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Road Map for the Development of Commercial Maritime Applications of Advanced Nuclear Technology

Accelerating Commercial Maritime Demonstration Projects for Advanced Nuclear Reactor Technologies

ABS NRIC INL Idaho National Laboratory

Table of Contents

Table of Figures

Table of Tables

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Introduction

1 Introduction

The U.S. Department of Energy (DOE) is making significant investments in advanced nuclear reactor development and demonstration programs such as the Advanced Reactor Demonstration Program (ARDP) [1]. The innovations in advanced nuclear reactor technologies (defined in Section 1.4.1), including concepts of microreactors and small modular reactors (SMRs), have opened the door to a wide range of applications beyond land-based power stations providing electricity to the grid. Applications for transportation and industrial operations could offer reliable carbon-free energy to achieve decarbonization goals by supporting energy-intensive activities such as alternative fuel production, water desalinization, and local power supply. The DOE recognizes the transformational power of these technologies and is investing in foundational research and development as well as reactor demonstration projects [2]. However, unique and significant challenges exist in each application domain to bring projects into reality beyond just the underlying reactor technology maturation.

This project focuses on addressing those challenges in the maritime domain so that new reactor technology can be deployed rapidly to transform the maritime industry and create market disruption that will provide unique competitive advantages for U.S. companies that design, build, operate, and support maritime assets. In these reports, 'maritime' may refer to vessels and offshore units, while 'marine' may specifically refer to the natural ocean environment or the operations of commercial ships.

Other report titles for this series are listed below.

- Configurations of Commercial Nuclear-Maritime Applications (Configurations Report)
- Report on Potential Challenges and Impacts of Advanced Nuclear-Maritime Applications in the U.S. (Potential Challenges Report)
- Readiness Report for DOE Support of Maritime-related Demonstration Projects of Advanced Nuclear Reactor Technology (DOE Readiness Report)
- Overcoming Challenges to Nuclear-Maritime Applications (Overcoming Challenges Report)

1.1 Goals and Objectives of this Report

This report outlines the preliminary considerations for strategic plans for achieving demonstration projects of advanced nuclear reactors for commercial maritime applications.

The road map report provides high-level value cases associated with expected application categories. This report is critically important for helping the National Reactor Innovation Center (NRIC) solicit engagement from both the nuclear and maritime industries for demonstration projects. The report highlights key gaps that may need to be addressed for each category, referencing other work products from this research on how to best address those challenges.

While the scope of this report focuses on applications and operations within the U.S., the authors recognize that the subject of this research is internationally relevant. The U.S. maritime market may not be representative of the global maritime market, but any nuclear maritime technology discussed to be applicable for U.S. operations may be capable in the future to be used internationally.

1.2 Project Members

The American Bureau of Shipping (ABS) is a not-for-profit classification society for the U.S. (designated in USC §3316) and a globally recognized standards organization/research organization for the maritime industry.

The National Reactor Innovation Center (NRIC) is a DOE program providing resources and guidance for testing, demonstration, and performance assessment to accelerate deployment of advanced nuclear reactor technology concepts, including support for commercial maritime applications.

Supporting Project Advisors include individual contracting industry experts, Morgan, Lewis & Bockius, LLP and Blank Rome LLP for insights into legal, licensing, and regulatory regimes.

1.3 Background

In recent years, industrial, social, financial, and political interests have shifted to reconsider nuclear solutions for various energy demand issues. Advanced nuclear reactor technologies show promise for global energy decarbonization efforts and national energy independence. Studies of damages related to anthropogenic climate change and the expected decline of oil reserves drive the adoption of renewable, sustainable, and decarbonized energy.

However, the trials of energy transition are acutely felt and re-emphasized in the wake of geopolitical instability [3]. Marine fuel prices are subject to many political fluctuations depending on global fossil fuel availability. Uncertainties regarding the future volatility of oil and gas prices encourage energy independence. They may require disruptive change and adoption of alternative fuels and renewable energy resources at a rate faster than expected. All options must be considered. In addition to fossil fuel prices, the need to accelerate decarbonization is also a key consideration to keep in mind. All options must be considered.

The current International Maritime Organization (IMO) strategy targets the reduction of the average carbon dioxide (CO2) and greenhouse gas (GHG) emissions per transport work from 2008 levels by at least 60 percent by 2030 and 100 percent by 2050 [4]. These emission reduction goals stand despite the continued expansion of maritime trade and offshore maritime operations, which account for over 90% of global trade. To that end, the U.S. Special Presidential Envoy for Climate has indicated that the U.S. will help deploy the technologies needed to rapidly reduce the sector's emissions to meet the 2050 goals [5] [6].

These initiatives are fundamentally changing the shipping and offshore industry's assets and infrastructure as the adoption of new fuels such as hydrogen and ammonia and alternative decarbonization strategies increase, which may potentially include the use of advanced nuclear reactors. To achieve these mandates, advanced nuclear reactor technology in the maritime environment is among the several promising technologies for:

1 powering the production of clean fuels like hydrogen and ammonia offshore or at port facilities,

2 providing mobile power onboard maritime assets (e.g., barges) to support a wide range of needs, such as remote power needs and disaster response support, and

3 generating electricity, heat and energy to power ships and other maritime assets.

If adopted, advanced nuclear reactor technology could serve as one of the most vital tools available to the industry to achieve aggressive decarbonization goals and transform the maritime industry. This transformation could create a range of unique economic and job creation benefits for the U.S.

Maritime emissions have increasingly attracted attention at international forums, including the United Nations Framework Convention on Climate Change Annual Conference of the Parties (COP). In 2021, COP26 in Glasgow, Scotland, produced the Clydebank Declaration for green shipping corridors

> *It is [the signatories'] collective aim to support the establishment of at least 6 green corridors by the middle of this decade, while aiming to scale activity up in the following years, by inter alia supporting the establishment of more routes, longer routes and/or having more ships on the same routes. It is our aspiration to see many more corridors in operation by 2030. We will assess these goals by the middle of this decade, with a view to increasing the number of green corridors.*

The 19 signatories at the time of signing included Britain and the U.S. [8]. In January 2022, the Port of Los Angeles, Port of Shanghai, and C40 Cities (a network of global mayors) announced a partnership to create the world's first transpacific green shipping corridor between ports in the U.S. and China [9].

In addition to COP, commitments to addressing maritime emissions have been made through Mission Innovation (MI), a global initiative "to catalyze action and investment in research, development and demonstration to make clean energy affordable, attractive and accessible to all this decade." In June 2021, MI announced its "Zero Emission Shipping" mission to be co-led by Denmark, the U.S., and Norway. As a global initiative composed of 23 countries and the European Commission (on behalf of the European Union), MI aims to "demonstrate commercially viable zero-emission ships by 2030, making vessels that operate on zero-emission fuels the natural choice for ship owners when they renew their fleet [10]." The U.S. DOE represents the U.S. on this mission and is contributing to it by [11]:

- Dedicating a full-time equivalent employee to staff the Mission Secretariat and a delegate to the Steering Committee.
- Leading Mission activities within the fuels pillar and contributed to the others as needed.
- Hosting and contributing to workshops, report writing, and monitoring Mission progress.
- Supporting research, development and demonstration activities that support Mission objectives and desired outcomes.
- Leveraging subject matter expertise across the federal government from other agencies and DOE national laboratories for technical and economic analysis.

The high-level commitments made in these diplomatic forums create the backdrop for recent developments involving the use of nuclear power for maritime applications. In general, a list of international early adopters for advanced nuclear reactor solutions integrated with maritime applications is shown in Table 1.

Advanced nuclear reactor technologies have great promise for transforming a wide range of transportation, industrial, and even residential utility operations as well as military activities (e.g., powering military bases and ships). Advanced nuclear reactor designs are auspicious for non-grid connected maritime applications for the following reasons. [16]:

- **Small Footprint:** Compact nuclear reactors could have a small enough footprint (e.g., a standard-sized shipping container) that would easily fit in engine rooms onboard maritime structures. In fact, they are likely to take up far

TABLE 1: Early adopters of Commercial Nuclear-Maritime Applications

Subject	Date	Countries Involved	Description
Floating Nuclear Power	May 2020 (plant commissioned)	Russia	*Akademik Lomonosov's* non-self-propelled power barge is owned by the Russian State corporation Rosatom.
Floating Nuclear Power	December 2020	Denmark	Danish nuclear company Seaborg received Statement of Feasibility for Compact Molten Salt Reactor installed on barge for clean energy in Southeast Asia [12].
Nuclear Ship Propulsion	June 2021	South Korea	South Korea's Atomic Energy Research Institute (KAERI) and Samsung Heavy Industries (SHI) signed agreement to develop molten salt reactor for ship propulsion, expecting to open new markets for nuclear technology [13].
Nuclear Ships Regulations	November 2022	United Kingdom	UK Maritime & Coastguard Agency (MCA) adopted Merchant Shipping (Nuclear Ships) Regulations (generated from IMO SOLAS Chapter VIII and resolution A.491(XII)) on Nuclear Ships [15].

less room than large combustion power systems when also considering associated fuel storage and the wide range of support systems (lubrication, air, etc.) needed for conventional power. This would free up space for cargo/industrial operations. Of course, the requirements will vary with advanced nuclear reactor designs, shielding requirements, and necessary support systems.

- **Scalability:** Applicable advanced reactors will likely produce between 1 to 20 MWt (megawatt thermal) of energy that can be used directly as heat (e.g., industrial process heat or steam production to drive mechanical systems), converted to electrical power (e.g., to drive turbines that would generate electricity to power electrical motors), or used to produce hydrogen for subsequent fuel production or other industrial operations. Given a small footprint, multiple reactors could be coupled together to meet more considerable energy demands and provide redundancy/backup capacity as needed. The scalability can allow this technology to meet any range of power demands for industrial process operations in the maritime environment and for ship propulsion.

- **Factory Fabrication:** Modular reactor systems could be fully assembled and shipped to location for installation. This unique arrangement could eliminate large-scale construction operations, reduce capital costs, and support rapid commissioning and adoption. The self-contained nature of the power source means that traditional shipyards would not need highly specialized personnel, technology, etc., to incorporate these devices into the ships or offshore assets they build or modify.

- **Self-Adjusting with Inherent/Passive Safety Features:** Modern reactor designs are typically unique from most current power reactors. The concept of operations for many provides for remote and autonomous operation coupled with inherent and passive safety features (e.g., low power, low accident source term, advanced fuel design or accident tolerant fuel (ATF), passive heat exchange, negative reactivity feedback mechanisms, etc.). The goal is to provide safe operations with reduced or eliminated operational burden of onsite licensed operators and engineers to run complex/expensive additional safety systems. The ability to operate a reactor remotely or autonomously onboard ships and offshore assets without extensive crewing requirements while minimizing any associated accident risks is of interest for maritime applications.

- **Long Fueling Cycle:** These advanced reactor designs may have a long core life that could last the entire life of the asset or require very few refueling operations compared to conventional vessel or offshore applications. Expected fuel cycles with long lifetimes of up to 20 years in some applications would likely last the life of some ships with just one or two refueling operations in other applications.

- **Replacement Rather Than Refueling:** The compartmentalization of some advanced reactor designs termed "nuclear batteries" may support efficient replacement rather than in-situ refueling. Exchanging reactors of this design type can minimize operational disruptions rather than have potentially complex and lengthy refueling operations that may be incompatible with the business demands of maritime operations. Exchanging reactors can also allow for offsite processing of spent nuclear fuel (SNF) and equipment by nuclear technology companies without involving maritime stakeholders. The replacement versus refueling strategy can also allow ease of adoption for maritime operators to advances in nuclear technology over time without being tied to one specific advanced reactor technology (e.g., gas, liquid metal, molten salt, or heat pipe-cooled concepts).

While these advanced features can present opportunities for maritime applications, there are many unique challenges even after current designs mature. The key challenges to adopting nuclear technology for maritime applications include the following:

- **Nuclear Licensing Challenges:** Licensing of SMRs and microreactors in the U.S. is a topic of ongoing discussion [17]. For U.S. marine applications, including ship propulsion, it is assumed that the reactors deployed will be licensed by the U.S. Nuclear Regulatory Commission (NRC). The NRC has provided guidance that outlines approaches to advance technical and regulatory readiness for advanced reactors under flexible review processes within the bounds of existing regulations. The uniqueness of advanced reactors compared to traditional reactors complicates licensing considerations. While the topic of licensing advanced nuclear reactors overall is still developing, additional risks associated with remote and mobile operations in the maritime environment must also be explored.

  When discussing nuclear propulsion specifically, licensing and regulatory challenges have been ranked by nuclear and maritime industry professionals as the most significant challenges for the development of commercial nuclear maritime propulsion. An October 2022 report released by the National Reactor Innovation Center (NRIC) titled "Challenges and Opportunities for the Development of Commercial Maritime Surface Vessel Nuclear Propulsion (CMNP)" was based on interviews with experts from the maritime and nuclear energy sectors and found that "Foreign Government Approvals" and "U.S. Government Approvals" were the most significant perceived challenges to developing this technology [18].

  Intergovernmental bodies like the International Atomic Energy Agency (IAEA) and Organisation for Economic Co-operation and Development – Nuclear Energy Agency (OECD-NEA) will have an important role to play by helping to harmonize different nuclear regulatory regimes found in each country. The NRC will also be able to contribute to this considering the influence that the U.S. regulator has through its bilateral engagements with a long list of foreign nuclear regulators [19].

- **Maritime Regulatory Challenges:** Maritime operations have their own complex set of regulatory requirements domestically and internationally. Introducing reactors into commercial maritime applications will require reviews and approvals by traditional maritime regulators, including the U.S. Coast Guard (USCG), the U.S. Maritime Administration (MARAD), classification societies (like ABS), the Bureau of Offshore Energy Management (BOEM)/Bureau of Safety and Environmental Enforcement (BSEE), and various state/local/port authorities, etc. within the U.S., as applicable. The IMO will play an essential role for international applications to influence national applications, and global applications will add a range of foreign regulators who must abide by their respective countries' statutory and regulatory regimes.

- **Security, Non-Proliferation, Safeguards, and Export Control Challenges:** In addition to nuclear licensing issues, concerns about security and safeguards of nuclear materials and export control apply to potential maritime use cases. Operations within the U.S. pose one set of concerns and set of approvals, but eventual international operations will be more complex. Security risk management strategies (prevention, protection, preparedness, response, and recovery) must be addressed. The IAEA defines nuclear security as "the prevention and detection of, and response to, criminal or intentional unauthorized acts involving nuclear material, other radioactive material, associated facilities or associated activities" [20]

  This is differentiated from safeguards, which are "the set of technical measures applied by the IAEA to independently and objectively verify that a State's nuclear material is accounted for and not diverted to nuclear weapons or other nuclear explosive devices." Safeguards include oversight and inspections, accounting of nuclear material, verifying facility designs, surveillance, and containment strategies using tamper-indicating tags and seals, for example [21]. In the U.S., the National Nuclear Safety Administration (NNSA) offices are associated with many security, safeguards and export control arrangements and verification activities for nuclear technologies.

- **Public Policy/Public Acceptance Challenges:** Nuclear power operations have been controversial in the U.S. and internationally. Past incidents like Three Mile Island, Chernobyl, and Fukushima, as well as concerns about SNF and nuclear waste handling, have elevated scrutiny and increased resistance towards nuclear operations in many locations [22]. However, new technological developments and strong support for decarbonization are creating increased interest in nuclear options even among traditional opposition. Maritime applications will face the same types of concerns from policymakers and the public at large.

- **Technical Challenges and Technology Risks**: Operating an advanced reactor at a stationary location on land is one accomplishment; however, operating an advanced nuclear reactor at sea presents a different challenge. The marine maritime environment brings uniquely harsh environmental loads and dynamic accelerations, especially with floating assets such as ships and certain types of offshore platforms [23]. Potential technology risks must be addressed systematically (using risk/reliability evaluation methodologies) to identify and evaluate currently unrecognized issues/concerns of integrating new technologies into novel applications

- **Business Case Challenges:** Nuclear reactor technology developers have typically had limited exposure to marine and offshore operations, while operators in the marine and offshore industries have typically had limited exposure to developments with advanced nuclear reactor technology. Early work on microreactor and SMR applications has focused on shore-based applications where developers are most familiar and comfortable with opportunities for remote onshore power needs, transportable temporary power for areas impacted by natural disasters or other emergencies, and emerging needs related to power for renewable fuel production. Business challenges within the maritime industries can be recognized as large opportunities but pose more unknowns to developers and investors.

Operators in the marine and offshore industries are faced with an inevitable and fundamental energy transition. However, much of the focus is on alternative fuels that provide only near-term partial solutions (liquefied natural gas (LNG), liquefied petroleum gas (LPG), methanol/ethanol, etc.) and longer-term solutions with challenging economics (e.g., ammonia and hydrogen) without a sufficient renewable power source to produce the fuels [24]. The promising opportunity to leverage advanced nuclear reactor technology for clean fuel production, power supply, and propulsion is gaining traction, but the learning curve will be steep for the industry to adopt it.

On top of the fundamental economic challenges, many other business challenges will need to be addressed, including:

1 Relationships between nuclear reactor operating/support companies and maritime operations companies, including leasing models and foreign ownership.

2 Liabilities for owners/operators and insurance availability/cost.

3 Crewing models/requirements.

4 Economics of 10- and 20-year cores in relation to planned ship or offshore structure life.

5 Cost of security personnel and associated security infrastructure.

- **Supply Chain and Fuel Availability:** Ongoing challenges associated with the global supply chain crisis in general and, more specifically, Russia's 2022 invasion of Ukraine, have created compounding challenges for the nuclear energy industry. After limited investment worldwide in new nuclear power plant construction, the larger nuclear energy supply chain is refocused on establishing new nuclear fuel suppliers for both conventional and advanced nuclear reactors. As Russia is currently one of the largest global suppliers of enriched uranium and effectively the only country with the capacity to produce high-assay low enriched uranium (HALEU, enrichment <20% U235) for advanced reactors, this has become a top priority for developers and the U.S. DOE [25]. For example, the U.S. Nuclear Industry Council's 2021 Advanced Nuclear Survey found that the top-ranked issues for advanced reactor vendors included fuel qualification and fuel availability [26]. This challenge is being addressed, and the 2022 Inflation Reduction Act included $700 million to develop domestic infrastructure to produce HALEU at scale [27]. In October 2024, various contracts were awarded by the DOE to U.S. companies to bid on developing HALEU production supply functions, offering up to $800 million USD for the services [28]. .

- **Support Infrastructure:** Even though self-contained small, advanced reactors are expected to be easier for commercial industry to adopt, use, and support compared to conventional reactors, there will be infrastructure and heavy manufacturing capability required that does not currently exist. There are no facilities in the U.S. that have been approved by the NRC to manufacture complete, fueled reactors. Also, few shipyards or ship repair facilities are equipped to handle radioactive materials or reactor installation/removal activities. Nuclear reactor operating companies may need remote operation control rooms and highly reliable remote operation/autonomous control systems. Transportation systems and processes will be needed to move both new and used microreactors. The nuclear operators must resolve the logistics of SNF and nuclear waste material in coordination with federal and state regulators. [22]

- **Nuclear Waste Management, SNF Transport and Disposal, and Nuclear-Maritime Decommissioning & Vessel Recycling / Salvage / Inventory of Hazardous Materials:** Combined with vessel scrapping, challenges related to managing the disposal of nuclear waste and SNF have the potential to create obstacles for the adoption of nuclear-powered vessels. Currently, SNF is maintained on-site at nuclear power plants, first in wet storage and later in dry storage. In the U.S., dry storage systems were developed in the early 1980s by utilities looking to increase the amount of spent fuel they could store on-site. These systems were ultimately licensed by the NRC [29]. While this approach has been a helpful placeholder, it is not a final solution, and the potential use of U.S. nuclear-powered vessels traveling between jurisdictions brings up significant questions of where a ship's SNF would be stored and where final disposal can be located. To identify a solution for spent nuclear fuel generated at terrestrial plants, the U.S. DOE has restarted its consent-based siting program to identify a final geological repository for the storing of spent fuel. This "approach to siting facilities that focuses on the needs and concerns of people and communities" has to date been successful for other countries, including Finland, Sweden, and France [31].

For maritime decommissioning, although vessel scrapping is an important end-of-life activity that is largely concentrated in India, Bangladesh, and Pakistan, few shipyards are equipped with the infrastructure needed to manage radiological decontamination [30]. To identify a solution for spent nuclear fuel generated at terrestrial plants, the U.S. DOE has restarted its consent-based siting program to identify a final geological repository for the storing of spent fuel. This "approach to siting facilities that focuses on the needs and concerns of people and communities" has to date been successful for other countries, including Finland, Sweden, and France [30].

1.4 Demonstrating New Nuclear Energy Technologies

The U.S. nuclear energy industry is developing a broad range of advanced reactor technologies designed to address today's changing energy markets and the climate crisis, resulting in notably increased activity in the sector. To usher in new technologies and their possible novel applications, they must first be appropriately prototyped and validated. U.S. Government support for demonstration projects can support this preliminary effort.

> **"We have not done this recently, but we have done this before."**
>
> **- NRIC**

Among the most exciting potential markets is the commercial maritime sector, a piece of the global economy that lives largely out of sight but accounts for roughly 80% of global trade by volume and over 70% of global trade by value [32]. The sector also accounts for roughly 3% of global carbon emissions due the use of marine diesel and heavy fuel oil. However, achieving net zero by mid-century will require a complete revolution in how ships are powered, a transition to which nuclear power can contribute. The first step in this transition will need to focus on demonstrations of technical maturity.

Fortunately, demonstrating advanced nuclear reactor technology is not a new challenge. At the desert site at Idaho National Laboratory (INL), formerly the National Reactor Testing Station, the U.S. has built 52 different reactors over 25 years. The X-10 reactor at Oak Ridge National Laboratory (ORNL) was built and started up in under a year.

Meanwhile, the U.S. Navy has safely used nuclear power for over 134 million miles and 5,700 reactor years [33]. Developing a new, non-military commercial offering for reactors will require technical demonstrations that can validate designs, test safety parameters in controlled environments, and bring conceptual technologies into reality to showcase their capabilities and potential to the world.

Although "demonstration" has multiple definitions within the context of 21st century advanced nuclear reactor development, each meaning is based on the idea of building a first-of-a-kind (FOAK) technology in a controlled setting. For example, demonstration may be understood to mean:

- An experiment, model or simulation used to test or demonstrate the validity of a hypothesis.
- A prototype to demonstrate a new product, in principle, but it is only a partially developed product.
- Conducting a series of activities in a controlled or limited market to demonstrate a business model.

In each of the above, demonstrations are a key factor used in risk-informed decision making. The results of planned demonstration activities are compared to pre-conceived criteria to derive lessons learned and make decisions about future investments in an effort to progress a concept.

The technical and economic viability of small water-cooled nuclear reactors was demonstrated (scientific, engineering and economic) under real world conditions in the 1960s by several countries including the U.S. There were many lessons learned from these activities that are currently being considered for modern commercial nuclear-maritime applications; however, there have also been substantial changes since the 1960s in areas ranging from scientific or engineering developments, geopolitical conditions and how economic decisions are made. Each of these changes can be substantive enough to drive the need for new demonstration activities to complement what was done in the past. One clear area is the introduction of advanced reactor technologies and how they might be used in nuclear-maritime applications. Demonstrations are typically needed for:

- Integrated technical performance (technology is sufficiently mature, safe and reliable).
- Testing interfaces between nuclear systems and external systems.
- Resilience to challenges from real-world environments.

FIGURE 1: NRIC-DOME Test Bed. Courtesy of INL.

- Readiness of both operators and the external processes that an operating facility will operate within (e.g., interfacing with port or deployment site operations).

A non-traditional owner or operator may warrant a demonstration under controlled circumstances, and these circumstances may be different in one country versus another.

FOAK technologies can either be commercial or experimental, and a "controlled setting" can be defined both in terms of where the demonstration takes place and how its costs are controlled. Some reactor vendors choose to build FOAK technologies to serve commercial power markets by working with power utilities to line up customers once their technologies are established. Other vendors are choosing to run demonstrations in non-commercial experimental facilities such as the test beds managed by the National Reactor Innovation Center (NRIC) at INL's Materials and Fuels Complex (MFC). As the U.S.' leading center for nuclear energy research and development, INL co-locates world-leading expertise and cutting-edge resources. As a whole, INL provides an ideal environment for testing and validating advanced reactor technologies. For example, Figure 1 below shows the NRIC Demonstration of Microreactor Experiments (DOME) Test Bed at INL's MFC, able to host microreactor demonstrations up to 20 MWt using HALEU fuels.

Many U.S.-based reactor vendors are reducing risks through DOE cost-share awards through programs like the Advanced Reactor Demonstration Program (ARDP) [34] and NRIC and Gateway for Accelerated Innovation in Nuclear (GAIN).

Vendors looking to build and demonstrate their first reactors in the U.S. also need to make a regulatory decision between the DOE or the NRC to solicit authorization to build and operate a nuclear reactor. The regulatory pathway will depend on many factors, including the intended use of the demonstration reactor.

All existing commercial nuclear power plants in the U.S. today are licensed by the NRC, and it is assumed that U.S. advanced nuclear reactors for maritime will also be licensed by the NRC. The NRC also licenses research reactors located at universities nationwide. According to its website, the NRC authorizes an applicant to conduct any or all of the following activities [35]:

- Construct, operate, and decommission commercial reactors and fuel cycle facilities.
- Possess, use, process, export and import nuclear materials and waste, and handle certain aspects of their transportation.
- Site, design, construct, operate, and close waste disposal sites.

NRC license applicants currently have two primary licensing pathways available to them: a two-step licensing path for construction and operation through 10 CFR Part 50 or a combined construction and operating license application through 10 CFR Part 52 [35]. A further description of the NRC licensing regime is provided in Section 2.1.1 of this Report. The NRC is currently in the process of developing 10 CFR Part 53: a "Risk Informed, Technology-Inclusive Regulatory Framework for Advanced Reactors," which is planned to be available to applicants for new commercial advanced nuclear reactor licenses no later than December 31, 2027 [36]. The NRC staff is scheduled to issue the Final Rule by July 2025 [37].

Advanced reactor projects like TerraPower's Natrium project in Wyoming or X-Energy's Xe-100 project in Washington (expected to be complete in 2028-2029) are pursuing NRC licenses for their first demonstration reactors. X-Energy also in Phase 2 of the Canadian (vender design review) VDR licensing process offered by the Canadian Nuclear Safety Commission (CNSC). [39].

Alternatively, many smaller reactor designs are pursuing authorization from the DOE for reactor tests, experiments, and demonstrations. These are non-commercial licenses for reactors that are operated for "research or experimental purposes (rather than commercial purposes), are constructed and operated at a DOE-owned or controlled site, and any participation by a private entity is pursuant to an adequate contractual arrangement with the DOE." This includes [40]:

- A research oriented, non-power reactor at a DOE site operated by a private entity pursuant to an agreement with DOE.
- A DOE or DOE-contractor operated nuclear reactor user test facility for use by private parties to facilitate research and development [41].

Currently, reactors being demonstrated at INL operate with DOE licenses in testbed phases and can't directly transition to NRC licensing. An important consideration is how to apply the lessons learned and regulatory insights gained from these initial demonstrations to subsequent NRC license applications.

Reactor licensing options through other federal departments, for example, the U.S. Department of Defense (DOD), are not commercial in nature, and therefore not specifically considered in this Report. However, some application cases may apply to government-owned assets for commercial-like operations, for example, dredges, ferries, or other offshore floating power facilities. Non-commercial advanced reactor applications, although not the subject of this Report, can provide information on the viability and feasibility of certain projects which can be transitioned or adopted by commercial operations.

1.4.1 Advanced Nuclear Reactors

In September 2018, the bipartisan Nuclear Energy Innovation Capabilities Act (NEICA) was signed into U.S. law, authorizing NRIC. This was followed by the authorization of ARDP in the Energy Act of 2020 [41]. NEICA defines "advanced nuclear reactor" as:

A. "a nuclear fission reactor with significant improvements over the most recent generation of nuclear fission reactors, which may include inherent safety features; lower waste yields; greater fuel utilization; superior reliability; resistance to proliferation; increased thermal efficiency; and the ability to integrate into electric and nonelectric applications; or

B. a nuclear fusion reactor[3] [43]."

Although considered "advanced," many reactor concepts being commercialized today were designed and demonstrated in the 20th century. Much of the technological progress has paired fundamental research and experiments from the last century with modern advanced materials, construction methods, simulations, and modeling. These innovations are being designed on a bedrock of experience using nuclear energy technologies: the U.S. fleet of commercial nuclear power plants has accumulated over 4,500 "reactor years" of operating experience since the first plant opened in 1957. This number does not include multiple decades of experience from research, experimental, and prototype reactors operating at U.S. universities and national laboratories. Characterized by their advanced features, advanced nuclear reactors include any type or size of reactor that is developed today.

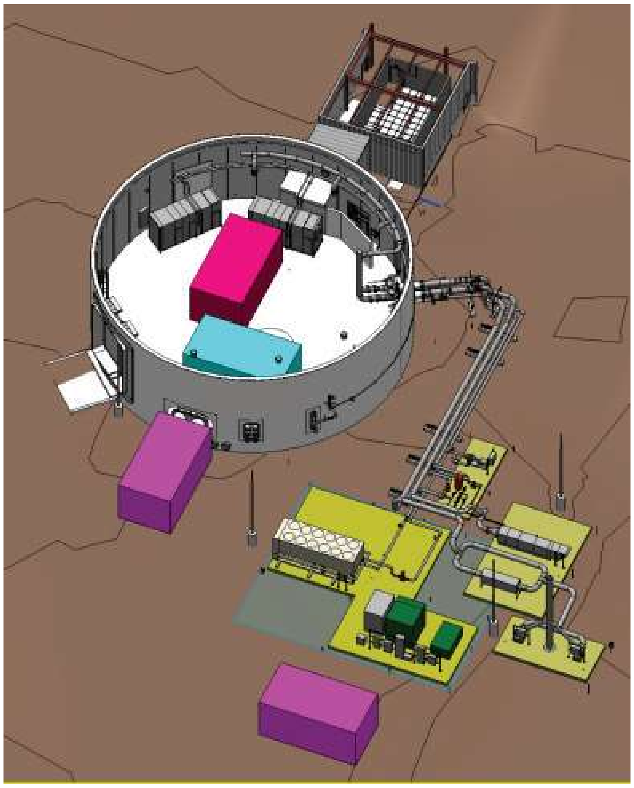

FIGURE 2: DOME updated Test Facility. Courtesy of INL.

1.4.2 NRIC's Reactor Demonstration Capabilities [43]

In addition to coordinating resources throughout the national laboratory system, NRIC is preparing physical test beds to facilitate the demonstration of various reactor technologies in controlled environments. These facilities can be retrofitted for a range of different applications, including for aspects of simulated maritime environments. The first of these test beds currently under development is the NRIC DOME facility, located at INL and intended to allow industry and other partners to test advanced reactors. The purpose of the DOME advanced reactor test bed is to provide the structure and auxiliary systems necessary to operate demonstration reactors successfully [45]. The goals of the testbed include:

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[3] Fusion technologies are not discussed under the scope of this research but may subject to future investigation.

FIGURE 3: LOTUS Digital Twin 3D model post Conceptual Design [45] Designation as Category 1 Demonstration Test Bed Capability Project. Courtesy of INL

- Facilitation of the commercial readiness of advanced reactors.
- Reduction of the time and money required to demonstrate a reactor.
- The development of a safety basis that is broad enough to cover a variety of reactors.
- Providing Safeguards Hazard Category 4 Facility.
- Providing Hazard Category 2 Nuclear Facility.
- Simplified access to the facility to allow for multiple efficient demonstrations at a faster pace to accommodate multiple user organizations.
- A contained environment with radiological controls, allowing demonstrators to test conditions for their reactors and power-generation modules.

DOME is envisioned to have the following features:

- Designed for Advanced Microreactors up to 20MWt.
- Designed for HALEU fuels.
- Accommodates shipping containers for easy reactor transportation into and out of the facility.
- Industrial-level electrical service.
- Sufficient internal space and crane for moving demonstration reactors and support equipment.
- Environmental cooling.
- Provides laboratory conditions for additional instrumentation, alternate test scenarios, easily reconfigurable testing equipment for expanding test programs.
- Utility access for compressed air, deionized water, and power.
- Access to transport equipment: forklift, crane, hydraulic ram slides.
- Proximity to customary and emergency services.
- Co-located with critical INL infrastructure and services such as fuel design and fabrication and post-irradiation examination.

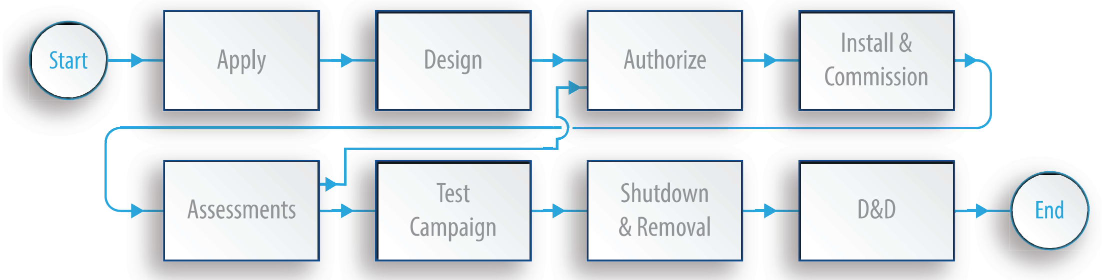

FIGURE 4: NRIC DOME Simplified End-to-end Demonstration Process

The DOME can be thought of as operating similar to a garage in which multiple different reactor demonstrations can be swapped in and out over time to test a range of technologies. The first demonstrations are expected to take place in 2025.

Given the relatively large amount of internal space provided by DOME, the facility could also potentially host maritime-focused environmental and component testing. For example, a multi-axis simulation table (MAST) to recreate ocean-like conditions for operating reactors in a controlled terrestrial experimental facility. In addition, NRIC's Integrated Energy Systems Demonstration approach through its testbeds can help to test various interfaces, controls, and other types of coupled nuclear-maritime systems to validate modeling and simulations results [45].

In addition to DOME, NRIC is developing the Laboratory for Operations and Testing in the U.S. (NRIC-LOTUS) test bed, which is envisioned to provide a Safeguards Category 1 Security posture as well as the following features for innovators:

- Mechanical and electrical penetration.
- Primary power and backup power.
- Ventilation system with monitoring.
- Direct reactor cooling system and decay heat removal system.
- Instrumentation and controls.

To efficiently test multiple reactor technologies, NRIC envisions a roughly 8-step lifecycle process for each demonstration that includes an application and agreement process, as well as phases for design through authorization, testing, shutdown, deactivation and decommissioning. This process is shown in Figure 4. Readers are encouraged to visit the website and contact NRIC[4] to learn more about starting this process.

The application and agreement process begins with a prescreening followed by a full application that addresses topics such as proposed nuclear safety, reactor information, testing schedule and procedures, regulatory compliance, data collection, staffing, transportation plans, fresh and irradiated fuel considerations, and deactivation and decommissioning (D&D) strategy. Applicants also need to provide rough estimates of costs and work orders with NRIC and INL to develop plans for scheduling, training, and contracting.

Design through authorization, testing, shutdown, and D&D falls within the project execution phase. This includes reactor design and integration in the DOME, National Environmental Protection Act (NEPA) compliance, nuclear safety documentation development, installation, commissioning, INL readiness reviews, DOE Operational Readiness Reviews, testing, final shutdown, and D&D of the irradiated fuel and reactor hardware.

While DOME will be a testing environment for microreactors, NRIC plans additional test beds that will follow similar processes for rapid demonstrations. This framework can also provide guidance for what will be needed to test advanced reactors in maritime environments.

1.4.3 Reactor Testing for Marine Conditions

The preliminary step towards nuclear power for maritime applications may require simulated marine environments within land-based laboratory testing and an approach to demonstrations on land.

This may include installing a nuclear test core on a dynamic platform under severe conditions, including exposure to simulated wind and wave-accelerated motions and performance when exposed to salt water, if applicable.

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[4] National Reactor Innovation Center Website: https://nric.inl.gov/

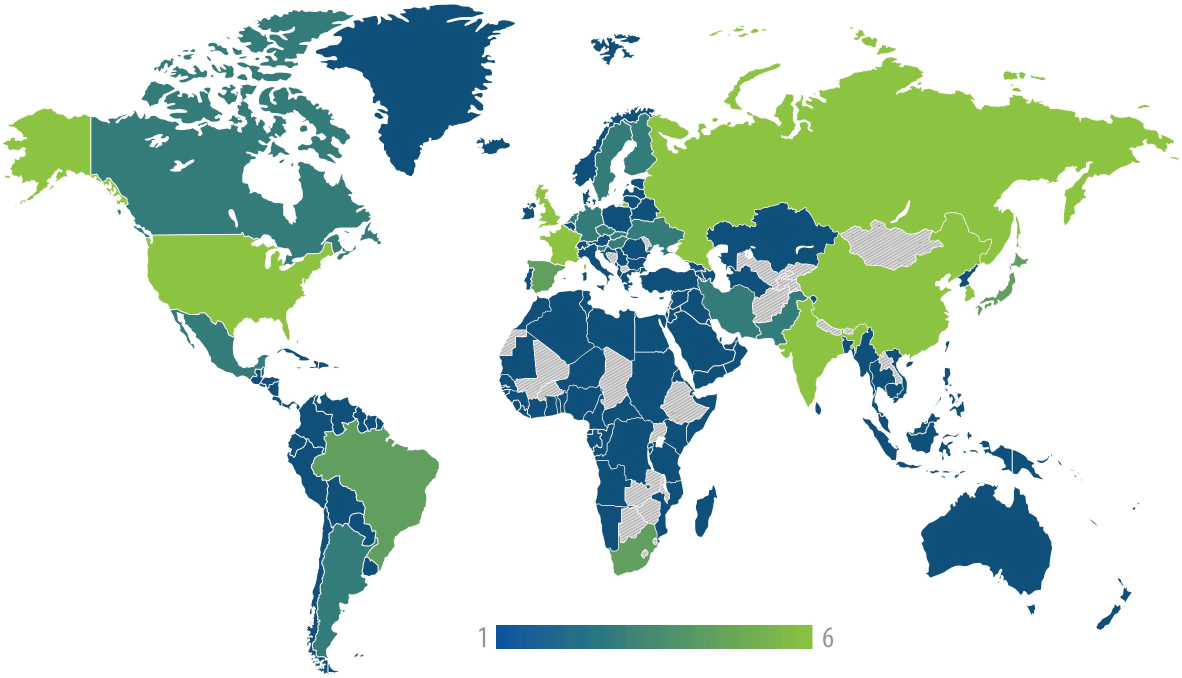

FIGURE 5: Commercial Maritime Surface Vessel Nuclear Propulsion (CMNP) Port Access Map

The primary goals of testing for the marine environment include evaluating the advanced reactor core performance and capabilities. The demonstration at this phase is directed at those reactors that may function in dynamic conditions and achieve successful demonstration credentials to continue testing in the field.

Test or simulation objectives can include:

- Operations (or simulated operations) for specific time frames under dynamic test conditions.
- Shutdown under (simulated) storm conditions (extreme environmental event).
- Power Stability.
- Steady and Predictable Fuel consumption rate.
- Reliability under dynamic conditions.
- Simulated or conceptual system power and control integration.
- power and controls integration.

1.4.4 Today's Nuclear Navies

When conceptualizing the potential development of commercial maritime reactors, military reactors used by today's six nuclear navies[5] are the primary reference point. However, there is no interest in the commercial nuclear or maritime sectors to replicate the naval model for merchant purposes. Naval reactors are designed for extended lifetimes of high performance and, as a result, rely on high enriched uranium (HEU) fuels and large teams of trained operators. This creates high economic costs and political arrangements in the form of bilateral diplomatic agreements that can only be managed by organizations at the scale of a national government. There are additional key differences between the operational profiles of merchant and naval vessels that require commercial technology to be drastically different from naval technology. This includes factors like the percentage of a commercial vessel's lifetime spent in transit and the power demand throughout that transit. The average container vessel, for example, spends far less time in port than the average aircraft carrier.

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[5] U.S., United Kingdom, Russian Federation, France, People's Republic of China, Republic of India

In Figure 5, the countries indicated in green have the most experience associated with commercial nuclear power and naval nuclear propulsion. Color scale examples: U.S. (6), Brazil (5), South Africa (4), Canada (3), Australia (2), Mongolia (1) [18].

1.4.5 Commercial Maritime-Applications

As the world rises to the challenge of addressing climate change, the maritime sector is increasingly concerned with meeting the approaching emissions reduction targets. The IMO—a United Nations agency responsible for regulating shipping—has adopted a 2050 target of reducing all GHG emissions from international shipping compared to 2008 levels [4]. The largest 3,000 commercial ships today are responsible for roughly 45% of all maritime sector emissions, and between 70% and 80% of the sector's emissions come from container ships, bulk carriers, and tankers. Although the maritime industry is beginning to invest in various solutions to achieve this transition, challenges remain related to mitigating emissions from conventional liquid or gas-fueled power generation. Nuclear power stands apart as a proven technology that has the potential to decarbonize high-powered maritime sectors.

Nuclear power can prevent emissions and present the opportunity to design an entirely new operational paradigm for commercial vessels and offshore units. Longer periods between refueling and the possibility of increased vessel speeds can revolutionize 21st-century maritime industries. In addition to repowering marine vessels, a range of offshore units and industrial applications that currently require large amounts of power could be locally addressed by an advanced nuclear reactor onboard or nearshore.

The current U.S. Administration is aligning with the DOE's climate goals, with the Secretary of Energy urging the nuclear industry to extend business cases beyond electrical generation applications [46]. At the 2021 COP 26 session, U.S. Special Presidential Envoy for Climate said "The technologies that we need to decarbonize shipping are known to us, so they need investment, and they need to be scaled up. It's incumbent on all nations to send a clear signal to the industry so they will make those investments in the near future [47]." At the 2022 COP27 in Sharm El-Sheikh, Egypt, he reiterated the current U.S. Administration's commitment to nuclear power as a climate solution [48]:

> *"We have a viable alternative in nuclear ... This is one of the ways in which we can achieve net-zero… We don't get to net-zero by 2050 without nuclear power in the mix."*

While today there are limited regulatory "drivers" in the U.S. for accelerating the development of maritime nuclear power, there is a regulatory precedent for using civilian reactors at sea. Most notably, this includes the nuclear ship NS Savannah, the first U.S. commercial nuclear-powered vessel that operated between 1959 and 1972, shown in Figure 6.

FIGURE 6: The NS Savannah at the 1962 World's Fair
Source: U.S. National Archives 326-NS-56

The NS *Savannah* was the result of the U.S.' 1953 Atoms for Peace initiative. The vessel was a joint project of the Atomic Energy Commission (AEC), MARAD, and the U.S. Department of Commerce (DOC). Her maiden voyage with both passengers and cargo was in August 1962.

The 595-foot-long vessel was powered by a single 74 MWt Babcock and Wilcox pressurized water reactor (PWR) utilizing fuel with a uranium enrichment of 4.2% to 4.6%. The total initial cost was $46.9 million (including $28.3 million for the reactor and fuel). The 124-person crew was a third larger than ships of comparable size, adding to operating costs. 60 first-class passengers could be accommodated [49]

The passenger service was discontinued two and a half years after it began. Cargo service was limited by the ship design and arrangements, where similarly sized ships could carry much more cargo. In addition, the design did not accommodate the automated cargo handling systems that became more common.

MARAD decided to decommission the NS Savannah in 1972 after travelling more than 450,000 miles and visiting 45 foreign ports in 26 countries. As of 2024, with its reactor and nuclear system removed, the ship is docked in Baltimore harbor [50].

The regulatory history of commercial maritime nuclear power also includes Offshore Power Systems, a fully licensed 1970 joint venture between Westinghouse Electric Company and Newport News Shipbuilding and Drydock to mass manufacture floating nuclear power plants (FNPPs). Even though initial site preparation work was completed in Florida for a manufacturing facility, this venture never materialized due to issues related to the 1973 oil crisis and safety concerns following the Three Mile Island incident in 1979 [51].

The Road Map

2 The Road Map

Following demonstration and testing activities in association with INL and NRIC, we anticipate the developmental road map for different nuclear-maritime applications will occur according to the complexity and feasibility of the application, as shown in Figure 7. Figure 7 aims to provide a qualified likelihood of what demonstrations would be pursued on land, on stationary offshore applications, or on vessels based on justified feasibility. The feasibility of a nuclear-maritime application is a complex and dynamic assessment composed of technical and technological maturity, regulatory complexity, and economic considerations. In this report, the term "demonstration" may be understood to mean either a DOE-authorized testing operation or an NRC-licensed FOAK nuclear-maritime deployment.

Example applications within each application category are provided in Figure 8.

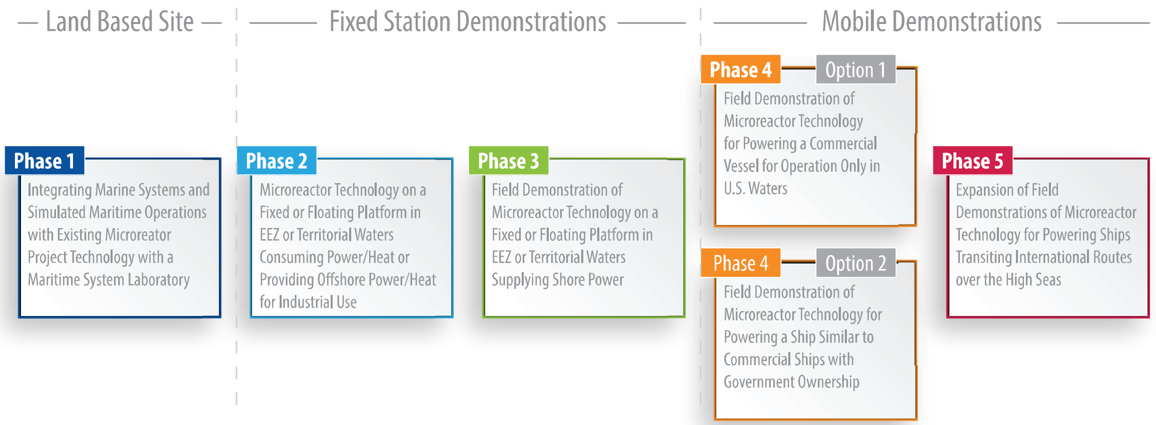

FIGURE 7: Road Map to Develop Commercial Maritime Applications of Nuclear Technology according to Complexity

LAND-BASED APPLICATIONS

Reactor Onshore
(See 2.4)

Applications:

- Microreactor or SMR sited at port producing electricity, heat, or synthetic fuels

OFFSHORE FIXED OR FLOATING APPLICATIONS

Reactor Offshore: Offshore Power Consumption
(See 2.5)

Applications:

- Small floating power station for offshore industry
- Floating datacenter *(See 2.5.1.1)*
- Small floating power station for offshore eFuels production *(See 2.5.1.2)*
- Floating desalination plant *(See 2.5.1.3)*

Reactor Offshore: Onshore Power Consumption
(See 2.6)

Applications:

- Small floating power station for coastal industry

MOBILE APPLICATIONS

Reactor Offshore: Nuclear Powered Vessels (International Transport)
(See 2.7)

Applications:

- Nuclear power container ship
- Nuclear electric dry cargo ship
- Nuclear electric gas carrier
- Nuclear electric car carrier with electric vehicle charging and power to shore
- Nuclear electric passenger ship
- Nuclear deep sea tug
- Nuclear electric ice breaker with reverse cold ironing facility
- Nuclear electric tanker

Reactor Offshore: Nuclear Powered Vessels (Domestic Transport)
(See 2.8)

Applications:

- Nuclear electric river towboat
- Nuclear electric offshore support vessel
- Nuclear electric tanker
- Nuclear drill ship
- Nuclear electric dredging vessel
- Nuclear power container ship
- Nuclear electric dry cargo ship
- Nuclear electric gas carrier
- Nuclear electric car carrier with electric vehicle charging and power to shore
- Nuclear electric passenger ship

FIGURE 8: Example Applications for Demonstration Categories

2.1 Regulatory Development Milestone in the U.S.

The demonstration effort includes not only investigating the functional capabilities of the applicable nuclear technology and its integrated systems, i.e., nuclear reactor technology certifications and/or maritime certifications, but also evaluating the feasible regulatory landscape that must be accommodated based on the specific application. It is not yet clear how the existing nuclear and maritime regulatory frameworks of each nation are expected to collaboratively fit together. However, investigating existing regimes is a first step to understanding the full scope of stakeholders that may be involved.

The regulatory environment of individual demonstration projects and eventual end-use cases is specific to the use case and the location of the application. See Figure 9 for a matrix of the likely demonstration milestones based on nuclear and maritime industry technologies.

Independent efforts to achieve regulatory certification of land-based reactor designs follow the nuclear regulatory path, while maritime technology or assets would follow their own existing pathways for approvals. To successfully achieve the technical and regulatory certification of a nuclear-maritime asset, these two pathways are expected to occur simultaneously and interact symbiotically.

Depending on the jurisdictions at the intended location and operational use, other regulatory milestones established by other authorities may need to be investigated or demonstrated to achieve certification.

2.1.1 New Reactor Technology Demonstration and Regulations

As previously indicated, the NRC licenses all existing commercial nuclear power plants in the U.S., and the maritime applications examined here assume that any reactor made commercially available would need an NRC authorization to operate. However, it is too early to speculate on how a licensing process for nuclear-maritime reactors would work and is, therefore, beyond the scope of this research at this time. Current licensing pathways for reactors are explained here to provide context.

In addition, the NRC continues looking to find solutions in advancements of technology as they have been directly engaged in stakeholder and pre-application meetings with microreactor developers. While the Nuclear Energy Institute (NEI) anticipates that many of the microreactors will include numerous features in the technological aspect, NEI has acknowledged that the designs of the microreactors submitted to NRC will need to incorporate detailed information on their advanced features [52].

NRC license applicants currently have two primary licensing pathways available: a two-step licensing path through the U.S. Code of Federal Regulations (CFR) Title 10 "Energy" Part 50 or a combined license application through 10 CFR Part 52 [36].

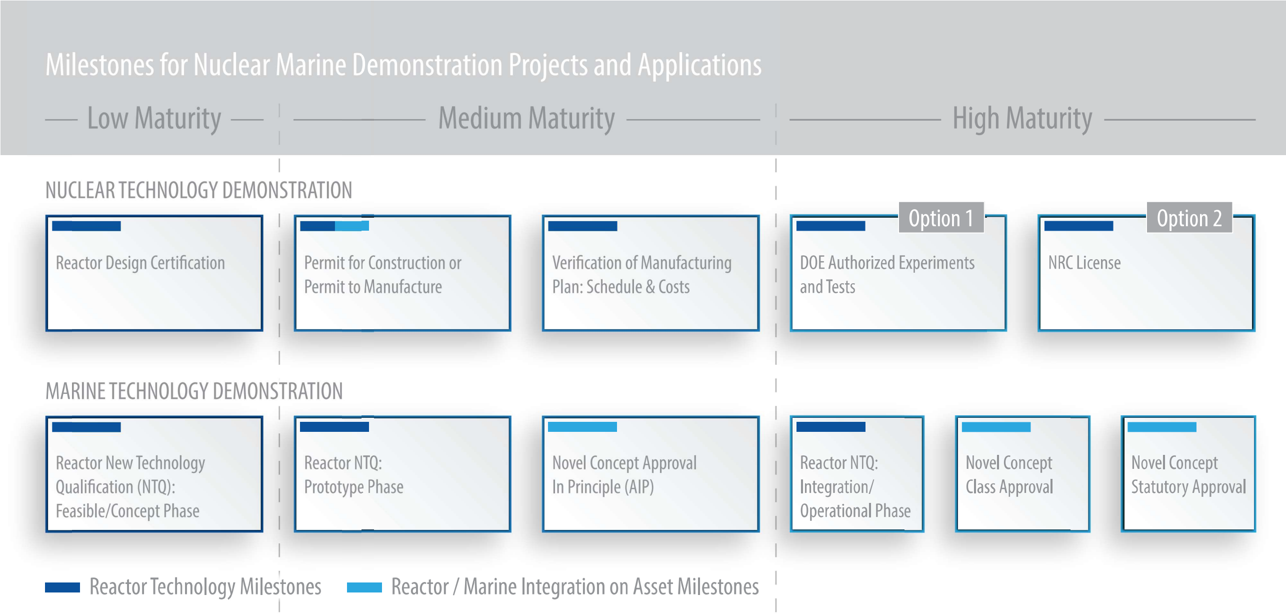

FIGURE 9: Example Demonstration Milestones Matrix

2.1.1.1 10 CFR Part 50

Part 50, "Domestic Licensing of Production and Utilization Facilities," contains the 'traditional' and well-known licensing process for commercial nuclear reactors. It is a two-step process composed of the construction permit and a subsequent license to operate [53]

The major technical submittal to support a construction permit is the preliminary safety analysis report (PSAR), focusing primarily on design and construction features. Both the general design criteria for the reactor and siting criteria are required aspects of an application for a construction permit. Part 50 contains the general reactor design criteria, while Part 100, "Reactor Site Criteria" contains criteria for proposed reactor sites [54].

For the operating license application, the PSAR is used as the basis for the final safety analysis report (FSAR), including several other important considerations for operations, including organizing plant operations, quality assurance programs, control and testing plans before startup, maintenance plans and emergency plans. Design and operational considerations for the public's protection against radiation is also an important part of the application, the criteria for which are established in 10 CFR Part 20, "Standards for Protection against Radiation" [55].

2.1.1.2 10 CFR Part 52

CFR Part 52 was developed to provide an alternative, more streamlined path to licensing reactor technologies and provide a pathway for the standardization of nuclear power plants. It also was intended to address issues related to resolving changes in the design during the licensing process. Part 52 requires an essentially complete reactor design to be submitted to the NRC as part of a combined construction permit and operating license (COL) application. If the reactor design is not essentially complete, an applicant would use Part 50 instead. Making design or siting changes during the licensing process, however, is allowed.

Beyond the COL, Part 52 includes licensing pathways for issuing early site permits, standard reactor design certifications, and manufacturing licenses. Early site permits allow for the early resolution of site-related environmental and site-specific design issues before any large financial resources have been committed to the construction.

The design certification works in a similar way to resolve reactor design issues and essentially certify a complete reactor design, independent from the site-specific issues. However, for design certification and manufacturing licenses, advanced untested designs would likely require full-scale prototypes to be built and tested first. Rather than submit a PSAR or a FSAR as per Part 50, Part 52 requires the submittal of only one standard safety analysis report (SSAR). Although site-specific information is not required for a design certification, conceptual general site parameters must be provided. If general site parameters are broad in the design certification, the design can theoretically be used at a greater number of locations. Part 52 also requires the submittal of proposed criteria for inspections, tests, analyses and acceptance criteria for the reactor. These requirements are in addition to the requirements of Part 50 with the goal for a final design to meet the expectations of the design certification. The early site permit and design certification are optional prerequisites to the COL. Obtaining early site permits or design certifications allows for appropriate investment into those arrangements prior to full resource commitments.

The safety analysis reports submitted for both Part 50 and 52 are approved by the NRC such that the design criteria and operational processes are implemented by law in the final license [55].

2.1.1.3 10 CFR Part 53

On January 14, 2019, the Nuclear Energy Innovation and Modernization Act (NEIMA) was signed into law, directing the NRC to develop the regulatory infrastructure to support the development and commercialization of advanced nuclear reactors. This includes developing Part 53, a new regulatory pathway option available to developers intended to be technology inclusive. This means that "[t]he regulatory requirements developed in this rulemaking would use methods of evaluation, including risk-informed and performance-based methods, that are flexible and practicable for application to a variety of advanced reactor technologies."

Based on the current rule development schedule, which has included public meetings and workshops with external stakeholders across multiple phases, the NRC staff have been instructed to advance the development of the Rule so that a final version is complete for September 2024 [57].

2.1.2 Maritime Regulations

The regulatory approval framework for commercial vessels is slightly different from that of offshore stationary units. In general, all ships and offshore units must be registered by a Nation (the "Flag Administration") and certified to fly that administration's flag. Further discussion of jurisdictional oversight based on location is provided in Section 2.2.2

2.1.2.1 New Technology Qualification (NTQ)/ Technology Readiness Assessment (TRA)

The nature of international shipping passing through international waters and visiting global ports has developed a regulatory framework based initially on Flag Registration and incorporating the standards of all destination port nations. To harmonize the requirements, the IMO Member states adopt International Codes of design, safety and management practices, which must be met by the Registered vessels of that State and all ships visiting that State's ports and coastal waters. Commercial ships traveling on international voyages are typically subject to international codes and conventions, and member flag states have the authority to implement and enforce them. When IMO Codes are adopted by Member States, they are known as statutory requirements in those nations and are enforced by the local maritime administrations, as discussed more in 2.1.2.4.

Additional provisions may be required, depending on the vessel type, operations, and routes. For example, vessels passing through certain environmentally protected trade routes may need to meet more stringent emissions regulations. Typical design and safety regulations include provisions for intact and damaged stability, structural performance, life-saving equipment, fire protection, equipment and electrical systems, protection from high-pressure systems and hazardous cargo, propulsion and maneuvering capabilities, and more.

Many conventions relate to vessel safety, primarily developed by the IMO and its committees, although other international organizations may develop codes for their members. The below list includes some well-known IMO conventions that apply to ships:

- International Convention for the Safety of Life at Sea (SOLAS)
    - Of specific interest is SOLAS Chapter VIII, Nuclear Ships, which gives the governing national administration ("Administration") the authority to approve the design, construction and standards of inspection and assembly of the reactor installation. SOLAS standards are generally regulated by the USCG in the U.S. The Code of Safety for Nuclear Merchant Ships (resolution A.491(XII)) was adopted in 1981 but is restricted to the use of conventional types of vessels propelled by nuclear propulsion installations with pressurized light water (PWR) reactors. This restriction creates a significant regulatory impediment to use nuclear reactors on marine units as a means of providing power other than for propulsion and, until modified, will curtail the adoption of nuclear reactors aboard commercial merchant vessels. Thus, the Code must be modified by the IMO for international use of reactors as a power source other than for just propulsion, and the USCG must also adjust to implement the Code accordingly.
- International Convention for the Prevention of Pollution from Ships (MARPOL)
    - MARPOL addresses oil pollution and air emissions (currently NOx, SOx, and in the future, GHG emissions) from vessels flagged in nations that are a party to the MARPOL Convention. The U.S. legislation that implements MARPOL is the Act to Prevent Pollution from Ships (APPS).
- International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW)
    - STCW addresses training and certification standards for seafarers on vessels flagged in nations that are a party to the STCW Convention.
- Code for the Safe Carriage of Irradiated Nuclear fuel, Plutonium and High-Level Radioactive Wastes in Flasks on Board Ships (INF Code)
- International Convention on Load Lines
- International Code for Fire Safety Systems (FSS Code)

2.1.2.2 Offshore Regulations

While UNCLOS and the IMO instruments are primarily focused on the safety of passenger and cargo ships transiting international waters, they do not necessarily apply to offshore installations temporarily or permanently installed for oil and gas or other resource exploitation. However, international standards for design and safety are produced by various bodies of experts and can be adopted and enforced by Flag Administrations and maritime administrations within their jurisdictional waters. For example, the International Standardization Organization (ISO) and the American Petroleum Institute (API) produce many industry standards that can be enforced by maritime administrations and their agencies. Additional requirements may be imposed by local agencies according to location, for example, BOEM and sister agency BSEE have jurisdiction over natural resources under the U.S. Department of the Interior, including activities on the Outer Continental Shelf (OCS). These national agencies can impose additional safety, administrative, and environmental protection requirements on offshore installations and their activities.

2.1.2.3 Classification Approval

Most Flag Administrations require Certification from a Classification Society to verify unit compliance with the local and international regulations. Classification Societies also establish their own set of Class Rules and offer mandatory and optional certifications. Throughout a vessel's life, Class Societies operate to independently verify compliance with Class Rules and on behalf of Flag Administrations to verify compliance with Statutory Requirements. Classification societies are not expected to act as recognized organizations for reviewing and approving advanced reactor designs or issuing reactor licenses.

Classification Rules form the basis for assessing the design and construction of new vessels and the integrity of existing vessels, as well as marine and offshore structures. New and existing vessels are assessed pursuant to the Rules to provide a standard of safety for engineering design, operations, and maintenance [58].

Engagement with Class Societies and Flag Administrations starts in the design stage to verify all requirements are understood and will be met before construction activities. Classification societies implement Rules through a process of technical review of asset design plans, and attendance and verification by Surveyors at shipyards, production facilities, at sea trials, and periodically over the asset's lifetime.

The International Association of Classification Societies (IACS) acts as a centralized organization to standardize the minimum technical standards and requirements for classification[6].

2.1.2.4 Statutory Approval

When a flag state mandates rules or standards by statute (i.e., legislation), they become Statutory items to be met, typically requiring certification. Classification societies, acting as a Recognized Organization authorized by the flag state, can act on behalf of flag states to carry out statutory reviews and surveys.

2.1.3 Integrating New Technology or Novel Concepts for Maritime Use

In the maritime industry, integration of new technologies and novel concepts is done following a process of technological maturity and risk mitigation. This section broadly describes certification and approval regimes for maritime equipment and novel vessel designs. It is to be noted, however, that while the necessary licensing and approvals for advanced reactors are not subject to maritime certification, certain supporting or auxiliary equipment integrated into maritime systems may fall under this regime.

2.1.3.1 New Technology Qualification (NTQ) / Technology Readiness Assessment (TRA)

When planning to install new or innovative technologies on vessels or floating structures that do not have previous service history in that application, it is often recommended for the technology to undergo a technology readiness level (TRL) assessment. As shown in Figure 10, this assessment evaluates the maturity of a technology from design phase to operations and provides insight for designers, integrators, planners, and investors as to the readiness of the technology for use in a new application.

At ABS, this assessment is done by the New Technology Qualification (NTQ)process, specifically addressing technologies that often do not have governing industry codes or regulations for maritime uses. The ABS NTQ process is aligned with the nine DOE TRLs according to Figure 10 and Table 2 below.

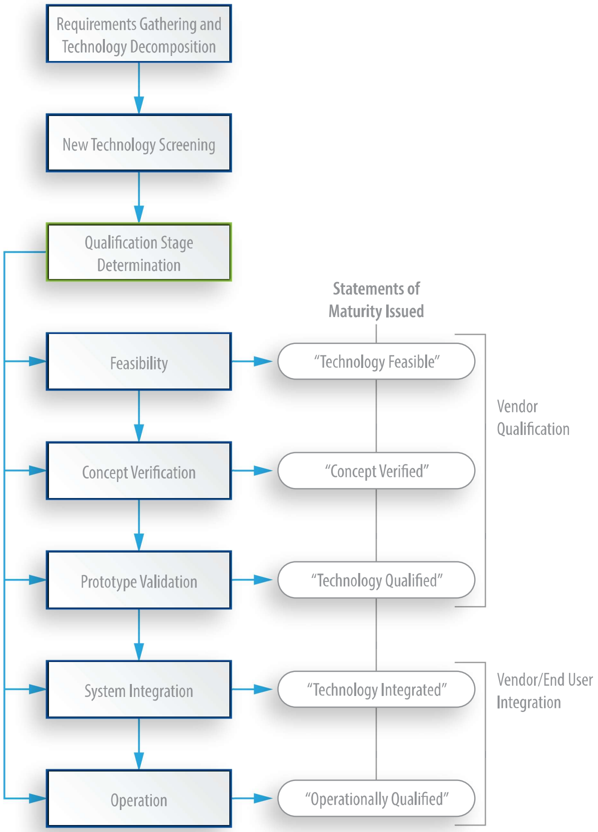

FIGURE 10: New Technology Qualification Levels

Without accepted industry standards for a technology's design, manufacturing, testing, installation, commissioning or operations, maturity assessments rely on risk assessments, as shown in Figure 11. With the phased approach for NTQ, the time to complete depends on the complexity and novelty of the technology.

It is the responsibility of the designer to provide functional and goal-based descriptions of the technology performance requirements in what is known as a Systems Requirements and Description Document (SRDD). ABS engineers simultaneously evaluate the technology design to verify if the technology meets the maturity level-aligned performance requirements. Feedback in the review process can support design modifications or other improvements that may need to be done to meet the requirements of each maturity level. When successful, the technology is provided a

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[6] Additional information on IACS, its members and activities are available at www.iacs.org.uk.

TABLE 2: Classification NTQ Alignment with U.S. DOE TRL [59]

ABS Qualification Stage	United States DOE Technology Readiness Levels	
Feasibility Stage	1. Basic principles observed and reported	Basic Technology Research
	2. Technology concept and/or application formulated	
Concept Verification Stage	3. Analytical and experimental critical function and/or characteristic proof of concept	Research to Prove Feasibility
	4. Component and/or system validation in a laboratory environment	Technology Development
Prototype Validation Stage	5. Laboratory scale, similar system validation in relevant environment	
	6. Engineering/pilot-scale, similar (prototypical) system validation in relevant environment	Technology Demonstration
System Integration Stage	7. Full-Scale, similar (prototypical) system demonstrated in relevant environment	System Commissioning
	8. Actual system completed and qualified through test and demonstration	
Operational Stage	9. Actual system operated over the full range of expected mission conditions	System Operations

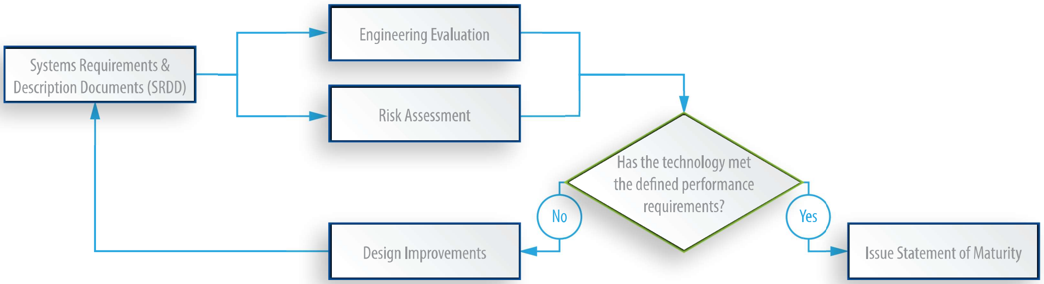

FIGURE 11: Process for New Technology Qualification

statement of maturity reflecting one of the five qualification stages [60]. When a high enough level of technological maturity is achieved, equipment can begin the process of Classification Type Approval to ease the adoption for use on Classified vessels and offshore units. Type approval involves a series of product design assessments, quality assurance verification and manufacturing assessments to approve standard equipment units can be built and supplied to multiple assets, without dedicated engineering and inspection oversight for each unit. Approaches such as type approval databases are common for Classification Societies to ease the amount of regulatory oversight and administrative burden of certifying equipment approved for use on Classified vessels and offshore units.

Although the process is optional, and it is unclear if type approval would be used for reactors, for nuclear reactor technology to be demonstrated as feasible and ready for installation and operation on a marine or offshore asset, the NTQ process and concept is a valuable starting point for designers to begin considering integrating the reactor core with maritime systems

2.1.3.2 Novel Concept Approval in Principle (AIP)

While the NTQ process is intended for individual technologies (systems, products, parts, components, materials, etc.) independent from a specific asset or platform, the Approval in Principle (AIP) Classification process assesses the readiness of vessels or offshore units overall to integrate new technologies or novel concepts.

At ABS, the overall class approval process for a novel vessel concept is divided into four milestones, shown in Figure 12. The first milestone determines the most appropriate approval route to obtain Class Society approval, including

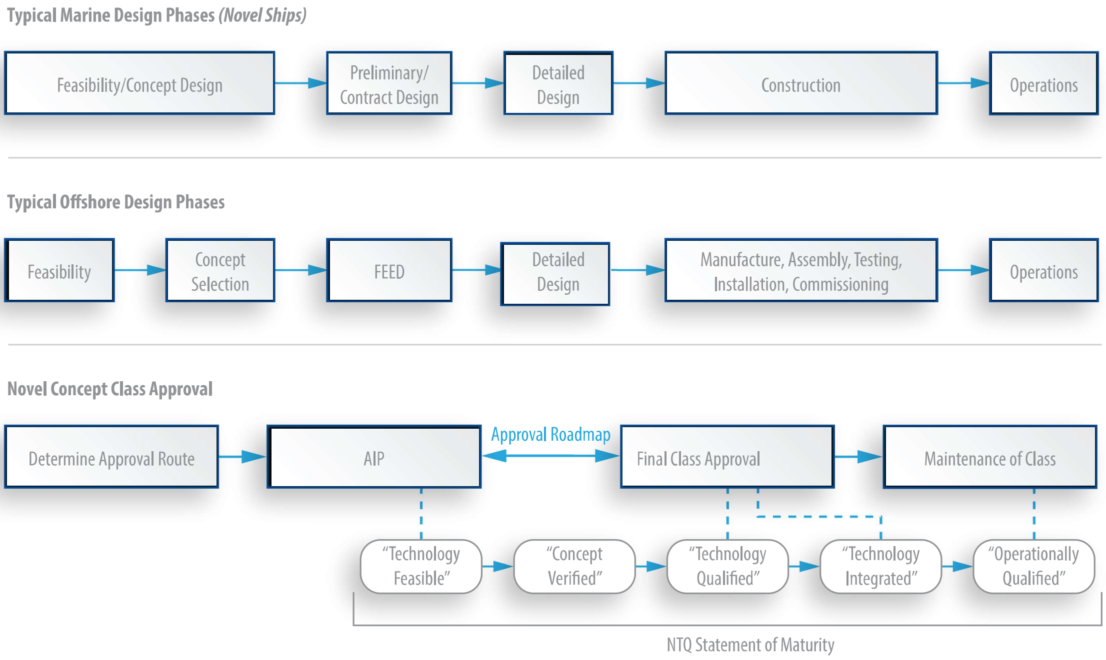

FIGURE 12: Process for ABS Approval In Principle

identifying standards or rules to meet. Second, an intermediary concept review confirms feasibility and outlines when and what to submit for final approval, the subsequent review process, and potential outcomes. Completion of the AIP results in a conditional set of requirements (an Approval Road Map) that must be met before final Class Society approval. The third milestone builds upon the AIP, with the project moving forward from concept design phase into detailed design, construction, and installation activities.

Although not integrated in the AIP process, the final milestone involves issuing Class Society final approval (Classification Certificate) and initiating subsequent maintenance of Class activities. This includes submittal and review of required deliverables. Finally, survey activities verify assumptions and predictions made throughout the process [61]. The AIP process can help an early design develop in several ways:

- Develop a road map towards final Flag State/ Classification Society approval.
- Aid in the maturation of the design.
- Avoid falling into the trap of an inadequate level of technology design detail through the NTQ verification process using equipment Statements of Maturity as the designer proceeds through the AIP phases.
- Aids the designer in choosing the appropriate standards and applicable requirements early in the design process.

An AIP can be used as a preliminary form of risk assessment to identify in the early stages of the design process any instances where risk is being layered and consequently magnified.

2.2 Governing Laws and Regulations

A key challenge that commercial nuclear-maritime concepts face is regulations and governing laws creating potential challenges, or imposing otherwise expected delays that are not aligned with the pace of technology development. This section introduces some expected regulatory authorities, which will or may interact with demonstrations or operations over a nuclear-maritime application's lifetime.

While there are numerous combinations of nuclear power for and maritime uses in different environments, end-use applications can be categorized generally by the location, either fixed (i.e., non-self-propelled) or mobile (i.e., self-propelled) and the purpose of nuclear energy (grid-connected or offshore consumption, etc.).

These general end-use categories are presented by their anticipated governing regulatory regimes such as standards for design, construction, commissioning, operations, inspection/survey, certification, decommissioning, licensing, insurance, and ownership requirements.

2.2.1 Corporate Social Responsibility (CSR)

Social license is a critical factor for the adoption and implementation of any new technology. The options for NRC licensing include public engagement through hearings and opportunities for public objection to generate acceptable compromise, consensus and approval through public acceptance (social license) [62].

The influence of social perception on the management of policies, regulations and laws when considering innovative technical solutions is notable. Although not necessarily tangible, the concept of a social license to operate refers to the acceptable or legitimate perception of society at a certain location. A society, in this case, may include population groups, companies, industries, or other stakeholders who have the right to hold and share opinions [63]. Corporate Social Responsibility (CSR) serves as a feature of social license activities, where companies take steps to adopt practices for the benefit of the communities beyond compliance with laws and regulations. To promote social license, companies' strategies should include provisions to address social and environmental concerns [64]. At present, CSR is viewed as a voluntary approach that a business enterprise takes to meet or exceed stakeholder expectations by integrating social, ethical, and environmental concerns together with the usual measures of revenue, profit, and legal obligation [65]. Some examples of CSR activities include environmental or social policy, public engagement or outreach activities, philanthropy, ethical labor practices, and volunteering [66]. Social license reflects the society's perceived level of acceptable risks, and if not met, can affect policies and regulations established for mitigating risks.

As shown in Figure 13, when risks cannot be first eliminated or substituted for a solution of lesser risk, engineering and administrative controls are put in place to minimize hazards caused by the perceived risk. Engineering and administrative controls are typically implemented as a code, policy, design standard, guideline, or other type of governing instruction. The last effort to protect against risks is to use personal protective equipment (PPE), which can also be mandated by codes, standards, and instructions [67].

Perceived risk is not always representative of actual or calculated risk, however, and can be adjusted or changed with new information or different situations. Education, as well as personal experience and social behaviors or cultures, are powerful tools for informing and changing perceived risk.

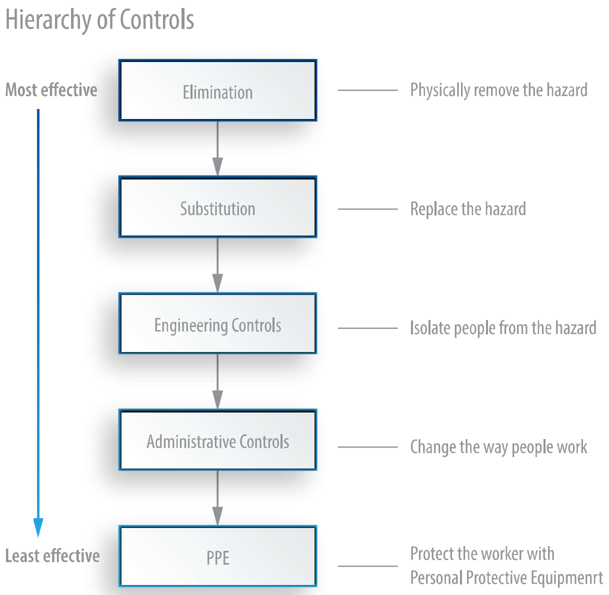

FIGURE 13: National Institute for Occupational Safety and Health Hierarchy of Risk Controls

2.2.2 Location

The location of the reactor will dictate the overarching jurisdictions for which the application must be approved. We expect that the fewer jurisdictions that apply, e.g., reducing the number of locations or shortening the distances over which nuclear materials travel, the simpler the process will be to achieve necessary approvals. For maritime applications, see Figure 14 below associated with the descriptions of seaborne jurisdictions.

2.2.2.1 Fixed Station

Fixed maritime applications, for example, may be offshore installations designed to remain on location for the operating life of that asset. Fixed offshore installations may be stationary, gravity-based structures secured to the seabed (and therefore not subject to the same accelerations due to wind and waves), or floating installations that are moored or otherwise tethered on location. Fixed installations are not normally self-propelled.

Installations within Flag Administration exclusive economic zones (EEZs) or Territorial Waters are subject to the jurisdictional authorities as presented below:

- Exclusive economic zones (EEZ) are defined in UNCLOS and "shall not extend beyond 200 nautical miles from the baselines [7] from which the breadth of the territorial sea is

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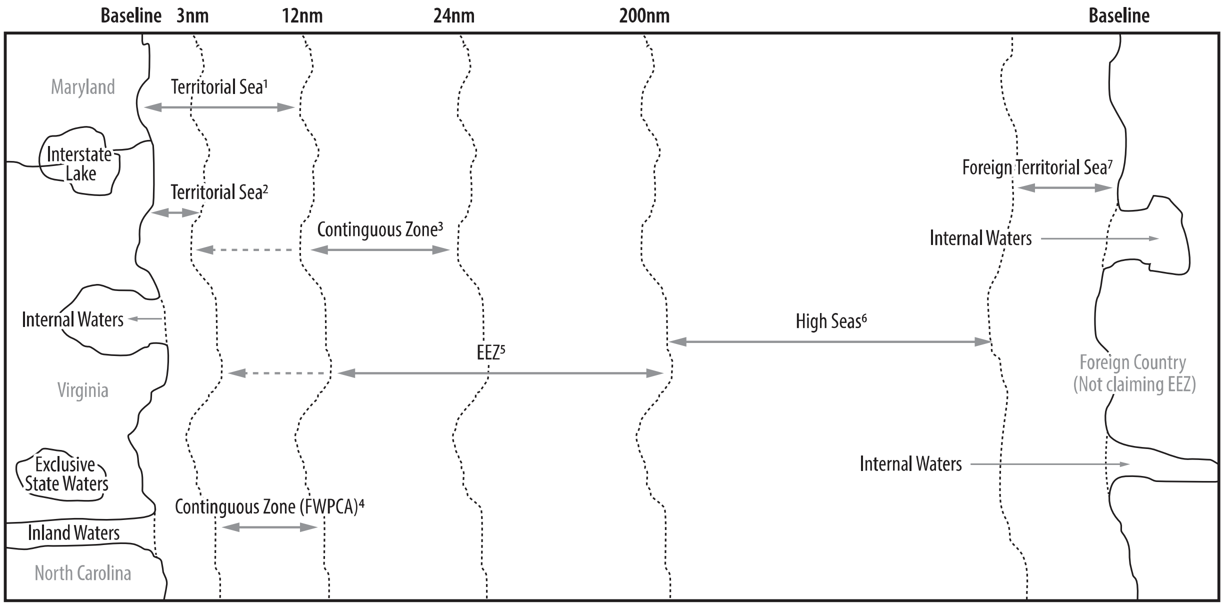
[7] Normal Baseline is defined in UNCLOSas "the low-water line along the coast […]"



[1] Territorial sea for purposes identified in §2.22(a)(1).

[2] Territorial sea for purposes identified in §2.22(a)(2).

[3] Contingous zone as described in §2.28(b), varies with territorial sea width for particular purpose involved.

[4] Contingous zone as described in §2.28(a), for Federal Water Pollution Control Act purposes.

[5] Exclusive Economic Zone (EEZ) is measured from the seaward limit of the territorial sea, as variously defined in §2.22(a), to a distance of 200 nautical miles from the baseline. The inner (shoreward) boundary of the EEZ will vary for particular purposes.

[6] High seas as defined in §2.32(d). When a nation has not proclaimed an EEZ, the high seas begin at the seaward edge of their territorial sea.

[7] The U.S. recognizes territorial sea claims of other nations up to a maximum distance of 12 nautical miles from the baseline.

FIGURE 14: Jurisdictional Areas defined by United States CFR [68]

measured." Within a Nation's EEZ, the governing sovereign establishes who has the right to explore and exploit natural resources, and the extent of jurisdiction over marine applications or offshore installations, including for example, regulatory oversight by federal agencies.

- Territorial waters, or the territorial sea, are generally (but not always) the waters within a zone that extends 12 nautical miles from shore. This zone is known to be sovereign territory of the adjacent nation, although marine innocent passage rights for the purpose of navigation may take precedence. In the U.S., regulatory bodies with oversight in territorial waters may include:
  - » U.S. Coast Guard (USCG)
  - » U.S. Army Corps of Engineers (USACE)
  - » U.S. Environmental Protection Agency (EPA)
- Internal waters are all waters that fall landward of territorial waters, including river deltas, sheltered ports, and tidewaters. These waters fall under the same jurisdiction as their state or local authority, where there is no right of innocent passage. Internal waters may also fall under the jurisdiction of local municipal or city jurisdictions.

Installations that are considered Foreign Stations may be those located in a different jurisdiction than that of the Flag Administration, for example:

- International Waters, where jurisdiction may be under UNCLOS.
- Other Nation's EEZ or territorial Waters (where jurisdiction would be the counterpart to USCG), where jurisdiction may be under the maritime authority of the local national sovereignty.

2.2.2.2 Regulations Related to Transport Between Jurisdictions

Activities related to the transportation of nuclear material will also be subject to the jurisdiction of location. In the U.S., the NRC works with the Department of Transportation (DOT) to oversee the transportation of radioactive materials, including spent nuclear fuel.

The DOT regulates shippers of hazardous materials, including radioactive material, and oversees vehicle safety, routing, shipping papers, emergency response, security and crew training. The NRC regulates users of radioactive material in 11 states (39 states regulate users within their borders), approves the design, fabrication, use and maintenance of shipping containers for the most hazardous radioactive materials, including spent nuclear fuel, and regulates the physical protection of commercial spent fuel in transit against malicious acts. The NRC requires radioactive materials shipments to comply with DOT's safety regulations for transporting hazardous materials. NRC regulations for the safety of transport packages for large quantities of radioactive materials, including spent nuclear fuel, are found in 10 CFR Part 71.

Marine transportation activities of nuclear material within the above waters must also follow the requirements of the jurisdiction. For vessels to transport nuclear fuel and materials, the USCG requires compliance with SOLAS [8], Chapter VII, Carriage of Dangerous Goods. This is applicable to all ships, including cargo ships of less than 500 gross tons, engaged in the carriage of INF cargo. Part D of Chapter VII includes special requirements for carrying packaged irradiated nuclear fuel, plutonium and high-level radioactive wastes on board ships to comply with the INF Code, adopted by the Maritime Safety Committee of the IMO by resolution MSC. 88(71). The INF Code does not apply, however, to the transport of fueled nuclear reactors.

If transportation will occur entirely within state waters, the applicable state's laws and regulations governing the transportation of nuclear materials also apply; whether such laws apply to transportation that passes through such waters to a position beyond the state territorial boundary is a function of whether such laws are preempted in whole or in part by applicable federal laws and regulations.

If nuclear material is carried from a foreign location to an offshore site aboard a foreign flag vessel, the vessel's flag state's regulations will also govern approval at the offshore site. Section 388 of the Energy Policy Act of 2005 gives the U.S. Secretary of the Interior, in coordination with other agencies, authority over offshore renewable energy developments on the OCS. BOEM is the lead implementing agency for this responsibility. Also, with a recent legislative change to the Outer Continental Shelf Lands Act ("OCSLA") an offshore structure on the OCS used to develop or produce renewable energy is also subject to federal law and the law of the adjacent state so long as it is not inconsistent with federal law. Such an offshore site also constitutes a point within the U.S for the purposes of the Jones Act, meaning that any personnel or merchandise carried between points in the U.S. (for example, from shore to offshore site) must be carried aboard a U.S. flag vessel.

2.2.2.3 Mobile

Mobile applications may be offshore installations or assets capable of operating in multiple locations for certain periods or designed for regular transits under self-propulsion or non-self-propulsion.

- Domestic Transportation (Port-to-Port transit without leaving national EEZ or territorial waters, e.g., San Francisco to San Diego). This activity is known as cabotage, where vessels transport goods and passengers between two ports within the same country. Vessels exclusively transiting between domestic ports are subject to the regulations of their Flag State Authority (where the vessel is registered) and the regulations imposed by the authority of the waters the vessel travels and the ports it enters. In the U.S., merchant cabotage vessels are subject to the Jones Act (Section 27 of the Merchant Marine Act of 1920), requiring vessels to be flagged in the U.S. and primarily built, owned, and operated by U.S. citizens or permanent residents [68].

- Transportation through International Waters (Port-to-port transit from national waters into international waters and returning to a port of the same nation, e.g., San Francisco to Honolulu, Hawaii). Other than transport to the U.S. Virgin Islands, American Samoa, and the Northern Mariana Islands, these vessels would also be subject to the Jones Act [69]. The difference in regulations between this type of transit and the former is the application of international regulations when vessels leave domestic waters and enter international waters.

- International Transportation (Port-to-Port transit from one Nation/Country Port to a different Nation/Country Port, e.g., San Francisco to Yokohama, Japan). Not subject to the Jones Act, vessels traveling internationally from one country to another are subject to their flag state requirements, both country's sovereign jurisdiction within waters under their control, port state requirements, and any applicable regulations for ships transiting international waters or trade routes.

2.2.3 Use of Nuclear Energy

The heat energy generated from nuclear fission can be used in various ways (e.g., direct heat supply, or the generation of mechanical or electrical energy). Regulations may differ for power sources connected to the grid or serving independent (micro-) grids. An anticipated application of nuclear-maritime is electrical supply to land-based grids or independent (offshore, in this case) microgrids.

Note that some applications may be capable of connecting and disconnecting to land-based grids. For example, temporarily stationed power barges or

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[8] The U.S. has adopted SOLAS Convention 1974, SOLAS Protocol 1978, SOLAS protocol 1988, but not SOLAS Agreement 1996.

Table 3: Preliminary Regulatory Gap Analysis

Gap Analysis	Activity or Milestone	Description (jurisdiction, authority, etc.)	Gaps – what may need to be addressed?
Nuclear Technology Demonstration	Authorized Experiments and Tests	DOE	Doesn't allow commercial applications
	Nuclear Regulator Authorization	NRC	Reactor Design Certification, Operating License, Manufacturing License for small modular or microreactors Fueled Reactor transportation and physical protection systems (10 CFR Part 73), etc. for small modular or microreactors
Marine Technology Demonstration	Equipment Certification & Type Approvals	Recognized Organization	Doesn't typically cover nuclear reactors
	Classification Approval	Classification Society	Rules to be updated to address Advanced Nuclear Reactors for ships and offshore units
	Statutory Approval	Flag State	Rules to be updated to address Advanced Nuclear Reactors for ships and offshore units
Other Maritime or Nuclear Regulatory Milestones: Location-Based	Territorial Waters & Internal Waters	National Authority, Local Authority	Issues involving or allowances of nuclear material and reactors
	EEZ Waters	National Authority	Issues involving or allowances of nuclear material and reactors
	International Waters	Enforced by member states	Rules to be updated to address Advanced Nuclear Reactors (Beyond SOLAS Chapter VIII) [70] Note: U.S. is not a party to UNCLOS
	Transport of Nuclear Fuel	Applicable transportation authority. In the U.S., the DOT	Covered under the IMO INF Code DOT regulations cover the transportation of nuclear materials within the U.S
	Transport of Fueled Reactor	Applicable transportation authority. In the U.S., the DOT	Rules for transporting reactors carrying unused or partially used nuclear materials to be updated
Other Maritime or Nuclear Regulatory Milestones: Application-Based	Power to Nearby Offshore Installations	Specific requirements for integration	Rules to be updated to address Advanced Nuclear Reactors
	(Grid) Shore Power Supply	Local & national energy department	e.g., State and Federal Power regulations governed by organizations such as State public utility commissions (PUCs) or the Federal Energy Regulatory Commission (FERC)
	Power Self-Consumption Onboard (integrated with marine systems)	Engineering Standards and Equipment Certifications	Rules to be updated to address Advanced Nuclear Reactors

Gap Analysis	Activity or Milestone	Description (jurisdiction, authority, etc.)	Gaps – what may need to be addressed?
End of Life Regulations – Nuclear Decommissioning, Waste Transport and Disposal	Nuclear decontamination & decommissioning, nuclear waste management/SNF management[9]	In the U.S., NRC, DOE, EPA, DOT	• NRC Licensing: storage and disposal of commercially generated nuclear wastes in the U.S. as well as disposal of SNF and high-level wastes generated by the DOE • DOE: oversees treatment and disposal of radioactive waste from weapons as well as siting, building, and operating a future geologic repository to dispose of nuclear waste • EPA: sets environmental standards for SNF disposal • DOT: establishes regulations for the transport of nuclear material
End of Life Regulations – Marine Decommissioning	Inventory of Hazardous Materials & Vessel Recycling	Flag State	Recycling codes generally do not include nuclear materials, but could be achieved by decommissioning to equivalent levels of safety

ships in port supplying power through a ship-to-shore power arrangement would generally be included in the category of a grid-connected power source.

Table 3 summarizes regulatory gaps related to technology, locations or use. For each milestone, preliminary gaps are provided which may need to be addressed in more detail to identify how nuclear-maritime applications can successfully achieve demonstration approvals and final success.

2.3 Value Case Approach

For each example value proposition in this section, assumptions are identified, and market opportunities described are constrained to FOAK limitations. Understanding that these limitations may change with advances in developing technology, these market opportunities are scoped to identify the initial value proposition of advanced nuclear reactors in the maritime domain. It should be noted that the values presented on future demand may not reflect the total number of reactors, but in some cases may be fitted with multiple reactors to meet the anticipated demand[10].

Estimates are provided on the production rate of advanced nuclear reactor installations for each use-case and assume the capture of no more than 10% market share between the 2045-2050 timeframe. This estimate is based on research that identifies the market growth rate for each use-case. Market growth rate forecasts are not typically projected out to the 2050 timeframe, so it is assumed that a constant compound annual growth rate (CAGR) over identified periods is used to project out to the specified timeframe. This model is subject to uncertainty as a constant growth rate is an unlikely scenario; however, this methodology allows for a framework to compare market needs for advanced reactors across various use-cases.

The rate at which an installation or vessel will need to be replaced with advanced reactors can be determined using Little's Law [71]:

$$L = \lambda * W$$

Where L is the market size between 2045-2050, λ is the annual frequency at which new installations or vessels needs to be put into the market to maintain market size, and W is the average lifespan of the installation or vessel.

Assuming advanced reactors can capture 10%[11] of the market by 2050, we factor λ by 10% to determine how many advanced nuclear reactors need to be put into the market each year. Market growth G for each application needs to be considered, so the following expression captures the annual production rate for nuclear-maritime use given

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[9] SNF management is discussed in later report in series as potential challenge for maritime applications.

[10] Every type of nuclear-maritime application described is assumed to have achieved a license from the appropriate authorities to operate in its intended environment and locations.

[11] This assumption is based on nuclear energy capturing 10% of the energy market from its inception with its first commercial nuclear power plant entering operations in 1958 to capturing 10% of electricity net generation in the U.S. over the next 20 years [98].

market growth A, market size L, average vessel lifespan W, market capture for advanced nuclear C, which we assume at 10%, and annual frequency for new vessel production λ:

$$A = \lambda * G * C$$

$$A = \frac{L}{W} * G * C$$

To capture additional capacity needed for new vessels by 2050, L^2050, we consider the growth rate over each time segment T to be constant from 2022:

$$L^{2050} = (L)(1+G)^{\frac{2050-2022}{T}} - L$$

To obtain the annual production rate for advanced nuclear-powered vessels to achieve an L^2050, A^2050, we scope our market size to vessels requiring over 10 MW installed power for propulsion in the U.S. market and 14 MW for the international market, as we assume vessels with this minimum power requirement stand a higher likelihood of using advanced nuclear reactors given market feasibility according to the following expression:

$$A^{2050} = \frac{L^{2050}}{W} * G * C$$

2.4 Reactor Onshore for Maritime Industrial Operations

Before considering installing nuclear power on stationary floating assets, it is important to discuss nuclear power applications for maritime purposes while still located onshore, identifying the lower bound of applications for advanced reactor use in the maritime sector. This category is identified as having a reactor on shore co-located with electricity, heat, or synthetic fuel production facilities which can be used for maritime industrial operations. This is primarily related to connecting the land-based nuclear power services to the electrical demands of ports, including shipyard and ship maintenance activities and supplies, cargo and equipment handling facilities, bunkering supply and delivery services, and onshore power supply (OPS) services to vessels in port or nearby. While the commercial grid may be able to support some of this activity (some of which may include electricity generated from distant nuclear power plants), increasing demand for high density power supply to port industries may call for additional, dedicated power sources.

Land

Reactor Onshore
See 2.4

Applications:

- Microreactor or SMR sited at port producing electricity or heat

2.4.1 Business Cases & Market Opportunity

It is expected that demonstration projects on land can assist in evaluating the functional feasibility of the nuclear technology in similar floating conditions. For land-based applications, two applications have been examined, where a nuclear facility produces electricity for port use, and where a nuclear facility powers synthetic marine fuel production.

FIGURE 15: Port Newark-Elizabeth © Mihai_Andritoiu/Shutterstock

2.4.1.1 Port Producing Electricity

Maritime infrastructure and port activities incur high power demands to the local grids. Port electrical demand is represented in this example by one of its highest demands, supplying shore power to visiting vessels. Advanced nuclear reactors could be connected to the port grid or isolated with supply agreements to supplement grid power.

The adoption of OPS for vessels is primarily driven by efforts and policies to reduce air and noise emissions from large vessels while in port. Ports within the U.S. with high-capacity (greater than 6.6 kV) OPS installed are listed in Table 4.

Table 4: High Capacity OPS Systems installed in U.S. Ports [71]

Port Name	Vessel Types using OPS	Year of Installation	Maximum Capacity (MW)	Average Usage
Juneau	Cruise	2001	11.00	4,107 MWh
Seattle	Cruse, Cruise Ferries (WSF Terminal)	2004, 2024 Planned, 2025 Onward	20	4,091 MWh (2019)
San Francisco	Cruise	2010	12.00	3,872 MWh (2019)
Brooklyn	Cruise	2015	20	596 MWh (2019)
Los Angeles	Cruise, Container	2004	40.00	19,560 MWh
Long Beach	Cruise, Container, Tanker	2011, 2009, 2000	16.00	10,182 MWh (2019)
San Diego	Cruise, Reefer	2010	12.00	3,308 MWh (2019)
Oakland	Container	2012-2013	8	32,087 MWh (2020)
Hueneme	Reefer	2014	3	4,420 MWh
Tacoma	Container, RORO	2009, 2022 Planned	—	—
Port Miami	Cruise	2023, Planned	—	—
Galveston	Cruise	2023, Planned	—	—
Philadelphia	Container	Planned	—	—

High-capacity OPS infrastructure can allow ports to leverage power generated from advanced nuclear reactors to power large visiting cruise, container, tanker, reefer, and roll-on/roll-off ships. Dependent on the price of electricity ($/kWh) from each city listed in Table 4, an average annual revenue can be determined for each port given the current capacity for using onshore power. This value can set a baseline for the potential for annual revenue, not considering future growth in usage of high-capacity OPS or additional power sources establishing high-capacity OPS capability.

In October 2022, the U.S. DOT announced more than $703 million to fund 41 projects in 22 states and one territory to improve port facilities through the Maritime Administration's Port Infrastructure Development Program. The funding, made possible by the Bipartisan Infrastructure Law and additional Congressional appropriations, will benefit coastal seaports, Great Lakes ports, and inland river ports, by helping to improve supply chain reliability through increased port capacity and resilience, more efficient operations, reduced port emissions, and new workforce opportunities [72]. This funding will allow a total of 51 U.S. ports to have high-capacity OPS services by 2050.

Assuming 10% market share by 2050, roughly five U.S. ports would utilize power supplied by advanced nuclear reactors.

2.4.1.2 Land-Based Heat and Synthetic Fuels

Advanced nuclear reactors at ports have the potential to leverage integrated energy systems that use both electricity and heat from reactors to drive synthetic fuel production that can be used to support maritime industry operations.

Hydrogen demand is expected to increase in the U.S. to support decarbonization in all industries, as shown in Figure 16. The U.S. projection of hydrogen production, which is used for the creation of synthetic fuels, conservatively forecasts an expected increase in demand by 2050 of clean hydrogen by 2.5 to 7 times compared to today's capacity.

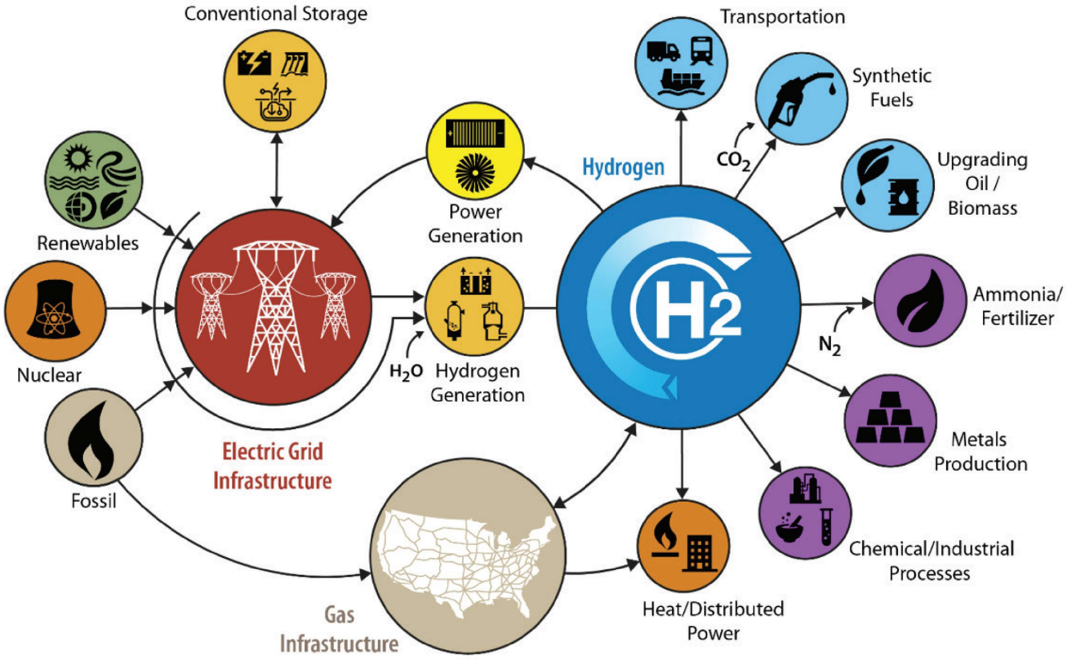

FIGURE 16: United States DOE H2@Scale

Nuclear plants coupled with electrolyzers can generate hydrogen using both low-temperature (electrical input only) and high-temperature (thermal integration) electrolysis. Theoretically, advanced reactors that operate at very high temperatures can produce hydrogen thermochemically, without the use of electrolyzers, but the technical maturity of this process is yet to be proven and commercialized. The unique characteristics of nuclear energy allow it to pair with low-cost, high-efficiency production processes, which can facilitate hydrogen production's economic competitiveness. Using synthetic fuels produced from nuclear power in the maritime industry may be a simple way to address decarbonization without major changes to existing power arrangements [74].

For the aviation and maritime sectors, hydrogen-based fuels may be the only viable at-scale decarbonization option, with significant potential for hydrogen to abate 13 gigatons of CO2 by 2050. Hydrogen-based fuels for maritime applications are expected to contribute to a demand of about 5 million metric tons in 2030. The shipping sector is one of the most challenging to decarbonize due to high power loads over long distances.

Pure hydrogen for shipping decarbonization can be either compressed or liquefied for onboard storage, or synthetic hydrogen-based fuels such as ammonia, methanol, or synthetic (liquefied) methane. In long-distance shipping, hydrogen-based fuels are scalable decarbonization alternatives, where each fuel has different characteristics and handling requirements, but all generally more feasible to handle onboard than pure hydrogen.

Overall, approximately six percent of ocean-going vessels should adopt hydrogen-based fuels to meet net-zero targets. Given the long lifecycles of ships and the long lead times required to replace fleets, industry stakeholders must plan for the transition by deploying "hydrogen-ready" ships. Engines must be adapted, and port infrastructure must support the bunkering of new fuels. The economics are challenging for maritime uses, with carbon prices well above USD $100 per metric ton required for hydrogen-based fuels to outcompete heavy fuel oil or marine diesel. In the short term, biofuels such as biodiesel and bio-methanol cost less than hydrogen-based fuels, yet resources for low-cost biofuels are finite and are not sufficiently scalable to decarbonize all maritime transport. Challenging economics are driven by the higher cost of hydrogen-based fuels, as well as additional capital expense for ships to operate on new fuels.

New port infrastructure must be built globally to enable the bunkering of new fuels such as ammonia or methanol. Bunkering infrastructure should ideally be nearby for renewable or low-carbon energy sources to limit transmission and distribution costs. Hydrogen fueled applications will require dedicated infrastructure to compress or liquefy and transport the hydrogen to end-users [75].

The $3 per kilogram credit within the Inflation Reduction Act can allow for nuclear-produced hydrogen to be highly competitive with fossil fuel-produced hydrogen. The DOE has as a goal to reduce the cost of clean hydrogen to $1 per kilogram by 2030, which would leverage both existing and advanced nuclear reactors. By 2050, the hydrogen economy could generate about $3 trillion in annual revenue, according to the Hydrogen Council and McKinsey report [75].

Nuclear-generated hydrogen could contribute to many end-users by 2050. According to Figure 17, to meet net-zero targets, approximately 700 million metric tonnes of hydrogen will be needed globally in 2050. Assuming nuclear power claims 10% of this market share, nuclear power could contribute to approximately 70 million metric tonnes of hydrogen production in 2050.

2.5 Offshore Reactor: Offshore Power Consumption

The next category implements nuclear technologies in a real marine environment. One option is to install the reactor on a permanently fixed or floating platform (supporting an offshore microgrid) in domestic or international waters.

Power consumption on station requires integration with other industrial systems on the same installation or a nearby installation. This may impose further requirements from applicable standards for equipment operating in marine environments.

Fixed

Reactor Offshore:
Offshore Power Consumption
See 2.5

Applications:

- Small floating power station for coastal industry
- Floating datacenter, see 2.5.1.1
- Floating power for offshore efuels production, see 2.5.1.2
- Floating desalination plant, see 2.5.1.3

Regulatory requirements for international applications may include both the national (Flag Administration) and international nuclear and maritime regulatory agencies. All nations involved in ownership/registration, construction, passage, and installation may impose independent requirements upon the application.

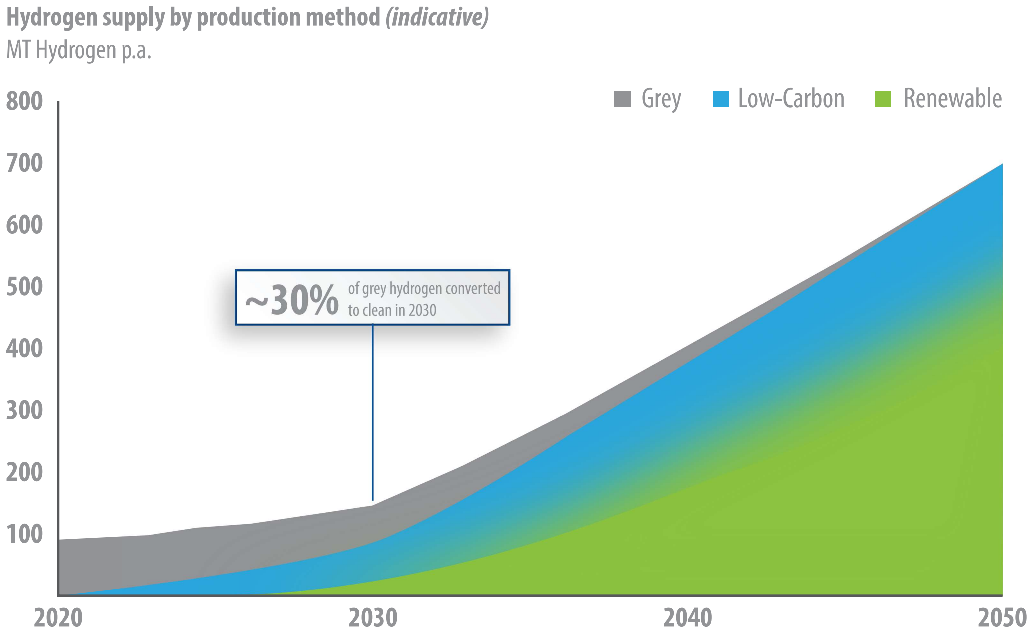

FIGURE 17: Hydrogen Supply Mix Over Time [75].

2.5.1 Business Cases & Market Opportunity

Value cases for fixed nuclear-maritime applications include floating nuclear-powered datacenters, floating e-fuels production, or floating desalination plants. While advanced nuclear reactor solutions may be applicable to decarbonize high powered offshore oil exploration, drilling, and production activities, these use cases are specialized according to location and operational profile, and difficult to gauge demand for nuclear power at this time. For this reason, offshore industry support use cases are not considered in this Report.

2.5.1.1 Floating Data Center

Floating data centers are a novel concept with growth in demand expected to increase over the coming decades. On-site co-located power generation for data centers can improve efficiency by allowing the capture and use of waste heat. Waste heat can be used to supply cooling services required by the data center through absorption or adsorption chillers, reducing chilled water plant energy costs by over 50%. High reliability power generation systems can be sized and designed to be the primary power source while utilizing the grid for backup, thereby eliminating the need for emergency generators and, in some cases, uninterruptible power supply (UPS) systems [76].

Floating data centers can offer a lower cost for consumers through high-density rack spaces, energy and resource-efficient cooling systems, and reduced construction time. They also utilize a water-cooled data center design with the lowest validated power utilization effectiveness (PUE) of any commercial data center, reducing energy usage by up to 30%. They have the flexibility of being constructed on a vessel, on land near a body of water, or some distance offshore. Vessels are proven structures that offer durability, mobility, stability, reliability, disaster resilience, and an economic alternative to what is sometimes scarce and expensive land near population centers [76].

Revenue in the data center market is projected to reach $123.20 Billion in 2024. Revenue is expected to show an annual growth rate (CAGR 2023-2027) of 4.12% in 2022 and 11.48% in 2024, resulting in a market volume of $212.10 Billion by 2029 [77]. The U.S. leads the world in data center demand. Growth worldwide is due to increasing digitization of business processes, cloud usage, and big data. However, spending in this market shows fluctuations caused by the high one-off cost of purchasing and setting up data centers. Investment in IT infrastructure increases in times of good economic conditions and high adoption rates of new technologies and applications, but usually decreases afterwards. As a consequence of the COVID-19 pandemic, investments were delayed, which might lead to catch-up effects in subsequent years [78]. The energy demand for datacenters can range from 5-100 MW [79]. There are currently 2,701 data centers in the U.S., and with a projected 4-year growth rate at 4.12%[12], the total addressable market for new data centers is roughly 882 new data centers by 2050.

If the floating data center market can capture 5% to 10% market share and advanced reactor-powered floating data centers make up 5% to 10% of that market share, then the U.S. market opportunity is roughly 2 to 9 nuclear-powered floating data centers by 2050 [80].

2.5.1.2 Floating power station for offshore hydrogen-eFuels production

Similar to the findings for onshore hydrogen-eFuels production, the near-shore use case may allow ports to free up space for increased throughput and may provide increased perceived safety distances from population centers.

E-fuels are promising fuels for decarbonizing the maritime sector, including methanol, ethanol, methane, or other hydrocarbons derived from hydrogen and carbon sources. However, ammonia is often perceived as a more attractive option due to its zero-carbon content. This characteristic excludes it from the cost of capturing and reprocessing CO2, which significantly adds to the final cost of e-methanol. The falling costs of hydrogen produced from renewable energy, coupled with the cost reduction of CO2 capture technologies, should enable 2050 production costs to reach around $107-145/MWh for renewable e-methanol. In the medium to long term, hydrogen-based fuels are expected to become the foundation of a decarbonized international shipping sector. By 2050, shipping is expected to require a total of 46 million tons (MT) of hydrogen. Of this total, 73% will be needed to produce e-ammonia, 17% for e-methanol and 10% for direct use as pure hydrogen in fuel cells or internal combustion engines (ICEs). We perceive E-ammonia as the potential backbone for decarbonizing international shipping in the medium and long term. By 2050, the production costs of e-ammonia are expected to range between $67-114/MWh. Renewable ammonia could represent as much as 43% of the mix in 2050, which would imply the use of about 183 MT of renewable ammonia for international shipping alone – a comparable amount to

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[12] For the purpose of this report, the 2022 values are used to match the datasets at the time.

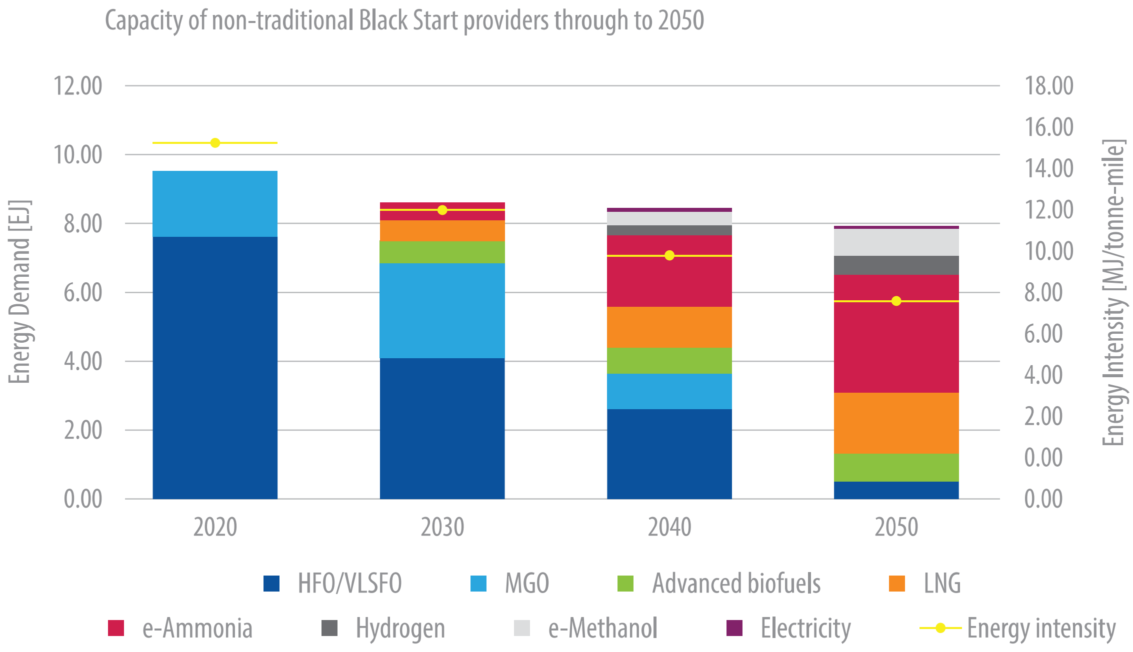

FIGURE 18: E-fuel Energy Pathways to 2050, 1.5°C Scenario Energy Pathway [81]

today's global ammonia production. The chart in Figure 18 identifies the fuel market share for the global marine industry to 2050, which highlights the growing need for e-fuels [81].

2.5.1.3 Floating Desalination Plant

According to Global Water Intelligence, the global water demand is expected to rise from its current value of 4,600 billion MT/year to 6,000 billion MT/year by 2050, with approximately 57% of the world's population expected to live in an area experiencing water scarcity. This demand likely will not be met from ground and surface water reserves and will have to be provided by increasing levels of industrial desalination.

The global desalination market was valued at $14.5 billion in 2021 and is expected to reach $35.5 billion by 2031. The key factor curtailing faster growth is the current relatively high price for desalinated water; however, moving to floating desalination can reduce this cost as scaling up desalination plants will mature and become competitive with other water supplies. The desalination market is understandably concentrated in those countries with arid climates, limited water resources, and high levels of urbanization. There are currently approximately 16,000 desalination facilities worldwide, with the largest capacity in the Middle East, where rapid urbanization has caused demand to overtake the already limited local water supply. Other key markets for desalination include Australia, China and coastal states in the U.S., which are increasingly water-stressed, as shown in Table 6. Modelling suggests that by 2050 7.8 million MT/day of additional desalination capacity will be required annually to keep up with demand. This required ramp-up in demand will mean desalination capacity must increase by a factor of 2.5, reaching 266 million MT/day by 2050 [81].

There are currently 406 desalination facilities within the U.S. [83], and applying the 2.5 increase factor suggested above, the U.S. will need to build an additional 609 desalination facilities by 2050 to meet demand. Assuming advanced nuclear reactor can capture a market share of 10%, 3 desalination plants/year using advanced nuclear reactor would need to be placed into operation to meet the U.S. capacity demands.

2.6 Offshore Reactor: Providing Power to Shore

Similar to the isolated offshore application, a grid connected or near shore fixed nuclear-maritime application may incorporate slightly more complex. Connecting to land-based grids may implicate the regulations of land-based energy agencies. Installation closer to shore, possibly within territorial waters, may also impose more stringent regulations on the unit.

Table 5: Breakdown of Desalination Plants by U.S. State [82]

State	Number of Plants
Florida	167
California	58
Texas	52
North Carolina	18
Iowa	16
Illinois	12
Arizona	10
Colorado	10
Ohio	8
North Dakota	7
South Carolina	6
Virginia	6
Kansas	6
Utah	3
Massachusetts	3
Montana	3
New Jersey	3
Alaska	2
Minnesota	2
Missouri	2
Nebraska	2
Nevada	2
New York	2
Oklahoma	2
Pennsylvania	2
Alabama	1
Georgia	1
Michigan	1
Mississippi	1
South Dakota	1
Tennessee	1
Washington	1
Wisconsin	1
West Virginia	1
Wyoming	1

Fixed

Reactor Offshore:
Providing Power to Shore
See 2.6

Applications:

- Floating power station for coastal industry

Regulatory requirements for domestic applications include the national nuclear and maritime regulatory agencies. Governing regulatory policies may differ depending on the location within territorial and EEZ waters.

Shore power supply implies connection to land-based grids, which may require additional criteria for the domestic energy or local electrical distribution agencies. We discuss below the following case of a grid-connected, near-shore nuclear-maritime application.

FIGURE 19: Seaborg Technologies Concept Floating Nuclear Power Barge

2.6.1 Business Cases & Market Opportunity

2.6.1.1 Floating Power for Coastal Energy

The value proposition for a floating power plant to support coastal industry has been examined on several occasions. The prospects allow for a black-start capability to coastal communities that have suffered natural disasters such as hurricanes. The immediate power needs for lifesaving activities are of increasing interest as climate change creates more erratic weather patterns and consequences from natural disasters.

Demand for additional power capacity in coastal communities is also increasing, particularly in urban regions with space constraints for power generation in high-population areas. Figure 20 shows the power generation sources and capabilities in the continental U.S. and illustrates the preponderance of energy generation along the East and Gulf coasts, areas that are prone to hurricanes, and the Southern California coast, an area subject to earthquakes and wildfires. These areas are likely to need a more resilient power infrastructure and black-start capability than others [84].

Figure 21 and Figure 22 below identify the additional capacity needed in the U.S.[13] for a black start capability. Figure 22 does not take into account advanced nuclear capability to support black start efforts but highlights the total addressable market for non-traditional providers by 2050 at over 50 GW with 20 GW of new generation attributed largely to solar and battery storage.

It is feasible that floating power for coastal energy markets in the U.S. could address 10% of the new generation capacity at roughly 2 GW of power generation.

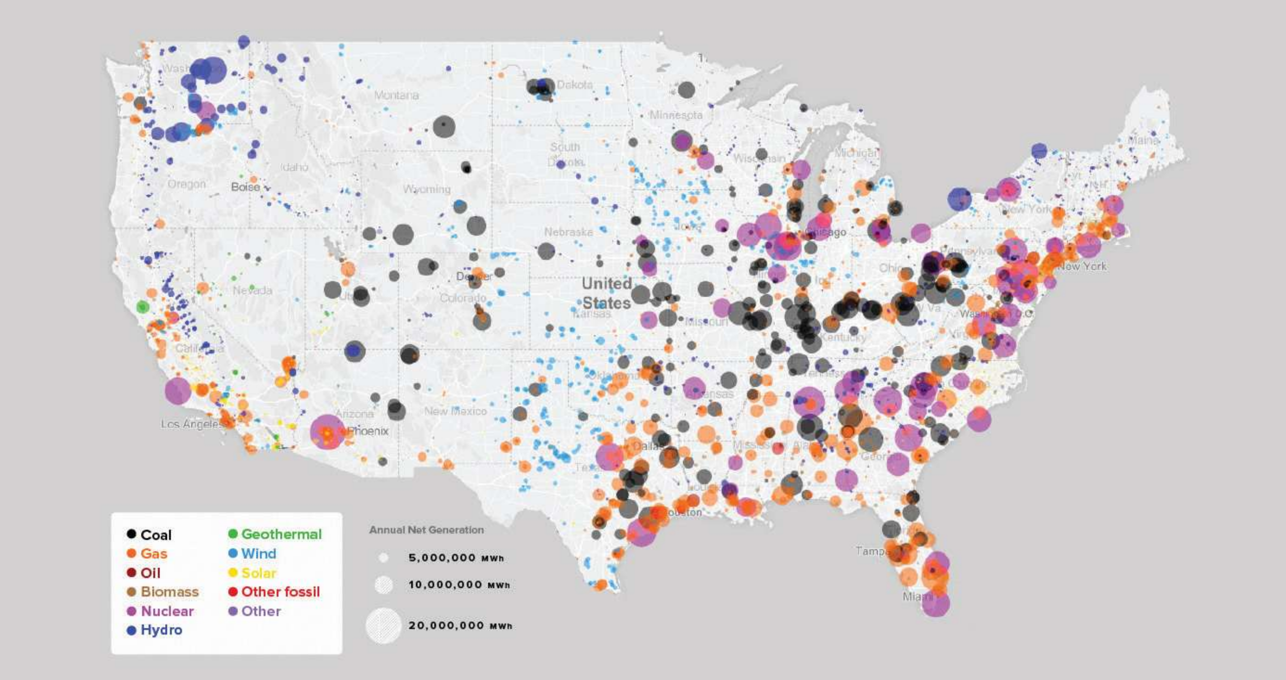

FIGURE 20: Total Addressable Energy Market in the U.S. [83]

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[13] Black start means the process of restoring electric power to a grid without relying on the external electric power transmission network to recover from a total or partial shutdown.

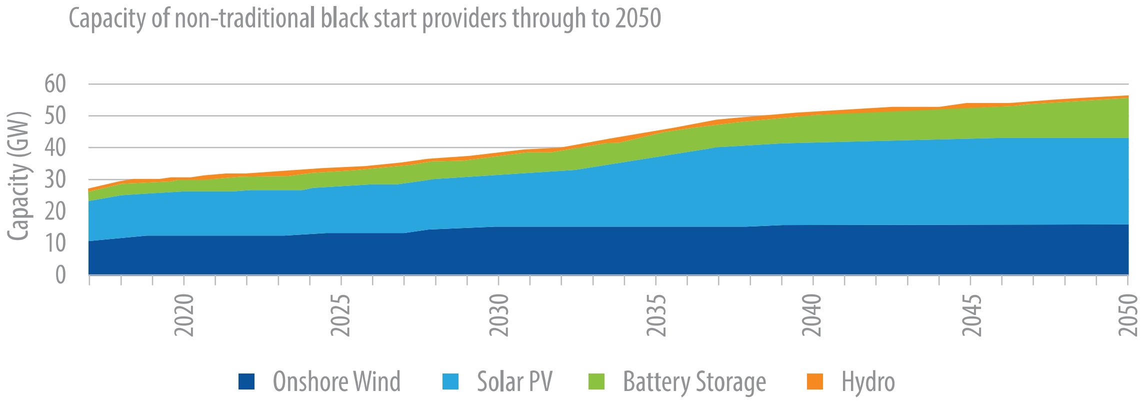

FIGURE 21: Forecast to 2050 for Black Start Capacity in the U.S with Non-traditional Providers (Nuclear not included) [84]

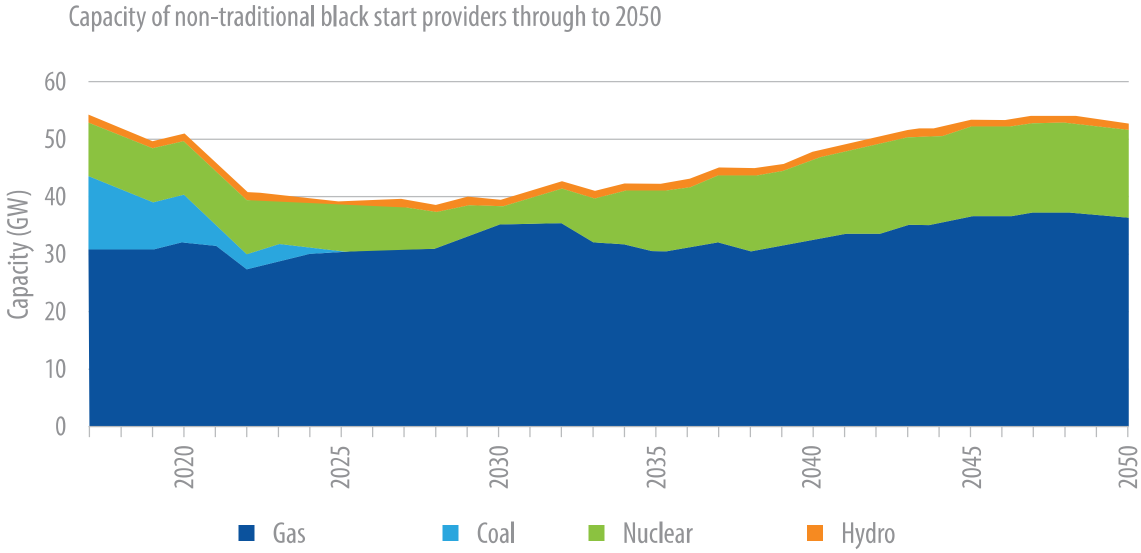

FIGURE 22: Forecast to 2050 for Black Start Capacity in the U.S. with Traditional Providers (Existing Nuclear included) [84]

2.7 Nuclear-Powered Vessel (Domestic Transport)

Mobile applications increase complexity by fitting nuclear propulsion technologies to maritime use cases operating in multiple locations. However, regulatory requirements and governing jurisdictions will vary in their oversight depending on the scope of the applicant's designed mobility.

For example, a domestic vessel or mobile offshore unit will have to meet certain statutory and regulatory requirements according to their operations, as discussed in 2.2.2. Regulatory requirements for domestic applications include those developed by the national nuclear and maritime regulatory agencies.

When considering power consumption onboard for propulsion, further requirements or design standards may be imposed beyond current applicable industrial or maritime standards for propulsion equipment and other systems operating in marine environments.

If connected to a land-based grid to supply shore power, additional criteria for the domestic energy or local electrical distribution agencies may apply.

This category explores two similar options for nuclear-propulsion applications: nuclear propulsion for commercial vessels within U.S. waters, and the same technologies installed on non-commercial assets, such as those owned and operated by government entities.

Mobile

Reactor Offshore:
Nuclear Powered Vessel
(Domestic Transport)

Applications:

- Nuclear river towboat
- Nuclear offshore support vessel
- Nuclear tanker
- Nuclear drill ship
- Nuclear dredge vessel
- Nuclear container ship
- Nuclear dry cargo ship
- Nuclear gas carrier
- Nuclear car carrier with electrical vehicle charging
- Nuclear passenger vessel

2.7.1 Option 1: Power for Commercial Vessel Operating in U.S. Waters

This Category would likely apply to Jones Act Vessels, for example, offshore wind farm support vessels, short sea/inland waterway shipping, or cabotage routes along U.S. coasts.

2.7.1.1 Business Cases & Market Opportunity

Table 7 provides a comparison across vessel types with a market opportunity for utilizing advanced nuclear reactors. The number of current U.S.-flagged in-service vessels as of August 2022[14] was identified using market data, and lifespans and growth rates were identified largely based on U.S. market projections. Where U.S. market growth data for segments were unavailable, global growth rates were used for that shipping vessel category, although it is recognized that the global rate is likely larger than the U.S. maritime market growth, possibly leading to overestimated values. In any case, the estimates are intended to be illustrative rather than projective. The table leverages Little's Law and assumes a 5% to 10% market share of advanced nuclear-maritime applications by 2050. The industry growth rate over the identified initial timeframe was used as a benchmark for constant future growth, which adds higher uncertainty to the findings.

Little's law was applied to the data below, with an example calculation below showing the calculated 2050 demand for Offshore Support Vessels (OSVs), with the assumption of a 10% market share for advanced nuclear.

First, the market size in 2050 (L^{2050}) is calculated from the industry growth rate extrapolated over the years between 2022 and 2050[15].

$$L^{2050} = 1.02^{\frac{2050-2022}{5}} * 8 = 9$$

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[14] Aggregated vessel numbers derived from Clarkson's Research Services as of August 12, 2022

[15] Growth rates are provided as a percentage of the current market over a certain number of years, e.g., 2% growth over 5 years. To apply this assumed growth rate over a longer period of time, effectively creating a larger growth rate, it is modified by the exponential equation shown here.

Then, the annual frequency at which new vessels are needed to maintain market size, λ, is calculated, where W (20 years) is the vessel lifespan, factored by the assumed percentage of market share (in this example, C = 10%):

$$\lambda = \frac{L^{2050}}{W} * C = \frac{9}{20} * 0.1 = 0.045$$

Therefore, over 20 years from the assumed first reactor deployment (2030) and leading up to 2050, this value is multiplied by 20 and rounded to the nearest unit:

$$20\lambda = 0.9 \ \approx 1$$

Modeling a variable growth rate to 2050 could be done, but additional research is required to determine growth ranges for each vessel type. While market demand may be identified in the table below, the economic value of each vessel type would also need to be determined.

2.7.2 Option 2: Power for Government Vessel

As an alternative to commercial vessels, there is also the opportunity for nuclear propulsion for government owned/operated vessels in non-military operations. Examples of such vessels include operations such as those of the Military Sealift Command's auxiliary support fleet, the U.S. Maritime Administration's (MARAD's) fleet, the USACE fleet of dredgers and navigational support vessels, or various national laboratory research vessels or those vessels used by the National Oceanographic and Atmospheric Association (NOAA).

These applications would likely be subject to the same regulatory frameworks for commercial nuclear and maritime approvals. Advanced reactors would likely still fall under the NRC's jurisdiction to license.

Even though these applications do not necessarily engage in commercial operations, many government-owned vessels carry out valuable operations, scientific missions, training voyages, and national support services which are difficult to monetize compared to the use of commercial vessels. For this reason, the predicted 2050 demand for nuclear-powered non-military government vessels is not provided but is recommended to be investigated in further research activities.

2.7.2.1 Business Cases & Market Opportunity

Rather than evaluate the national investment or value cases of government-owned opportunities for nuclear-maritime applications, we emphasize that these first

Table 6: Lifespans and Market Growth of U.S. Flagged Vessels by Type

Vessel Type	Total Current # of Vessels > 10MW	Average Lifespan (years)[1)]	Projected Industry Growth Rate	Growth over Time Segment (years)	Demand by 2050 with 5% to 10% market share for vessels requiring > 10 MW installed
Offshore Support Vessel (OSV)	2	27	2% [86]	5 [86]	0–1
Container Ship	12	34	5% [87]	5 [87]	1–1
Dry Cargo Ship (Bulkers)	6	50	4% [88]	8 [88]	0–1
Ro-Ro	7	35	5% [89]	7 [89]	0–1
Tanker	6	23	6% [90]	6 [90]	0–1
Total	**33**				**1–5[2)]**

Notes

1) Unless otherwise noted, vessel average lifespans derived from IHS Fairplay data as of January 2023 for the age of vessel at scrapping for all vessels scrapped since 1996. This lifespan data is not exclusive to vessels with installed power greater than 10MW, but representative of all vessel sizes of that category that have been scrapped. It should be noted that vessels operating primarily in freshwater (e.g., passenger ferries and Great Lakes ships) typically have longer lifetimes which can be contributed in part by reduced structural corrosion in fresh water.

2) Data aggregated by rounding up to next whole number.

FIGURE 23: Renderings of Commercial Nuclear Vessels [96]

movers may provide the ideal platform to validate, verify, and prove various technologies and novel vessel concepts. Under the Government's ownership, and independent from commercial investment, government-owned applications can showcase technical and economic feasibility of nuclear-maritime applications.

2.8 Phase 5: Mobile Reactor for International Ship Propulsion

Similar to domestic mobile applications, this category is expected to be the most complex, but not necessarily due to technological challenges.

Operating a nuclear-powered commercial vessel within the controlled waters of one nation is the achievement of domestic mobile nuclear applications, while international mobile applications incorporate the regulatory challenges and policy agreements that will be necessary for commercial nuclear vessels to travel internationally.

2.8.1 Business Cases & Market Opportunity

The value case of international merchant ships expands with access to global trade routes and markets compared to domestic ships. This is likely expected to increase the value case of commercial vessels on international routes.

Mobile

Reactor Offshore:
Nuclear Powered Vessel
(Domestic Transport)

Applications:

- Nuclear river towboat
- Nuclear offshore support vessel
- Nuclear tanker
- Nuclear drill ship
- Nuclear dredge vessel
- Nuclear container ship
- Nuclear dry cargo ship
- Nuclear gas carrier
- Nuclear car carrier with electrical vehicle charging
- Nuclear passenger vessel

Additional risks will exist, however, concerning safety and security while transiting international shipping channels or routes, arrangements for port entry, allowances for safe harbor or shelter, and provisions for international services to the vessel if needed.

We expect that nuclear-maritime technology integration will be demonstrated first under a more controlled regulatory environment, such as those applications described in the previous categories.

For global demands, we assume here that vessels with power requirements over 14MW[16] are of primary focus for using advanced nuclear reactors to drive emissions reduction goals. Additionally, we modeled advanced nuclear reactors capturing 2% to 5% of the addressable global commercial maritime market, given that historical precedent of adoption of nuclear energy lags behind the U.S. adoption rate, and the global market share for nuclear energy was 2.3% 20 years after the first commercial nuclear reactor went into operation [91]. According to Table 8 below, the leading vessel type from a global market perspective for using advanced nuclear reactors would be containerships.

TABLE 7: Lifespans and Market Growth of Global Vessels by Type

Vessel Type	Total Vessels > 14MW installed power	Average Lifespan (years)[1)]	Projected Industry Growth Rate	% Growth over Time Segment (years)	Demand by 2050 with 2% -5% market share for vessels requiring greater than 14 MW installed power
Tugs	95	42	15% [92]	4 [92]	3-6
Offshore Support Vessel	203	33	5% [93]	8 [93]	3-8
Dredging Vessel	42	30 [94]	3% [95]	10 [95]	1-2
Container Ship	3971	24	5% [87]	5 [87]	87-216
Dry Cargo Ship	1970	30	4% [88]	8 [88]	31-76
Ro-Ro	468	30	5% [89]	7 [89]	8-20
Passenger Ship	798	38	10% [96]	7 [96]	13-32
Tanker	1711	29	6% [90]	6 [90]	32-79
Total	**9258**				**178-439**[2)]

Notes

1) Unless otherwise noted, Vessel average lifespans derived from IHS Fairplay data as of January 2023 for the age of vessel at scrapping for vessels scrapped since 1996. This lifespan data is not exclusive to vessels with installed power greater than 14MW, but representative of all vessel sizes of that category that have been scrapped. It should be noted that vessels operating primarily in freshwater (e.g., passenger ferries, tugs) typically have longer lifetimes which can be contributed in part by reduced structural corrosion in fresh water.

2) Data aggregated by rounding up to next whole number

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[16] While U.S. data allowed differentiation of installed power to be less than or greater than 10MW, the data set for global vessel numbers differentiated installed power into buckets by multiples of 14 MW.

Conclusion

3 Conclusion

3.1 Application Categories

The purpose of the Road Map is to provide a qualified likelihood of what types of maritime demonstrations and first movers fitted with nuclear power technologies would be pursued first based on demand. The feasibility of a nuclear-maritime application is a complex and dynamic assessment composed of technical maturity, regulatory complexity, and economic incentives.

When technology is advancing and preparing to transition from concept designs to prototype and systems testing, engineering challenges must first be addressed and resolved to support technical feasibility. However, technical feasibility is challenged by the regulatory and economic uncertainties, as well as the checks and verifications mandated by regulations and policies.

Economic feasibility is a combination of the initial estimates for capital costs of the application (e.g., design, testing, materials procurement, components manufacturing, construction and installation) and operations costs over its lifetime (e.g., operation and expected economic returns). However, economic feasibility can also be affected by regulations where there may be policies to subsidize certain applications or types of advanced reactors, or fund certain research areas. For example, there may be more economic incentive to develop an application focused on decarbonization, whereas other applications may not address that issue effectively.

Regulatory feasibility is the expected bottleneck for the demonstration and development efforts of nuclear-maritime applications, where Figure 7 and Figure 8 categorize the applications by expected regulatory complexity based on location and use case. The following subsection describes the preliminary assessment of the example applications provided in this report to give a general understanding of each application's potential and where the industry may see first adopters.

3.2 Assessment of Applications

Detailed market analyses were not considered within the scope of this funded research series of reports, however, considerations for value assessments can be discussed and established based on the preliminary high-level research. First adopters of advanced nuclear-maritime applications will be those applications where the cost, effort, and time needed to establish the design, license(s), and various approvals is low, while the application value during its lifetime should be high. We reasonably assume that first adopters will pursue applications of value or demand first.

Based on the preliminary application assessments provided in Sections 2.4 through 2.8, the 2050 demand is listed along with market assumptions for comparison purposes in Table 9. Note that the future demand values may not reflect the total number of reactors, but in some cases may be fitted with multiple reactors to meet the anticipated demand. These values and assumptions are subject to change according to future related research or further investigation. More detailed investigations into demand and power requirements would also allow normalization of the data for a more quantifiable comparison.

Table 9: Nuclear-Marine Applications 2050 Demand

Application	Assumption(s) for 2050	Potential 2050 Demand
1. Port Producing Electricity	• A total of 51 ports in the United States will be fitted with OPS infrastructure • Advanced nuclear power has 5% to 10% market share of those ports	+3 to 5 U.S. ports powered by nuclear
2. Land-Based Heat and Synthetic Fuels	• 700 million metric tonnes of hydrogen being produced in 2050 to achieve global net-zero targets • Advanced nuclear reactor power has 5% to 10% market share	+ 35 to 70 million metric tonnes of global hydrogen production powered by nuclear
3. Floating Data Center	• Approximately 882 new data centers in the U.S. • Floating data centers contribute 5% to 10% of the market share • Advanced nuclear reactor powered floating data centers contribute another 5% to 10% of the market share	+ 2 to 9 nuclear-powered floating data centers in the U.S.
4. Offshore Synthetic Fuel	• Global shipping requires 46 million metric tonnes of hydrogen produced from renewable energy • Offshore synthetic fuel production by advanced nuclear reactor facilities contributes 5% to 10% of market share	2.5 to 5 million metric tonnes of floating hydrogen production powered by nuclear
5. Floating Desalination	• U.S. will build an additional 609 desalination facilities by 2050 to meet demand • Advanced nuclear-powered land-based desalination plants contribute 5% to 10% of the market share • Floating advanced nuclear reactors powered desalination plants contribute another 5% to 10% market share	+2 to 6 floating nuclear powered desalination plants by 2050 in U.S
6. Floating Power for Coastal Energy	• New, traditional nuclear and non-traditional floating nuclear capacity for U.S. black-start capacity will increase to approximately 20 GW • Advanced nuclear reactor-powered floating power for black-start capability contributes 5% to 10% of new generation	+ 1 to 2GW advanced nuclear-powered floating black-start capacity in the U.S. coastal energy
7. Domestic Commercial Ship Propulsion	• See Table 7 for U.S. Vessel fleet growth using advanced nuclear reactor power. • Constant growth for each vessel type with 5% to 10% market share of advanced nuclear	+1 to 5 commercial U.S. ships using nuclear propulsion
8. Global Ship Propulsion	• See Table 8 for Global Vessel fleet growth using advanced nuclear power. • Constant growth for each vessel type with 2% to 5% market share of advanced nuclear. • Access to global markets increases potential trade value of vessel applications	+178 to 439 global merchant ships using nuclear propulsion (including U.S. vessels)

Notes

1) Demand is not reflective of the number of nuclear reactors, as multiple reactors may be used to meet the demand for each unit.

3.3 Further Research and Recommendations

This report introduced example applications of nuclear-maritime solutions in Figure 8, and generally describes the initial expected issues of adoption. Subsequent reports and deliverables will focus on describing the challenges and proposing potential solutions to accelerate nuclear reactor technology demonstration projects for commercial maritime applications.

Further research is to include a deeper dive into specific market analyses (especially those with high 2050 potential demand), the magnitude of expected capital and operational costs, technical details and suitability of advanced nuclear reactors for maritime applications, further investigation of regulatory regime gaps and recommendations for policymakers considering the use of advanced nuclear reactors in novel commercial maritime applications.

4 List of Acronyms

ABS	American Bureau of Shipping
AEC	Atomic Energy Commission
AIP	Approval In Principle
API	American Petroleum Institute
APPS	U.S. Act to Prevent Pollution from Ships
ARDP	Advanced Reactor Demonstration Program
BOEM	Bureau of Offshore Energy Management (U.S.)
BSEE	Bureau of Safety and Environmental Enforcement (U.S.)
CAGR	Compound Annual Growth Rate
CFR	U.S. Code of Federal Regulations
CMNP	Commercial Maritime Nuclear Propulsion
COL	Combined Construction Permit and Operating License
COP	United Nations Framework Convention on Climate Change Annual Conference of the Parties of the UNFCCC
D&D	Deactivation & Decommissioning
DOC	U.S. Department of Commerce
DOE	U.S. Department of Energy
DOI	U.S. Department of the Interior
DOME	Demonstration of Microreactor Experiments (at INL)
DOT	U.S. Department of Transportation
EEZ	Exclusive Economic Zone
EPA	U.S. Environmental Protection Agency
FNPP	Floating Nuclear Power Plant
FOAK	First-of-a-Kind (only mentioned once up to you if you want to include as an Acronym)
FSAR	Final Safety Analysis Report
FSS Code	International Code for Fire Safety Systems (IMO)
GAIN	Gateway for Accelerated Innovation in Nuclear
GHG	Greenhouse Gas
HALEU	High-Assay Low-Enriched Uranium
HEU	High Enriched Uranium
IAEA	International Atomic Energy Agency
IACS	International Association of Classification Societies
IMO	International Maritime Organization
INF Code	International Code for the Safe Carriage of Irradiated Nuclear fuel, Plutonium and High-Level Radioactive Wastes in Flasks on Board Ships (IMO)
INL	Idaho National Laboratory
ISO	International Standardization Organization
KAERI	Korean Atomic Energy Research Institute
LNG	Liquefied Natural Gas
LOTUS	Laboratory for Operations and Testing
LPG	Liquefied Petroleum Gas
MARAD	Maritime Administration (U.S.)
MARPOL	International Convention for the Prevention of Pollution from Ships (IMO)
MAST	multi-axis simulation table
MFC	Materials and Fuels Complex (INL)
MI	Mission Innovation
MW	Megawatt
MWt	Megawatt Thermal
MWh	Megawatt hours
NEI	Nuclear Energy Institute
NEICA	Nuclear Energy Innovation Capabilities Act
NEIMA	Nuclear Energy Innovation and Modernization Act
NEPA	National Environmental Protection Act
NIOSH	National Institute for Occupational Safety and Health

NNSA	National Nuclear Safety Administration (U.S.)
NOAA	National Oceanic and Atmospheric Administration
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission (U.S.)
NRIC	National Reactor Innovation Center
NTQ	New Technology Qualification
NS	Nuclear Ship
OECD-NEA	Organisation for Economic Co-operation and Development – Nuclear Energy Agency
OCS	Outer Continental Shelf
ORNL	Oak Ridge National Laboratory
OPS	Onshore Power Supply
PPE	Personal Protective Equipment
PSAR	Preliminary Safety Analysis Report
PWR	Pressurized Water Reactor
SNF	Spent Nuclear Fuel
SOLAS	International Convention for the Safety of Life at Sea (IMO)
SRDD	Systems Requirements and Description Document
SSAR	Standard Safety Analysis Report
STCW	International Convention on Standards and Training, Certification and Watchkeeping for Seafarers
TRA	Technology Readiness Assessment
TRL	Technology Readiness Level
U235	Uranium Isotope 235
UNCLOS	United Nations Convention on the Law of the Sea
UPS	Uninterruptible Power Supply
U.S.	United States of America
USACE	U.S. Army Corps of Engineers
USCG	U.S. Coast Guard

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