers a potential solution, the challenges have made its widespread adoption a complex endeavor. However, organizations like the International Atomic Energy Agency (IAEA) anticipate that the number of nuclear-powered commercial, passenger, and military vessels in operation will increase over time, so they are actively working with diverse groups of state governments to "strengthen arrangements for international assistance in radiation measurements and decontamination if any accidents would occur" (Jayarajan, 2023). As we delve into the current state of the nuclear industry, it is essential to understand these multifaceted issues that have historically shaped nuclear power's trajectory in the maritime sector.

5. The Current State of the Nuclear Industry

5.1. General Overview

The next generation of nuclear power plants will include the newest Generation IV reactors. In 2000 the Organisation for Economically Developed Countries (OECD) Generation IV International Forum (GIF) defined four goals for Generation IV reactors:

- Safe and reliable;
- Economically viable;
- Sustainable;
- Proliferation resistant and physically secure (Generation IV International Forum, 2014)

These goals would help ensure that operational power plants could be economically advantageous, minimally wasteful, and maximally safe for the duration of the reactor's operation (Generation IV International Forum, 2014). To spur American development of advanced nuclear reactors, US Congress passed the Nuclear Energy Innovation and Modernization Act of 2018 (NEIMA), defining advanced nuclear fission reactors as those that have "significant improvements over the most recent generation of nuclear fission reactors, which may include:

i. Inherent safety features
ii. Lower waste yields
iii. Greater fuel utilization
iv. Superior reliability
v. Increased resistance to proliferation
vi. Increased thermal efficiency, and
vii. The ability to integrate into electric and nonelectric applications" (MNAG, 2022)

The GIF defined six reactor types for development focus by 14 signatory nations: gas-cooled fast reactor (GFR), lead-cooled fast reactor (LFR), molten salt reactor (MSR), sodium-cooled fast reactor (SFR), supercritical-water-cooled reactor (SCWR), and very-high-temperature reactor (VHTR). A summary of each reactor can be found below:

KEY DETAILS AND DEVELOPMENTS OF VARIOUS GEN IV REACTORS

Reactor Type	Key Details and Developments
Gas-cooled fast reactor (GFR)	- Reference concept of 2,400 MWth reactor capable of breakeven breeding deemed unviable; 600 MWth SMR reactor being explored. - Improvements in design for safe management of loss-of-coolant accidents and robust removal of decay heat without external power. - Design studies for small experimental reactor underway (ALLEGRO).
Lead-cooled fast reactor (LFR)	- Prototypes expected after 2020: Pb-Bi-cooled SVBR-100, BREST-300 in Russia, and the 300MWth ALFRED by Euratom. - Proceeding with detailed design and licensing activities. - Main R&D efforts concentrating on on materials corrosion and development of a lead chemistry management system, core instrumentation, fuel handling technology, advanced modeling, fuel development.
Molten salt reactor (MSR)	- Two test reactors already operated in the United States between 1950 and 1976. - A baseline concept: the molten salt fast reactor (MSFR). - Commonalities with other systems using molten salts. - Further R&D on liquid salt physical chemistry and technology, especially on corrosion, safety-related issues, and treatment of used salt. - One company, Terrestrial Energy, signed on to the GIF in 2019 because of their involvement in developing an MSR
Sodium-cooled fast reactor (SFR)	- Three baseline concepts (pool, loop, and modular configurations). - Several sodium-cooled reactors are operational or under construction in countries like China, India, Japan, and Russia. - Development of advanced national SFR demonstrators for near-term deployment in countries like France, Japan, Russia, China, Korea, and India. - Main R&D efforts focusing on safety, operation, fuel development, component design, system integration, and economic evaluations.
Supercritical-water-cooled reactor (SCWR)	- Two baseline concepts: pressure-vessel-based and pressure-tube-based. - R&D in the next decade will focus on advancing conceptual designs of baseline concepts, fuel assembly testing, computational tool qualification, and design studies for a prototype.
Very-high-temperature reactor (VHTR)	- Main focus in the near future will be on VHTR with core outlet temperatures of 700-950°C (increases in temperature will lead to increases in reactor efficiency) - R&D on materials and fuels to enable higher temperatures up to above 1,000°C and a fuel burnup of 150-200 GWd/tHM. - Development of high-temperature process heat consortia for end-users and safety analyses of coupled nuclear processes for industrial sites using process heat.

Table 4: key details and development of various generation IV nuclear reactors (Generation IV International Forum, 2014)

GEN IV NUCLEAR REACTOR CHARACTERISTICS

	Coolant	Temp (°C)	Pressure*	Fuel	Fuel cycle	Size (MWe)	Use
Gas-cooled fast reactors	helium	850	high	U-238 +	closed, on site	1200	electricity & hydrogen
Lead-cooled fast reactors	lead or Pb-Bi	480-570	low	U-238 +	closed, regional	20-180** 300-1200 600-1000	electricity & hydrogen

Molten salt fast reactors	fluoride salts	700-800	low	UF in salt	closed	1000	electricity & hydrogen
Molten salt reactor - advanced high-temperature reactors	fluoride salts	750-1000		UO2 particles in prism	open	1000-1500	hydrogen
Sodium-cooled fast reactors	sodium	500-550	low	U-238 & MOX	closed	50-150 600-1500	electricity
Supercritical water-cooled reactors	water	510-625	very high	UO2	open (thermal) closed (fast)	300-700 1000-1500	electricity
Very high temperature gas reactors	helium	900-1000	high	UO2 prism or pebbles	open	250-300	hydrogen & electricity

* high = 7-15 MPa
+ = with some U-235 or Pu-239
** 'battery' model with long cassette core life (15-20 yr) or replaceable reactor module.

Table 5: Characteristics of different generation IV nuclear reactors (Source: World Nuclear, 2020)

5.2. Molten Salt Reactors (MSR)

Of the generation IV designs, MSRs have received growing attention over the past 5 years, especially as a shift to green propulsion energy in the maritime domain resulted in numerous studies into the most feasible reactor type to replace PWRs on ships (de Freitas Neto et al., 2018; Houtkoop, 2022; Hagen, 2022; MNAG, 2022; Bennett, 2022). These reactors, such as the one being developed by Canadian company Terrestrial Energy, use molten salts as both coolant and moderator (Rapier, 2023), giving MSRs the following advantages over LWRs:

- higher operating temperatures (making them more efficient),
- able to utilize different fuel types (such as thorium),
- passive safety features inherent to the reactor design (Rapier, 2023).

One of these critical safety features is that that the reactor is safe from meltdowns because the fuel is already molten (Rapier, 2023) and, in the event of an issue, the fuel can be dumped from circulation into collection tanks (MNAG, 2022). These upgraded safety features make MSRs an attractive future option for nuclear energy production.

To identify a truly zero GHG emitting propulsion option, governments and members of maritime industry have begun investigations into MSRs as a viable FNPP solution. A consortium of South Korean companies and governmental organizations signed a memorandum of understanding on February 9th 2023, agreeing to cooperatively work to develop and demonstrate an MSR on marine vessels (World Nuclear News, 2023). This group noted that one of the key benefits of CMNP is that “there would be no need to replace nuclear fuel during operation of the ship, and when an abnormal signal occurs inside the reactor, it is designed so that the molten salt... hardens, preventing serious accidents from the source” (World Nuclear News, 2023). In the United States, the INL’s Nuclear Research and Innovation Center (NRIC) Maritime Nuclear Application Group (MNAG) is also investigating maritime application of advanced reactor technology, stating that “Some novel reactor designs could find the maritime sector to be ideal to prove their value in new, scalable markets, while other novel reactor designs may be better suited to operate on land or in more controlled environments” (MNAG, 2022). The MNAG is pushing to have an advanced reactor demonstration completed by 2025 and commercially available by 2030, a more ambitious timeline than GIF’s 2014 “Timelines for the MSR” as seen in Figure 1 (MNAG, 2022).

GIF TIMELINES FOR THE MSR

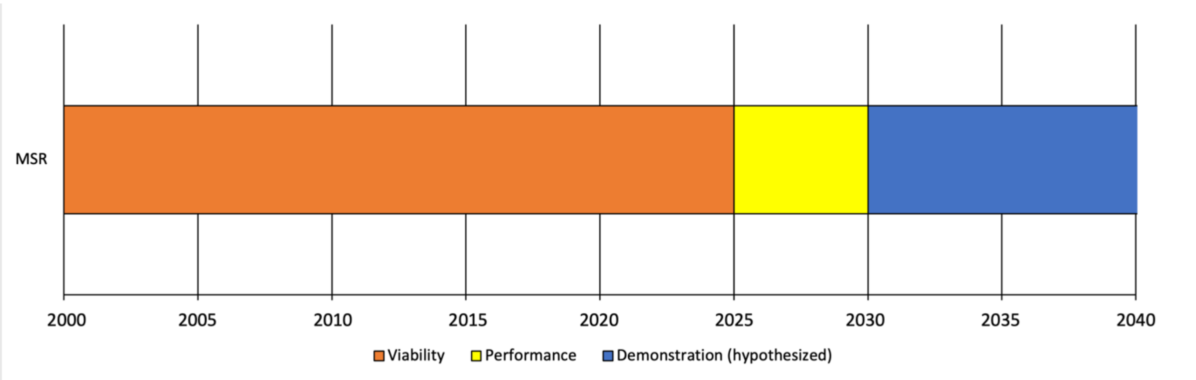


Figure 1: GIF anticipated timeline for the MSR (Generation IV International Forum, 2014)

In December 2022, the government of the UK updated its Nuclear Code from the edition previously published in 1981 (Mandra, 2022). This update will enable UK-based CorePower to pursue development of MSRs for adoption onboard 14,000 TEU container ships or other similarly sized vessels (Mandra, 2022) and chooses to use chloride instead of fluoride salts (MarineLink, 2022). Similarly, the Norwegian University of Science and Technology are working to develop their own shipboard generation IV reactor, though they’re pursuing a lead-cooled design and will validate the MSR design being produced by CorePower (MarineLink, 2022).

5.3. Small Modular Reactors (SMR)

5.3.1 Feasibility

Despite challenges faced by commercial reactors on vessels and on land, nuclear industry continues to innovate and adapt. Lessons learned from past incidents and concerns about future energy security have driven public and private funding and development of more robust and reliable reactor designs. Though PWR reactors have a reliable history, their size and complexity make them a far less appealing option for commercial use than a smaller and more advanced nuclear reactor. Generation IV reactors, particularly small modular reactors (SMR), are being explored for their potential in both maritime and terrestrial settings.

One of the chief benefits of an SMR is its size to power ratio. In a feasibility study conducted by Hagen (2022), the 23,992 TEU "Ever Ace" was selected as the primary baseline ship. This is the largest container ship currently sailing in the merchant fleet, with a power need of 117.2 MWe for propulsion. Hagen determined that the optimal way to power a vessel with nuclear reactors wouldn't be direct drive propulsion, but using a nuclear-electric format wherein the reactor powers an electric switchboard that can then support myriad systems, such as propulsion. She then estimated the power demand of the baseline vessel to be 20% higher, or around 140 MWe and that a smaller secondary baseline ship would likely only require around 50 MWe. Currently the world's first FNPP barge, 144 meter by 30 meter floating power barge named the Akademik Lomonosov, is producing energy from two 35 MWe small modular PWRs (Lobner, 2021; IAEA Power Reactor Information System, n.d.; Liou, 2021). These first of their kind powerplants are very nearly able to meet the power needs of Hagen's (2022) hypothetical second ship, which better represents a majority of the world's fleet. In a conversation with Compagnie Maritiem Belge CEO Alex Saverys (2023), he suggested that small MSRs would likely provide a lot of the alternative energy answers to decarbonizing shipping, especially for larger vessels. As we will see later, it is very likely that other reactor designs will be able to meet or exceed the power demand for both theoretical vessels in her investigation.

5.3.2 Scalability

Another benefit of the SMR that experts tout is that it will be standardized and easily produced. They argue that modularization and standardization will allow for efficient factory fabrication, allowing for dramatic cost reductions for initial fabrication through economies of scale (Abou Jaoude et al., 2023). When producing a terrestrial NPP, schedule and cost overruns are often attributed to the fact that each NPP constructed is a bespoke product being built to very stringent specifications, requiring new environmental studies, licensing, certification, and more (Abou Jaoude et al., 2023). Small modular reactors address this problem in two ways. The first is that though initial set up and production costs will be high, costs will decrease rapidly over time as more of these standardized reactors are ordered. The second is that these costs can be shared between maritime and terrestrial power needs. A standardized SMR can be either part of an shipboard or barge FNPP or NPP, where the overall power generating capacity depends on the number of reactors installed within the facility. This scalability theoretically can speed up deployment of terrestrial NPPs because these facilities can install banks of SMRs to meet local power needs (Real Engineering, 2023).

5.3.3 Nuclear "Battery"

A residual benefit of sharing reactor production lines and costs is that the maritime industry and terrestrial power industry will both benefit from more rapid production of initial reactors. Indeed, an NRIC survey conducted with members of the maritime industry found that they believed the easiest way to manage a nuclear reactor onboard a ship would be to turn it into a plug-and-play "battery" (Bennett, 2022). In this way, the original equipment manufacturer (OEM) would outfit, maintain, and dispose of the reactor installed onboard ships (Bennett, 2022). By using a fully modular power package, a ship would be able to quickly swap a depleted nuclear reactor for a fully fueled reactor (Idaho National Laboratory, 2023). Additionally, assuming that nuclear "batteries" are of similar size and density to engines currently used onboard commercial vessels, retrofit of these ships or design of new ships should be relatively straightforward, avoiding costly redesigns and retrofit of vessels using other alternative fuel or energy. The small size of these nuclear islands would also be a significant change from their Generation II forebears, which often took up large portions of the vessels like NS Savannah and NS Otto Hahn, rendering them economically inviable beyond operating as state-sponsored proofs of concept (World Nuclear Association, 2021).

Chapter 6: Infrastructural Preconditions

6.1 Introduction to Infrastructural Preconditions for Shipboard FNPPs

In maritime industry, adoption of shipboard FNPPs in shipping will be a pivotal innovation promising a transformative shift toward cleaner and more efficient operations. Nuclear technology powering maritime propulsion both heralds a new era of energy use but also necessitates a comprehensive reimagining of the existing infrastructure. This integration is contingent upon establishing robust and well-conceived supply and support infrastructure, capable of supporting the intricate demands of advanced nuclear technology. In this chapter, we will investigate the necessary supply and support infrastructural changes that must be in place to successfully integrate nuclear power with the maritime industry. We will analyze various infrastructural points, from vessel construction within specialized shipyards and maintenance facilities to establishment of diverse and secure fuel supply chains.

Our exploration will identify the hard and soft infrastructural elements critical to shipboard FNPP success, assess the current state of these infrastructural components, and envision the developments needed to bridge the gap between current capabilities and future needs. Hard infrastructural elements in need of update include physical infrastructure such as ports infrastructure and fuel supply chains. Soft infrastructural elements to be updated include regulations and policies at international and national levels. Wide-scale deployment of shipboard FNPPs will necessitate reevaluation of laws governing nuclear powered ships and international engagement to properly establish a network of nuclear-friendly trade routes and ports to support a global fleet. Navigation protocols that govern routes and facility access will need to be developed, as will emergency response protocols from international to local governmental levels. By understanding the infrastructural imperatives, we will enable stakeholders to make informed decisions that will influence the trajectory of shipboard FNPPs in the maritime industry.

6.2 Regulatory Landscape and Approvals for FNPP Deployment

The policy and regulatory environment plays a crucial role in nuclear maritime propulsion infrastructure development. Policies must be designed to facilitate the smooth operation of nuclear-powered vessels while ensuring environmental safety and compliance with international standards.

6.2.1 International Regulatory Foundation

The deployment of FNPPs presents a unique set of regulatory challenges and requirements. These challenges stem from the integration of maritime and nuclear regulatory frameworks, as well as the need for international cooperation due to the inherently transboundary nature of FNPP operations.

The regulatory landscape for FNPPs is governed by a combination of international conventions and national regulations. The two primary international conventions that govern FNPPs are the IMO Convention for Safety of Life at Sea (SOLAS) Chapter VIII (1974) and the IMO Code of Safety for Nuclear Merchant Ships (1981) (CSNMS) which supplemented SOLAS Chapter VIII (Policy Mogul, n.d.). Both conventions seek to regulate:

- the design and construction of FNPPs ensuring ships are built to safely contain and manage nuclear reactors;
- setting operational guidelines for safe operation of nuclear-powered vessels, including reactor management;
- establishing maintenance and inspection intervals and practices to ensure ongoing safety and compliance with nuclear standards;
- adequate crew training and qualifications;
- establishing guidelines for the safe decommissioning of nuclear powered ships and disposal of their waste;
- development of protocols for handling nuclear accidents;
- and creating measures to prevent and mitigate environmental contamination from nuclear materials.

These documents were developed when the prevailing design for shipboard nuclear power production were versions of the PWRs used onboard the NS *Otto Hahn*, NS *Sevmorput*, NS *Mutsu*, and NS *Savannah* (Houtkoop, 2022). The information in this Code was written to be as general and broad as possible, assuming exclusive use of PWRs onboard merchant vessels (Safety4Sea, 2023). The IAEA also plays a crucial role in setting international standards and guidelines for nuclear safety, security, and safeguards, pertinent to shipboard FNPP development and critical to their deployment (IAEA Power Reactor Information System, n.d.).

6.2.2 National Regulations

National regulatory bodies also have a significant role in overseeing the deployment of FNPPs. For instance, NEIMA (2018) specifically encourages development of generation IV advanced nuclear reactors. This national regulation incentivizes development of advanced reactors that could be capable of deployment as FNPPs, especially because it eases the process for the US Nuclear Regulatory Commission (NRC) to update federal code as it pertains to nuclear reactors. By comparison, the Dutch government formally adopted the CSNMS and codified it into law in 1981 (Netherlands Regulatory Framework - Maritime, 2023). This national regulation directly echoes the CSNMS, indicating it is a direct adoption of the treaty including broad restrictions that make development and adoption of advanced reactors onboard ships difficult.

The UK currently has the most up to date and relevant nuclear ships policy, having updated their nuclear ships regulation with the Merchant Shipping (Nuclear Ships) Regulations. This new policy document, passed in 2022, contains requirements for nuclear-powered vessels for the purposes of ensuring safety and environmental protection, with special attention to radiation hazards and enables innovation and development of technological progress (Government of the United Kingdom, 2022). This action sets an example for other nuclear nations, like the Netherlands, to follow. These actions at the national level are essential, as there is no information from the IMO regarding when the next formal review of the CSNMS will be (Government of the United Kingdom, 2022). These updated regulations encourage development of new, innovative, and safe shipboard FNPP technologies and support their deployment. They also provide specific requirements for the design, construction, and operation of nuclear-powered vessels (UK Government, 2023). For example, this new law allows the Secretary of State to enact future amendments to the Nuclear Code by issuing a Merchant Shipping Notice to bring UK regulations up to date with the latest technological or scientific developments instead of going through a lengthy regulation update process (Policy Mogul, n.d.). This enables development and deployment of new reactors with advanced safety features for use as shipboard FNPPs. In fact, comprehensive safety protocols and thorough risk assessments are essential to prevent accidents and to mitigate any potential impacts that might arise in the normal operation of shipboard FNPPs (NRC, 2023). Bayraktar and Yüksel (2023) confirm this by emphasizing the necessity of incorporating robust active and passive safety systems into advanced reactor designs. Such innovations are not only crucial for ensuring safe operation of shipboard FNPPs, but are also vital for gaining public trust, a hurdle that needs to be overcome to clear the way for broad adoption of nuclear-powered propulsion.

6.2.3 Regulatory Hurdles

Transparent communication and robust safety assurances exemplified through extensive testing are foundational to establishing this public trust, complex processes which underscore the challenge of integrating shipboard FNPPs into the maritime industry. The need for a comprehensive and highly publicized approach to convince regulators and the general public alike of their promise is essential for ensure broad adoption.

While floating nuclear power plants offer clean energy provision and decarbonization benefits in the maritime industry, Tsiakaraki (2023) and Barnard (2023) highlight that they also face substantial regulatory hurdles. Key among these challenges is the need to align international regulatory frameworks with national policies. For example, while nuclear ships may be able to enter and leave American, Japanese, and Korean ports at will, they aren't allowed to enter ports in New Zealand (Barnard, 2023). Moreover, Barnard (2023) points out that there are many differences between national nuclear exclusion zone policies. Nuclear technology has come a long way since the inception of nuclear energy over 60 years ago. This requires updates to Harmonizing national policies with international regulatory frameworks is a task that will require extensive coordination and cooperation.

It is also likely that without a comprehensive IMO regulation, the adoption of national level nuclear regulations will lag technological development. This lag could prevent wide-scale adoption of shipboard FNPPs in a coordinated way and hinder efforts to persuade the public of the inherently safe and manageable operation of conventional and advanced shipboard nuclear reactors. As highlighted by Bhattacharyya, El-Emam, and Khalid (2023), there is a pressing need for a common, harmonized framework to estimate lifecycle material and energy flows, carbon footprints, and the development of harmonized standards for new carbon-free or low-carbon fuels in the maritime industry. This regulatory framework is essential to weigh the pros and cons of nuclear-powered shipping against other decarbonization methods. The authors emphasize that such a framework would facilitate a comprehensive understanding of the environmental impact of various shipping fuels, including nuclear power, thereby aiding in informed decision-making for sustainable maritime operations (Bhattacharyya, El-Emam, & Khalid, 2023). Failure to update international agreements would also deeply limit port access, which is essential for the maritime industry to enjoy the benefits of FNPP at scale.

The MNAG's Introduction to Advanced Commercial Nuclear for Maritime Applications (2022) provides a comprehensive overview of opportunities challenges in deploying FNPPs, with a special look on the regulatory framework issues related to FNPPs (MNAG, 2022). According to this document, coordination demands collaboration among regulatory bodies such as the IAEA and the IMO, which are instrumental in establishing a secure framework for the transport and operation of FNPPs. The document emphasizes the importance of the IAEA's Transport Safety Standards Committee's work on transportable nuclear power plants (TNPP), which are crucial in shaping safety standards that countries can adopt (MNAG, 2022). Moreover, it underscores the necessity for bilateral agreements to navigate the varying national laws regarding nuclear energy use, particularly for vessels in international waters. The document also highlights the UK's efforts in leading regulatory modernization through the Merchant Shipping (Nuclear Ships) Regulations 2022, as mentioned above, setting a precedent for other nations to follow (MNAG, 2022). International regulatory updates are essential to encourage broad development of shipboard FNPPs that safely and efficiently contribute to decarbonizing the maritime industry through coordinated investments.

6.3 Shipyards and Vessel Construction Requirements

6.3.1 Shipyard changes

The integration of nuclear-powered propulsion in maritime transportation significantly redefines the role and operational requisites of shipyards and the vessel construction process. To enable future shipboard FNPP use, traditional shipyards must evolve to accommodate the specialized needs of nuclear vessels, which are complex and markedly different from those of conventional ships (Bhattacharyya, 2023). This includes development of dedicated areas for nuclear component assembly, reinforced structures for enhanced safety, and containment facilities to address radiological risks. Work on modular reactors can be done either through designed access points or allowing for installation, refueling, maintenance, and removal (Kourasis, 2023). The latter process is already familiar with shipyards, but will require certification from state-run nuclear regulatory authorities to conduct this sensitive work on shipboard FNPPs.

Furthermore, the specialized nature of nuclear-powered vessels require that these facilities have technology and expertise to manage nuclear reactors (Bhattacharyya, 2023; Bennett, 2022). This includes hiring nuclear engineers and training personnel in regular and emergency radiological safety. Shipyards may need the capability to temporarily store nuclear materials on site during fueling operations for contingency purposes. Mr. Kourasis (2023) mentioned that it may be possible to design ships with “remote maintenance” in mind, conducting advanced reactor maintenance without needing direct physical access or taking the reactor offline. Mr. Kourasis (2023) confirmed that other ship maintenance and construction activities would be similar to current practices, such as those on steam turbine generators.

Shipyards will require regular state nuclear regulatory agency compliance inspections for shipbuilding and maintenance activities. Additionally, a robust reactor test operation, maintenance, and emergency response procedural framework must be established. This framework should encompass rigorous personnel training programs, safety drills, and a clear decision-making chain of command for critical situations (Bhattacharyya, 2023; International Maritime Organization (IMO), n.d.; Bennett, 2022). All shipyard workers will need to understand the basics of maritime reactor designs to better understand the different risks that they might encounter during maintenance and repair activities (Stopford, 2023). While not a large departure from current shipyard risk management practices, reactor shut down and cooling will require special considerations, allowing high temperature equipment to cool prior to any scheduled maintenance activities (Eidelpes et al., 2022).

6.3.2 Ship building changes

Ship building and decommissioning activities also require a paradigm shift. Vessel construction will require adherence to stringent design and safety protocols, including incorporation of advanced materials designed to shield against radiation. While some shipbuilders, such as General Dynamics in the United States, currently employ these practices, others will need to modify their infrastructure to adopt them. Per IMO regulations, shipyard layouts will need reorganization to include nuclear material handling and storing zones, with clear demarcations from conventional shipbuilding activities

(International Maritime Organization (IMO), n.d.). This will also involve development of emergency nuclear accident and radiological risk response plans based on the types of reactors that could enter the shipyard.[5] In an interview, Martin Stopford mentioned that some proponents have claimed that shipboard FNPPs may be built in ship construction facilities (Stopford, 2023). While this may be possible, it is likely that shipyards currently lack the level of accuracy and sophistication required for this work.

Ultimately, the transition to nuclear-powered shipping necessitates changes in shipyard design and function. It requires a collaborative effort between engineers, naval architects, environmental scientists, and policymakers to ensure that shipyards and vessel construction protocols are realigned with the technological sophistication and safety imperatives of nuclear-powered propulsion.

6.4 Nuclear Fuel Supply chain and Distribution Channels

6.4.1 Fuel enrichment supply chain

Expansion of nuclear power will require rigorous analysis of infrastructure essential for handling, enriching, storing, and transporting nuclear fuels. One of the key issues is the fuel enrichment bottleneck. The fuel choice for these advanced reactors, predominantly HALEU, is another critical factor that will require technological innovation and adaptation for future success. The supply chain for HALEU faces challenges, such as the Russian war in Ukraine affecting uranium imports, which underscores the importance of strategic planning in future fuel sourcing and selection of one or several new partner countries to enrich fuel to this HALEU standard. Rosatom, the Russian state atomic company, produces 48% of the world's HALEU supply (Euratom Supply Agency, n.d.). Most enriched nuclear fuel currently comes from Russia because the uranium ore is mined in Khazakstan and refined in Russia in a relatively cheaper way than what is done in the United States or Canada (Stopford, 2023; Burton, 2024). Companies like Centrus Energy in the US, Cameco in Canada, Orenco in Europe, or Orano in France could provide much needed balance to the otherwise Russian-dominated market, but would have to do so at competitive prices (Euratom Supply Agency, n.d.). Russian supply of HALEU is also very difficult to get in the US and, though Urenco could also produce HALEU for the US, the company does not yet have a license to do so (Gardner,

[5] Responding to incidents involving reactors operating at high pressure will differ from responses to incidents involving reactors operating at ambient pressure.

2024). The use of alternative fuel mixtures also may not solve the problem, as some nuclear fuels have technical challenges yet to be solved, creating fuel refinement bottlenecks in the meantime (Zhong et al., 2022)[6]. Ongoing research and development into alternative fuel sources is needed, especially into thorium as an alternative fuel to uranium and plutonium, to overcome these challenges.

This research is made more urgent by the depressed demand of nuclear reactors experienced in the late 2010's to early 2020's following the Fukushima power plant accident, reduced production of uranium ore due to a depressed uranium market, and depletion of the commercial stock following the new practice of financial buying (NEA, 2017; Goehring & Rozencwajg, 2023). Moreover, Kazakhstan's national uranium mining company Kazatomprom and world's biggest uranium miner is uncertain of its ability to meet production guidance in 2025 due to "considerable supply chain risks" (Burton, 2024). Due to its role in the energy transition, including deployment of large and small NPPs as well as research into FNPPs, the uranium market is expected to recover slowly as mines previously mothballed are reopened and operations resumed following increasing demand. However, with uranium consumptionexpected to increase from 188 to 240 mm lbs and far outpace production growth (expected to be 140 to 174mm pounds) by the end of the decade, it is predicted that the uranium commercial stockpiles will be completely depleted by the end of the decade, resulting in a very tight market (Goehring & Rozencwajg, 2023). Expanding fuel recycling programs like those envisioned by Moltex or employed in France may play an outsized role in easing strain on the market.

6.4.2 Transportation upgrades

Transportation infrastructure also plays a crucial role. If reactors are built away from shipyards and then transported to or from ship maintenance or construction facilities, they will need to be built to withstand minor or major collision risk presented during the reactor's transportation for deployment as well as during transportation for decommission (Eidelpes et al., 2022). Kourasis (2023) briefly explained a few fueling strategies for different reactor types, noting the potential of online refueling for MSR reactors, highlighting that relatively small portions of fuel will be needed for online refueling activities. This design is supported

[6] Zhong et al. cite uranium-zirconium alloys, specifically. This may not apply to all fuel types, especially HALEU and other uranium enrichments.

separately by Canadian MSR developer Moltex Energy, who believe their Waste to Stable Salt process will be able to recycle fuel previously considered “spent” and deploy it into operating SMRs (Moltex Energy, n.d.). In these cases, the amount of fuel needed for refueling will never be something like 50 – 60% of total capacity, but something much smaller. This development in refueling methods will dramatically streamline the logistics and infrastructure required for nuclear maritime fuel distribution (Kourasis, 2023).

Moreover, fuel will need to be moved safely to and from construction and maintenance facilities. Eidelpes, Ibarra and Medina (2019) stress the necessity for high-capacity fuel packages that comply with regulatory demands, particularly for the transport of high-assay low-enriched uranium (HALEU) fuel. These packages are pivotal for ensuring secure and efficient movement of nuclear fuel. However, the transportation of HALEU material for initial installation into reactors present challenges that haven’t yet been explored and fall outside of the scope of this investigation. These added transportation considerations also do not entirely remove the need for conventional bunkering infrastructure, as shipowners will likely be slow to transition to costly alternative-fueled vessels. The additional nuclear energy infrastructure will increase the scope of energy management within a port and demand robust safeguards against accidents.

6.4.3 Nuclear waste transport and storage

Addressing regulatory and logistical challenges in spent nuclear fuel transportation is equally critical. A report published in 2015 describes challenges in transporting spent nuclear fuel in the US and suggested that “there are uncertainties” surrounding the transportation of certain wastes, though did not specify what they were or who the claimant was (U.S. GAO, 2015). It also established that the US Department of Energy (DOE), which manages all nuclear items in the US, does not have authority to dispose of spent fuel permanently or temporarily in a site other than at Yucca Mountain, as specifically designated by the 1982 Nuclear Waste Policy Act.

Waste is managed more diligently in the EU, where all member states generate radioactive waste, and “20 of them also manage spent fuel on their own territory” (European Commission, n.d.). Finland will become the first nation in the world to have permanent deep geological disposal for spent nuclear fuel, while Sweden and France have also selected sites for similar disposal of intermediate and high level nuclear energy waste

(European Commission, n.d.; Simičević, 2023). Within the EU, transport of radioactive waste and spent fuel is commonplace and occurs regularly. The EUs Directive on Shipments of Radioactive Waste and Spent Fuel (2006/117/Euratom) establishes a system of prior authorization for spent fuel shipment within the EU and:

- requires operators to notify national authorities about shipments of radioactive materials which depart from, go through, or end up in the EU
- allows EU countries to ship spent fuel to each other for reprocessing and organise the return of the resulting radioactive materials
- allows EU countries to send shipments of radioactive materials that do not comply with the directive back to their country of origin
- prohibits the export of radioactive waste to African, Caribbean or Pacific countries, to Antarctica, or to any country which does not have the resources to safely manage it (European Commission, n.d.)

Additionally, France has been engaged in industrial reprocessing and recycling of spent fuel for decades, a process that no other EU member states are involved in (European Commission, n.d.)

International transportation outside of the EU of spent nuclear fuel involves navigating a labyrinth of different jurisdictional regulations, which often lack uniformity and can lead to significant complications (Williams, 2018). This complexity is compounded by the varied technical standards and societal attitudes towards nuclear waste across countries. Williams (2018) argues for a systems theory approach to tackle these challenges, suggesting that understanding the interdependencies and interactions within the global nuclear fuel cycle can lead to more effective and coherent policies and practices. He also suggests that system-theoretic analysis techniques are essential to ensure safe and secure transportation, in line with standards set by bodies like the IAEA (Williams, 2018). His work underscores the need for international cooperation and consensus in developing standardized, safe, and secure methods for transporting spent nuclear fuel, reflecting the interconnected nature of the modern world.

6.5 Technological Innovations and System Integration

6.5.1 FNPP Reactor Safety Considerations

The development of advanced reactors and their application in maritime vessels is a prime example of the technological shift needed for FNPP success in the maritime industry. Reactor design research emphasizes the need for continuous operation of reactors under heavy weather conditions, moving away from the traditional approach of reactor shutdown during weather emergencies (Hagen, 2022). This is especially important because shipboard FNPPs will need to operate in both good and bad weather conditions. These reactors offer active and new passive safety features, such as the hardening of molten salt in dump tanks below MSRs to prevent accidents, and their compact design facilitates the handling of larger cargo quantities (Kourasis, 2023; Hagen, 2022).

In scenarios where vessels with advanced reactors might sink, historical instances involving sunken nuclear submarines revealed that there is no significant increase in radiation levels surrounding the sunken vessel, validating the safety of these reactors to the surrounding environment (Gwynn and Shpinkov, 2018; Høibråten, Thoresen, and Haugan, 1997). This is because water, which has historically been chosen as a moderator for radiation. Concrete, which is widely used as reactor shielding, also contains a lot of water, which further shields external environments from the reactor's radiation (Kourasis, 2023). The exceptional shielding property of water against radiation contributes significantly to this safety feature (Hagen, 2022).

During normal operation, advanced reactors are expected to operate safely enough that reactor suppliers may convince regulators to establish an Emergency Planning Zone (EPZ) to the boundary of the plant, rather than a larger radius (World Nuclear News, 2022). All NPPs have an EPZ, which is a pre-planned protective area surrounding a nuclear facility wherein the public may be at high risk of exposure to nuclear material in the early stages of a nuclear accident (NRC, 2020). Limiting an EPZ to the boundary of the plant is integral to maintaining safety standards and mitigating risks in maritime operations. This is especially possible in SMRs because the amounts of radioactive materials that might potentially be released in an accident are significantly less than large reactors (World Nuclear News, 2022). Shipboard FNPPs designed with an EPZ limited to the plant would, by extension, limit that zone to the vessel's hull.

6.5.2 FNPP Deployment in the Shipping Fleet

The potential application of advanced nuclear reactors spans various types of maritime vessels, with energy requirements tailored to suit large ships, container ships, and potentially cruise ships with continuous power needs (World Nuclear Association, 2021). This highlights the versatility of advanced reactors in meeting diverse energy demands within the maritime sector (Hagen, 2022; Bhattacharyya, El-Emam and Khalid, 2023; Stopford, 2023). Specifically, a 2022 study revealed that the total number of reefers loaded on a container ship was a significant driver in energy consumption, more than other factors like seawater temperature and wind direction (Yeh et al., 2022).

To optimize the use of FNPPs on ships, these 15 MWe reactors will need to be installed on vessels that have power needs close to or below the amount of power being produced and will require a constant load during normal operations. Container ships with reefers onboard are specifically well-suited to accommodate these reactors, with 8,500 TEU container ships having around a 4.15 MWh energy need and 24,000 TEU container ships having around an 11.4 MWh energy need (Yeh et al., 2022). This leads us to understand that installation of an MSR on a <11,000 TEU very large container ship (VLCS) would be impractical. An NRIC survey of nuclear and shipping industry members corroborated this by saying the "sweet spot" of shipboard FNPP deployment would be 10,000 – 14,500 TEU vessels, with one respondent highlighting that the 12,000 TEU vessel size is popular for north-south routes with large volumes of reefers onboard (Bennett, 2022). Dry bulk carriers would likely not have the same energy needs, though shipboard FNPPs on capesize and post-panamax size dry bulk carriers and suezmax and VLCC tankers might be worth consideration (Saverys, 2023; Stopford, 2023; Bennett, 2022). These larger vessels can provide zero carbon linkages between major shipping hubs and short-sea/hinterlands shippers.

The applications for shipboard FNPPs extend beyond the skin of the ship to power the environment around it. During cargo transfer, ships with FNPPs could connect to the electrical grid to sell power to the port while at the quay (Stopford, 2023; Kourasis, 2023; Hagan, 2018; Houtkoop, 2022). The power provided by reverse cold-ironing would power battery-powered autonomous vehicles used to move cargo around the port. This reverse cold-ironing could also support production of another alternative fuel that could then be used to fuel smaller vessels engaged in short-sea shipping or hinterland transit operations.

Supporting fuel production for something like hydrogen would enable operations by smaller vessels in port operations and hinterland transit by rivers onboard 5000 TEU freighters (Saverys, 2023; Stopford, 2023).

6.5.3 Port Readiness for Nuclear Ships

Inclusion of various types of alternative fuels and energies in the maritime industry demands careful consideration and coordination to be done correctly. As such, the World Ports Climate Action Program (WPCAP) convened a work group, WG4, comprised of port authorities from various European countries, Canada, the U.S., and Japan, to think about how best to implement sustainable low carbon fuels in marine industry (WPSP, n.d.). To do this, WPCAP and the International Association of Ports and Harbours collaborated to create the Port Readiness Level for Alternative Fuels for Ships (PRL-AFS) tool in 2022 (WPSP, n.d.). This tool, developed and employed by WG4 members including the Port of Rotterdam, Port of New York & New Jersey, and the Port of Yokohama to name a few, establishes a nine-step system that sensibly and comprehensively guides ports down the path towards adoption and deployment of a new alternative fuel or energy system in maritime industry. The nine steps are as follows:

PORT READINESS LEVELS

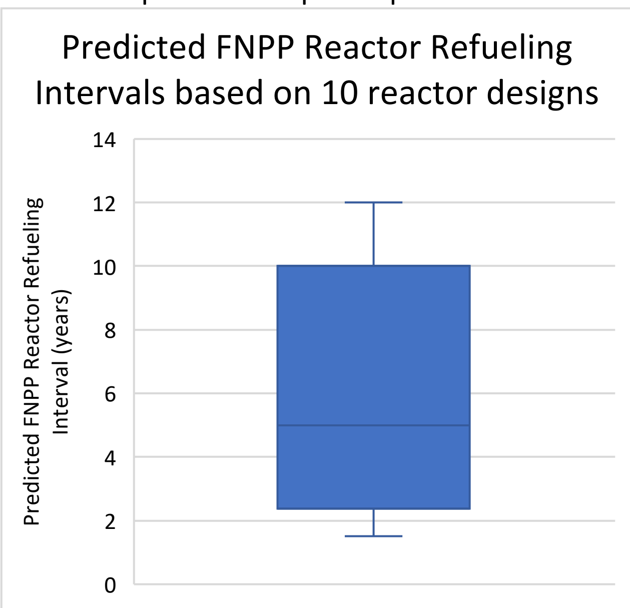
		Readiness Level
Stage	Research	1. Fuel relevance assessed
		2. Interest of port stakeholders determined
		3. Sufficient information gathered
	Development	4. Vessel call or bunkering approach decided
		5. Vessel call or bunkering framework designed
		6. Vessel call or bunkering framework demonstrated in a controlled environment
	Deployment	7. Vessel call or bunkering system established on a project basis in an operating environment
		8. Vessel call or bunkering system completed and qualified
		9. Vessel call or bunkering service readily accessible

Table 6 Port Readiness Levels, Source: (Boon, 2023)

As a specific example, the Port of Rotterdam has been using the tool for various kinds of fuels since its creation in 2022. They employed it successfully to complete preparation for LNG bunkering and are continue using it for other alternative fuel systems (Boon, 2023; van den Brink, 2024). In the deployment of shipboard FNPPs Ms. Françoise van den Brink, a senior advisor for the port's energy transition, mentioned that ports will need to assess the technology to ensure it is safe to bring into the port, it is something the port wants operating within its area of responsibility, and that it is sufficiently safe to accommodate during regular vessel and port operations (van den Brink, 2024). The lack of bunkering need for nuclear-powered ships might also enable simultaneous activities that may not be permitted during bunkering operations. Once ports are generally comfortable with the governmental, safety, and infrastructure elements of the research and development phases, a port will need to be identified as a pilot, which will help inform how to translate lessons learned into a more systematic approach for having nuclear calls (van den Brink, 2024). Acceptance of nuclear-powered ships in ports will certainly require solving a lot of logistical and operational challenges.

6.6 Logistical and Operational Challenges

As we saw previously, the deployment of nuclear-powered ships will present a series of logistical hurdles that require careful consideration and strategic planning. The unique nature of nuclear-powered ships necessitates infrastructure that can accommodate not just the technology but also operational nuances previously explored. Ports specializing in handling and storage of nuclear fuel will need to be identified.



6.6.1 Fueling Logistics

Fuel storage and handling are key concerns in an industry used to bunkering with fuel stored on-site and delivered at the quay. One benefit to operating shipboard FNPPs is long fuel endurance, with reactor designs anticipating between 1.5 and 12 year refueling intervals, though most will likely fall between 2.35 and 10 years (as seen in the plot to the right).[7]

However, if we assume that only container ships will be using nuclear powered propulsion and that the classes of ships using this power source are limited to neo-panamax class and larger, we will only see the need to service a fleet of approximately 1,600 ships (U.S. Department of Agriculture, n.d.). These large container vessels can only visit specific ports because of draft restrictions, meaning logistics support will need to focus on larger deep draft container ports.[8] Third party logistics services will exist near these ports to support shipboard FNPP fueling, contracted as one would contract bunker companies or traders for fuel. These waterfront fuel providers may be extensions of private firms, such as Cameco, Urenco, or Centrus; through state-controlled organizations, such as Orano, Rosatom, or CNNC; or through a third party energy company such as a subsidiary of Vitol or Cargill. These services may also alternatively be contracted through the FNPP original equipment manufacturer (OEM), such as Core Power, TerraPower, Westinghouse, or NuScale as part of a larger maintenance services package or included in the reactor's lease. Due to the sensitive nature of nuclear fuel storage and transport, including the associated security requirements, refueling operations will need to be carefully planned events. This need to plan contrasts sharply with the on-demand nature of heavy fuel oil (HFO) bunkering operations.

It is also worth noting that HFO will not go away immediately during the alternative energy transition, or even entirely by 2050. Because of this, new alternative energy infrastructure will need to be developed and deployed along-side any nuclear energy or alternative fuel infrastructure deployed within ports. This will especially be the case considering that installing nuclear power will not be possible on all vessel sizes. In the way most people talk about the future of alternative fuel or alternative energy in the maritime industry, it is important to remember that any transition will not happen absolutely or immediately.

Figure 2: Box and whisker plot of predicted FNPP Reactor Refueling Intervals. Source: (IAEA, 2023)

[7] This information is from the ten reactors listed in Table 7, with the average refueling interval among all reactors being around 5.85 years.

[8] For example Singapore, Rotterdam, Los Angeles-Long Beach, Shanghai, Tokyo, New York, and Antwerp

6.6.3 Specialized Personnel

One additional issue often cited with the deployment of FNPPs is that crews will require sufficient training to operate a shipboard reactor. Terrestrial nuclear power plants already employ nuclear operators who are specially trained to operate the reactor at the plant. A company like Westinghouse produces reactors to specifications provided by nuclear operators like EDF, who are responsible for building the nuclear power plant, then running, operating, and maintaining the reactor in cooperation with Westinghouse (Mallet, 2023; Westinghouse, n.d.). In the case of shipboard FNPPs, a company like Core Power might sell the reactor to a company like EDF or a subsidiary as the operator. If a pre-existing terrestrial nuclear operator like EDF is unwilling to manage a shipboard FNPP, the opportunity exists for creation of a new owner/operator firm that specializes in shipboard FNPPs. This company would need to follow procedures like those laid out by the IAEA (2009), loosely summarized in Figure 5 below, though they would also differ slightly due to the mobile nature of the shipboard FNPPs. These owner/operators could then lease the reactor to a ship owner and provide the required personnel to manage the shipboard FNPP, a model that is becoming more popular in various industries (Frost & Sullivan and Westinghouse, 2021).

Alternatively, reactor operations could be simplified or automated as much as possible in the design process. This might enable development for a training program that ship engineers can complete in six to twelve months[9] (U.S. Navy, n.d.). However, it was made clear in an MNAG report that survey participants "agreed that the immersive instructional model and large crew sizes used by the U.S. Navy would be too expensive for a commercial setting" (Bennett, 2022). If ship owners opted to hire trained crew, specialized engineers would likely be higher paid as they would bring a specialized skillset to the vessel (Baraniuk, 2023). It is very likely that a specialized school or certification scheme will need to be developed to ensure reactor operators are adequately trained both in reactor operations and shipboard operations[10]. These schools should be created as a public private partnership to ensure that the curriculum doesn't just train personnel in the operation of FNPPs, but also complies with rigorous national and international standards.

[9] These timelines are based on the U.S. Navy's Nuclear Power School timelines
[10] To include firefighting, vessel survival, and regular shipboard activities

PHASES TO DEVELOP A NEW NUCLEAR POWER PROGRAM

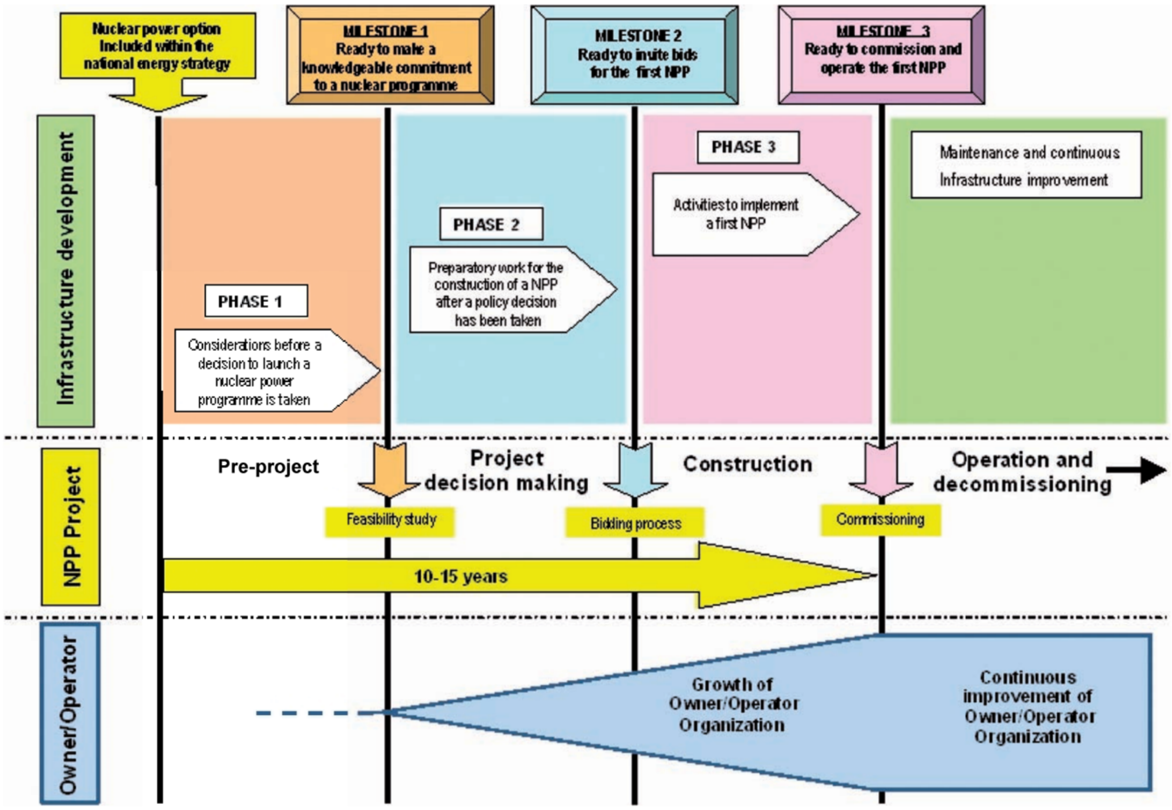


Figure 3: Three distinct phases in the development of the infrastructure for a nuclear power program (IAEA, 2009)

6.7 Conclusion

The use of shipboard FNPPs in the maritime industry underscores a shift towards more sustainable and efficient shipping practices. The deployment of shipboard FNPPs, while promising significant environmental and operational benefits, brings forward a multitude of logistical, infrastructural, and regulatory challenges that require comprehensive and strategic solutions.

From the construction of specialized shipyards to the development of secure fuel supply chains and maintenance facilities, the infrastructural preconditions for shipboard

FNPPs will be significant to integrate advanced nuclear technology into maritime industry. It necessitates not only physical infrastructure but also robust procedural frameworks including safety protocols and emergency response plans, to name a few. The logistical challenges associated with shipboard FNPPs, particularly regarding fuel storage, handling, transportation, and disposal, highlight the need to reevaluate existing practices and develop new strategies. The limited scope of deployment, primarily to larger container ships, necessitates targeted logistical support in key deep draft container ports worldwide. This support could potentially be provided by a mix of private firms and state-controlled organizations, or even through contracts with FNPP OEM's, resulting in a diverse and collaborative solution.

Moreover, A shift in the regulatory environment is critical for successful integration of shipboard FNPPs into the maritime industry. The current lag in the adoption of national-level nuclear regulations, coupled with the absence of specific international regulations, could hinder wide-scale adoption of shipboard nuclear power. Training and management of crew operating FNPPs is also crucial. The need for specialized nuclear operators, akin to those used by terrestrial nuclear power plants, highlights the need for a skilled workforce capable of managing the intricacies of nuclear-powered ships. The development of FNPPs and dedicated operator training schools, possibly through public-private partnerships, would ensure that personnel are not only proficient in operating shipboard FNPPs but also adhere to rigorous safety and operational standards.

While shipboard FNPPs offer a path towards a more sustainable and efficient maritime industry, their successful deployment hinges on overcoming a series of complex challenges. This requires a coordinated effort among various stakeholders and across several industries, including shipbuilders, nuclear fuel suppliers, national and international nuclear and maritime regulatory bodies, and the maritime industry at large. By addressing these challenges head-on and fostering collaboration and innovation, shipboard FNPPs can play a pivotal role in shaping the future of sustainable shipping, contributing to a greener and more efficient global maritime industry.

Chapter 7: Economic Preconditions

7.1 Introduction to Economic Preconditions in Maritime Nuclear-Powered Propulsion

In this chapter, we delve into the economic preconditions necessary for the adoption of shipboard floating nuclear power plants (FNPPs) in maritime industry. Our goal is to provide a comprehensive understanding of the economic factors that are pivotal in the successful implementation of nuclear power generation systems for the decarbonization of shipping. This involves an evaluation of pertinent regulations and approvals needed for nuclear reactor deployment. We will also conduct a capital investment review, which is fundamental to understanding the economic preconditions necessary for the deployment of even a single nuclear-powered ship. This section will also outline potential investment strategies, funding schemes, and sources of investment. We will also explore financing options for nuclear-powered propulsion projects to include current public-private partnership (PPP) funding schemes for the deployment of nuclear technologies. This includes evaluating whether PPPs or private funding will be most effective.

Finally, we will conduct a comprehensive SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis to further elucidate the economic viability of FNPPs. This analysis will be instrumental in identifying the internal and external factors that could influence successful maritime industry use of FNPPs. This SWOT analysis will provide a balanced and nuanced understanding of various factors that could influence adoption of FNPPs. This approach enables us to identify strategic pathways and recommendations for stakeholders in the maritime industry, maximizing FNPPs potential in the context of global economic and environmental goals. The insights from this analysis will help shape the future of maritime propulsion and guide the industry towards more a sustainable and economically viable future. We will conclude this chapter by offering a forward-looking perspective on the role of FNPPs in the global quest for sustainable shipping.

7.2 Capital Investment Analysis

This section provides a comparative overview of CAPEX and OPEX between conventional fuel vessels and FNPPs. It evaluates the economic feasibility of FNPPs, contrasting them with fossil-fueled systems to highlight long-term viability. Investment strategies are scrutinized alongside diverse funding schemes and sources. This section also examines risk management considerations for FNPPs, addressing technology adoption risks, operational challenges, and environmental considerations.

7.2.1 CAPEX and OPEX Analysis

In a comprehensive economic assessment of marine nuclear power, Koen Houtkoop (2022) delves into the CAPEX and OPEX associated with nuclear-powered propulsion systems compared to traditional fuel-based engines. The initial CAPEX for conventional fuel-based engines is highlighted as significantly lower than that for nuclear options. For instance, conventional systems are estimated to cost around 400 USD/kW installed, nearly a tenth of the cost compared to the lower end of nuclear power estimates (Houtkoop, 2022). This stark difference necessitates careful consideration of the long-term benefits and cost-effectiveness of nuclear systems.

Mr. Houtkoop's (2022) OPEX analysis presents a contrasting picture where nuclear power demonstrates an economic advantage due to its lower overall operational costs (Houtkoop, 2022). Moreover, the fluctuating prices of conventional fuels, which ranged from 400 USD/ton to a peak of 1500 USD/ton in March 2022, complicate the OPEX for conventionally fueled vessels, while nuclear-powered vessels will likely not see such large swings in fuel prices. The potential addition of CO2 taxes by the IMO and regional schemes like the European Union's Emission Trading System could significantly increase maritime operating costs in the future, a factor that currently does not impact nuclear options (Houtkoop, 2022). This carbon pricing is estimated to raise between $1 - 3.7 trillion by 2050, costs that will ultimately be passed on to the consumer (Lewis, 2023).

Houtkoop (2022) also presents an analysis of the lifetime costs for conceptual vessels under various scenarios. His findings suggest that while the CAPEX for nuclear power is substantially higher, the OPEX efficiencies could lead to a more favorable cost balance over the lifespan of a vessel. This is particularly evident in high uptime and loading scenarios where the breakeven point between nuclear and diesel fuel costs can be reached relatively quickly, despite the high initial investment (Houtkoop, 2022). The study also outlines the fuel costs for nuclear vessels, considering factors such as raw material prices and the expenses associated with converting these materials into usable nuclear fuel. The fuel fabrication costs are based on conventional fuel assemblies, acknowledging that prices could vary for marine applications (Houtkoop, 2022). This research document underscores the economic viability of marine nuclear power, which, despite its higher CAPEX, could potentially offer lower OPEX and lifetime costs compared to conventional fuel-powered vessels. The analysis thus provides a crucial economic perspective for stakeholders considering the transition to nuclear-powered marine propulsion.

7.2.2 Evaluation of possible financing model

In the development, deployment, and operation of FNPPs, the choice of funding—whether private, public, or through public-private partnerships (PPPs)—plays a crucial role in determining the project's feasibility and success. Each funding model comes with its own set of advantages and challenges.

Private investment in FNPPs is driven by the potential for high returns, given the innovative nature of the technology. Private funding allows for greater flexibility and efficiency in project management and decision-making. However, it also entails higher risks due to the substantial initial capital required and the long-term nature of the investment. Private investors may be hesitant due to the technological and market risks associated with FNPPs, as well as the regulatory uncertainties (Rahman, Miraj, and Andreas, 2019). A few companies, such as TerraPower in cooperation with Core Power are going this route with support from industry partners.

Public funding, typically sourced from government budgets, can provide a stable financial base for FNPP projects. This model can facilitate large-scale infrastructure development, ensuring compliance with safety and environmental standards. Public funding is essential, especially in areas where private investment is scarce. However, reliance on public funds can lead to bureaucratic delays and may be subject to political influences, which can affect the project's timeline and scope (Dick-Sagoe et al., 2023). The Russian and Chinese governments are using state nuclear energy corporations Rosatom and the China National Nuclear Corporation (respectively) to pursue SMR production and FNPP deployment. Russia has already succeeded in construction and operation of an FNPP on a barge and a Chinese shipyard announced on 05 December 2023 plans to design and fabricate a 24,000 TEU SMR-powered cargo vessel (Chen, 2023).

Public-private partnerships combine the strengths of both public and private sectors. They can leverage private sector efficiency and innovation alongside public sector support, which can include subsidies, tax incentives, or regulatory support. PPPs can also mitigate risks by distributing them between the public and private entities (Acciaro et al., 2x022). However, establishing successful PPPs requires careful alignment of interests, transparent agreements, and effective communication between all parties. PPPs in infrastructure projects, like railway transport, have shown that such collaborations can be complex but beneficial when managed effectively (Rahman, Miraj, and Andreas, 2019; Ruiters and Matji, 2016). Public private partnerships have already been observed in the United States, through development of SMR technology jointly between NuScale and the INL and, more recently in partnership with the Oak Ridge National Laboratory (NuScale, 2023). This company's development process has used a combination of private and public funding and private and public resources to develop molten salt SMR technology on an accelerated timeline compared to other organizations using exclusively private or exclusively public resources. Additionally, NuScale and other companies are partnering with countries beyond their own borders to accelerate development of their technology (U.S. Embassy in Jakarta, 2023, 2023; U.S. Department of State, 2023). A table of various FNPP-specific SMR projects can be found below:

FNPP REACTORS CURRENTLY IN DEVELOPMENT

	Name	Producer	Country	Electrical Capacity (MWe)	Fuel Enrichment (%)	Reactor footprint (m2) (est)	Refueling Interval (months)	Refueling interval (years)
FNPP Reactors (in Development)	KLT-40S	JSC "Afrikantov OKBM"	Russia	35	18,6	3,5	30	2,5
	ACPR-50S	CGN	China	50	<5	3,8	30	2,5
	ACP100S	CNNC/NPIC	China	125	< 4,95	9	24	2
	BANDI-60	KEPCO E&C	South Korea	60	4,95	6,1	48	4
	Prodigy MPS	NuScale Power	USA	77	< 4,95	5,7	18	1,5
	ABV-6E	JSC "Afrikantov OKBM"	Russia	6	< 20	4,5	120	10
	KTM-50M	JSC "Afrikantov OKBM"	Russia	53	< 20	11	120	10
	VBER-300	JSC "Afrikantov OKBM"	Russia	325	4,95	11	72	6
	SHELF-M	NIKIET	Russia	10	19,7	5,3	96	8
	CMSR	Seaborg Technologies	Denmark	100	LEU	4,9	144	12

Table 7 FNPP reactors in development with details. Source: (IAEA, 2023)

It's clear that PPP funding and purely public funding[11] are yielding successes in development of SMR technologies, though this may not be the best funding model for SMR deployment, especially in the case of FNPPs. Governments can fund research and development efforts, employ PPPs to raise venture capital, and issue early deployment grants (IEA, 2019). Private energy-intensive sites such as military bases, server farms, and ports could all stand to benefit from the deployment of SMRs, making development of

[11] The Chinese and Russian projects listed in Table 6 are run by state-owned companies

advanced SMR technology appealing from an investment point of view. Once the technology is mature, FNPPs could be leased to ship owners as jet engines are leased to airlines. The technical management, including staffing, would be retained with the OEM. This might work because all risk associated with the power generator would rest with the OEM. This also may be interesting following successful instances of ship leasing models in both China and South Korea. In this case, privately funded reactor ownership and management would provide flexibility, innovation, and regulatory compliance to ship owners. On the other hand, PPPs offer a balanced approach, combining the strengths of both private and public sectors that are useful in development and deployment of SMR technology.

7.3 Risk management considerations

Managing capital risk is a multifaceted challenge that encompasses technology, operational concerns, and environmental issues. The development of FNPPs involves significant innovation and technological advancement. However, this innovation comes with inherent risks, particularly in the realms of system reliability and performance. The technology used in FNPPs must be robust and reliable, as technical failures in a transnational mobile nuclear context, can have severe consequences as "deploying FNPPs may encounter more safety and environmental issues than encountered by land-based nuclear power plants, posing challenges to the marine environment and marine ecosystem" (Wang, Zhang and Zhang, 2023). Additionally, cybersecurity is a critical concern, given the reliance of modern nuclear reactors on digital control systems (Ayodeji et al., 2023). The risk of cyber-attacks and the possible destructive nature of a successful cyber-attack to a nuclear-powered ship necessitates stringent cybersecurity measures to protect the integrity of FNPP operations.

The operation of any nuclear reactor requires highly skilled personnel, and the human element introduces risk of operational errors. Comprehensive training programs and the development of specialized expertise are essential to mitigate these risks. Indeed, the IAEA (2021) states that "effective training and qualification of personnel are necessary for the achievement of high safety and efficiency standards in nuclear facility performance." Though members of industry believe shipboard FNPPs should be simplified to be as easy to use as possible (MNAG, 2022), companies like Maersk, CMA-CGM, and COSCO will still need to invest time and money into training their own personnel to run FNPPs, pay third party companies like EDF to provide nuclear operators, or will need to include a cost for operators with their nuclear reactor lease. Furthermore, the logistics and supply chain for nuclear fuel used in FNPPs present unique challenges, we previously explored in Chapter 6.

Environmental considerations are paramount in FNPP operation. The potential radiological impact on the marine environment in the event of a leak or spill is a significant public concern. Robust safety systems and containment measures are necessary to mitigate these risks. Additionally, the management and disposal of nuclear waste generated by FNPPs pose environmental challenges. Effective waste management strategies are required to protect human health, the environment, areas outside of national borders, and future generations (World Nuclear Association, n.d.). The impact of nuclear waste on marine ecosystems, including thermal pollution and habitat disruption, must also be considered and addressed (IAEA, 2016). The long-term storage or recycling of nuclear waste will also come with a cost, either paid by the shipping company or by the reactor lessor. Regardless of who pays, these waste management costs will need to be considered in long-term reactor purchase or leasing models.

7.4 SWOT Analysis of FNPPs

In this section, we conduct a SWOT analysis to methodically evaluate the strengths, weaknesses, opportunities, and threats associated with FNPPs in the context of a hypothetical shipping company. By examining the strengths, we highlight the advantages FNPPs offer, such as their potential for significant emissions reduction, operational efficiency, and technological advancements. The weaknesses section delves into the internal challenges and limitations of using FNPPs, including high initial capital costs, technological complexity, and high workforce training demands. Opportunities will explore potential market growth, job creation, and technological innovation driven by FNPPs, while the threats section addresses external factors like regulatory hurdles, geopolitical considerations, competition, and public perception. This SWOT analysis aims to provide a balanced perspective on FNPPs, offering insights into their feasibility and strategic positioning in the evolving landscape of maritime propulsion.

7.4.1 Strengths

The "strengths" portion of our SWOT analysis reveals several advantages of nuclear-powered ships. Foremost is the proven safety and expertise inherited from the US Navy's impressive nuclear-powered propulsion history, boasting over 5,400 reactor-years without incident (MNAG, 2022). This established expertise suggests a strong foundation for safety standards translatable into commercial practices (Bennett, 2022). With ongoing improvements in nuclear reactor designs and the readiness of the supply chain to produce critical components, there is a clear pathway for innovation and deployment (Lohse et al., 2023).

Environmental sustainability forms another pillar of strength. Use of shipboard FNPPs aligns with global emission reduction goals; it produces no CO_2 during operation, thereby supporting the IMO's strategies for reducing emissions from ships (Hagen, 2022; Abou Jaoude et al., 2023; Bhattacharyya, El-Emam and Khalid, 2023; Beard and Scott, 2022). The use of MSRs also minimizes the production of high-activity nuclear waste, enhancing the eco-friendly profile of nuclear technology in shipping. The energy density and sustainability of nuclear power provide ships with extended range and operational efficiency. Mature technologies from military and icebreaking vessels offer a reliable and sustainable path forward, ensuring that nuclear-powered shipping can meet the demands of modern commerce while adhering to stringent environmental standards (Bhattacharyya, El-Emam and Khalid, 2023; Beard and Scott, 2022).

Equally compelling are the cost and operational efficiencies associated with shipboard FNPP's. The adoption of advanced reactor technologies has the potential to significantly slash fuel costs owing to reduced refueling demands (NRIC Challenges; de Freitas Neto et al., 2018). Over time, this could lead to substantial economic benefits as operational costs fall, creating long-term savings (Hagen, 2022; Abou Jaoude et al., 2023). The economic argument is further bolstered by the economies of scale achieved through the installation of reactors in on land (Bennett, 2023; DNV, 2023). The prospect of semi-autonomous reactor operation also presents cost savings by reduce staffing needs.

7.4.2 Weaknesses

A few weaknesses related to the use of shipboard FNPPs are notable and worth consideration. Outdated regulatory frameworks and classification systems need modernization to meet contemporary standards, a process potentially hindered by the disparate operations of classification societies. The stringent quality assurance standards required in the nuclear sector could lead to increased costs for suppliers and parallel increases for ship owners (Dowling, 2023; Bennett email, 2023).

The substantial initial investment required for shipboard FNPPs, when compared to conventional systems, presents a large economic hurdle. Nuclear-powered ships are currently viewed as less economically viable than their conventionally fueled counterparts. This is exacerbated by the significant investment needed to increase advanced reactor production capabilities that would create economic efficiencies experts cite, an issue by complexities associated with advanced reactor components acquisition, which could result in long lead times (Lohse et al., 2023; Hagen, 2022; Abou Jaoude et al., 2023; DNV, 2023).

The industry must also navigate insurance and environmental risks, as current frameworks may not adequately cover incidents involving advanced nuclear reactors. This could affect the financial attractiveness of nuclear-powered ships. If significant reactor shielding is needed to protect the environment from radiation, vessel cargo capacity would be reduced, impacting the operational (cargo) efficiency benefits to powering a ship with an SMR (Bhattacharyya, El-Emam and Khalid, 2023; Beard and Scott, 2022).

Finally, the protracted and expensive licensing processes for new reactor designs, coupled with uncertainties in reactor cost estimations represent significant barriers. The limited range of reactor sizes could restrict the optimization of ship designs for efficiency and profitability (DNV, 2023; Beard and Scott, 2022).

7.4.3 Opportunities

Despite these weaknesses, careful evaluation shows that several opportunities emerge that could reshape the industry. The shift toward nuclear power is poised to open a wealth of job opportunities across various sectors, including STEM fields, which could bolster overall welfare of multiple regions and nations. (MNAG, 2022). These jobs may be tied to new business opportunities in geographically disbursed servicing business models targeting the support needs of shipboard FNPP operations (Frost & Sullivan and Westinghouse, 2021).

Technological advancements are one of the biggest opportunities, with advanced reactor technology promising to enhance both the economic and safety aspects of nuclear-powered ships. The potential for collaboration between governments, industries, and international bodies could catalyze progress in fuel and advanced reactor component supply chain development, as well as establish updated safety and operational standards for nuclear-propelled vessels (Dowling, 2023; Lohse et al., 2023; Bennett, 2023; Bhattacharyya, El-Emam and Khalid, 2023). The maritime industry's regulatory structure and the potential for international collaboration promise a robust framework for the adoption and standardization of nuclear-powered propulsion (Dowling, 2023). Standardization and mass production of SMRs may further decrease costs and create a more predictable regulatory environment (Bhattacharyya, El-Emam and Khalid, 2023; DNV, 2023; Beard and Scott, 2022). Growing market interest in advanced reactors, coupled with government interest and subsidies, signals robust potential for industry expansion (Lohse et al., 2023; Hagen, 2022; Abou Jaoude et al., 2023). Innovative financial strategies such as reactor leasing models could make nuclear-powered ships more accessible and financially viable.

The integration of shipboard FNPPs with alternative fuels could significantly contribute to long-term sustainability and energy security. Investments in nuclear-powered ships are aligned with the maritime industry's goals to reduce greenhouse gas emissions and can lead to immediate environmental benefits (Beard and Scott, 2022). Environmental urgency to address climate change present a chance for nuclear-powered propulsion to provide a zero-carbon solution, especially as potential carbon taxes incentivize low-emission alternatives (Bennett, 2022). This may also spur development of more sustainable power generation methods, such as the U233-thorium fuel cycle (de Freitas Neto et al., 2018).

7.4.4 Threats

The consensus is that the biggest external barrier to success is public perception. Shaped by historical nuclear accidents like Chernobyl and Fukushima, the public's current view of nuclear power creates a backdrop of skepticism and concern that influences regulatory attitudes and the widespread acceptance of nuclear energy in commercial applications (DNV, 2023; Bennett, 2022). The maritime industry faces public skepticism and hesitancy, influenced by previous nuclear endeavors such as the NS Savannah, and an inherent resistance and hesitance to deviate from conventionally propulsion modes (NRIC Challenges; de Freitas Neto et al., 2018; Beard and Scott, 2022). Coupled with extensive licensing procedures and regulatory complexities associated with nuclear reactors, this presents significant barriers to large-scale acceptance of shipboard FNPPs (de Freitas Neto et al., 2018; Hagen, 2022; Abou Jaoude et al., 2023; Beard and Scott, 2022). Furthermore, limited port access for nuclear-powered ships poses safety concerns, complicating emergency response and potentially endangering crews and the environment (Dowling, 2023).

Environmental concerns surrounding potential maritime accidents underscore the need for rigorous protocols, adding public hesitancy and opposition. The maritime industry's conservatism and the prevailing dominance of conventionally fueled engines also hinders market interest and competitiveness for nuclear-powered propulsion (Saverys, 2023; Bennett, 2022; de Freitas Neto et al., 2018). This is partly owed to high development and commercialization costs associated with maritime nuclear technology which are daunting, associated with unknown insurance, liability, and interest rates (Abou Jaoude et al., 2023). These costs must compete with those of conventional ships to prove nuclear-powered propulsion as an economically viable option (Hagen, 2022).

This is made more challenging by a complex regulatory landscape involving multiple classification societies and regulatory bodies, complicating standardization, delaying the benefits of resulting pricing efficiencies, and posing additional hurdles for the integration of nuclear-powered propulsion in shipping (Dowling, 2023; Bennett, 2023). Similarly, port state controls and regulatory compliance for nuclear-powered vessels demand extensive coordination and international cooperation. Negotiating liability and accessibility for ports, as illustrated by the NS Savannah, highlights the difficulties that nuclear-powered propulsion faces in gaining widespread acceptance and integration into the existing maritime infrastructure (Beard and Scott, 2022; DNV, 2023).

Financially, the cost of transitioning to nuclear-enabled decarbonization remains a significant challenge, particularly as nuclear-powered propulsion competes with other low-carbon solutions that may be more economically feasible in the short-term or for smaller vessel classes or have a lower environmental impact (Bhattacharyya, El-Emam and Khalid, 2023; DNV, 2023). FNPP competition with these alternatives will hinder growth, especially as shipboard FNPPs need a specially trained workforce required to be both nuclear operators and sailors (Lohse et al., 2023). This specific specialization increases shipping companies' resource barrier for entry, making alternative fuels more competitive.

This SWOT analysis only focused on economic and infrastructural aspects associated with deployment of nuclear-powered propulsion to the maritime industry. Legal, psychological, and societal aspects were not considered as standalone issues, but associated with infrastructural or economic issues. For example, “waste transport” is both a legal and infrastructural problem, “nuclear not being the preferred alternative power” is a psychological, economic, and infrastructural issue, etc.

The SWOT Matrix and Confrontation Matrix can both be found below. The items in the above sub-sections are included in simplified formats in the below Figure 2 and in no particular order. Three items within each category are bolded to indicate selection for use in the confrontation matrix. These items were selected because they can also represent some items within their own category that are not bolded. For example: “Cost efficient” in the strengths category can also include “operationally efficient” and “low waste production”. These items were then plotted on the confrontation matrix (figure 3) and analyzed to show the level of interaction between external issues and internal issues based on the author’s perception. External and internal items with a clear interaction were assigned “++” or “-/-“, those items with a strong but debatable interaction were assigned a “+” or a “-“, items with a weak but debatable interaction were assigned a “0”, and those items with no interaction were left blank. Analyzing the intersections of external and internal factors is interesting because it enables us to identify key strategic issues in the development and deployment of shipboard FNPPs. These key issues will drive our long-term economic viability assessment, laid out in section 6.6.

SWOT Matrix

	Internal	External
Positive	Strengths - Proven safety record - Technological & regulatory advancements [i] - Environmental sustainability [i] - Low waste production [e] - Operationally efficient [e] - **Cost efficient [e]** - **IMO 2023 compliant [i]** - **Extremely low OPEX [e]**	Opportunities - **Technological advancements improve nuclear reactor safety and economy [i]** - Growth of mobile nuclear energy industry will result in job growth [e] - Government subsidies for reactor development [e] - **Environmental urgency to find zero carbon solutions [i]** - Nuclear fuel supply chain development [e] - **Reactor leasing [e]** - Reactor design standardization [e] - Integration with alternative fuels: nuclear for long range and alt fuel for short range [i] - International regulatory coordination [i]
Negative	Weaknesses - Inconsistent vessel classification standards [i] - Outdated regulatory framework for nuclear-powered vessels [i] - **Extremely high CAPEX [e]** - **Insurance issues [e]** - Unknown licensing process for new reax design [i] - Uncertainties in cost estimation for reactor construction [e] - Environmental risks with fuel disposal [i] - **Will need specialized workforce to manage and maintain reactors [i]**	Threats - **Nuclear energy not the preferred non-fossil fuel energy source [i] [e]** - **Limited port access [e] [i]** - **Growing public resistance to nuclear energy proliferation following Fukushima incident (NIMBY) [i]** - No FNPP shipwreck salvage protocol [i] - No nuclear waste storage solution identified [i] - High reactor research and development costs [e] - Resource scarcity and competition for nuclear fuels [e] - Conservative maritime sector hesitant to shift [i]

[i] – infrastructural issue *[e] – economic issue*

Figure 4: SWOT Matrix

Confrontation Matrix

Internal

		Strengths			**Weaknesses**		
		S1 (Cost efficient)	**S2** (IMO 2023 compliant)	**S3** (Extremely low OPEX)	**W1** (Extremely high CAPEX)	**W2** (Insurance issues)	**W3** (Specialized workforce)
External **Opportunities**	**O1** (Technological advancements improve nuclear reactor safety and economy)	++	0,0	++	-	-/-	-/-
	O2 (Environmental urgency to find zero carbon solutions)		++		-		
	O3 (Reactor leasing)	+		+	-/-	-/-	-
Threats	**T1** (Nuclear energy not the preferred non-fossil fuel energy source)	0,0	+	+	-		-
	T2 (Limited port access)		+		0,0		
	T3 (Growing public resistance to nuclear energy proliferation following Fukushima incident (NIMBY))	+	0,0	+	-/-		

Figure 5: SWOT confrontation matrix

7.5 Long-term Economic Viability Assessment

For shipboard FNPPs to be an attractive solution, they need to first be seen as a long-term economically viable one. The confrontation matrix above helps us identify and evaluate the possible strategic options for shipboard FNPP deployment, given the SWOT. As we saw in the SWOT analysis, one of the key benefits to shipboard FNPPs is that they will be very cost efficient and have an extremely low OPEX especially when compared with volatile fossil-fuel markets (Wang, Zhang, and Zhu, 2023). This coupled with the technological advancements already being made into advanced nuclear reactors will improve reactor safety and economy, causing reactors to stay in service for a long time and reducing long-term investment costs for ship owners (Hagen, 2022). Additionally, we know that nuclear-powered ships will be the most IMO 2023 compliant when compared with other alternative fuel options. This coupled with the environmental urgency to find zero carbon solutions means shipboard FNPP deployment will likely be increasingly supported by national governments and international organizations through subsidy programs and fuel supply chain development.

However, there are several challenges that need to be kept in sight. While technological advancements will improve nuclear safety and economy, it will also require a highly specialized workforce that shipping companies or a third party will need to staff reactors with nuclear operator/sailors. While nuclear reactor leasing may provide a one-stop-shop to help address this staffing issue, growing public resistance and extremely high CAPEX means that shipping companies will likely have a hard time finding risk-tolerant investors willing to support high up-front costs of an unpopular energy source and provide favorable long-term financing (Wang, Zhang, and Zhu, 2023). Additionally, nuclear energy may not be the preferred alternative energy source. This may limit the overall shipboard FNPP support infrastructure, meaning shipping companies will only be able to take their vessels to specific ports for servicing. This may also limit the amount of qualified nuclear operator/sailors available to staff FNPPs on ships.

To mitigate these issues, shipping companies should understand that shipboard FNPPs provide them with a significant competitive advantage that will radically change the dynamic of ocean shipping (Wang, Zhang, and Zhu, 2023). Ships would no longer be restricted to traveling at reduced speeds to reduce GHG emissions (MNAG, 2022). shipboard FNPP adoption would disrupt global shipping as we know it, influencing fuel procurement strategies, route planning, and reshaping the dynamics of international trade. Deployment of shipboard FNPPs will also open new markets within the maritime industry, including the emergence of new service industries specifically tailored to nuclear-powered ship support. The need for specialized maintenance and operational services for shipboard FNPPs will lead to job creation and economic growth in strategic locations around the world, likely in nuclear nations such as Brazil, America, Canada, Indonesia, India, China, the Netherlands, France, Russia, South Africa, Japan, and others. To convince the public of shipboard FNPP safety, it is essential to engage in transparent communication and public outreach efforts, emphasizing reactor safety features, environmental benefits, and technological advancements (Budnitz, Rogner, and Shihab-Eldin, 2018). Demonstrating a strong track record of safety and reliability can be pivotal in changing public perception, which will be the most challenging issue to solve (MNAG, 2022).

7.6 Conclusion and Future Perspectives

In this chapter, we assessed economic pre-conditions for shipboard FNPPs in maritime industry. To do this, we assessed the regulatory landscape, conducted a capital investment analysis, and evaluated the risks that would need to be managed. We also conducted a SWOT analysis and used the results to conduct a long-term viability assessment. Though numerous challenges presented themselves, we determined that the benefits of shipboard FNPP deployment greatly outweigh the risks and stand to reshape the entire maritime industry.

Chapter 8: Conclusion

8.1 Charting the Course for a Nuclear-Powered Maritime Future

In this thesis, we explored the transformative potential of shipboard FNPPs in maritime industry. Our investigation illuminated both the challenges and opportunities that lie ahead in replacing traditional fossil-fuel based propulsion systems with nuclear technology and sought to determine what support structures are necessary to enable shipboard nuclear powered propulsion to decarbonize the maritime industry. To make this determination, we briefly reviewed the history of nuclear energy and assessed the current state of the nuclear industry to better understand the issues with third generation nuclear power plants and how generation IV advanced nuclear reactors will differ. This information also gave us insight into previous and ongoing operations of shipboard FNPPs to help us understand what didn't work and what the future of shipboard FNPPs may look like. The assessment of the nuclear industry also gave us insight into how the industry operates in terms of safety standards and global reach, as well as what technological advancements are being considered not just for terrestrial power plants, but for shipboard FNPPs as well. We also conducted an economic analysis of the economic factors and market pre-preconditions necessary for the widespread adoption of shipboard FNPPs. In this assessment, we analyzed the relevant regulatory foundations at the international and national levels, conducted a capital investment analysis and evaluated potential financing models, evaluated risk management considerations, and conducted a SWOT analysis for shipboard FNPPs, including determining the long term economic viability for these nuclear power sources. Finally, we infrastructure pre-conditions necessary to support long-term and wide-spread deployment of shipboard FNPPs. This research addressed shipyard and vessel construction needs, nuclear fuel supply chain and distribution channel requirements, technological innovations and system integration, and various logistical and operational environment issues.

This research underscored the environmental benefits, economic feasibility, and technological superiority of nuclear power over traditional and alternative maritime fuels. It also evaluated the technological advancements that make shipboard FNPPs a viable solution for the future of the maritime industry. Despite the advancements, we also determined that nuclear-powered ships are not without limitations. We identified significant challenges, including safety and regulatory concerns, infrastructural needs, and initial economic outlays.

Despite these challenges, the opportunity to significantly reduce GHG emissions and move towards a more sustainable and efficient maritime industry is a compelling motivator for further development in this field. This study highlights the broader implications of adopting nuclear-powered propulsion, from marine and terrestrial environmental impacts to shifts in global shipping and energy dynamics. The readiness of the industry for such a transition, while growing, still requires significant collaboration and innovation. This study also determined that adoption of shipboard FNPPs is most appropriate for large vessels. Those vessels not suitable for shipboard FNPP use will need to employ an alternative fuel, such as hydrogen or ammonia, for the maritime industry to achieve zero-carbon shipping.

By adopting shipboard FNPPs, maritime industry can help tackle climate change and reduce GHG emissions. This shift to FNPPs should mostly occur for large container vessels, especially those carrying high numbers of reefers, as well as other large vessels like bulkers and possibly cruise ships. Adoption of FNPPs will have three major impacts:

1. Elimination of CO2 emissions on larger vessels,
2. Creating consumer demand for zero carbon power production solutions in the form of advanced nuclear reactors which, when coupled with terrestrial power demand, will ultimately reduce the cost to produce small modular reactors and micro reactors,
3. Improving maritime industry efficiency by increasing vessel speeds and increasing cargo capacity on vessels through the reduction or elimination of extensive fuel storage tanks.

The combination of market demand in the energy industry and maritime industry, along with environmental urgency to find low- or zero-carbon energy solutions in both industries will drive innovation in all alternative fuel and energy sources. This drive is taking form in broad investigation into generation IV nuclear reactor technologies, which will provide safe and reliable energy.

Challenges that must be addressed before broad adoption of shipboard FNPPs include:

- Completion of small modular MSR design and terrestrial deployment. While no MSR reactors are currently in operation, most companies developing these reactor types anticipate a late 2020’s activation with commercial production following a few years later.

- Identifying sources of investment and appealing financing schemes for the first shipboard FNPPs. This will likely be a combination of public and private funding, especially for the first batch of ships with nuclear-powered propulsion
- Getting national governmental support for upgrade of port and energy infrastructure to support deployment and maintenance of FNPPs. Governmental buy-in will be essential to allow for the development of nuclear infrastructure in ports.
- Updating international regulatory frameworks to enable global FNPP operation. Covered at length in this paper, most of the relevant regulations are outdated and only apply to shipboard PWR's. This doesn't take into consideration vast technological advancements in active and passive safety features that will be the cornerstone of fourth generation reactor designs.
- Establishing multiple sources of supply for various nuclear fuel types. This will both reduce the risk of a fuel bottleneck and decrease the overall cost of fuel by increasing its availability.
- Winning maritime industry and public support for shipboard FNPP deployment. Governments and nuclear reactor developers can best win support by conducting public information campaigns to assure the public that solutions to safety and waste storage issues are in development and showcasing them with large and impressive public relations campaigns.

8.2 Areas for Future Research

Having determined that shipboard FNPPs are a viable propulsion power source for the maritime industry, three areas seem relevant for further research:

- **In depth research into national and international regulatory frameworks**. Investigation into national policies preventing vessels like Sevmorput from entering foreign ports for maintenance are essential to determining the regulatory barriers for access to port for vessels during regular operation and following emergencies. For shipboard FNPPs to be successful, ships using them will need access to ports around the world for business and maintenance. This will also likely include industry-wide discussions on implementation strategies.

- **Further and specific exploration into economic models and infrastructural redesigns will be critical for the successful integration of nuclear-powered propulsion in commercial shipping**. We recommend exploring the following:
    - Determining the optimal mix of shipboard FNPP and alternative fuel/energy deployment
    - Analyzing the timeline for advanced nuclear reactor adoption on ships, what the capital investment for those projects will be, and how much of those costs will be passed along to potential maritime customers like Maersk, CMA CGM, COSCO, etc.
    - Analyzing cost information from a government(s) related to nuclear energy programs, to include long-term waste storage. Also analyzing cost information related to construction and management of terrestrial nuclear energy facilities to establish a parametric cost model for operation of a much smaller shipboard nuclear reactor. Information related to powerplant operation will also help determine how best to design ship support infrastructure to allow the researcher to extrapolate a specific design based on that information.
    - Development and testing of an economic model to help predict financial strategies for shipping firms looking to adopt shipboard FNPPs and help determine the best point of entry and pace of transition from fossil fuels to nuclear-powered propulsion.
- **Naval architectural review of cargo and bulk carrier ship designs incorporating proposed small modular MSR footprint**. This will help determine how nuclear-powered vessels of the future may differ from fossil-fueled vessels currently in service. This change may also identify new space efficiencies realized by removal of extensive fossil fuel storage tanks or determine that repurposing this space is not feasible.

8.3 Vision for the Future

In envisioning a sustainable and efficient maritime industry, the role of nuclear-powered propulsion cannot be overstated. With collaborative efforts, innovative solutions, and adaptive policies, shipboard FNPPs stand as a beacon of hope in our pursuit of decarbonizing maritime transport. As we stand at the threshold of this new era, the promise of nuclear-powered propulsion in achieving global environmental goals while maintaining economic viability is not only possible but imperative for a sustainable maritime future.

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Appendix A – Definitions List

Pressurized water reactor – “A common nuclear power reactor design in which very pure water is heated to a very high temperature by fission, kept under high pressure (to prevent it from boiling), and converted to steam by a steam generator (rather than by boiling, as in a boiling-water reactor). The resulting steam is used to drive turbines, which activate generators to produce electrical power. A pressurized-water reactor (PWR) essentially operates like a pressure cooker, where a lid is tightly placed over a pot of heated water, causing the pressure inside to increase as the temperature increases (because the steam cannot escape) but keeping the water from boiling at the usual 212°F (100°C). (NRC, 2019)

Molten salt reactor – “Molten salt reactors (MSRs) are a Generation IV nuclear reactor that use molten salts (high temperature liquid salts) as their nuclear fuel in place of the conventional solid fuels used in the world's current reactors. The use of fluids allows for it to act both as their fuel (producing the heat) and coolant (transferring the heat).[2]

These reactors have been designed in many different ways using different fuels. All of these reactors initially have their fuel chemically bonded to fluoride, which is then dissolved into a molten carrier salt. The most commonly proposed carrier salt is a mixture of LiF (Lithium Fluoride) and BeF_2 (Beryllium Fluoride) commonly referred to as FLiBe.[3] MSRs have not been implemented since the shut down of the Molten Salt Reactor Experiment (MSRE) in 1969. This is primarily due to technical issues associated with the high temperature and corrosive nature of the salts.” (University of Calgary, n.d.)

FNPP - a factory manufactured, transportable and/or relocatable nuclear power plant that floats either on a barge, platform, or ship which, when fuelled, can produce final energy products such as electricity and heat intended for use beyond the boundary of the barge, platform, or ship on which it is produced. An FNPP includes the nuclear reactor (with or without fuel, depending on the FNPP option considered), the balance of the plant (e.g. turbine, generator) and fuel storage facilities, if necessary. The FNPP is physically transportable, but is not designed to either produce energy during transportation or provide energy for the transportation itself. The installed FNPP is intended for use in the host State for different purposes such as electricity supply for remote areas, district heating, desalination of sea water and hydrogen production, while preserving its capability for relocation if necessary. (IAEA, 2013)

Shipboard FNPP – a factory manufactured, transportable nuclear power plant installed on a ship that is designed to provide primary power for regular ship operations including but not limited navigation, propulsion, and hotel services to support its live aboard crew. The sFNPP is a small modular reactor of yet to be determined type/s that enables sustained operations for a long duration with infrequent refueling intervals. The sFNPP is intended for use onboard large military and commercial vessels to conduct endurance operations such as intercontinental shipping of large volumes of cargo.

Infrastructural pre-conditions – Physical and legal conditions which must be in place prior to broad adoption of shipboard FNPPs. This includes logistical, technical, and regulatory changes necessary for the acceptance of this advanced shipboard power plant. Physical infrastructure includes ports, shipyards, trade routes, logistics chains, and physical support networks including personnel. Non-physical infrastructure includes regulations, protocols, and practices employed to optimize safety and efficiency of every step in the shipboard FNPP lifecycle. This includes vessel fabrication and power plant installation, to operations and maintenance, and finally to nuclear waste disposal and vessel scrapping.

Economic pre-conditions – Financial and market conditions which must be determined prior to broad adoption of shipboard FNPPs. This includes financing and insurance structures, risk assessments, and uranium market stability. The maritime industry must also have interest in adopting shipboard FNPPs, given the high CAPEX needed to commission a vessel with such a power plant.

Conventional fuels – traditional marine fuels, such as marine gas oil, marine diesel oil, and heavy fuel oil (HFO). These bunker fuels are distillates of oil and extremely cheap.

Appendix B – Table of Interviewees

Table of Interviewees			
Name	Function	Company	Date
Dowling, Megan	Corporate Technology Engineer	American Bureau of Shipping	08 Aug 2023
Kourasis, Ioannis	Nuclear Engineer	Core Power	01 Sep 2023
Saverys, Alexander	CEO	Compagnie Maritiem Belge	30 Aug 2023
Stopford, Martin	Shipping Analyst	Self employed	15 Dec 2023
van den Brink, Françoise	Senior Advisor Energy Transition	Port of Rotterdam	12 Jan 2024

Table 8 Table of interviewees