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Considerations for Maritime Nuclear Technologies, Economic Viability and Public Acceptance

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ABSTRACT

The Maritime Nuclear Application Group (MNAG) is a working group convened by the National Reactor Innovation Center at Idaho National Laboratory (INL), the American Bureau of Shipping, and Morgan, Lewis, and Bockius LLP. This report documents an MNAG examination of considerations relevant to implementing nuclear technology in commercial maritime applications. In general, two types of use case are examined: maritime nuclear power plants and nuclear reactors used on board shipping vessels for propulsion and other ship needs. The report finds that there may be economic benefits related to maritime nuclear technologies, including the flexible deployment of maritime nuclear reactors, which would allow them to complement land-based nuclear projects, and operational differences for nuclear cargo ships that may lead to an overall increase in revenue. High-level analyses in this report show that, based on general small modular reactor and microreactor cost estimates developed by INL, maritime nuclear reactors may be economically competitive for electricity production in remote regions and for use in the propulsion of large cargo ships. Besides economic viability, public acceptance will be key to implementing maritime nuclear technologies. The report discusses the public's current perception of nuclear technologies. Engaging with the public will be important to improving this perception. The report discusses some key benefits and risks associated with maritime nuclear technologies. Benefits include the creation of jobs, the production of reliable energy, and the potential to improve air quality. Risks that concern the public are the potential for radioactive releases during operation and decommissioning, as well as those related to waste management. Communicating the benefits and the risks of maritime nuclear technologies will be essential to improving public perception.

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ACRONYMS

ABS	American Bureau of Shipping
DOE	U.S. Department of Energy
FNPP	floating nuclear power plant
FOAK	first-of-a-kind
FPSO	floating production, storage, and offloading
GN-COA	Generalized Nuclear Code of Accounts
HTSE	high-temperature steam electrolysis
IMO	International Maritime Organization
INL	Idaho National Laboratory
IRA	Inflation Reduction Act
ITC	investment tax credit
MNAG	Maritime Nuclear Application Group
NRIC	National Reactor Innovation Center
OCC	overnight capital cost
O&M	operation and maintenance
PTC	production tax credit
SMR	small modular reactor
SNF	spent nuclear fuel
STEM	Science, Technology, Engineering, and Mathematics
TNPP	transportable nuclear power plant

Considerations for Maritime Nuclear Technologies, Economic Viability and Public Acceptance

1. INTRODUCTION

1.1 The Maritime Nuclear Application Group

The Maritime Nuclear Application Group (MNAG) is a working group convened by the National Reactor Innovation Center (NRIC) at Idaho National Laboratory (INL), the American Bureau of Shipping (ABS), and Morgan, Lewis, and Bockius LLP. MNAG is a research hub and resource center that brings together experts from the maritime and nuclear energy sectors to facilitate the demonstration of advanced nuclear technologies for a range of marine applications. MNAG fulfills this mission by performing strategic studies of potential maritime applications, by identifying legal and regulatory hurdles, by cataloging and sharing relevant information resources, and by collaborating and coordinating with global stakeholders of all types. MNAG aims to support near-term field demonstrations of advanced reactor technologies in marine settings by partnering with the U.S. Department of Energy's (DOE) NRIC.

MNAG's membership includes representatives of organizations and firms in these areas:

- Nuclear industry: structure and system designers, vendors, national laboratories, policy nonprofits, academia
- Maritime: vessel owner/operators, classification societies, maritime law, insurance, flag states
- U.S. government: independent regulatory organizations and executive branch departments
- Environmental: industry groups.

1.2 Purpose and Scope

The purpose of this report is to document MNAG's examination of considerations relevant to implementing nuclear technology in commercial maritime applications (hereafter, "maritime nuclear technologies"). First, the report examines the perspective of developers in the maritime nuclear industry, focusing on the economic viability of these technologies through various use cases (Section 3). Next, the report shifts to the public's perspective, starting with an overview of the public's perception of maritime nuclear (Section 4), followed by a discussion of both the benefits and concerns associated with its potential use (Section 5). This knowledge could further enable designers/developers, governments, and energy end users to understand the complexities of maritime nuclear technology.

In this report, two types of use cases for maritime nuclear technologies are examined:

1. Maritime nuclear power plants for onshore electricity generation, and for providing power and heat to offshore industrial processes.
2. Advanced nuclear reactors used on board shipping vessels to provide power for propulsion and/or other ship needs.

Their specifics are discussed in Section 2.

While this report specifically examines nuclear propulsion for use in the commercial shipping industry (i.e., propulsion for cargo ships), nuclear propulsion could serve other civilian uses.

Also, this report generally focuses on considerations relevant to the U.S., though global examples are considered. This report does not cover technological or regulatory considerations for maritime nuclear technologies, though there are important hurdles to understand and overcome in those areas as well [1].

The work in this report supports the recently issued nuclear Executive Orders (EOs). Specifically, EO 14299, “Deploying Advanced Nuclear Reactor Technologies for National Security”, and EO 14300, “Ordering the Reform of the Nuclear Regulatory Commission,” by ensuring the rapid development, deployment, and use of advanced nuclear technologies; and increasing the deployment of new nuclear reactor technologies, such as Generation III+ and IV reactors, modular reactors, and microreactors to support America leading the commercialization of affordable and abundant nuclear energy.

2. MARITIME NUCLEAR USE CASES

This section describes maritime nuclear technology use cases for offshore power production, supplying energy to offshore industrial processes, and commercial shipping. This section also discusses the motivation behind using maritime nuclear technology in these industries.

2.1 Maritime Nuclear Power Plants

2.1.1 International Atomic Energy Agency Definition

The International Atomic Energy Agency defines a transportable nuclear power plant (TNPP) as a factory-manufactured, transportable and/or relocatable nuclear power plant capable of generating products such as electricity and heat when fueled. They are not designed to produce energy during transport or to power the transportation itself [2]. TNPPs can be land based or marine based. This paper refers to marine-based TNPPs as “maritime nuclear power plants.” Maritime nuclear power plants could be located at or near the shore as structural platforms connected to the seabed or shore. They also could exist as more easily relocatable floating nuclear power plants (FNPPs), similar to vessels, which could be located close to shore or in deeper waters. Maritime nuclear power plants would include the necessary auxiliary equipment to produce the reactor’s final product, be it electricity or heat [3]. They could make use of a reactor of any size, from a full-sized reactor resembling those of the existing land-based nuclear fleet, to a small modular reactor (SMR) or microreactor,[a] which generate smaller power outputs.

2.1.2 History of Commercial Maritime Nuclear Power Plants

Commercial maritime nuclear power plants were proposed in the U.S. in the 1970s. They did not gain traction due to a failure to address safety, environmental, and regulatory concerns, as

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[a] Varying definitions exist for SMRs and microreactors. The International Atomic Energy Agency defines an SMR as an advanced nuclear reactor with a power capacity of up to 300 MWe per unit. It defines a microreactor as a type of SMR with a power capacity up to ~10 MWe per unit [4]. In either case, multiple units may be used in one application (e.g., five 10-MWe microreactors could be used in a use case requiring 50 MWe).

well as due to economic struggles associated with the 1973 oil crisis and a downturn in interest in nuclear power after the Three Mile Island incident in 1979 [4]. The one contemporary example of an FNPP is the *Akademik Lomonosov*, deployed by Russia in 2019 in its far-north Chukotka region [5]. Russia is currently executing plans to deploy several more of these systems across their domestic far-eastern coast and has begun developing export opportunities [6, 7]. New concepts for commercial maritime nuclear power plants have been proposed in the U.S., such as MIT's Offshore Floating Nuclear Plant [8]. In recent years, several different organizations, many of which participate in MNAG, have begun pursuing design work to enable near-term deployment.

2.1.3 Use Cases for Commercial Maritime Nuclear Power Plants

There are various use cases for maritime nuclear power plants. If used primarily for electricity generation, nuclear reactors could be deployed to remote, grid-disconnected locations, or areas that lack sufficient land or a trained workforce, where it would be significantly more expensive to build a land-based nuclear reactor. Examples could include coastal communities [9]. Assuming a sufficiently agile deployment, maritime nuclear power plants may be able to provide power as part of disaster relief efforts, such as after a hurricane.

Another use case for maritime nuclear power plants is combining them with floating production, storage, and offloading (FPSO) units. FPSO units can be used to produce industrial commodities, such as hydrogen. Hydrogen is a precursor to many key industrial products [10]. One method of producing hydrogen is high-temperature steam electrolysis (HTSE), which uses steam as the primary input and requires both heat and electricity. If paired with an appropriate advanced reactor technology that provides heat and electricity, FPSO units could be integrated with a maritime nuclear power plant to produce hydrogen [11].

2.2 Commercial Civilian Ship Propulsion

Currently, most ships internationally are bulk carriers, container ships, oil tankers, and liquefied gas tankers. The dominant fuel for these ships is heavy fuel oil, with marine diesel oil and liquid natural gas comprising a growing portion of the fuel types used [12]. Nuclear propulsion could serve as an alternative fuel source for these ships, the potential benefits of which are discussed in Section 3.2. However, if existing ships are not retrofitted to use nuclear power for propulsion, there must be another source of opportunity within the commercial shipping sector to make commercial nuclear propulsion viable.

One source of opportunity for nuclear propulsion in the commercial shipping sector stems from the continuous growth of the shipping sector itself. Global shipping has seen a compound annual growth rate of 2% over the last 30 years [13]. Given the historical growth rate, near-term projections pose opportunities for a market to utilize commercial vessels that utilize nuclear power for propulsion.

Another source of opportunity stems from the limited lifespan of shipping vessels. Tankers have an expected life of roughly 15 to 25 years, and bulk carriers and container ships 25 to 30 years [13]. Roughly two-thirds of U.S. flag ships are older than 15 years [14]. Globally, the average age of a merchant ship is more than 20 years [13]. Therefore, globally there will be an inevitable aging out of many existing fossil-fueled commercial ships in the coming decades. As these ships retire, nuclear-propelled commercial ships could offer an emission-free alternative, if the economics of the nuclear systems align with both the lifespan and commercial needs of the ships.

There are few examples of nuclear power being used for propulsion in the commercial sector outside of Russia. In Russia, nuclear-powered icebreakers, which are used to navigate through thick ice, are particularly relevant to supporting routes and ports in Russia's arctic regions. Historic examples from the 1960s to 1980s, such as the U.S.'s NS *Savannah* and Germany's NS *Otto Hahn*, were able to show that commercial nuclear propulsion was technically possible and reliable. However, these vessels were not intended to be economically competitive and could not compete with ships using low-cost and readily available fossil fuels [15].

Besides economics, another factor that has limited the use of nuclear power technologies for propulsion is that highly enriched uranium, which has been used successfully in military nuclear propulsion, is safeguarded to ensure it is not used for malevolent purposes. Also, the commercial reactors in use today are based on large land-based reactor designs; it would be difficult to modify existing designs for use in commercial marine propulsion applications [15]. However, there are many new nuclear reactor designs and configurations with characteristics—such as compact sizes and enhanced safety features—that may make the case for use in ships more compelling. Some studies have examined using different advanced reactor designs, sizes, and configurations to power a commercial nuclear ship [16].

Overall, the growth of the shipping sector, coupled with the age of the current fleet, creates a potential opportunity in the market for commercial nuclear propulsion.

3. ECONOMIC VIABILITY

To achieve commercial success, maritime nuclear use cases must be economically competitive with their alternatives. Alternatives may be the status quo (i.e., fossil fuel–based technologies) or potential future competitors (i.e., other energy sources). This section examines the beneficial and detrimental economic considerations associated with two maritime nuclear use cases:

- Maritime nuclear power plants, which may be used for electricity generation, or as part of industrial processes
- Advanced nuclear reactors used for the propulsion of a commercial cargo ship.

The economic considerations associated with maritime nuclear power plants are examined in Section 3.1. The economic considerations of using a nuclear reactor for the propulsion of a commercial ship are examined in Section 3.2. In each section, the economic benefits and costs associated with each use case are summarized. Some of these considerations are quantified for use in economic analyses that approximate the overnight capital costs (OCCs) that the maritime nuclear reactors would need to achieve to be competitive with alternative power sources in different use cases (see Sections 3.3 and 3.4).

3.1 Economic Considerations for Maritime Nuclear Power Plants

3.1.1 Flexible Deployment

Maritime nuclear power plants can be designed to use SMR or microreactor designs that can be sited where land-based reactors cannot. For example, many, but not all, SMR technologies are being designed for compact sites, such as those found near cities and industrial regions. However, not all these locations will have suitable siting conditions for a land-based system, or even smaller land-based SMRs. Constraints can include lack of space to construct and operate the facility and the need to make costly adaptations to the site to support long-term safety and security. In remote areas, there may be a lack of regional infrastructure (e.g., roads, logistics) to support a land-based facility. In these scenarios, siting a nuclear reactor offshore may result in lower costs for site preparation and site-based infrastructure. This flexibility allows maritime nuclear power plants to be located in infrastructure-poor areas.

Deploying maritime nuclear power plants to remote areas offers several direct and indirect economic benefits. In such places, competition with existing nuclear technologies would be less relevant. Instead, maritime nuclear power plants would be able to directly:

- Augment fossil fuel generation and simultaneously eliminate the need for costly and often subsidized fossil fuels to be periodically delivered
- Provide heat energy to both communities and industries.

The economic opportunity realized by a reduction in energy scarcity is often overlooked in energy studies for remote sites. Fossil-fueled facilities in remote regions require fuel logistics, which can be costly and energy intensive. These costs have the effect of inhibiting growth opportunities in the region. A reliable and sufficiently large supply of energy, such as that from a nuclear reactor, leads to energy security, resulting in economic growth, which benefits the region, its inhabitants, and the economic security of the power plant itself [17].

One key industry for which maritime nuclear power could be impactful is desalination. Desalination is a process that removes the salt and minerals from seawater to make potable and industrial-quality water, often for communities with scarce freshwater supplies, such as those found in the Middle East [18] and on islands [19]. The need for desalination, and the power it requires, is growing worldwide, and nuclear energy has already been used to provide energy to desalination [20]. Maritime nuclear's flexibility could allow for desalination plants to be developed more easily in water-scarce remote communities. This same principle would apply to other industrial use cases as well.

Overall, maritime nuclear power plants can be designed to be deployed in regions where land-based nuclear power plants would not be economically feasible. Therefore, maritime nuclear power plants may be particularly beneficial to remote, coastal areas that lack suitable locations for onshore nuclear power.

3.1.2 Tax Incentives

Maritime nuclear power plants may benefit from tax incentives afforded to clean energy while potentially avoiding carbon taxes and levies.

Tax incentives currently exist in the U.S. for some forms of energy, including nuclear energy, which may potentially apply to maritime nuclear use cases that produce energy. The Inflation Reduction Act (IRA), passed on August 16, 2022, includes two types of tax incentives for some energy projects, though project developers may only access one type for a given project. In short, an investment tax credit (ITC) is based on a percentage of a project's initial capital cost, whereas a production tax credit (PTC) is based on the MWh of energy produced for the first 10 years of a project. Though the exact magnitude of the impact of the IRA credits on maritime nuclear projects may vary depending on the implementation, as of this report's publishing, they may allow for cost savings of roughly 20–30% [21].

There are several carbon tax measures around the world [22, 23]. While carbon taxes do not exist in the U.S. at a federal level, some states have implemented carbon-trading schemes, and some carbon-taxing schemes have been proposed [24]. The magnitudes of the proposed U.S. carbon taxes are generally in line with average carbon taxes throughout the European

Union and Singapore [22–24], though great variety exists within the European Union. It is also notable that carbon-taxing schemes generally involve escalation, which increases the tax on carbon over time. Examining carbon taxes can provide guidance in understanding the impact of potential future carbon taxes on the maritime nuclear industry, whether in the U.S. or in regions where carbon taxes are currently implemented. Maritime nuclear technologies could avoid these taxes, which could increase their competitiveness in relevant regions.

Overall, both tax incentives from the IRA and potential carbon taxes may help maritime nuclear power plants be cost competitive with fossil-fueled alternatives.

3.1.3 Modularity and Shipbuilding Practices

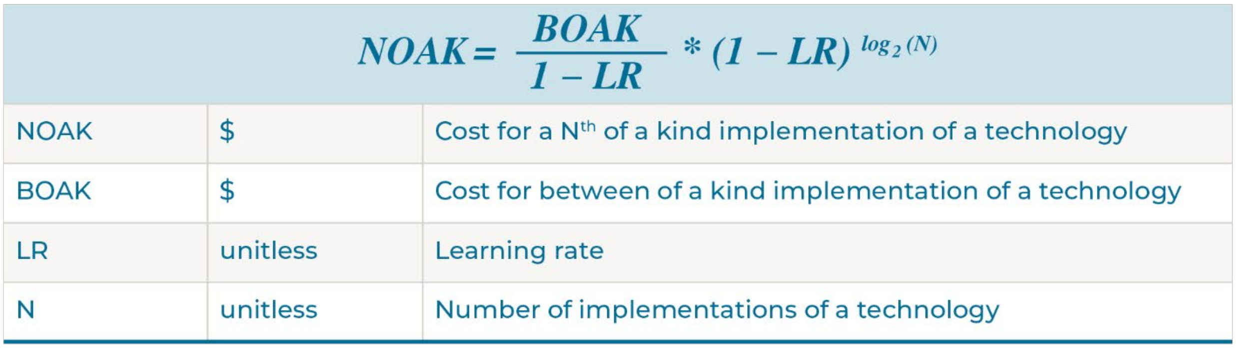
Maritime nuclear power plants that utilize advanced reactors could have higher capital costs than traditional nuclear reactors due to being first-of-a-kind (FOAK) deployments [16]. However, these increased costs could potentially be offset if modularity and shipbuilding practices are used.

Maritime nuclear power plants would combine two existing industrial fabrication processes. First, they would be built in shipyards using modern shipbuilding practices. Second, they would be constructed and regulated under the quality assurance and safety standards of the existing land-based commercial nuclear industry.

Modular design and shipbuilding practices can produce cost-effective and high-quality results by standardizing and centralizing where maritime nuclear power plants are constructed. They would also reduce labor costs during construction, increase labor force retention, improve knowledge management, simplify decommissioning (assuming it could also take place in qualified shipyards), and eliminate many of the on-site construction-related economic issues that site-by-site construction projects face [25]. It is estimated that using modular construction for maritime nuclear power plant projects, which could occur in shipyards or on land, could lead to capital cost savings of 10–20% compared to traditional reactor construction practices [25].

The higher labor force retention and improved knowledge management would also enable the workforce to operate in a continuous improvement environment that would reduce labor and process costs over time as more units are produced. This cost reduction can be quantified using a learning rate, which has been estimated to reside between 5 and 15% for advanced nuclear reactor projects. Learning rate, LR, affects the cost of the Nth implementation of a project in accordance with the following equation [26]:

Equation 1



$$NOAK = \frac{BOAK}{1 - LR} * (1 - LR)^{\log_2(N)}$$

NOAK	$	Cost for a N^{th} of a kind implementation of a technology
BOAK	$	Cost for between of a kind implementation of a technology
LR	unitless	Learning rate
N	unitless	Number of implementations of a technology

However, despite these advantages, establishing a manufacturing line and decommissioning facilities in shipyards for maritime nuclear power plants would be significantly more complex than shipbuilding given the highly regulated nuclear activities being conducted.

The costs related to these issues will need to be examined as maritime nuclear power plant concepts progress.

3.1.4 Investor Project Concerns

Proponents of maritime nuclear power plants may have to consider the inherent investor and lender aversion to financing capital-intensive projects without clear signals and evidence that a deployment project can be executed on time and on budget; traditional commercial nuclear projects face this issue as well [1], but this aversion would be exacerbated for maritime nuclear because of its FOAK nature. Investors and lenders are also fearful of lengthy project assessment and permitting processes, and these processes are not yet clearly understood for maritime nuclear power plants. Ultimately, the economic reality of offshore advanced nuclear power plants will not be known until a FOAK implementation of the technology. Government programs do exist, however, that provide loans for high-risk, capital-intensive projects to help enable these technologies to come to fruition [27].

3.1.5 Nuclear Security and Perception

There are several economic factors to consider that relate to the security of a nuclear reactor used in a maritime nuclear power plant. For example, nuclear facilities will have more stringent staffing requirements (i.e., nuclear engineers, operators, and security personnel) compared to non-nuclear power sources. This is expected to increase costs due to the more specialized training that is required [16]. For example, traditional nuclear power plant employees earn salaries on average 50% higher than other power generation sources [28]. Maritime nuclear power plants could also be attractive targets for malicious acts and, like traditional nuclear power plants, be at risk of severe accidents. Historically this consideration has led to high insurance costs for nuclear power plants. For example, the Price-Anderson Act obligates U.S. commercial nuclear reactors to secure private insurance to cover potential damage inflicted on off-site third parties. This increased financial burden is likely to apply to any commercial maritime nuclear power plant as well [29].

On the other hand, many advanced reactor designs have enhanced safety features such as passive safety systems and simpler designs (which require fewer components, less maintenance, and fewer workers) [30]. If advanced nuclear reactors are built with these safety enhancements in place, insurance premiums may be lower, which has the potential to reduce the overall financial burden on maritime nuclear power plants that use advanced reactors.

Another economic factor for maritime nuclear power plants that must be considered is the perception of nuclear globally. Nuclear power has fallen in and out of favor around the world and is controversial in many countries. Therefore, there is the potential for maritime nuclear power plants to be confined to specific deployment locations due to legal conditions imposed by various governing bodies.

3.2 Economic Considerations for Commercial Nuclear Propulsion

The economic considerations that are relevant to maritime nuclear power plants are also relevant to commercial nuclear propulsion because they both will use an advanced nuclear reactor. These considerations include tax incentives (see Section 3.1.2), the effects of modularity and shipbuilding practices (see Section 3.1.3), and the risks inherent to capitally intensive FOAK technologies (see Section 3.1.4). The often-negative perceptions and risks associated with nuclear technologies (see Section 3.1.5) apply to nuclear ships as well but present themselves slightly differently. Rather than limiting the deployment location, perceptions and risks could limit the routes and ports of call available to nuclear ships, which could hurt the flexibility of their use and possibly introduce logistical challenges.

There are also economic considerations specific to commercial nuclear propulsion. In this section, a hypothetical commercial nuclear cargo ship is compared to a similarly sized fossil-fueled ship and similarly sized ammonia-fueled ship to explore these considerations.

3.2.1 Operational Differences

Nuclear propulsion may allow ships to reach faster speeds, leading to quicker shipping times and potentially lowering costs by reducing delays and the number of operating vessels required to meet shipping demands. Additionally, the operators of many fossil-fueled ships practice “slow-steaming”—that is, intentionally running ships at speeds lower than their maximum design speeds to increase fuel efficiency and reduce carbon emissions [31]. Nuclear ships may have fewer incentives to slow-steam, allowing them to potentially run at faster speeds closer to their maximum design speed [31]. The relationship between speed and revenue is complex, and nuclear ships may find a niche in market segments that benefit specifically from faster ship speeds [32].

Additionally, nuclear ships could have increased cargo capacity; onboard nuclear reactors would be more compact than the large fossil-fueled engines used in today’s fleet, and nuclear ships would not need large fuel tanks [32].

Nuclear ships would likely need to make specific trips to specialized, regulated facilities for refueling. It is possible that these refueling outages would take the ship out of service for significant periods of time (i.e., weeks), depending on the reactor refueling and maintenance arrangements. In contrast, fossil-fueled ships generally refuel while in port, sometimes concurrently with other processes such as the loading and unloading of cargo. The frequency of SMR refueling outages, however, would be significantly lower than that of fossil-fueled ones (e.g., some SMR designs propose no refueling outages during their lifetime), though it would depend on the specific SMR and its refueling strategy [33]. Ultimately, a nuclear ship with infrequent and short outages has the potential to have greater availability and to generate more revenue, especially if other scheduled ship maintenance is performed during refueling outages. The opposite would be true of ships with frequent or long outages.

3.2.2 Reverse Cold Ironing

A potential secondary revenue stream for nuclear-powered ships is reverse cold ironing. Cold ironing is the process of a docked ship turning its engines off and drawing energy from the shore to power ship needs [34]. In contrast, reverse cold ironing is the process of selling electricity produced on board to the port at which the ship is docked [15]. The technological feasibility of this in commercial settings, for both the nuclear ship and the port and grid infrastructure, has not yet been proven. However, it may be a potential source of revenue for commercial nuclear ships and, if the ships were docked at U.S. ports, a pathway to accessing IRA PTCs (see Section 3.1.2). Reverse cold ironing would also allow ship reactors to remain operating continuously while in port, which is in line with current commercial nuclear reactor operating procedures.

A high-level estimate of revenue from reverse cold ironing is calculated in Appendix 8.2.

3.2.3 Capital Intensiveness

As is the case with maritime nuclear power plants and traditional nuclear power plants, the primary economic obstacle of nuclear-propelled ships—compared to fossil-fueled ships—may be high capital costs. However, technologies fueled by fossil fuels compete with the historically lower operating costs of nuclear power [15] and the greater price volatility of fossil fuels compared to nuclear fuel.

3.3 Estimating Revenue for Nuclear Shipping

Using the assumptions and inputs detailed in Appendices 8.1.2 and 8.1.3, Table 1 shows the percent difference in annual revenue for a nuclear ship compared to a baseline fossil-fueled ship. Revenue differences due to differences in speed, weight, and outage times associated with nuclear refueling are accounted for and itemized in Table 1. The calculations show that, given the assumptions detailed in Appendix 8.1.3, most of the increase in revenue for a nuclear ship is due to increased speed (8.2% revenue increase). Increased outages associated with nuclear refueling lead to a roughly 4.6% decrease in revenue. Changes in weight do not significantly affect the revenue for a nuclear ship (0.3% increase in revenue) because the representative ship that was examined is sufficiently large that the difference in power system weight is negligible compared to the amount of cargo.

This annual revenue of a nuclear ship is used in Section 3.4.2 to calculate a breakeven OCC for nuclear long-haul cargo ships compared to fossil-fueled and ammonia-fueled cargo ships.

Table 1. Revenue differences for a nuclear ship compared to a baseline fossil-fueled ship.[1]

Difference	% Change in Revenue
Speed of Ship at Sea	+8.2%
Cargo Capacity in Weight	+0.3%
Outage Time for Refueling	-4.6%
Overall Effect	3.5%

1. These conclusions are specifically tied to the assumptions made in Appendices 8.1.2 and 8.1.3, and the specific scenario examined, which are meant to reflect one potential use case of nuclear shipping. Different ships, outage scenarios, and routes, and cargo would lead to varying conclusions.

It is worth reiterating that increases in speed would only lead to increases in revenue if ports can logistically manage increased shipments, and if there is demand for more shipping on a certain route. Therefore, nuclear ships may be best used in shipping corridors with these characteristics.

Notably, while a representative refueling outage frequency and length was assumed for the nuclear ship (which averages to 16 days per year [35]), outages may vary significantly depending on the reactor design. As a result, a breakeven analysis was performed to estimate the maximum number of refueling outage days it would take for the baseline ship to outperform the nuclear ship. This analysis found that nuclear ships may outperform fossil-fueled ships if the average yearly refueling outage for a nuclear ship's reactor is kept below 27 days.

3.4 Estimating Breakeven Overnight Capital Costs for Maritime Nuclear Technologies

The ABS/NRIC report *Configurations of Commercial Advanced Nuclear-Maritime Applications* determined breakeven OCCs for maritime nuclear reactors under various scenarios, such as those involving varying fossil fuel prices and potential tax incentives for nuclear energy [16]. It assumed a between-of-a-kind implementation (calculations specifically assume the 10th implementation of the given technology) and a learning rate of 10%, which reduce costs according to Equation 1. An unadjusted case was presented alongside cases with learning assumed, as there is uncertainty on learning rates for nuclear reactors.

This report presents an adjustment of this ABS/NRIC analysis with further considerations and use cases. All analyses herein include the following two adjustments:

- The analyses in this report use an adjusted maritime SMR and microreactor OCC that accounts for expected cost differences for maritime reactors (see Appendix 8.3), as well as to an updated operation and maintenance (O&M) cost based on an updated metanalysis [36].
- When applicable, the analyses in this report use a representative fossil fuel price, which reflects the recent prices of various fuels that are weighted by usage in the shipping industry.

The breakeven OCCs presented below are estimates, but they may provide a quantitative basis for understanding the economic competitiveness of maritime nuclear technologies compared to fossil-fueled alternatives. The OCC range estimates for SMRs and microreactors are derived from Abou-Jaoude [26], and the conclusions drawn for the economic competitiveness of maritime nuclear use cases are dependent upon reaching these OCC estimates.

3.4.1 Maritime Nuclear Power Plants for Power and Industrial Applications

The first use case is the production of synthetic fuels in an FPSO unit. A breakeven OCC was calculated by comparing the levelized cost of energy of synthetic fuel produced using nuclear power in an FPSO unit versus conventional (fossil) fuel. I. Table 11 in Appendix 8.4 details all inputs and assumptions for this breakeven OCC model. Key attributes for the modeled use case are:

- The calculation examines a maritime nuclear power plant that has a 400-MWe reactor and is assumed to have O&M costs similar to those of a land-based SMR.
- A nuclear plant life of 60 years is used, and a synthetic fuel plant life of 20 years is used. The synthetic fuel plant creates synthetic fuel using hydrogen produced via HTSE (see Section 2.1.3).
- Conventional fuel costs are assumed to be an average of commonly used maritime fuel costs, weighted by usage.

Using nuclear power to produce electricity for onshore use in a remote location is also considered. The breakeven OCC for electricity generation compares the cost of electricity from a floating nuclear microreactor to the cost of electricity from a diesel-generating station. Table 12 in Appendix 8.4 details all inputs and assumptions for this breakeven OCC model. Key attributes for the modeled use case are:

- The calculation examines a nuclear plant and diesel generator facility that each produce 2.49 MWe, which is meant to be representative of a small remote community's energy needs.
- The nuclear power plant is in the microreactor power range. Therefore, land-based microreactor O&M costs are used in this calculation (see Appendix 8.4).
- Both systems have an operating life of 30 years.
- Diesel fuel costs are incorporated into the O&M cost of the diesel generator facility and reflect fuel costs for remote communities, including the cost of transporting the fuel.

Figure 1 and Figure 2 show the range of breakeven OCCs for a maritime nuclear reactor used for each use case. Each row represents a different fuel or nuclear cost scenario, and each column represents a different IRA tax credit usage and learning rate scenario. The colors represent where each breakeven OCC stands relative to the expected OCCs of maritime nuclear reactors, depending on whether the use case models an SMR or a microreactor, as given in Appendix 8.3. These OCC estimate ranges are based on high-level cost estimates developed by INL [26].

Figure 1 shows that it is unlikely that synthetic fuels produced using nuclear power in an FPSO unit will be cost competitive compared to fossil fuels, unless IRA tax credits are taken and learning is achieved to drive costs down. Even then, maritime-nuclear-produced synthetic fuels would likely only be cost competitive in areas where carbon tax legislation has been passed. Without the tax incentives, the advanced reactor would need to achieve OCCs lower than would be reasonably expected—given the current estimates described in Appendix 8.3—to break even with alternative technologies.

On the other hand, nuclear-produced synthetic fuels are considerably more likely to be competitive with synthetic fuels produced via renewable energy, with or without IRA tax incentives and learning. This is due to the higher cost associated with synthetic fuels produced with renewable energy.

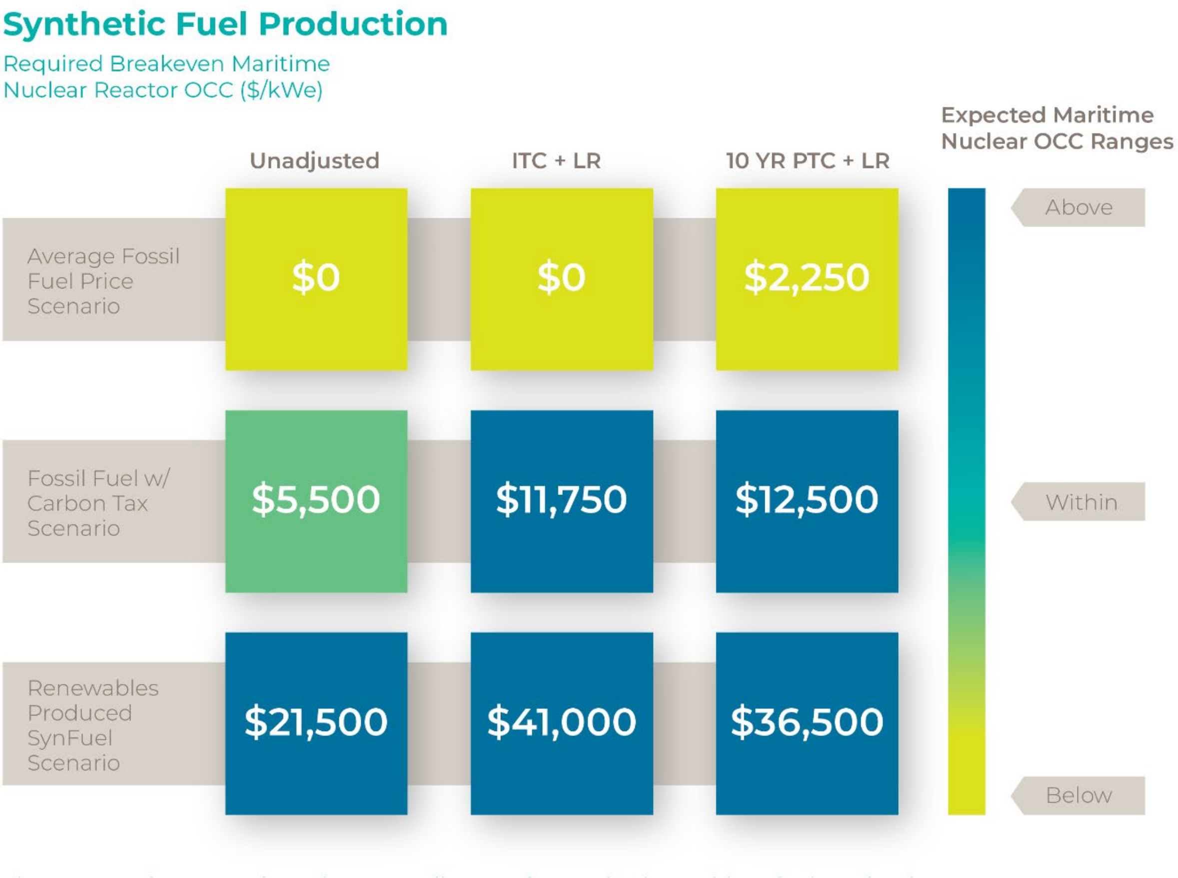
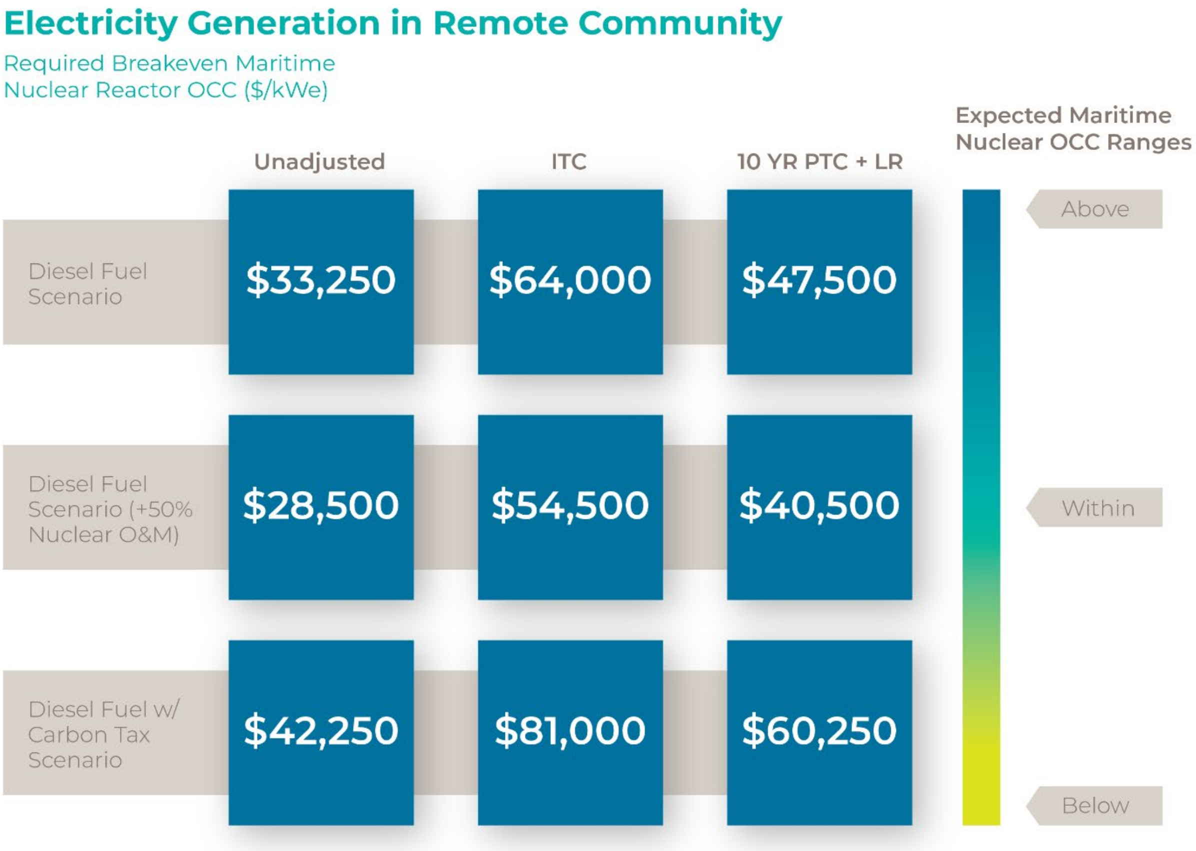


Figure 1. Breakeven nuclear plant OCC diagram for synthetic maritime fuel production.

Figure 2 shows that FNPPs may be more broadly cost competitive, even without IRA tax credits, for producing electricity in small, remote communities. This is because all scenarios allow for the FNPP powering the remote community to have OCCs far above the microreactor OCC estimates described in Appendix 8.3. The higher breakeven OCCs are mostly due to the high cost of the diesel fuel used by these communities (assumed to be $5/gal in this report). Microreactors are expected to have higher operating costs [37]. Therefore, the O&M cost of the reactor reflects O&M costs for microreactors. As a sensitivity, a case is presented in Figure 2 that assumes a 50% increase in microreactor O&M costs. However, the economic advantage of maritime nuclear remains in all investigated cases.

Notably, while this report investigates electricity usage for onshore, remote communities, FNPPs could provide electricity to industrial and offshore applications as well. However, such applications would likely have larger power needs and possibly use different fuels, such as bunker fuel. Therefore, this analysis is not directly applicable to those use cases.


Electricity Generation in Remote Community

Required Breakeven Maritime Nuclear Reactor OCC ($/kWe)

	Unadjusted	ITC	10 YR PTC + LR
Diesel Fuel Scenario	$33,250	$64,000	$47,500
Diesel Fuel Scenario (+50% Nuclear O&M)	$28,500	$54,500	$40,500
Diesel Fuel w/ Carbon Tax Scenario	$42,250	$81,000	$60,250

Figure 2. Breakeven nuclear plant OCC diagram for remote community electricity production.

Overall, these analyses show that maritime nuclear power plants are less likely to be cost competitive for producing alternative fuels in the maritime industry but more likely to be cost competitive for producing electricity in remote communities currently relying on diesel generators. Also, synthetic fuels produced by nuclear power may be more competitive than synthetic fuels produced by renewable energy.

Though maritime nuclear power plants may not be economical for producing synthetic maritime fuel compared to fossil-fueled alternatives, it may be cost competitive for other industrial use cases, and these should be examined in future analyses.

3.4.2 Commercial Nuclear Propulsion for Long-Haul Cargo Ships

The ABS/NRIC report *Configurations of Commercial Advanced Nuclear-Maritime Applications* [16] determined the breakeven capital expenditure for nuclear-propelled cargo ships under various scenarios. The model used in that report relied on various assumptions and inputs, including but not limited to:

- Only the costs of the power systems were compared (i.e., onboard nuclear reactor versus fossil fuel engine), assuming similar costs for crews and maintenance.
- Nuclear and fossil fuel engines (based on a representative engine used in current fossil-fueled ships) with the same power production and lifetime were compared. It was assumed that the nuclear power had a thermal efficiency of 33%.
- ITCs as detailed in the IRA passed by U.S. Congress in 2022 were used.

This report extends this analysis by including an estimate for the revenue for each ship technology, contributions to a decommissioning fund, and accounting for the cost of debt to finance the vessel and corporate tax (see Table 13 in Appendix 8.4). Some inputs, such as engine size, were adjusted to match the representative ship described in the revenue estimate (see Table 7 in Appendix 8.1). A full characterization of the use case can be found in Table 13 in Appendix 8.4, which details all inputs and assumptions for this breakeven OCC model. Key attributes for the modeled use case are:

- The modeled ship has an engine size of 59.36 MWe, which matches the power output of the diesel engine of a representative large long-haul cargo ship.
- A 30-year project timeframe is assumed.
- Only the capital and O&M costs of the power systems (i.e., the nuclear power plant on the ship and the diesel engine) are compared.
- The O&M cost of the ship's nuclear power plant is assumed to match those of a land-based SMR.
- The model also compares nuclear propulsion to propulsion from ammonia generated with renewable energy as a non-nuclear alternative to fossil-fueled ships.

Figure 3 below shows the range of breakeven OCCs for a maritime nuclear reactor used for nuclear propulsion. Each row represents a different fuel scenario, and each column represents a different IRA tax credit usage and learning rate scenario. The colors represent where each breakeven OCC stands relative to the expected OCCs of maritime nuclear reactors, as given in Appendix 8.3.

Figure 3 shows that large nuclear cargo ships are likely to be cost competitive with ships fueled by fossil fuels or by ammonia produced with renewable energy. This is because the breakeven OCC for the advanced reactor on the nuclear ship is far above the maritime nuclear SMR cost estimates described in Appendix 8.3. In this case, the added revenue from nuclear-powered ships helps to justify higher costs than were modeled in the ABS/NRIC report. This is particularly true when learning rates and/or ITCs from the IRA are considered.

Additionally, as the third row in Figure 3 shows, the advantage predicted for nuclear cargo would be larger in regions with a carbon tax, as the tax quickly becomes a substantial financial burden for fossil-fueled ships as the cost of emissions outpaces the cost of fuel within a matter of years (see Appendix 8.5). It is also notable that ammonia-fueled ships have additional complications, such as the lack of ammonia fuel at ports, which may influence the corridors in which they would be able to operate. This, coupled with the higher average cost of ammonia fuel when produced with renewable energy and its higher usage in ships makes this application even less competitive than the fossil fuel scenario.

When compared to either alternative fuel option, the cost competitiveness of nuclear cargo ships is improved by the presence of a carbon tax or a learning rate, or if IRA tax credits are claimed, but none of these variables may be necessary for nuclear to be the most competitive option.

Nuclear Propulsion

Required Breakeven Maritime Nuclear Reactor OCC ($/kWe)

	Unadjusted	ITC	ITC + LR
Average Fossil Fuel Price Scenario	$11,750	$17,750	$22,500
Fossil Fuel w/ Carbon Tax Scenario	$19,250	$29,000	$37,000
Ammonia Fuel Scenario	$62,750	$94,000	$120,000

Figure 3. Breakeven nuclear system OCC diagram for large nuclear cargo ship propulsion.

4. PUBLIC PERCEPTION AND ENGAGEMENT

Public perception is important when considering implementing nuclear technology for maritime uses. Understanding how the public perceives the implications of nuclear technology can help inform key issues that should be addressed when gathering support for the development of these technologies.

Navigating the implementation of nuclear energy projects in both international and national politics remains complicated. Many studies have been completed and continue to be undertaken to better understand the public's perception of nuclear energy. For example, in 2023 the Radiant Energy Group published a study it had done to understand international public perceptions of nuclear energy [38]. In the U.S., participants indicated “reliability,” “health/safety,” and “ability to address climate change” as the most important attributes for any energy source. The respondents had a positive perception of nuclear energy's reliability, a negative perception as it relates to health and safety, and a positive perception of its ability to effectively address climate change [38].

Most of the existing information regarding the public's perception of nuclear technology exists in the context of land-based nuclear plants. Due to maritime nuclear energy's lack of maturity and presence in the public eye, very little, if any, research has been done to study the public's perception of it. Given that the major concerns about using nuclear technology for maritime applications are likely to be similar to those for land applications, the available studies can provide a baseline example of how the public would feel about nuclear in maritime applications.

The dialogue with the public regarding the use of nuclear power in a marine setting is still relatively new, and it has revived the typical concerns people have for nuclear power that need to be addressed up front. It is important to reflect on how major events in the nuclear power sector have had a significant and lasting negative effect on not only public and government support for nuclear power but also on the financing of new nuclear projects. For example, the feasibility analysis study of Hagen [15] notes that "Following the Chernobyl accident in 1986, new construction remained low until it underwent a period of revitalization and renewed interest in the early 2000s." As another example, public perception played a significant role in New Zealand choosing in 1987 to ban nuclear-powered military ships from docking at its ports.

Understanding how the public perceives the implications of nuclear technology can help inform key issues that should be addressed while gathering community support for these technologies. When engaging stakeholders, it will be important to emphasize that nuclear power used in marine applications will not be inherently connected to military applications, and that it can be integrated into a broader, reliable energy infrastructure.

4.1 Perception of Nuclear Power

Several studies have shown that there are different levels of support for nuclear based on demographic group. The Radiant Energy Group study discusses demographic opinion in terms of "net support," which is defined as the difference between the percentage of the demographic that supports and the percentage of the demographic that does not support [38]. Using this metric, the Radiant study found that that Americans over age 65 have the highest net support of nuclear power (~43%); however, all age groups demonstrate some net support for nuclear power.

Regarding gender, the study found that the difference in net support between men and women was 32%. A Pew Research study from 2023 also noted a similar difference, finding that support for nuclear was 26% higher with men [39]. The reason for this disparity between genders is not well understood; however, an Organization for Economic Co-Operation and Development Nuclear Energy Agency study in 2023 [40] found that women are significantly underrepresented in the nuclear industry. The Radiant Energy Group study found that net support for nuclear among groups that claimed to "know a lot about how [nuclear] works" was 42% higher than in groups that claimed to "not know how [nuclear] works" [38]. These two findings may contribute to the gender disparity, as groups with more knowledge related to nuclear energy are more supportive of it, and naturally those who work with or in the nuclear industry are likely to know more about it [38]. A study done by Bisconti Research Inc. in 2023 corroborated these findings. The study found that the more informed people felt they were about nuclear energy, the more they favored it [41]. This study also observed how people perceived the safety of nuclear power before and after learning about how the U.S. Nuclear Regulatory Commission monitors plants. People were more likely to say they supported nuclear energy after learning this information [41].

A Pew Research study found that U.S. political parties are more closely aligned in support of nuclear than any other power source, making it a politically viable energy source in the country [39].

These survey results show that while proponents of maritime nuclear may have work to do in improving the public's perception of nuclear, particularly in some demographics, there is broad support for nuclear power on average.

The Radiant study [38] also collected information on people's perception of nuclear in relation to safety and waste management. The study found that 80% of U.S. respondents were concerned about the safety implications of nuclear energy. Regarding waste management, the study found that 80% of U.S. respondents were concerned about the management of nuclear waste. Concerns about safety and waste management may act as a roadblock to developing maritime nuclear technologies by reducing public interest in funding, hosting, and staffing maritime nuclear facilities. Proponents of maritime nuclear may need to address these concerns to increase the feasibility of the industry.

Overall, more research should be done on the public's perception of maritime nuclear technology specifically. As there are no modern examples of commercial maritime nuclear technology being used in the U.S. [15], one option for gaining a deeper understanding of public perception would be to survey the public about a hypothetical commercial maritime nuclear technology in the U.S. The survey could be integrated into general nuclear energy–focused public engagement events. While such a survey will not provide information about a real-life commercial maritime nuclear technology, it could be evaluated in conjunction with the known perceptions of existing commercial nuclear applications to gain additional insights. These additional insights would assist technology developers by informing them of the new challenges their solutions would have to overcome to gain public acceptance.

4.2 Community Engagement

Section 4.1 shows that there is work to be done to improve the public's perception of nuclear technology. Maritime nuclear proponents need to address common misconceptions about the state of nuclear technology before they can expect the public to accept new applications. Research from several studies [38, 39] suggest that the best way to reduce these misconceptions is to provide the public with accessible information on the potential benefits of nuclear energy in maritime applications.

Maritime nuclear industry leaders could partner with professional organizations to promote awareness for topics such as nuclear energy's safety record and its economic benefits. Table 2 offers examples of organizations that could be influential in this role.

Table 2. Organizations relevant to the nuclear and maritime industries.

Category	Agency	Description
Nuclear Advocacy	American Nuclear Society (ANS)	Professional organization for people who support using nuclear science and technology to improve lives and preserve the planet.
	Nuclear Energy Institute (NEI)	Organization that promotes the use and growth of nuclear by improving operations and advocating for effective policy.

Category	Agency	Description
	Nuclear Innovation Alliance (NIA)	Nonprofit think tank that does policy analysis, research, outreach, and education to help create the conditions for success for advanced nuclear energy so it can play a major role as an energy security solution.
	U.S. Nuclear Industry Council (USNIC)	Organization with a mission to advance the development and implementation of new nuclear technology and services to secure the U.S. economic supply chain in the U.S. and abroad.
	Nuclear Energy Maritime Organization (NEMO)	Organization that assists national and international regulators in creating appropriate future-oriented standards and rules for deploying, operating, and decommissioning floating nuclear power with the highest standards of safety and security.
	International Atomic Energy Agency (IAEA)	An intergovernmental forum for scientific and technical cooperation in the nuclear field. It works for the safe, secure, and peaceful uses of nuclear science and technology.
	Nuclear Energy Agency (NEA)	Intergovernmental agency under the Organization for Economic Co-Operation and Development (OECD) that focuses on connecting countries with advanced nuclear technology infrastructures to seek excellence in nuclear safety, technology, science, the environment, and the law.
Maritime Organization	American Maritime Partnership (AMP)	Coalition that represents U.S. vessel owners and operators, shipboard and shoreside workers, shipbuilders and repair yards, equipment manufacturers and vendors, dredging and marine construction contractors, and maritime trade associations and national security organizations in an effort to support and maintain U.S. maritime policy.
	The International Brotherhood of Boilermakers, Iron Ship Builders, Blacksmiths, Forgers, and Helpers (IBB)	Union that represents crafters and industrial workers, including those in the maritime industry.
	American Maritime Officers (AMO)	Union of U.S. merchant marine officers.
	Seafarers International Union (SIU) of North America	Organization made up of different maritime industry unions.

Category	Agency	Description
	American Association of Port Authorities (AAPA)	Organization representing port authorities across the U.S., Canada, the Caribbean, and Latin America.

Although the resources provided in this section focus on U.S. organizations and U.S. census data, nuclear vessels are expected to eventually navigate in international waters, so some international organizations were also included in Table 2. Similarly, maritime nuclear power plants developed in the U.S. could be deployed internationally. Working with international maritime and nuclear organizations will be critical to deploying commercial maritime nuclear technologies in the U.S. Lessons can also be learned from other nations and their projects with similar technologies.

Additionally, information gleaned by U.S. maritime nuclear proponents may be valuable to other countries with similar goals. The Radiant Energy Group study shows that for the 20 countries studied, on average the public's perception of nuclear power's reliability, emissions, and cost is comparable to that of the U.S. The main differences identified in this study relate to the public's perception of and political support for nuclear power [38]. Community engagement in different regions will have to be addressed within the context of each country's government structures and political climates.

Promoting awareness can be particularly potent when combined with direct community engagement. As maritime nuclear use cases mature, proponents should engage with local communities at potential sites to understand that community's perception of nuclear, as well as its needs and hesitancies. This direct engagement can help ensure that a maritime nuclear application benefits the community, which can improve the likelihood of gaining the local community's social license to operate.

5. BENEFITS AND RISKS OF MARITIME NUCLEAR USE CASES

To achieve the public's support for using advanced nuclear in maritime applications, the nuclear and maritime industries both may need to work with potentially affected communities to address their needs and concerns with maritime nuclear technologies. Communicating the benefits and showing an understanding of concerns could greatly improve public perception and could be essential to facilitating the implementation of maritime nuclear technologies. The following sections discuss both the potential benefits and risks of different maritime nuclear use cases, and how these may affect communities in the U.S.

5.1 Potential Benefits of Maritime Nuclear Use Cases

5.1.1 Job Creation

The development of maritime nuclear technologies could create jobs in the trades, engineering, and manufacturing, all of which offer good economic opportunities to workers. The maritime nuclear industry will need people to staff and operate nuclear vessels and run the land-based facilities that support an implementation's supply chain. According to the U.S. Bureau of Labor Statistics in 2023, salaries for jobs in the nuclear and maritime industries (such as power plant operators, distributors, dispatchers, nuclear technicians, and water transportation workers) were generally higher than the U.S. median income across a range of education levels and professions [42, 43]. Assuming the maritime nuclear industry has a job creation profile that is similar to that of traditional nuclear power plants, it would also have a strong need for jobs outside of STEM (Science, Technology, Engineering, and Mathematics) roles, such as security guards, business analysts, and administrative support staff [44].

Studies, such as one done by the National Institutes of Health in 2023 [45], show that socioeconomic status is a strong predictor of quality of life and social capital. The development of new jobs in this new economic sector could provide people with the opportunity to improve their socioeconomic status.

Not only would the creation of high-paying jobs for workers within the maritime nuclear industry directly benefit those workers, but it may have indirect benefits for people outside of the industry. The implementation of a maritime nuclear technology would increase the number of high-paying jobs in an area, leading to increased household spending, which would benefit local businesses. The overall increase in economic activity could spur job growth in industries such as service, retail, healthcare, education, and construction [44].

Additionally, these economic benefits would not necessarily be limited to where a maritime nuclear application is deployed. Maritime nuclear technologies would require an entire supply chain involving research and development, resource extraction, and manufacturing. For example, fabrication facilities would similarly create high-paying jobs in the communities where they are sited and would therefore have similar indirect benefits.

Therefore, investment in a maritime nuclear implementation would not only benefit those in the maritime nuclear sector but could lead to indirect benefits for a range of business sectors in a range of localities.

5.1.2 Reliable Energy

One specific potential outcome of maritime nuclear power plants would be increased access to reliable power. As mentioned in Section 4.1, energy reliability is the most important factor for people when considering a power source. The DOE Office of Nuclear Energy considers nuclear energy to be the most reliable energy source, about twice as reliable as natural gas or coal and three times more reliable than wind or solar [46]. The reasons for this are that nuclear power plants experience less frequent outages for maintenance compared to fossil-fueled plants, and renewable plants are intermittent energy sources. Reliable energy is necessary for a functioning society, as it serves to keep important infrastructure and systems running (electricity for houses, hospitals, data centers, food storage facilities, etc.) [47]. Access to more reliable power sources could be especially beneficial to remote and low-income communities, as these communities have a more difficult time accessing reliable energy due to historically lower investment in those communities [48, 49], higher energy burdens (the percent of a household's income that is spent on energy costs), and greater energy insecurity (the inability of a household to adequately meet its energy needs) [48].

As discussed in Section 3.1, maritime nuclear power plants could be developed cheaper and faster than land-based nuclear power plants. This would be most beneficial for in-need communities situated near the coasts or other large bodies of water, or for dispersed island nations that lack extensive energy infrastructure, where maritime nuclear power plants could be deployed. One area that could be of interest to nuclear power developers is the Gulf of America. According to the Center for American Progress [50], four of the five U.S. states that have a Gulf coastline (Alabama, Louisiana, Mississippi, and Texas) were ranked in the bottom 10 for poverty rate in the nation in 2022. A 2022 American Public Media study showed that all five states in that region were among the most energy burdened and energy insecure in the nation [48]. A maritime nuclear power plant in this region would provide reliable energy to areas struggling with energy access and poverty.

According to the U.S. Energy Information Administration [51], nearly all U.S.-based offshore oil and natural gas industrial activity takes place in the Gulf of America. The potential to use maritime nuclear reactors to power oil and natural gas industrial activities in these areas would improve the business case for these units. However, there is a demonstrated precedent that oil and gas companies are hesitant to own or operate reactors, historically preferring power purchase agreements [52, 53]. This means that vendors and operators of maritime nuclear power plants would have to work with the fossil fuel producers to negotiate realistic ways to integrate maritime nuclear reactors with oil and gas industrial activities.

Energy insecurity can also be acute. Climate Central found that weather-related events have contributed to 80% of major power outages in the U.S. These power outages have been twice as likely to occur in the last 10 years than the preceding 10 years [54]. Maritime nuclear power plants could be quickly deployed to coastal communities to provide reliable energy in the wake of these increasingly frequent natural disasters and power outages.

High energy costs provide another potential reason to deploy a maritime nuclear power plant. For example, according to the Energy Information Administration [55], states in the Atlantic coast region of the Northeast U.S. (Connecticut, Maine, Massachusetts, New Hampshire, New York, Rhode Island, and Vermont) ranked among the highest in the nation for electricity costs per kilowatt-hour in December 2022 and 2023. Maritime nuclear power plants are a potential reliable energy source solution for reducing energy costs there. Over time, maritime nuclear power plants could help reduce the energy cost burden that people face in such regions.

5.1.3 Improving Nearshore Air Quality

Ports have been shown to have increased levels of major air pollutants such as particulate matter, nitrogen oxides (NO_x), and sulfur oxides. These compounds have been linked to negative health outcomes in the surrounding port communities, such as higher rates of diseases related to the respiratory system (such as asthma, lung cancer, and pneumonia). These negative health outcomes can contribute to higher school absenteeism and lower economic productivity [56].

Many of the activities associated with ports, such as heavy equipment running on diesel fuels, produce these pollutants. Notably, ships run on fuels that have particularly high emissions (such as bunker fuel), and ships have been shown to emit a significant portion of these harmful pollutants around ports [56].

Maritime nuclear technologies can provide paths to reduce the concentration of these air pollutants around port communities by offering alternative sources of power for port activities and ships. Ships using nuclear power for propulsion would not produce these pollutants, as nuclear power itself does not produce any point emissions.

Moreover, another possible benefit of maritime nuclear technologies is their ability to power onshore activities, reducing emissions produced by other port activities, such as cargo handling. This could be done either via reverse cold ironing (see Section 3.2.2) or a maritime nuclear power plant stationed nearby. However, there are caveats to both pathways.

For reverse cold ironing, it is important to note that the process is still conceptual and implementing it could require costly changes to local grids so they could receive, transmit, and utilize that energy. It would also be subject to certain regulatory requirements and lead to less of the nuclear fuel being used for vessel propulsion, which affects the business case of the ship.

In both cases, maritime nuclear power (via reverse cold ironing or a nearby maritime nuclear power plant) would only improve air quality around ports if a significant number of port activities could reasonably use the electricity provided by the maritime nuclear power source (as opposed to the commonly used diesel). However, assuming greater electrification of port activities, maritime nuclear power could help improve air quality around port communities [13], which could improve health outcomes and increase economic productivity.

Maritime nuclear power plants could also potentially improve air quality for nearshore communities without ports. This would be particularly applicable in remote communities where diesel or other fuels that emit major air pollutants are often used to generate electricity. As with port communities, a maritime nuclear power plant could provide an alternative source of electricity that does not emit a significant of harmful pollutants.

5.2 Potential Risks for Maritime Nuclear

As noted in Section 4, two primary concerns from the public regarding maritime nuclear are nuclear safety and waste management. In line with these concerns, this section discusses the challenges related to the actual or perceived risks of building, operating, and decommissioning maritime reactors from a safety and waste perspective.

While there are safety and waste considerations regarding maritime nuclear, as is discussed in this section, the consequences of severe reactor disasters such as Fukushima, Chernobyl, and Three Mile Island involved plants that are not representative of the design and scale of the nuclear maritime applications discussed in this report. Lessons were learned from these events, and current guidelines for reactor design and operation greatly reduce the risk of such accidents, as do the increased safety features present in modern reactors and advanced reactor designs.

The challenges and risks presented below are typically qualitative because reactor designs are still in development, and because location-specific oceanic impacts are more difficult to quantify because of the possibility of geographically diverse operations. More quantitative analysis (for example, through the processes described in the National Environmental Policy Act [57] and reactor-licensing processes) will need to be completed after detailed designs are developed.

Safety concerns discussed here relate to radiation dose from emissions and the potential for secondary contamination of water, soils, and sediments, which can be consumed by plants and animals, resulting in a further dose to the public. More so than with land-based nuclear reactor facilities, there may be concern that maritime nuclear technologies will negatively impact seawater and harm aquatic life. This section also discusses waste management concerns through the lens of spent nuclear fuel (SNF) handling.

This section examines potential impacts of maritime nuclear technologies at different times in the life cycle of a technology:

- Impacts during operation
- Impacts from decommissioning and waste management.

Impacts related to fuel production are also relevant but are not expected to have many maritime-nuclear-specific considerations. For context, these impacts are discussed in Appendix 8.6.

5.2.1 Releases During Operation

The operating experience from current U.S. commercial nuclear power plants has shown that nuclear reactors infrequently release unsafe radiation into water, and releases have rarely affected the public [58].

Regarding commercial nuclear ships, the limited historic examples from the 1960s to 1980s, such as the NS *Savannah* and the NS *Otto Hahn*, operated with no notable incidents [15]. As discussed in Section 4, the environmental consequences of severe reactor disasters such as Fukushima, Chernobyl, and Three Mile Island involved plants that are not representative of the design and scale of the nuclear maritime applications discussed in this report. Current guidelines for reactor design and operation greatly reduce the risk of such accidents, as do the increased passive safety features present in modern reactor designs.

It is also worth noting that the advanced reactors being proposed to propel commercial ships are expected to be significantly smaller than the current commercial land-based nuclear reactors, and therefore, in the event of a nuclear accident, their potential source term released to the environment is expected to be comparatively low [59].

These facts stand in contrast to the consistent maritime releases of petroleum from offshore oil infrastructure and vessels [60]. For fossil-fueled vessels, the petroleum-contaminated releases and waste generated during O&M are well known. For example, contaminants typically enter a vessel's bilge from equipment leakage or maintenance [61]. This bilge water contains water, diesel fuel, lubricants and grease, and other wastes from the ship. Bilge water is released periodically into the sea in areas where doing so is allowed by IMO's International Convention for the Prevention of Pollution from Ships (MARPOL) guidelines [62, 63]. Notably, not all pollutants in bilge water would be removed if nuclear propulsion was used instead, but the most concerning contaminants (diesel fuel; glycol-based coolants; and engine, transmission, and hydraulic oils [62]) would likely be significantly reduced.

Besides radiation pollution and the release of contaminated water, there is also a concern regarding thermal pollution. Thermal pollution happens when industrial processes release heat into the environment. Maritime nuclear power plants would likely use the surrounding water as a heat sink, which could cause thermal pollution if excessive amounts of warm water are released into the environment. This may affect the marine ecosystem, potentially causing the local water to be inhospitable to fauna and flora, an imbalance of nutrients resulting in eutrophication, or a reduction in biodiversity [64]. Similar water-heating issues exist for any thermal power generation technology (such as fossil-fueled power plants), including those onshore that use inland water sources as a heat sink. However, nuclear power plants generally release a higher percentage of their wastewater as a liquid rather than a vapor. As a result, a water-cooled nuclear power plant would release a larger volume of warm water in its immediate environment than a similarly sized fossil-fueled power plant. Overall, nuclear power plants have the potential to have a larger effect on the local ecosystem, particularly if they release warm water into smaller bodies of water or close to shore [64]. Notably, the magnitude of thermal pollution for smaller nuclear reactors, such as those used for propulsion, would be reduced. Thermal pollution would not apply to advanced reactors that do not use the surrounding water as their ultimate heat sink.

During their operation, all vessels and structures in the ocean are at risk for environmental releases due to accidents, such as collisions and groundings. A 2017 safety analysis on the NS *Savannah* studied contemporary collision data to understand the probability and severity of collisions, and how they might affect a nuclear ship [65]. Based on historical collision data, the study found that collisions involving a nuclear ship are unlikely to damage reactor components, and collisions severe enough to cause a rupture in the reactor containment would be limited to areas far outside of harbors (>100 miles at sea), where speeds are higher. Even then, the probability was estimated to be extremely low (on the order of 1 in 10,000 over the lifetime of a ship), and the ship would likely be isolated, which would limit its environmental impact. The study also considered grounding, or a ship hitting land under the water. It distinguished between grounding in protected areas where ship speeds are low, such as a harbor, and grounding in unprotected areas. The report concluded that grounding in protected areas is unlikely to cause damage to reactor components or lead to "even a very limited release of low-level waste."[b] Grounding in unprotected areas may lead to more severe impacts, such as more extensive ship damage and the potential release of low-level waste found outside of containment. However, the reactor containment itself is unlikely to be damaged. The magnitude of this release would vary, and the report noted that the likelihood of this is even less than that of collisions. Newer fuel forms that may be used in advanced reactors could further reduce the probability and magnitude of radioactive releases to the environment [67]. Ultimately, the safety analysis report on the NS *Savannah* showed that while accidents involving nuclear ships could potentially lead to radioactive releases to the environment, the probability of harmful impacts from these accidents is expected to be very low, particularly when the accidents occur close to shore [65].

It is also important to consider scenarios perpetrated intentionally by malicious actors, such as pirates and terrorists. Malicious actors are of particular concern for nuclear maritime use cases due to the presence of nuclear material. As there is a scarcity of historical examples of commercial nuclear maritime use cases, the environmental impacts of these scenarios are not well understood. Impacts will also be highly variable depending upon the use case, the location of the incident, and meteorological factors, all of which are difficult to specify at this early stage in development of maritime nuclear technology.

The modeling, prevention, and mitigation of both the accident and malicious actor scenarios will need to be part of the design basis of maritime nuclear technologies. This could resemble how events such as tornadoes and aircraft impacts are analyzed as part of the design of land-based nuclear reactors [68, 69].

5.2.2 Releases During Decommissioning and Waste Management

Decommissioning activities at the end of a ship's life have an impact on the environment. For nuclear ships, these decommissioning processes would involve both a radiological component and the conventional shipbreaking component.

The added challenge of decommissioning the onboard nuclear power plant would make the overall decommissioning process for nuclear ships a more expensive and complex undertaking. For fossil-fueled ships, shipbreaking occurs when a ship's performance deteriorates sufficiently that it is no longer economically sensible to keep the ship in service [70]. For nuclear ships, the added complexities and costs associated with the regulated removal of irradiated components would factor into their decommissioning timelines.

There are different logistic options for decommissioning a nuclear ship. One option is to first radiologically clear the nuclear ship and then take it to a non-nuclear shipyard for regular shipbreaking activities. The first step in this process would still require the licensing of an onshore facility unless radiological decommissioning activities could be performed entirely within the ship. Alternatively, the ship could be decommissioned in its entirety at a shipyard capable of

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[b] Low-level waste items are those that have become contaminated with radioactive material or have become radioactive through exposure to neutron radiation [66].

performing nuclear work. While the latter option would be logistically simpler and likely less expensive, there are no commercial U.S. shipyards that can perform nuclear work.

SNF, the irradiated fuel that is left in a nuclear reactor core after it is no longer useful for power generation, will be one notable irradiated component of maritime nuclear technologies. After SNF has been removed from a maritime nuclear technology, it will have to be safely stored and transported to storage sites, and this may have an environmental impact (e.g., releases from SNF casks if they crack). Since SNF produced from maritime nuclear use cases is expected to fall under the same regulations as that of current commercial nuclear operations, the potential effect of SNF transportation on the environment can be understood by examining the current handling of commercial SNF.

In the U.S., SNF from the commercial nuclear industry is generally stored in casks on-site, and this could be done for maritime applications if SNF storage is built into the designs. For long-term storage, SNF is transported in casks (generally seen in military applications). In these instances, both the casks and transportation have robust regulatory requirements. As a result, there have been “no transportation accident[s] involving [SNF] in which a release of radioactive material has caused any significant negative effect to the public or the environment” [71]. Canada, Japan, the U.K., and continental Europe also have good track records for the safe transportation of SNF [71]. Japan’s clean track record is of note, as its SNF has been transported via ship, which would be a likely scenario for the U.S.’s SNF transportation for maritime nuclear use cases. As SNF transportation for commercial maritime nuclear use cases would be handled under the same regulatory regimes as current commercial nuclear operations, it is therefore expected to have negligible environmental impact.

It may also be important to consider the volume of SNF produced, given nuclear power’s high energy density and the potential use of advanced reactor and fuel designs. For example, the U.S. generates approximately 2,000 metric tons of commercial SNF each year; this is enough to fill half an Olympic-sized swimming pool [72]. Commercial maritime nuclear activities would generate a fraction of this, especially if they use smaller SMRs rather than larger commercial nuclear reactor designs.

Overall, while the presence of SNF at the end of life for maritime nuclear use cases introduces challenges and complexities, historically the handling of such challenges and complexities has not led to any significant impact to surrounding communities.

6. SUMMARY AND CONCLUSIONS

The considerations identified provide a general overview of the benefits and risks of maritime nuclear applications to enable designers/developers, governments, and energy end users to bring maritime nuclear technologies to fruition in a timely and effective manner. Two different types of maritime nuclear use cases were discussed in this report:

- Maritime nuclear power plants for onshore electricity generation, and for providing power and heat to offshore industrial processes
- Advanced nuclear reactors used on board shipping vessels to provide power for propulsion and/or other ship needs.

This section summarizes the considerations discussed in this report, draws various conclusions, and suggests future work.

6.1 Summary

Table 3, Table 4, Table 5, and Table 6 summarize the considerations discussed in each section of this report.

Table 3. Summary of economic viability considerations.

Consideration	Summary
Tax Incentives	(1) Maritime nuclear technologies may be able to access tax incentives introduced in the IRA of 2022 by the 117th U.S. Congress, particularly if they produce power for the grid. (2) Carbon tax laws exist internationally but not in the U.S. Maritime nuclear technologies can avoid taxes on carbon emissions where such taxes are present.
Capital Intensive and FOAK	Maritime nuclear technologies will have large up-front capital expenses. This, along with their FOAK nature, will likely create investor and lender aversion to maritime nuclear projects. This may be partially offset by government loan programs aimed at high-risk, capital-intensive energy projects, such as those provided by DOE's Loan Programs Office.
Modularity and Shipbuilding Practices	Maritime nuclear reactors for maritime nuclear power plants may be modular and built utilizing shipyard construction techniques that are expected to decrease the time and cost of construction.
Flexible Deployment	Maritime nuclear power plants may be sited in places not conducive to land-based reactors, such as remote locations and island nations, allowing developers access to novel markets.
Operational Differences	Commercial nuclear cargo ships may have operational differences that influence their ability to generate revenue: (1) The need to refuel at specialized, regulated facilities rather than while docked at port will add downtime to nuclear-powered ship operation. However, the infrequent need for refueling will allow nuclear-powered ships to take longer nonstop voyages compared to conventionally fueled ships. (2) Commercial nuclear ships will have the potential to operate at higher speeds and carry more cargo, allowing them to potentially generate more revenue during their lifetime. (3) Reverse cold ironing may introduce a pathway for ships to generate revenue when docked by selling electricity produced in the ship's reactor to the port.
Nuclear Security and Perception	For commercial nuclear cargo ships, the presence of a nuclear reactor: (1) May make them more attractive for malicious acts and susceptible to nuclear-related accident scenarios. This could increase insurance premiums and security/staffing requirements. (2) May confine them to specific transport routes/ports based on local laws.

Consideration	Summary
Revenue Differences for Nuclear Ships	Differences between the operation and capabilities of nuclear ships and conventionally fueled ships may lead to differences in revenue. Preliminary estimates calculated in this report show that nuclear-powered ships may generate roughly 3.3% more revenue. This is contingent upon minimizing outage periods and ensuring that nuclear-powered ships operate in areas where ports can logistically accommodate faster speeds.
Breakeven OCCs	High-level analyses in this report show that maritime nuclear reactors may be economically competitive for electricity production in remote regions and for use in the propulsion of large cargo ships. It is unlikely that synthetic fuels produced by maritime nuclear power plants would be competitive with existing fossil fuels. However, different industrial use cases not examined in this report may have different economic feasibilities.

Table 4. Summary of public perception and engagement.

Consideration	Summary
Public Perception[1]	(1) People who are more informed about nuclear energy favor it more. (2) Support for nuclear power is growing and has bipartisan support in the U.S. (3) Surveys show that the public has concerns over nuclear safety and waste management. Proponents of maritime nuclear may need to address these concerns to increase the feasibility of the industry.
Community Engagement	Maritime nuclear proponents should engage with local communities at potential sites where maritime nuclear technologies may be implemented. This could be done by partnering with organizations, such as those listed in Table 2, to provide the public with accessible information on the potential benefits of maritime nuclear technologies. Direct engagement can help proponents better understand the needs and concerns of a community.

1. As maritime nuclear technologies are in early stages of development, the public's perception of traditional nuclear technology was used as a proxy for this report.

Table 5. Summary of benefits.

Consideration	Summary
Job Creation	Maritime nuclear technologies may create well-paying jobs both where the technology is implemented and in areas that support the supply chain. Current salaries for both maritime and nuclear workers are higher than the U.S. median income, and they are higher than those for jobs across a range of education levels and professions. Jobs would be created within the STEM field, but also outside of it, such as for security, business analysis, and administration. There may also be indirect benefits for people outside of the maritime nuclear industry due to high-paying jobs leading to increased spending,

Consideration	Summary
	which could spur growth in other local industries, such as service, retail, healthcare, education, and construction.
Improving Air Quality	Major air pollutants such as particulate matter, nitrogen oxides, and sulfur oxides have been shown to have detrimental health impacts; such pollutants are created by diesel fuel, which is often used in ships, at ports, and in remote areas. Maritime nuclear power would not produce these air pollutants, and in some cases it could be used to provide electricity to activities that require diesel. Therefore, maritime nuclear power could provide a path to improving air quality in affected areas.
Reliable Source of Energy	Maritime nuclear power plants may create a reliable source of energy for communities that have historically lacked it, such as those on remote islands and in underserved coastal regions. Notable examples of underserved communities are along the Gulf of Mexico in some of the poorest and most energy-insecure states in the U.S. Maritime nuclear power plants could also provide reliable energy in the wake of natural disaster–related power outages, which have been increasing in frequency in recent years.

Table 6. Summary of risks.

Consideration	Detail
Risks During Operation	When examining the environmental impact of operating maritime nuclear technologies, two forms of emissions were considered: (1) For water-cooled maritime nuclear reactor designs that use smaller bodies of water as their ultimate heat sink or exist close to shore, thermal pollution from maritime nuclear may have a larger effect on the local marine environment than fossil-fueled plants. (2) There have been few releases of radiation into the environment from the U.S. commercial nuclear industry; the limited number of historic commercial nuclear ships operated without incident. Due to the regulatory environment, maritime nuclear technologies can be expected to operate in line with these cases regarding radiation releases.
Risks for Decommissioning and Waste Management	The decommissioning of maritime nuclear technologies will have to occur at specialized, regulated facilities due to the presence of SNF. The radiation dose to the environment and public from SNF, in facilities or during transit, is highly regulated and has historically and internationally been shown to be negligible. Maritime nuclear technologies, such as cargo ships, may use smaller reactors and therefore produce much less SNF.

6.2 Future Work

The following suggestions for future work would provide a more accurate and specific understanding of key considerations for implementing maritime nuclear technologies.

- A bottom-up cost estimate for a maritime advanced nuclear reactor rather than one derived by adjusting land-based advanced reactor cost estimates.
- An analysis of the cost competitiveness of maritime nuclear power plants used in other industrial applications, such as desalination, oil drilling and exploration, and other chemical-manufacturing processes.
- A more detailed evaluation of the technical requirements and regulatory considerations relating to repurposing nuclear reactor designs for maritime applications.
- A characterization of the environmental effects of accident scenarios and scenarios perpetrated by malicious actors for maritime nuclear technologies, and potentially more explicit modeling of these scenarios as designs and sites are chosen.
- A better understanding of the public's perception of nuclear in maritime applications specifically, and a better understanding of the perception of communities that may be particularly affected by maritime nuclear, such as those near shipbuilding sites, near ports, and in remote regions.
- A more quantified understanding of the job creation and job growth that may happen in the shipbuilding, maritime, and nuclear industries if maritime nuclear technologies are successful.

It likely will not be possible to determine many of these items with a reasonable degree of accuracy without more mature maritime nuclear designs.

6.3 Conclusions

From an economic perspective, various economic headwinds may make maritime nuclear technologies more expensive than fossil-fueled alternatives, such as their capital intensiveness, their FOAK nature, and the higher costs associated with managing nuclear material.

Despite this, high-level analyses in this report show that maritime nuclear reactors may be economically competitive for electricity production in remote regions and for use in the propulsion of large cargo ships. For remote electricity production, the high costs associated with fuel logistics may make maritime nuclear cost competitive. For nuclear-powered ships, operational differences may lead to a small overall increase in the revenue generated over their lifetime, though this is contingent upon advanced reactor designs that are able to increase ship availability and ports that can logistically support faster ships.

One industrial use case was examined in this report: the use of maritime nuclear power plants to provide heat and electricity to produce hydrogen via HTSE, which is then used to produce synthetic fuels. The high-level economic analyses found the synthetic fuels produced by this process would likely not be competitive with existing fossil fuels, though nuclear-produced synthetic fuels may still be competitive with renewable-energy-produced synthetic fuels. However, different industrial use cases not examined in this report may have different economic feasibilities.

Notably, different use cases have aspects that might otherwise improve the economic desirability of maritime nuclear technologies (discussed in Sections 3.1 and 3.2). For example, maritime nuclear power plants that produce power have the benefit of flexible deployment; this would allow them to operate as a complement to traditional nuclear power rather than in competition. Therefore, a higher cost could be justified.

Besides economic viability, the feasibility of maritime nuclear power will also be determined in part by the public's perception of it (discussed in Section 4). Surveys show that the public is concerned with the safety and waste management related to nuclear power. Maritime nuclear proponents should work to ensure that these potential risks of maritime nuclear are modeled and mitigated. Maritime nuclear proponents should also work with local communities and communicate the positive impacts that maritime nuclear technology can have on their community, as discussed in Section 5.

Ultimately, if implemented in the maritime space nuclear power will be an alternative energy source with unique challenges. However, this report finds that there is potential for economically viable use cases for maritime nuclear technology, and that maritime nuclear has the potential to bring positive change to the communities where it is implemented by creating jobs, providing reliable energy, and improving air quality.

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8. APPENDIX A

FURTHER INFORMATION ON CONSIDERATIONS FOR MARITIME NUCLEAR TECHNOLOGY

8.1 Revenue Estimation Calculation

Nuclear-powered ships may differ from fossil-fueled ships in key ways that could affect revenue generation (see Section 3.2.1), such as operating at higher speeds and being able to carry more cargo. However, there are operational challenges associated with nuclear-powered ships as well; nuclear propulsion is more economically feasible for larger ships, which may not be able to fit through some canals, and the ship's nuclear reactor would need to be refueled at specialized facilities. Fossil-fueled ships, however, can be refueled at most ports.

This appendix presents an estimate of the annual revenue for a nuclear-powered ship by first estimating the annual revenue for a representatively sized fossil-fueled ship as a baseline[c] breakeven OCC. Then, speed, operational, and cargo factors are applied to this baseline revenue to estimate the revenue for a similarly sized nuclear-powered ship. These factors are each defined in Equation 4.

8.1.1 Revenue Estimation Methodology

The annual revenue of the fossil-fueled ship ($R_{baseline}$) can be estimated using the following equation:

Equation 2

$$R_{baseline} = N_T \cdot C \cdot F_R$$

$R_{baseline}$	\$/yr	Annual revenue of a representatively sized fossil-fueled cargo ship.
N_T	Trips/yr	Number of trips made each year. Varies depending on the route.
C	FEUs/trip	The amount of cargo transported each trip.[1]
F_R	\$/FEU	Freight rate: the average price per FEU. Varies depending on the route.

1. The amount of cargo carried on a cargo ship is often given in twenty-foot equivalent units (TEUs) or forty-foot equivalent units (FEUs), which represent the standardized size of containers used for carrying cargo.

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[c] This baseline revenue is also the revenue for the ammonia-fueled ship in the breakeven OCC analyses (see Appendix 8.1.2).

N_T can be represented by Equation 3, where it is rounded down to the nearest whole number:

Equation 3

$$N_T = \frac{\#\ Operating\ Days\ per\ Year}{Path\ Duration}$$

To estimate the revenue of a nuclear-powered ship, $R_{baseline}$ is multiplied by the following three factors that reflect the operational differences between nuclear-powered and fossil-fueled ships: speed factor (X_S), operating factor (X_O), and cargo factor (X_C).

Equation 4

$$R_{nuclear} = (N_T \cdot X_S \cdot X_O) \cdot (C \cdot X_C) \cdot F_R$$

$R_{nuclear}$	\$/yr	Annual revenue of a representatively sized nuclear-powered cargo ship.
X_s	unitless	Speed factor: ratio of operational speeds between nuclear and fossil-fueled cargo ships.[1]
X_o	unitless	Operating factor: ratio of operational days per year between nuclear and fossil-fueled cargo ships.
X_c	unitless	Cargo factor: ratio of TEUs carried per trip between nuclear and fossil-fueled cargo ships.

1. This report indirectly calculates XS as the ratio of the % of maximum speeds that the ships operate at. See Appendix 8.1.2.

8.1.2 Revenue Estimation Assumptions

The following assumptions are made for revenue estimations of the fossil-fueled and nuclear-powered ships:

- The baseline ship is assumed to resemble a Maersk Triple-E class container ship, Generation 1. This is a particularly large container ship that could be well suited to nuclear propulsion [73].
- The baseline ship is carrying 18,270 twenty-foot equivalent units (TEUs), which is the Maersk Triple-E class ship’s carrying capacity [73].
- The TEUs on the ship are assumed to be at payload capacity.
- The baseline ship is assumed to have an optimum operating speed of 18.6 knots [74], compared to a maximum speed of 23 knots [75]. Therefore, the operating speed is 81% of the maximum.
- The nuclear-powered ship is assumed to operate at the same percent of its maximum speed as the NS *Savannah*, which had an operating speed of 21 knots and a maximum speed of 24 knots [76]. Therefore, the operating speed is 87.5% of maximum.

- Rather than compare the absolute speeds of the two ships, this report compares the percent of maximum speed at which the ships operate. This assumes that these ratios are representative of each technology, which allows for a more general comparison of fossil-fueled and nuclear-powered ships.
- The revenue for the baseline ship is estimated for the Maersk route “TP2 Eastbound,” which connects Nansha New Port in China to the Port of Long Beach in the U.S., across the Pacific Ocean [77].
- Revenue is assumed to be linear with speed. This assumes that there is sufficient demand for more cargo and that ports can logistically accommodate nuclear-powered ships if they can complete more trips in a year because of faster ship speeds.
- The freight rate used in this estimation, F_R, is based on the S&P Global Platts Trans-Pacific Container Rate 13, North Asia–to–West Coast North America, on June 18, 2024 [78]. These freight rates may vary significantly over time but are not expected to vary depending on the propulsion technology.
- Freight rates are given in $/forty-foot equivalent units (FEUs). The value of freight rates for TEUs is assumed to be half, as TEUs are half the length.
- The baseline fossil-fueled ship is assumed to always be able to refuel while performing other port activities, which allows it to not lose operating time to refueling activities.
- Both ship types are assumed to be out of operation for scheduled maintenance 3 months every 5 years [79].
- The refueling outage for nuclear ships is assumed to occur once every 2 years, based on common outage frequencies for advanced SMR designs [33].
- The refueling outage is assumed to last for 32 days [35].[d]
- The difference in weight between the nuclear reactor and the diesel engine system is assumed to be the only weight difference between the two ships. It is assumed that the weight of auxiliary systems, and the ship itself, are the same for both ships. The weight of fuel for the fossil-fueled ship is not considered, nor is the weight of shielding for the nuclear systems. There is a high margin between the engine weight and nuclear reactor weight (nuclear is much lighter per MW, see Table 8), which may deemphasize the effect of these assumptions.
- The cost to staff the nuclear-powered and fossil-fueled ships is assumed to be the same despite the operational differences discussed in Section 3.1.5.
- The revenues used in the breakeven OCC analyses for the fossil-fueled and ammonia-fueled ships are the same because it is assumed there are no operational differences between the two types.

8.1.3 Revenue Estimation Inputs

Table 7 describes the inputs for the representative fossil-fueled ship used for this revenue estimation; the ship resembles a Maersk Triple-E class container ship per assumptions in Appendix 8.1.2.

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[d] As refueling outages can vary significantly between SMR designs, a breakeven analysis was done to determine the maximum nuclear refueling outage days per year (see Appendix 8.1.4).

Table 7. Inputs for the representative fossil-fueled ship used for revenue estimation.

Item	Variable	Value	Notes/Source
Carrying capacity (TEUs)	$N_{TEU,tot}$	18,270	Reference [73], searched for *Majestic Mærsk*, a Maersk Triple-E class Generation 1 ship
Maximum TEU weight (kg)	$W_{TEU,max}$	23,952	Reference [80]
Power (MWe)	P	59.36	Reference [81]
Path	—	TP2 Eastbound	Reference [77]
Path duration (days)	—	44	22 days each way; reference [77]
Operating days per year (days/yr)	$D_{operating}$	346.75	See Appendix 8.1.2.
Number of trips per year (trips/yr)	N_T	7	See Equation 3
Freight rate ($/FEU)	F_R	7,300	Reference [78]

Table 8 describes the inputs related to the operational differences between the baseline fossil-fueled ship and a theoretical nuclear-powered ship of similar size.

Table 8. Inputs for calculating operational difference factors.

Item	Variable	Value	Notes/Source
Nuclear-powered operational speed to max speed ratio	$S_{nuclear}$	0.875	Reference [76]
Baseline ship operational speed to max speed ratio	$S_{baseline}$	0.809	References [74, 75]
Nuclear refueling period per year (days/yr)	D_{refuel}	16	32 days every 2 years; Reference [35]
Ship planned maintenance per year (days/yr)	D_{maint}	18.25	90 days every 5 years; Reference [79]
Time spent bunkering per year (days/yr)	D_{bunker}	0	See Appendix 8.1.2
Nuclear reactor weight per MWe (kg/MWe)	$\bar{W}_{nuclear}$	8,248	Reference [82]
Engine weight per MWe (kg/MWe)	$\bar{W}_{engine}$	28,750	Reference [83]
Fraction of usable space[1]	F_{usable}	0.90	Reference [32]

1. Fraction of usable space is only used toward calculating the mass of TEUs that a nuclear-powered ship could support after replacing the weight of diesel engines with a nuclear reactor.

8.1.4 Revenue Estimation Results

Equation 2 is used to calculate $R_{baseline}$ using inputs from Table 7; this results in a value of \$467 million per year in revenue. Inputs from Table 7 and Table 8 are used to calculate the operational difference factors using the equations below:

Equation 5

$$X_S = \frac{S_{nuclear}}{S_{baseline}}$$

Equation 6

$$X_O = \frac{365 - D_{maint} - D_{refuel}}{365 - D_{maint} - D_{bunker}}$$

Equation 7

$$X_C = \frac{N_{TEU,\,tot} - \left(\frac{P \cdot (\overline{W}_{nuclear} - \overline{W}_{engine})}{W_{TEU,\,max}} \right) \cdot F_{usable}}{N_{TEU,\,tot}}$$

These operational difference factors are then used to calculate $R_{nuclear}$ (see Equation 4). Table 9 summarizes these results.

Table 9. Revenue estimation results for a nuclear-powered ship.

Item	Variable
$R_{baseline}$	\$467 million
X_S	1.082
X_O	0.954
X_C	1.003
$R_{nuclear}$	\$483 Million

8.2 Reverse Cold Ironing Revenue Estimation

The technological feasibility of reverse cold ironing in commercial settings, for both the ship and the port and grid infrastructure, has not yet been proven. However, it may provide a potential source of revenue for commercial nuclear-powered ships and a potential pathway to accessing IRA PTCs (see Section 3.1.2) if the ships were to reverse cold iron at U.S. ports.

This section contains a high-level estimation of reverse cold ironing revenue tto give a sense of the magnitude of the revenue this process could produce. This estimation assumes:

- The nuclear-powered ship's power matches that of the baseline ship (59.36 MWe) described in Appendix 8.1.2.
- The nuclear-powered ship uses 4 MWe to power ship activities while at port [84].
- The ship takes port and sells electricity only to the Port of Long Beach, where it generates revenue in accordance with the 12-month energy cost for the Los Angeles–Long Beach–Anaheim area between May 2023 and May 2024, which was $0.283/kWh [85].
- Each time the ship docks at the Port of Long Beach, it is in port for the global average time in port for container ships [86], which is 0.79 days. The ship makes the same journey (TP2 Eastbound) described in Appendix 8.1.2. These assumptions allow for roughly seven docks per year.
- The port community can establish the regulatory framework and physical infrastructure to directly buy and use power from the nuclear ship.

The revenue from reverse cold ironing, R_{RCI}, can be estimated using the following equation:

Equation 8

$$R_{RCI} = P_{RCI} \cdot T_{port} \cdot E_{cost}$$

R_{RCI}	$/yr	Annual revenue from reverse cold ironing	Calculated
P_{RCI}	MW	Power available for reverse cold ironing	55.36 MW
T_{port}	hours/yr	Hours in port, per year	132.72 hr/yr
E_{cost}	$/MWh	Cost of electricity in the Los Angeles–Long Beach–Anaheim area	$283/MWh

The yearly revenue from reverse cold ironing, given the assumptions listed above and using Equation 8, may be roughly $2.1 million. This is a simplified estimate that only accounts for gross revenue. Also, this estimate does not account for how the production of power at port may allow nuclear ship projects to claim PTCs introduced by the IRA, nor does it account for how ship owners and ports may adjust operation (i.e., increase time in port) to potentially utilize reverse cold ironing as a revenue stream.

This estimate is therefore most useful for understanding a rough order of magnitude of reverse cold ironing revenue. In that context, it is notable that this revenue represents less than 1 percent of the revenue that ships generate per year. Therefore, it is unlikely that the potential for reverse cold ironing will be the primary driver for the increased financial performance of nuclear ships. There may be some cases, however, where ships may be stuck at ports for prolonged periods of time, and the ability to reverse cold iron could give these ships an alternative method of producing revenue.

8.3 Maritime Advanced Reactor Cost Estimation

This estimation assumes that advanced SMRs are used for the use cases discussed in this report.

INL estimated advanced SMR OCCs and operating costs based on a review of estimates for advanced SMR designs, assuming a between-of-a-kind implementation (i.e., between FOAK and Nth-of-a-kind), in the report *Meta-Analysis of Advanced Nuclear Reactor Cost Estimations* [36]. These OCC estimates did not incorporate any cost adjustments specific to a maritime implementation.

The nascent nature of maritime-specific advanced reactors makes it difficult to accurately quantify the additional costs of SMRs in maritime applications. OCCs are broken down into subcosts following the Generalized Nuclear Code of Accounts (GN-COA) [87]. This report presents adjustments to the OCCs determined by INL [36], which are calculatedby subtracting subcosts not relevant to maritime-specific advanced reactors, including costs for “land and land rights” and “site permits.” These subcosts were removed as land rights and site-permitting processes are expected to be insignificant costs for maritime advanced reactors, as they will be sited in water.

The “structures and improvements” GN-COA subcost from the advanced SMR OCCs from INL’s *Meta-Analysis* [36] is adjusted in this report. This subcost encompasses the cost of civil structures for the nuclear plant, which is expected to differ for maritime reactors. Land-based reactors are required to pour significant amounts of concrete for civil structures, whereas maritime reactors may instead use maritime platforms that are rated for nuclear uses. The “structures and improvements” subcost is replaced by an estimated cost for a “nuclear maritime platform” [88]. For a nuclear ship, this added maritime platform cost is assumed to reflect the cost of ship structures used to support the ship’s reactor.

Table 10 summarizes the relevant GN-COA subcosts from INL’s *Meta-Analysis* [36] for three different cost estimation levels (high, moderate, and low) and shows the estimate for the maritime advanced SMR OCC based on the aforementioned adjustments.

The cost range for microreactors [26] that was used in the remote community electricity production breakeven analysis was adjusted to reflect the cost of a maritime microreactor. This way the maritime microreactors and maritime SMRs have the same factor cost difference from their respective non-maritime counterparts.

Table 10. OCC of maritime advanced SMRs and microreactors.

Cost	Low	Moderate	High
Advanced SMR cost, no adjustment ($/kWe)	5,500.00	7,750.00	10,000.00
Land and land rights ($/kWe)	(11.21)	(15.80)	(20.39)
Site permits ($/kWe)	(6.54)	(9.22)	(11.90)
Structures and improvements ($/kWe)	(1,099.46)	(1,549.24)	(1,999.02)
Nuclear maritime platform estimated cost ($/kWe)	441.00	441.00	441.00
Advanced SMR cost, adjusted for maritime ($/kWe)	**4,823.79**	**6,616.74**	**8,409.69**
Maritime factor	0.877	0.854	0.841
Microreactor cost, no adjustment ($/kWe)	8,000.00	13,000.00	17,000.00
Microreactor cost, adjusted for maritime ($/kWe)	**7,016.42**	**11,099.05**	**14,296.47**

The advanced SMR costs adjusted for maritime applications in Table 10 should represent a reasonable range of OCCs. This range is compared to the breakeven OCCs discussed in Section 3.4 to determine how attainable these estimated breakeven OCCs are, as shown in Figure 1, Figure 2, and Figure 3.

8.4 Breakeven OCC Inputs

This appendix details the inputs that were used to determine the breakeven capital cost (see Section 3.4) for various nuclear maritime use cases.

Table 11 and Table 12 detail the inputs for the breakeven OCC model for maritime nuclear power plants to power synthetic fuel production and electricity production, respectively. Table 13 details inputs for the breakeven OCC model for nuclear propulsion. Results from the breakeven OCC estimates are summarized in Sections 3.4.1 and 3.4.2.

Table 11. Breakeven OCC model inputs for a maritime nuclear power plant used for synthetic fuel production.

Input	Value	Notes/Source
Discount rate	8%	Reference [16]
Synthetic fuel output (MT/yr)	185,055	Reference [16]
Maritime Nuclear Power Plant Information		
Nuclear plant size (MWe)	400	Reference [16]
Variable O&M cost for SMR ($/MWh)	13.6	Reference [36]; combines moderate estimates for fuel and variable O&M cost
Fixed O&M cost for SMR ($/kW-yr)	136	Reference [36]; moderate estimate
Maritime nuclear power plant learning rate	10%	Reference [16]
Nuclear plant life (years)	60	Reference [16]
Nuclear capacity factor	90%	Reference [16]
Nuclear thermal efficiency	33%	Reference [16]
Synthetic Fuel Plant Information		
Synthetic fuel plant life (years)	20	Reference [16]
Synthetic fuel plant capital costs ($)	115,000,000	Reference [16]
Synthetic fuel plant fixed costs ($/kWe)	37	Reference [16]
Synthetic fuel plant variable costs ($/MWh)	3	Reference [16]
Other Fuel Costs for Comparison		
Average fossil fuel cost ($/MT)	632.89	Fuel prices from References [89, 90], weighted by fuel usage in Reference [12]
Fossil fuel carbon intensity (g CO_2/g fuel)	3.112	Reference [12], weighted by fuel usage

Input	Value	Notes/Source
Carbon tax	See Appendix 8.5	Average value, based on proposed carbon tax bills in the U.S. 117th Congress (2021–2022)
Renewables produced synthetic fuel levelized cost of energy ($/MT)	4,633.22	Reference [91], Figure 2

Table 12. Breakeven OCC model inputs for a maritime nuclear power plant used for electricity generation.

Input	Value	Notes/Source
Discount rate	8%	Reference [16]
Maritime Nuclear Power Plant Information		
Maritime nuclear power plant size (MWe)	2.49	Average power of select communities in Reference [92]
Operating expenditure for microreactor ($/MWh)	100	Reference [26], medium value from Table 7
Nuclear plant life (years)	30	Reference [16]
Nuclear capacity factor	90%	Reference [16]
Maritime nuclear power plant learning rate	10%	Reference [16]
Diesel Generator Information		
Diesel generator facility size (MWe)	2.49	Match maritime nuclear power plant size, seen above
Diesel generator capital cost ($/kWe)	2,120.16	Adjusted for inflation, from Reference [93], Figure 1
Diesel generator operation cost (not including fuel) ($/MWh)	30	Reference [93], Figure 2
Diesel fuel price ($/MT)	1,422.58	Fuel price of $5/gal, from Reference [93]
Diesel generator life (years)	30	Assumed to match maritime nuclear power plant life, seen above
Diesel generator fuel usage (MT/day)	17.54	Reference [93]
Diesel fuel carbon intensity (kg CO_2eq/gal diesel fuel)	10.19	Reference [94]
Carbon tax	See Appendix 8.5	Average value, based on proposed carbon tax bills in the U.S. 117th Congress (2021–2022)

Table 13. Breakeven OCC model inputs for nuclear propulsion.

Input	Value	Notes/Source
Discount rate	8%	Reference [16]
Tax rate	27%	Generic economic assumption for U.S. corporate tax rate
Depreciation schedule	10-year modified accelerated cost recovery system	Generic economic assumption; see Reference [95]
Financing split	50% debt, 50% equity	Generic economic assumption
Cost of debt	6%	Generic economic assumption
Decommissioning fund costs ($/yr)	280,855	Generic economic assumption. Assumes the decommission trusts yield a return of 4.75% a year and must reach a total value of $17,880,000 by end of the reactor lifetime.
Nuclear Ship Information		
Nuclear engine size (MWe)	59.36	Match fossil-fueled ship engine size
Nuclear engine life (years)	30	Reference [16]
Variable O&M cost for SMR ($/MWh)	13.6	Reference [36]; combines moderate estimates for fuel and variable O&M cost
Fixed O&M cost for SMR ($/kW-yr)	136	Reference [36]; moderate estimate
Fossil-Fueled Ship Information		
Fossil fuel engine size (MWe)	59.36	Reference [81]
Fossil fuel engine life (years)	30	Reference [16]
Fossil fuel consumption (MT/day)	240.31	Estimated from nitrogen oxides emission mode values from Reference [96]

Input	Value	Notes/Source
Fossil fuel engine capital costs	Proprietary	Reference [16]
Average fossil fuel cost ($/MT)	632.89	Fuel prices from References [89, 90], weighted by fuel usage from Reference [12]
Fossil fuel carbon intensity (g CO_2/g fuel)	3.112	Reference [12], weighted by fuel usage
Carbon tax	See Appendix 8.5	Average value, based on proposed carbon tax bills in the U.S. 117th Congress (2021–2022)
Fossil-Fueled Ship Information		
Ammonia fuel engine size (MWe)	59.36	Match fossil-fueled ship engine size
Ammonia engine life (years)	30	Match fossil-fueled ship engine life
Selective catalytic reduction system capital cost ($/kWe)	44	Reference [97]
Ammonia engine capital cost ($/kWe)	485	Average value from Reference [97]
Ammonia fuel consumption (MT/day)	551.67	Based on ratio of ammonia's energy content to marine gas oil from Reference [97], and the fossil fuel consumption rate seen above in this table
Ammonia fuel cost ($/MT)	1,083.69	Reference [91], Figure 2

8.5 Carbon Tax Estimation

Table 14 summarizes the carbon taxes that are used in the breakeven OCC analyses, detailed in Section 3.4 and Appendix 8.4. The carbon taxes described below are based on the average of five proposed bills [24]. These bills have not been approved and are only included in a theoretical case to examine the effect of carbon taxes on the breakeven OCC for maritime nuclear technologies.

Year 0 is treated as the year that the maritime nuclear project begins, rather than the proposed start year given by the bill. No inflation in the general economy is accounted for, but costs are adjusted in accordance with each bill's prescribed annual adjustment rate.

Figure 4 gives a visual representation of these carbon taxes over time.

Table 14. Carbon taxes from proposed U.S. bills [24].

Tax Rate (per metric ton of CO_2 equivalents)						
Year	Market Choice	America Wins	Energy Innovation	Clean Future Fund	Save Our Future	Average
0	$35.00	$59.00	$15.00	$25.00	$54.00	$37.60
1	$36.75	$62.54	$25.00	$35.00	$57.24	$43.31
2	$38.59	$66.29	$35.00	$45.00	$60.67	$49.11
3	$40.52	$70.27	$45.00	$55.00	$64.31	$55.02
4	$42.54	$74.49	$55.00	$65.00	$68.17	$61.04
5	$44.67	$78.96	$65.00	$75.00	$72.26	$67.18
6	$46.90	$83.69	$75.00	$85.00	$76.60	$73.44
7	$49.25	$88.71	$85.00	$95.00	$81.20	$79.83
8	$51.71	$94.04	$95.00	$105.00	$86.07	$86.36
9	$54.30	$99.68	$105.00	$115.00	$91.23	$93.04
10	$57.01	$105.66	$115.00	$125.00	$96.71	$99.88
11	$59.86	$112.00	$125.00	$135.00	$102.51	$106.87
12	$62.85	$118.72	$135.00	$145.00	$108.66	$114.05
13	$66.00	$125.84	$145.00	$155.00	$115.18	$121.40
14	$69.30	$133.39	$155.00	$165.00	$122.09	$128.96
15	$72.76	$141.40	$165.00	$175.00	$129.41	$136.71
16	$76.40	$149.88	$175.00	$185.00	$137.18	$144.69
17	$80.22	$158.87	$185.00	$195.00	$145.41	$152.90
18	$84.23	$168.41	$195.00	$205.00	$154.13	$161.35
19	$88.44	$178.51	$205.00	$215.00	$163.38	$170.07
20	$92.87	$189.22	$215.00	$225.00	$173.19	$179.05
21	$97.51	$200.57	$225.00	$235.00	$183.58	$188.33
22	$102.38	$212.61	$235.00	$245.00	$194.59	$197.92

Tax Rate (per metric ton of CO_2 equivalents)						
Year	Market Choice	America Wins	Energy Innovation	Clean Future Fund	Save Our Future	Average
23	$107.50	$225.37	$245.00	$255.00	$206.27	$207.83
24	$112.88	$238.89	$255.00	$265.00	$218.64	$218.08
25	$118.52	$253.22	$265.00	$275.00	$231.76	$228.70
26	$124.45	$268.41	$275.00	$285.00	$245.67	$239.71
27	$130.67	$284.52	$285.00	$295.00	$260.41	$251.12
28	$137.20	$301.59	$295.00	$305.00	$276.03	$262.97
29	$144.06	$319.68	$305.00	$315.00	$292.59	$275.27
30	$151.27	$338.87	$315.00	$325.00	$310.15	$288.06

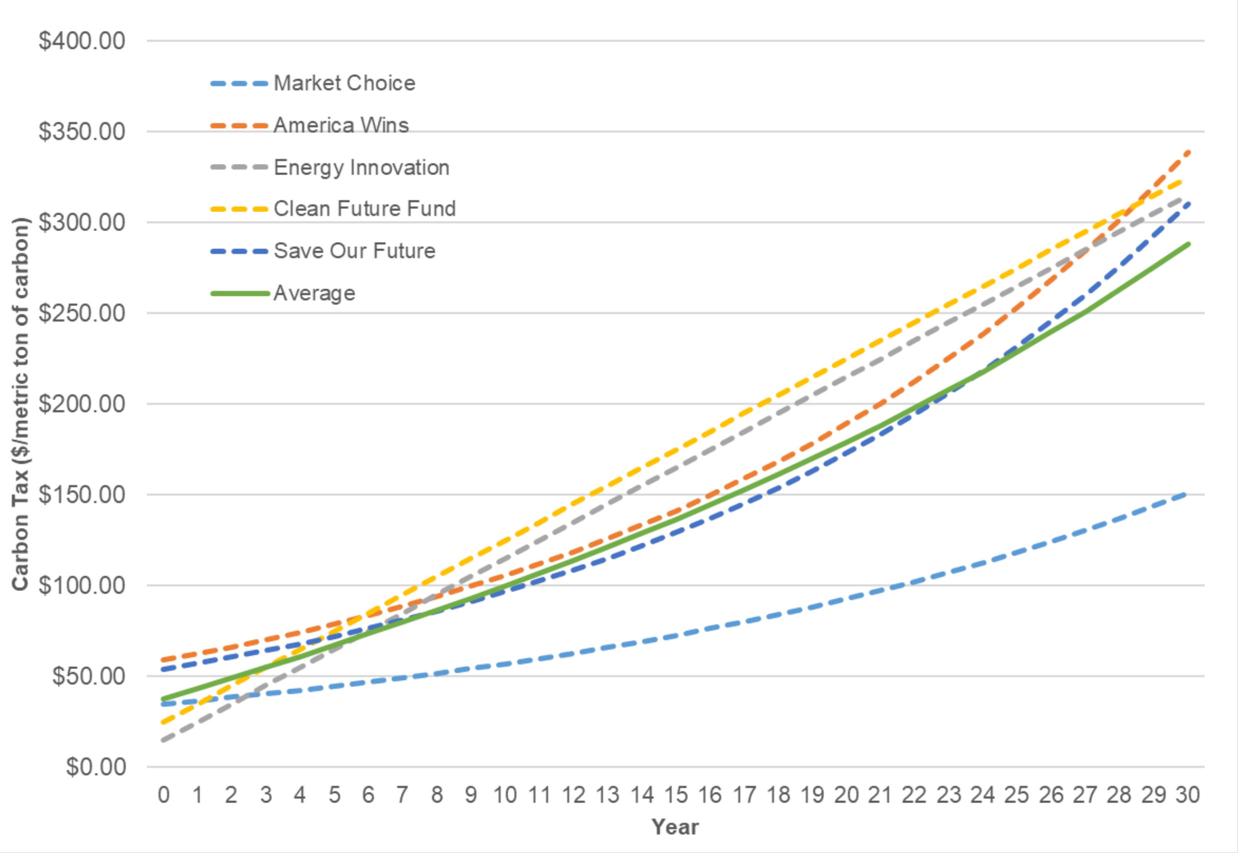

Figure 4. Proposed U.S. carbon taxes, over time.

8.6 Environmental Impacts from Fuel Production

The environmental impacts from fuel production result from the mining, processing, and transporting of the raw materials used to make nuclear fuel.

The process of creating nuclear fuel from uranium has several steps. First, the uranium ore must be mined and milled. The milled uranium is converted into uranium hexafluoride (UF_6) and then enriched and made into the desired fuel forms. Each step in this process generates some amount of radioactive waste, but the largest volume of waste comes from the uranium mill tailings. Uranium mill tailings are the sandy byproduct of what remains after uranium is extracted from uranium ore during the milling process [98]. These tailings contain residual uranium and uranium decay products that remain radioactive for a very long time (thousands of years). Like other mining waste, they are typically disposed of in a dry or slurry form in surface level impoundments [99].

Early mining operations were not performed in accordance with today’s strict regulations, and they have resulted in contaminants reaching nearby surface water, groundwater, soil, and vegetation. These mining activities happened before ionizing radiation effects were well understood, and before radon was identified as being carcinogenic [100]. Advances in the understanding of radiation have led to stricter environmental protection regulations [99]. As a result, recent and ongoing environmental remediation programs in the U.S. have substantially reduced radiation doses to the public from uranium mill tailings [99, 100]. Mining sites now have stringent decommissioning processes and long-term monitoring requirements set by the federal government to ensure that radiation does not harm the environment or the public [101].

Regarding maritime nuclear use cases, the mining process to produce their nuclear fuel should be similar to that for conventional nuclear power. The fuel’s raw materials would be mined, processed, and transported under modern and more strict environmental regulation and radiation protection laws.