Navigating the Future: Exploring Small Modular Reactors in Maritime

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The maritime industry has undergone dramatic transformations over the past 250 years, evolving from the early days of sail ships to steamboats to the modern era of advanced motorships. Technological advancements have continually pushed the boundaries of speed, efficiency, and environmental cleanliness. The introduction of diesel engines and gas turbines marked significant leaps forward, enhancing the speed and efficiency of ships. However, over the past decade, the industry has faced increasing scrutiny due to its greenhouse gas (GHG) emissions, which contribute significantly to global pollution. The maritime sector is responsible for about 3% of global GHG emissions, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The primary sources of this pollution are fossil fuels such as marine gas oil (MGO), marine diesel oil (MDO) and heavy fuel oil (HFO). Additionally, the maritime industry contributes over 25% of the world's toxic nitrogen oxides (NO_x) and sulfur oxides (SO_x) emissions.

In response to these environmental challenges, the International Maritime Organization (IMO) has adopted various strategies to reduce GHG emissions from international shipping. One key objective is to decrease the carbon intensity of international shipping, aiming to cut CO_2 emissions per transport work by at least 20% by 2030 compared to 2008 levels and striving towards net-zero emissions by 2050. Achieving these goals requires a significant revolution in marine power systems to enhance efficiency, reduce HFO consumption, and consequently lower GHG emissions. The reason for focusing on HFO is that the specific GHG emission from HFO is far greater than for MGO and MDO and the overall consumed amount.

Following the end of the Cold War, the Advanced Surface Machinery Programs (ASMP) introduced Integrated Power Systems (IPS) for future shipboard power systems. IPS provides electrical power for both service loads onboard and electric propulsion systems, commonly referred to as diesel-electric propulsion system. This technology not only reduces energy costs and crew requirements but also significantly lowers GHG emissions while increasing overall efficiency particularly for ships where the operational modes change often unlike for the cargo ships that steam at the same speed for days on end that still use diesel-mechanical propulsion. Recent advancements in power electronics have facilitated the transition to all-electric ships (AES) for various types of maritime vessels, leveraging IPS to enhance performance and efficiency.

The core function of IPS is to supply the electric propulsion system, which is more efficient, occupies less space, and reduces operational costs. Onboard power demands can range from a few hundred kilowatts to more than 100 megawatts. This power is typically generated by prime movers such as diesel engines, gas turbines, or nuclear reactors and distributed through low-voltage (LV) or medium-voltage (MV) AC or

DC systems. Additionally, the integration of various energy storage systems, such as batteries, supercapacitors, and flywheels, adds flexibility to the shipboard power system.

Replacing traditional propulsion systems with electric ones in IPS increases flexibility and efficiency but also necessitates more onboard power generation and the usage of thrusters or pods, which are expensive. To meet this demand and comply with environmental regulations, alternative power sources are being explored. Future ships could be powered by Liquefied Natural Gas (LNG), hydrogen fuel, ammonia, battery-electric systems, and nuclear power. Among these, nuclear propulsion stands out as a zero-emission alternative with high energy density, ideal for large ships on long voyages. Recent advancements in small modular reactors (SMRs) have made it feasible to power future ships with these compact and scalable nuclear reactors, which range in output from a few megawatts to 100 Megawatts. SMRs are designed for factory fabrication, easier transportation, and assembly on, for example maritime vessels. They can be deployed incrementally, allowing for scalable capacity by adding more modules as needed. Moreover, SMRs feature advanced safety measures, enhancing their reliability.

This article examines the application of SMRs for future maritime vessels. Section 1 provides an overview of various SMR technologies and their considerations for maritime applications. Section 2 focuses on the modeling of shipboard power systems (SPS) and SMRs for various types of power system analyses. Section 3 explores the energy management of SMR-based SPS, covering dynamic, operational, and planning levels of analysis. Section 4 delves into the economic considerations, safety, regulation, and licensing of SMRs for maritime applications, followed by the conclusion Section.

Section 1: SMR Technologies and Considerations for Maritime Systems

Nuclear reactors have been utilized in marine systems since the 1950s, beginning with the USS Nautilus, the first nuclear-powered submarine commissioned by the US Navy, and the Lenin, the first nuclear-powered icebreaker launched by the Soviet Union. Despite a long operational history, only a few maritime vessels have been nuclear-powered, including the NS Savannah by the United States, Mutsu by Japan, Otto Hahn by Germany, and Sevmorput by Russia. The limited adoption of nuclear power in commercial ships can be attributed to several factors, including the large volume and size of conventional reactors, high operational costs, and concerns regarding safety and security. Advancements in reactor design have aimed to address these limitations.

SMRs can be considered part of the advanced Generation III and Generation IV nuclear reactors, designed for enhanced safety, economic efficiency, and versatility. Unlike traditional large-scale reactors, SMRs offer a more scalable and flexible approach to nuclear energy. These reactors are characterized by their smaller size, modular construction, and ability to be deployed in remote locations and expeditionary environments. Advanced reactor designs are typically categorized by size: large (or full-size) reactors, SMRs between 20-300 MWe, and microreactors below 20 MWe. The suitability of each reactor size category for maritime applications can differ, as the power requirements for civilian ships vary significantly, from a few kilowatts for small boats to over 100 megawatts for ultra-large container ships, cargo ships, bulk carriers, and cruise ships. Given this range, SMRs are suitable for very large ships, while microreactors offer a wider range of applications for small- and medium ships.

Figure 1 shows an overview of an SMR-based all-electric maritime vessel. The SMR serves as the prime mover, providing the necessary heat to run the turbine and generator, thus supplying the significant electric demand onboard. Figure 2 presents a notional shipboard power system used in all-electric maritime vessels, which transmits and distributes the generated power to the loads.

At its core, the basic principle of an SMR is the same as any nuclear reactor. A nuclear reactor operates by initiating a chain reaction in the fissile material within the reactor core, which generates heat. This heat is then transferred to a power conversion system via a coolant. Most conventional reactors are thermal, using moderators like water or graphite to slow down neutron speeds, thereby increasing the likelihood of sustaining fission reactions before neutrons escape the system. In contrast, fast neutron reactors utilize fast neutrons to maintain the fission chain reaction and therefore do not require a moderator. SMRs could be categorized into four main types based on the reactor technology as follows:

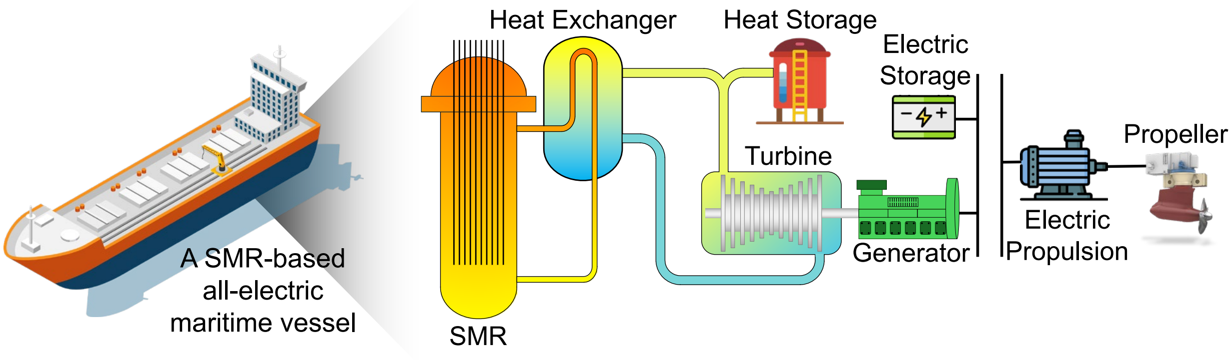


Figure 1: Schematic model of an SMR-based all-electric ship

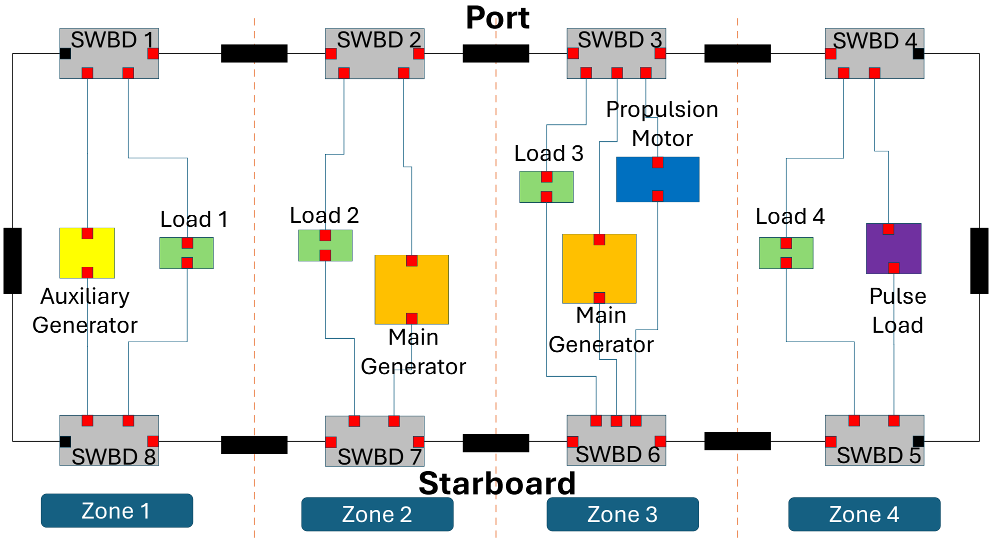


Figure 2: A four-zone Medium-Voltage Direct current (MVDC) network of an all-electric ship

Subsection 1.1: Light Water Reactors (LWRs)

LWRs are currently the most prominently used technology in SMRs, including in marine applications. The RITM-200M, RITM-200S, KLT-40S, and ACPR50S reactors used for marine applications belong to this class, which use water as both coolant and moderator. LWRs are already proven marine-based technology, with their roots traced back to the first reactor technology used in the USS Nautilus submarine. There are two main types of LWRs: Boiling Water Reactors (BWRs) and Pressurized Water Reactors (PWRs), with PWRs being the most prevalent in nuclear-powered maritime vessels. PWRs operate in the thermal neutron spectrum and use pressurized water to prevent boiling and increase efficiency. Besides the pressurizer requirement and need for containment structure, PWRs are also constrained by the low outlet temperature (around 300°C) compared to Generation IV designs. The lack of passive safety mechanisms, low burnup, and susceptibility to reactor poisoning are some of the other disadvantages. However, natural circulation coolant has been considered in some newer versions. Additionally, these reactors must be shut down during refueling. However, the non-toxic, abundant, and inexpensive nature of their coolant, along with extensive maritime experience, still makes LWRs a desirable technology for nuclear-powered ships.

Subsection 1.2: Fast Reactors

Generation IV fast reactors use gas or liquid metal as coolants, categorizing them as gas-cooled fast reactors (GFRs) and liquid metal-cooled reactors (LMRs). These reactors operate in the fast neutron spectrum, require no moderator, and are suitable for breeding. Additional features include high burnup and reduced fuel waste per power production. The reactor design can be either pool or loop type, based on the configuration of the primary heat exchanger that transfers heat from the primary to the secondary loop. In the pool design, the heat exchanger is placed within the reactor, while in the loop design, the coolant circulates through a closed loop outside the reactor. In GFRs, helium or supercritical carbon dioxide is utilized as coolant, with high-pressure operation in loop designs. LMRs can be either loop or pool type and operate at ambient pressures. For LMRs, coolants include lead, lead-based alloys, or liquid sodium, eliminating the need for pressurizers due to high boiling points in these configurations. These reactors operate at high-temperature ranges, i.e., 850°C for GFRs and <600°C for LMRs, resulting in higher efficiencies. They can also be cooled passively (except GFRs for high power density) and do not suffer from reactor poisoning effects. However, safety concerns include high-pressure gas leaks in GFRs and the production of toxic polonium due to neutron capture in lead-bismuth-based LMRs. Additionally, liquid sodium is unsuitable as a coolant due to its combustibility when reacting with water if the reactor or the primary loop is penetrated as, for example, as consequence of ship collision.

Subsection 1.3: Molten Salt Reactors (MSRs)

MSRs represent a significant advancement in nuclear energy technology, utilizing molten fluoride or -chloride salts as coolants mixed with fuel. This design is distinct from other reactors where the fuel is clad or encapsulated, resulting in increased burnup and reduced waste. However, the highly corrosive nature of fluoride- and chloride salts poses significant engineering challenges for long-term use. Another concern is the irradiation of the heat exchanger and other components by the flow of the coolant salt mixed with fuel. MSRs can be designed to operate in the fast neutron spectrum or the thermal spectrum. Graphite or heavy water is used as a moderator in the latter design. These reactors operate at high temperatures (600-700°C) and also exhibit high conversion efficiency. MSRs are characterized by a strong negative temperature coefficient of reactivity, contributing to intrinsic passive safety. Additionally, the nature of fuel in MSRs minimizes the risk of neutron poisoning. Their operation at nearly atmospheric pressure eliminates the risks associated with high-pressure systems, such as explosions. Innovative safety mechanisms, like the freeze plug system, enable the reactor to passively shut down in emergencies without the need for active controls. Due to these advantages, the MSR is the second most popular reactor concept for marine applications. The ThorCon 500, CMSR, and FLEX reactors are based on this technology.

Subsection 1.4: High-Temperature Gas-Cooled Reactors (HTGRs) and Very High-Temperature Gas-Cooled Reactors (VHTGRs)

HTGRs and VHTGRs are Generation IV reactors characterized by high outlet temperatures (750°C for HTGRs and >950°C for VHTGRs). These high temperatures make HTGRs suitable for heating applications in addition to power generation, thereby improving conversion efficiency. This class of reactors operates on a thermal neutron spectrum, using graphite as a moderator and gas coolants such as helium. HTGR fuel can be arranged in two forms: a pebble bed, consisting of spheres with a uranium center enveloped by carbon and ceramics, or prismatic fuel blocks, where fuel pins or compacts are placed in dedicated channels within graphite blocks. Online refueling is possible with the pebble bed concept, while not in the prismatic arrangement. However, in the pebble bed reactors, the position and packing of the spheres affect reactivity and may pose issues during excessive movement. HTGRs have increased burnup, resulting in reduced waste compared to the PWRs. However, since the fuel in HTGRs is enclosed, xenon poisoning is a concern. Although these reactors exhibit passive safety due to their negative temperature coefficient and large core size, the low power density makes them less suited for marine applications.

Section 2: Technical modeling

Shipboard power systems are essentially islanded microgrids where generation, distribution, and consumption occur onboard. Power consumption levels can reach up to 100 MWe in some large ships. The diversity in load types, load patterns, and the physical constraints of shipboard power systems make them unique structures that require advanced control mechanisms.

Historically, SPSs were designed and implemented using AC systems due to the operational challenges and fault isolation difficulties associated with DC systems and power electronic converters. In these traditional setups, onboard generators, all synchronous, were connected to a main AC busbar. However, using terrestrial power network designs for ships offered no specific advantages. This led to the adoption of high-frequency AC systems, which reduced power loss and allowed for smaller generator and transformer sizes, with designs reaching up to 400 Hz SPS networks.

Recent advancements in power electronics have introduced the IPS concept, making DC power systems more viable. In a DC SPS topology, generators connect to the DC distribution system through rectifiers, and the DC distribution network supplies loads via DC/DC or DC/AC converters. DC SPS networks provide a more efficient and flexible solution compared to AC networks, especially for IPS, and offer greater resilience in handling stochastic loads.

Table 1: Comparison of the reactor concepts considering maritime applications

Reactor Type	Coolant	Moderator	Operating Characteristics			Advantages	Limitations
			Efficiency (%)	Pressure (MPa)	Temperature (˚C)		
LWRs	Water	Water	33 - 36	15 - 16	< 330	• High technology readiness level • Long maritime experience • Water is non-toxic, cheap and abundant	• Low burnup • Low temperature and efficiency • Prone to reactor poisoning • No passive safety • Safety concerns due to high pressure
FRs (GFRs or LMRs)	LMR: Sodium, lead, or lead alloys	None	35 - 40	LMR 0.1 - 0.5	LMR 500 – 550	• High burnup and reduced waste • High temperatures and high efficiency • Not prone to reactor poisoning (except GFR at high power density) • Passive safety measures • Low pressure and high-power density	• Low technology readiness level • Sodium water reactions are explosive • Formation of toxic polonium in lead-bismuth coolants • High-pressure leak in GFRs
	GFR: Helium			GFR 7 - 8	GFR < 850		
MSRs	Fluoride or Chloride salts	Typically graphite (None in fast reactor designs)	40 - 45	0.1 - 0.5	600 - 700	• High temperatures and efficiencies • High burnups • Not prone to reactor poisoning • Passive safety measures • Low pressure and high-power density • Long fuel cycles, online refueling, and capability to operate in thorium cycle	• Low technology readiness level • Corrosion due to salt • Irradiation of components due to fuel mixed with salt requires shielding and heat transfer considerations
HTGRs	Helium	Graphite	40 - 45	4 - 7	750 - 950	• Very high temperatures and high efficiencies • High burnups and reduced waste • Passive safety measures • Online refueling for pebble bed concept	• Prone to reactor poisoning • Pebble bed HTGR is susceptible to movement • Comparatively large size and low power density

Subsection 2.1: Maritime All-Electric Ship Power System Modeling

Power generation onboard a ship usually ranges in Megawatts (MW). Consequently, low-voltage distribution is often insufficient. Recent research focuses on implementing MVDC SPS for future maritime vessels. There are three different DC network architectures for MVDC SPS networks: Radial, Zonal, and Ring.

Radial distribution is a conventional architecture endorsed by IEEE Std. 1709-2010. It features a simple and cost-effective design where two DC buses distribute power to consumers. Generators and energy storage systems (ESSs) feed each bus, with propellers and onboard services powered separately for higher reliability. This system, exemplified by the MVDC AES cruise ship "Royal Princess," is practical for redesigning traditional ships but becomes cumbersome with increased loads and lacks flexibility during faults. The Royal Princess has over 60 MW of generation onboard and two electric propellers consuming 18 MW each.

The second architecture is zonal distribution, which divides shipboard loads into several independently managed zones, each with dual connections to port and starboard buses. This configuration, now a U.S. Navy standard, enhances survivability by allowing loads to switch to an alternative power source during faults. It reduces cable length and cost and enables fault isolation with minimal impact. Although not widely implemented in practice, it shows promise for future applications, particularly in naval ships with specific high-power needs like radars.

Ring distribution involves a looped DC bus with bus-tie switches closed during normal operations. It offers higher survivability and reconfigurability than radial systems by isolating faults through nearby circuit breakers while maintaining normal operation elsewhere. However, each load center has a single link to the bus, making it vulnerable to faults. This architecture serves as a transitional design between radial and zonal systems and is rarely used in shipboard power systems.

Comparatively, the radial scheme is the simplest and least costly, making it ideal for smaller or less critical applications, but it performs poorly in terms of reliability, survivability, and reconfigurability. The zonal scheme excels in reliability, survivability, and reconfigurability, making it the preferred choice for large, reliability-critical ships; however, its complexity and the high number of breakers required increase both initial costs and maintenance efforts. The ring scheme provides a balanced performance with moderate reliability, survivability, and reconfigurability, but its relative scarcity and the need for more sophisticated control systems limit its adoption. Despite its limitations, radial systems remain prevalent due to their ease of integration into refitted all-electric ships, particularly when budget constraints are a concern.

From a functionality point of view, there are two major components in an all-electric SPS: the power generation module and the electric propulsion system. A detailed study of these components, with a focus on SMR-based SPS, is presented in the following subsections.

Subsubsection 2.1.1: Power Generation Module

The Power Generation Module (PGM) is responsible for generating the required power onboard from the prime mover, which can be a diesel engine, gas turbine, or SMR. It is common practice to use multiple generators in parallel rather than a single generator to increase reliability, cut fuel consumption as well as independently supply the starboard and port sides. In maritime vessels, generators are predominantly synchronous machines due to their stable power output and ease of control.

SMRs, however, are typically less flexible than diesel engines and gas turbines. Addressing this inflexibility in power generation is crucial. One significant advantage of MVDC networks is the elimination of the need for generators to operate synchronously, as required in AC systems. Consequently, generators can operate at different speeds and do not need to maintain a rated speed. This flexibility allows SMRs to adhere to their operational constraints while still providing power to the generators.

Moreover, since generators do not need to rotate at a rated speed, it is possible to couple the turbine outputs directly to the generator without using a gearbox. This results in considerable savings in cost, weight, space, and maintenance. Additionally, because the generator connects to the MVDC network through a rectifier converter, the low-frequency transformer is also eliminated. This further reduces cost, weight, and space requirements.

Subsubsection 2.1.2: Propulsion system

Given that the SPS network is DC, it would seem logical to use DC motors for the propulsion system. However, there are significant limitations associated with DC motors that prompt a shift towards AC motors. DC motors are known for their high maintenance requirements and low power-to-weight density. The remarkable advancements in power electronic converters have enabled the use of AC motors with improved control through direct torque control using inverters. For example, the use of AC motors in the USS Zumwalt allowed for a more flexible power distribution system, enabling the ship to direct power to various systems as needed, including its advanced radar and weapons systems. The AC motors also provided better torque control and reduced the overall weight of the propulsion system, contributing to the ship's stealth capabilities. This progress enhances the feasibility of employing AC motors in marine ships. Synchronous motors, particularly permanent magnet synchronous motors (PMSMs), are emerging as a viable solution for future SMR-based ships. These motors can be designed to consume up to 60 MW of power and even more. Additionally, they require low maintenance due to the absence of commutation. Furthermore, the inverters connected to the propulsion system provide high flexibility in maneuvering.

Subsection 2.2: Modeling of SMR Systems

Modeling and simulation of SMRs and their balance of plant are performed for steady-state, dynamic, and transient analyses. The reactor plant model facilitates performance optimization, behavior analysis, and validation of the design and operational safety under different conditions, including normal and accident scenarios. Detailed models can also be used to study the feasibility of operation schedules and the SMR's response to varying parameters. However, modeling such complex interactions often involves uncertainty and requires high-fidelity models to accurately represent system dynamics. The following modeling components are employed to describe the SMR plant:

Subsubsection 2.2.1: Reactor Physics and Core Neutronics

The physical models are developed by considering the core geometry, fuel arrangement and composition, material type and thickness, and other structural characteristics. Neutronics models describe the diffusion and absorption of neutrons, the fission process, and the production and depletion of isotopes. Reactor kinetics are represented by mathematical equations for neutron flux distribution, reactivity, and power generation, taking into account the effect of the control rods, criticality, and fuel burnup.

By ignoring the spatial distribution of the neutron population and considering the reactor as a point, the point-reactor neutron kinetics model is developed using a set of mathematical equations. This model describes the neutron density within the core as it varies over time, including concentrations of prompt and delayed neutrons. The model accounts for neutron balance within the core and measures the reactivity, incorporating temperature feedback and control rod position.

Subsubsection 2.2.2: Thermal-Hydraulics

The thermal-hydraulic modeling involves developing mathematical descriptions that represent coolant flow, state of coolant, core thermal power, fuel thermal conductivity, and heat transfer processes. The flow conservation and heat transfer equations are the main aspects of modeling. The main thermal modeling considerations include conduction, convection, and radiation-based heat transfer between the fuel, coolant, and other components. Fluid dynamics aspects considered in the modeling include flow of fluid, pressure drop, and distribution of velocity. Thermal-hydraulic models represent the operating temperatures and pressures of SMRs, enabling monitoring and control within prescribed safe limits. The thermal energy generated by the reactor core is carried by the primary coolant, which transfers the heat through a steam generator or heat exchanger for power conversion. Both the primary and secondary coolant loops are modeled using physics-based thermal-hydraulic equations.

Subsubsection 2.2.3: Steam Generators and Heat Exchangers

The heat generated by the nuclear process is used for steam generation. In SMRs with gas as the working fluid, this process is replaced by direct heat transfer to the gas which drives the gas turbine through a heat exchanger. Therefore, either a Rankine or Brayton cycle is modeled based on the type of the SMR. Steam generators are modeled using differential equations that describe mass and energy conversion, the energy balance for both primary and secondary loops, and the thermal behavior of tube metals. This modeling the heat transfer processes and ensures energy and mass conservation within the subsystem.

Subsubsection 2.2.4: Turbine-Generator

The steam generated drives the turbine, converting thermal energy into mechanical energy, which can be used for propulsion and is also transformed into electricity by the connected generator. The turbine-generator set is modeled by considering thermal, mechanical, and electrical conversion processes. This is described by equations representing steam flow, turbine torque, mechanical power, and electrical power production. Additionally, incorporating a governor model to regulate the turbine generator's performance is important when integrating the SMR plant with the ship power system. The governor is representative of the generator control that maintains stability during variations in power demands.

The detailed physical plant model also includes component models for the pressurizer, condenser system, and water-cooling system. Additionally, models representing chemical reactions, fuel composition estimation, and xenon poisoning effects may be added. Incorporating such comprehensive SMR models into shipboard power system models allows for detailed evaluation of design options and performance optimization.

Subsection 2.3: Modeling and Designing Control for SMR Integrated Systems

A dynamic model of individual units along with the plant-wide model is essential for designing the control system. The control architecture employed in this ''system of systems'' follows a master-slave configuration, comprising a supervisory control and control modules assigned to each subsystem or process. The demand on the SMR to supply the ship's power and/or propulsion requirements is fed as a continuous signal to the supervisory controller. This module translates the information into various control signals for lower-level control modules to set values, including neutron flux, coolant flow rate, etc. Varying control mechanisms, ranging from PID to fuzzy and reinforcement learning control, may be adopted as the system transitions toward greater intelligence. The control architecture used is often tailored to the specific type of SMR, as illustrated in Figure 3, which provides an overview of control in SMR systems. The key controls considered for safe and efficient operation of SMRs are as follows:

Subsubsection 2.3.1: Reactivity Control

Reactivity within the core is controlled by the position of the control rods. The functionality of control-rods is to absorb the neutrons, thereby affecting the reactivity and the thermal power generation. The objective of this control is to maintain the core stability while generating the desired power output from the reactor. When the control rods are withdrawn, more neutrons are available for fission, leading to an increase in power output, and vice versa. The control rods can also be used for automatic shutdown during emergencies. In addition to controlling the rod position, reactivity is also regulated by managing the core temperature, as temperature variations can affect neutron moderation and absorption. This temperature regulation, along with control rod adjustments, ensures reactor stability, power regulation, and safety.

Subsubsection 2.3.2: Primary Coolant Control

A control module is assigned to the primary coolant loop, responsible for maintaining thermal balance and flow conservation. This means of control is specific to the type of SMR. For example, in HTGRs, this includes controlling the rotational speed of the helium fan to regulate the temperature and pressure of the reactor. In PWRs and LMRs, this involves monitoring and regulating the water or liquid metal coolant flow rate to maintain temperature and pressure. These controls are essential for preserving the structural and thermal integrity of the reactor core.

Subsubsection 2.3.3: Secondary Coolant and Steam Generator Control

The secondary loop transfers heat from the primary loop to the steam generator or gas turbine system for power conversion. Controlling the flow rate and temperature of the secondary coolant allows for the regulation of the primary coolant temperature and efficiency of downstream components. The feedwater flow rate is controlled to regulate the temperature and pressure of the steam generator. In specific SMRs, additional controls may be implemented in the primary and secondary loops, such as fuel salt composition monitoring and replenishment in MSRs.

Subsubsection 2.3.4: Load Following Control

The coordinated control mechanism implemented by the supervisory control system and individual controllers ensures that power generation follows the demand signal while maintaining safe operating conditions. This involves monitoring and controlling reactor power, thermal conditions, coolant temperature, steam generator pressure, and neutron flux, all in unison. Essentially, the feedback control mechanism that compares the measured values to the setpoints is used to generate corrective actions. These setpoints originate at the supervisory level and are transmitted down the hierarchy. The reactivity and the corresponding power generated are adjusted to meet demand while attaining desirable operating conditions in the reactor, coolant, steam generator, and turbine-generator set.

Subsubsection 2.3.5: Safety or Emergency Control

The emergency control system monitors the reactor system and, upon receiving warnings, functions to initiate a shutdown of the system. Control rod position control serves as the preeminent emergency shutdown mechanism available in reactors. Safety systems employed may also be unique to each type of SMR. For example, in MSRs, a freeze valve system is incorporated which causes the molten salt to freeze and solidify during emergency conditions, preventing the fuel from flowing through the core.

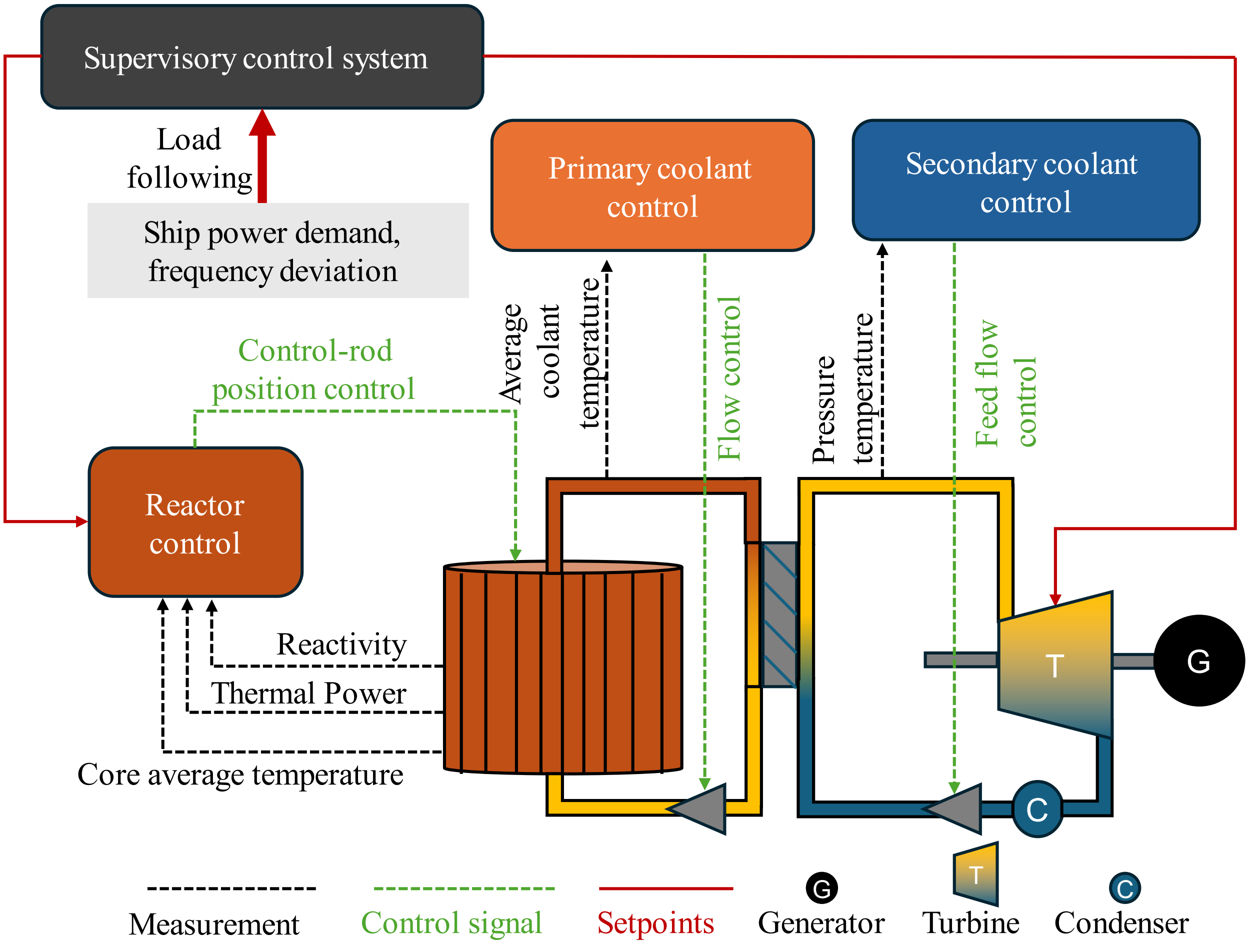


Figure 3: Overview of control in SMR systems

Subsection 2.4: Energy Storage Modeling for SMR-based Maritime Applications

Both electric and thermal energy storage systems can be integrated with SMRs to effectively manage energy demands on maritime vessels.

Subsubsection 2.4.1: Electric Energy Storage

Electric Energy Storage (EES) systems are vital for enhancing the operation of SMR-based maritime vessels. It was previously mentioned that SMRs cannot instantly change their power output level. To this end, it is necessary to use EES to cover sharp fluctuations in power demand.

EES systems are efficient as they store electrical energy directly, avoiding the need for intermediate conversions and reducing energy losses. Common types include lithium-ion batteries, solid-state batteries, and supercapacitors. Each has unique advantages: lithium-ion batteries are widely used for their high energy density and long life; solid-state batteries offer higher energy densities and safety; and supercapacitors allow rapid charge and discharge for quick power bursts. Selecting the right EES system depends on the SMR design, vessel type, and operational needs. Ideal EES systems for SMR ships should have high energy and power densities, long cycle life, high efficiency, robustness in marine environments, low self-discharge rates, fast charging capabilities, safety, and minimal maintenance.

The maritime industry favors lithium-ion batteries for their established performance. Emerging technologies like solid-state batteries promise better future performance. In SMR-powered ships, EES systems store excess energy for later use, enhancing operational flexibility, reducing auxiliary power dependence, and ensuring stable power for critical systems.

Subsubsection 2.4.2: Thermal Energy Storage

Thermal Energy Storage (TES) systems can be utilized with SMRs to increase the flexibility of the power production systems and store excess thermal energy from the SMR on the scale of hours to days. TES can be more efficient at storing energy from an SMR because it will require fewer energy conversions between storing heat and discharging it to the ship power and propulsion systems. TES systems will require additional generation capacity if the SMR is not available to convert the heat to usable electricity.

There are three main types of TES system mediums: sensible heat, latent heat, and thermochemical heat. Sensible heat storage materials store heat in one phase state, either liquid or solid. Latent heat storage materials store heat in a phase-change material which releases thermal energy during phase transition. Thermochemical heat storage materials store heat through reversible chemical reactions. Ideal TES materials will have favorable thermo-physical properties such as high latent heat, high specific heat, high thermal conductivity, high technical readiness level, and an ideal operational temperature for the given applications. Other desirable properties that are relevant for material selection are low supercooling, low cost, high availability, thermal stability, chemical stability, low volume change, low toxicity, low vapor pressure, and low flammability.

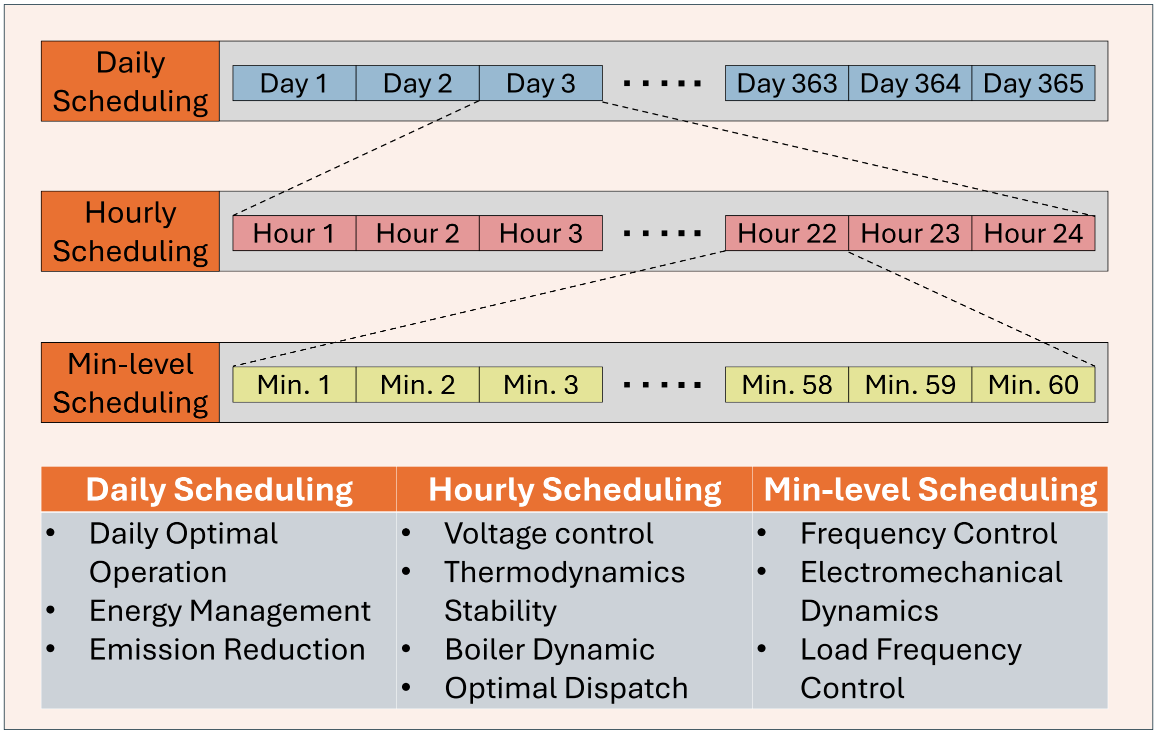
The energy industry has the most operational experience with sensible TES systems using molten salt, usually HITEC or solar salt, as they are currently used in conjunction with concentrated solar power plants. Thermochemical heat storage has the highest average energy density of all the storage mediums but the lowest average technical readiness level. In a maritime environment where space is extremely valuable, the sensible heat storage capacity of a thermal energy storage system is one of the most important metrics for selection. As the operational temperatures of SMRs will be 300°C or above, molten salts, liquid metals, or solid-state materials will most likely be the most suitable storage mediums.

In an SMR system, steam will likely be the working fluid to heat the storage medium. The utilization of a two-tank hot and cold molten storage system has been considered for SMRs. The working temperatures of the cold and hot tanks are designed at 180°C and 240°C respectively. During discharge, a heat exchanger utilizes molten salt from the hot tank to convert feedwater into saturated steam. The final selection of an ideal thermal energy storage system for SMRs will depend on the constraints of the specific SMR design, the ship type they are utilized for, and operational requirements.

Section 3: Operation and Energy Management in SMR-based All-Electric Ships

In an SMR-based all-electric ship, multi-timescale scheduling ensures optimal performance and reliability in operation and control. Figure 4 illustrates the process of a multi-timescale scheduling in an SMR-based all-electric ship. At the daily level, the focus is on optimal operation, energy management, and emission reduction. This involves planning to balance power generation and consumption and implementing strategies to meet environmental regulations.

At the hourly level, the emphasis is on voltage control, thermodynamic stability, boiler dynamics, and optimal dispatch. Real-time adjustments are made to maintain voltage levels, ensure stable thermodynamic processes, and manage boiler dynamics. Optimal dispatch strategies efficiently allocate generation resources. Minute-level scheduling addresses frequency control, electromechanical dynamics, and load frequency control. This involves rapid responses to changes in demand and supply to maintain system stability, ensuring correct frequency and smooth operation of critical components.



Daily Scheduling	Hourly Scheduling	Min-level Scheduling
• Daily Optimal Operation • Energy Management • Emission Reduction	• Voltage control • Thermodynamics Stability • Boiler Dynamic • Optimal Dispatch	• Frequency Control • Electromechanical Dynamics • Load Frequency Control

Figure 4: Multi-timescale scheduling of SMR-based maritime vessels.

Subsection 3.1: SMR and Energy Storage Operation and Planning for All-Electric Ships

Energy management in all-electric ships involves the efficient production, storage, and distribution of electrical energy to meet the diverse needs of the ship's operations, including propulsion, auxiliary systems, major power-consuming equipment and onboard amenities. One of the challenges in energy management for all-electric ships is ensuring the reliable operation of primary energy resources under various voyaging conditions. Ships encounter diverse environmental conditions, such as rough seas, high winds, and extreme temperatures, which can affect the performance and reliability of energy systems.

The power demands of a ship can vary significantly based on its operational profile, including cargo load and operational mode (e.g., cruising, docking, dynamic positioning or maneuvering). The load demands of different ship types also need to be considered, as some ships will have increased load variability compared to others, such as those requiring dynamic positioning systems. These varying demands require the energy system to be flexible and responsive. SMRs must be capable of handling these fluctuating power demands without compromising performance. This includes managing transient conditions, such as sudden power demands or system faults, without compromising reactor stability or shipboard operations. Energy storage systems, including batteries, supercapacitors, flywheels, and thermal storage, can significantly enhance the reliability of SMR-shipboard power systems by addressing these challenges.

By providing a stable power output, batteries reduce the stress on SMRs, which are more efficient when operating at a steady state. Batteries can help shave the peaks of power consumption fluctuations, preventing interruptions during transient conditions or power-switching events. Supercapacitors can discharge and recharge very quickly, making them ideal for handling rapid changes in power demand and short-term power spikes. During periods of sudden high demand, batteries can provide additional power, reducing the load on the SMR and preventing potential overload situations. Flywheels can store and release a large amount of energy quickly, making them suitable for short-term energy storage and rapid power delivery. SMRs generate a significant amount of waste heat, and thermal storage systems can capture and store this heat for later use, improving system efficiency.

Advanced energy management and power control systems are essential for coordinating the operation of nuclear-powered electric ships, optimizing energy flows, and ensuring dynamic load balancing. This includes optimally sizing thermal energy storage to reduce the electrical load on batteries, allowing smaller and less expensive batteries to be reserved for critical loads, peak shaving, and backup power. The design also needs to consider uncertainties related to voyage conditions and weather impacts. Figure 5 shows the proposed overall joint optimization scheme that coordinates the optimal sizing and efficient dispatching of loads.

The first step in designing such a system involves conducting a thorough analysis of the ship’s energy demand profile for different sections to determine the optimal size and capacity of shipboard power system components. This includes integrating various components such as primary energy resources, batteries, thermal energy storage systems, and power converters. A robust solution will be developed to address uncertainties in power loads, particularly those arising from varying weather conditions during voyages with electric propulsion systems. In the first step, decisions focus on determining optimal capacities for storage systems and the advanced reactor. In the second stage, the decision variables for optimal operation, with related constraints, must ensure operational integrity. The objective is to minimize overall capacity and operational utilization across scenarios, facilitating resilient and cost-effective resource management. This scheme coordinates the optimal sizing and reliable dispatching of energy resources. The model should consider various operational conditions of electric ships during voyages, different paths, weather conditions, and operational constraints of SMRs/microreactors, batteries, and TES for reliable sizing of energy resource components. This efficient and multi-faceted sizing approach ensures a well-balanced and reliable energy system capable of meeting diverse and dynamic energy demands.

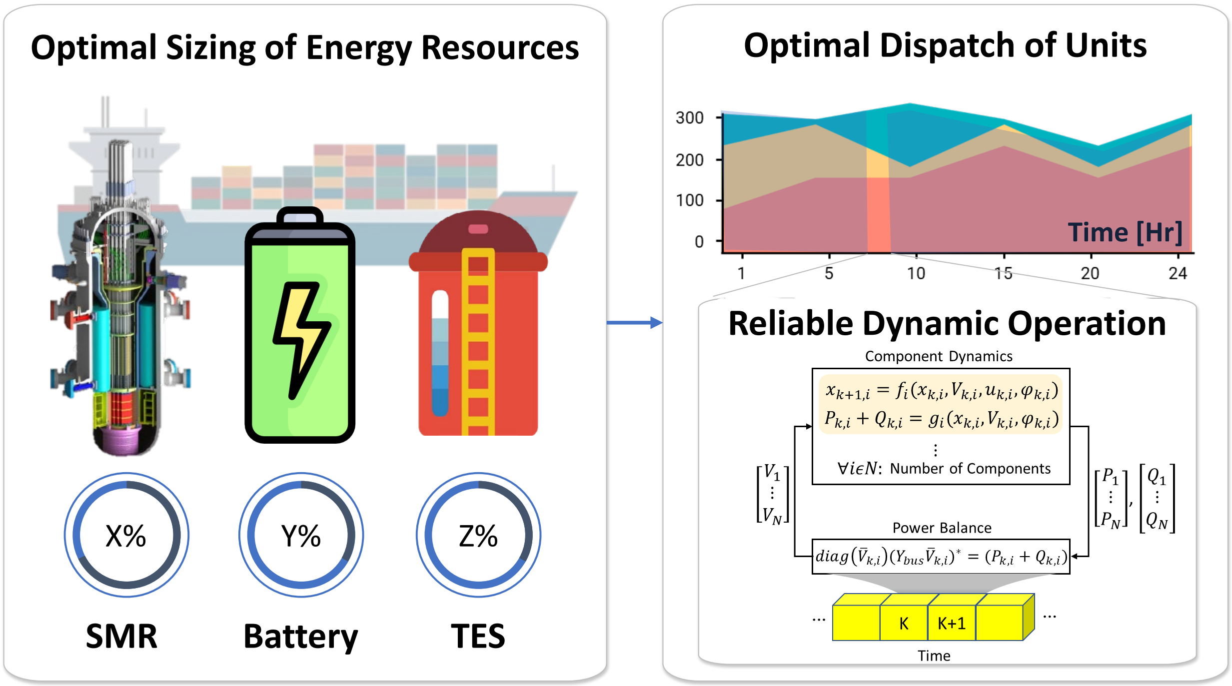


Figure 5: Joint optimization scheme that coordinates the optimal sizing and reliable dispatching of loads.

Subsection 3.2: Operational Constraints of Energy Storage and SMR for Optimal All-Electric Ship Planning

Modeling the optimal sizing and operation of SMR and energy storage in all-electric shipboard power systems requires considering a variety of constraints:

- *SMR Capacity Limits:* Maximum and minimum power output of the SMR.
- *SMR Ramp Rate Limits:* Constraints on how quickly the power output of an SMR can be increased or decreased over time. These limits ensure safe and efficient SMR operation, avoiding rapid changes that could cause mechanical stress or operational instability.
- *EES and TES Capacity:* Maximum energy storage capacity and state-of-charge limits.
- *State of Charge (SOC) Limits:* Defines the permissible range within which the battery's charge level must remain. Ensures the EES does not get overcharged, which can reduce its lifespan or cause damage, nor excessively discharged, which can impair its ability to supply power and shorten its operational life.
- *Power Balance:* Ensuring that total power generation always meets total power demand.
- *Load Following Capability:* The ability of SMRs, EES, and TES to ramp up or down to meet changing power demands.
- *Charging/Discharging Rates of EES and TES:* Maximum and minimum charging/discharging rates.
- *Cycle Life:* Limiting the number of charge-discharge cycles to ensure battery longevity.

By combining different energy storage types into hybrid systems, we can harness the unique benefits of each. For example, battery energy storage offers rapid responses to sudden electricity load changes, while thermal energy storage excels in applications requiring thermal energy (like heating or cooling). Batteries primarily store electrical energy, making them less efficient for converting stored energy into thermal energy.

The reliable operation of the SMR and energy storage systems under different loading conditions is crucial due to the varying load profile caused by weather changes during voyages. All-electric ships must supply all the load during voyages with energy resources such as SMRs and energy storage systems. Normally, the base load is supplied by SMRs as the main units, and the flexibility of the energy storage systems enhances the reliability of operations by reducing the stress of load fluctuations on the SMR units. Optimal operation of the charging and discharging of storage systems, while maintaining their SOC within reliable limits, further improves this reliability.

By accurately sizing components such as SMRs/microreactors, batteries, and TES, we can model and simulate the dynamic responses of ships. This helps us understand how the shipboard power system responds quickly and effectively to changes in load, speed, and environmental conditions. Such understanding is essential for maneuverability, particularly in demanding scenarios like docking, navigation, or responding to emergencies. Optimal sizing ensures energy resources operate within design limits, mitigating risks like overheating, overloading, and premature wear during dynamic situations and transient responses. This is crucial for ship power systems, which must rapidly adapt to load, speed, or environmental fluctuations, such as sudden power demands or changes in propulsion loads.

Section 4: Economic Study, Regulatory, Licensing, and Safety Considerations

While nuclear-powered vessels have been utilized for many decades by navies and state-owned entities, government vessels operate under distinct frameworks for economics, regulations, licensing, and safety/security considerations. When considering a nuclear-powered commercial vessel, new frameworks may need to be established. Existing mechanisms used to license the NS Savannah may be referenced but would require updates to modernize the requirements. Other areas of economic, regulatory, licensing, and safety/security considerations will need to be developed to reflect the advancements of modern nuclear engineering and practices.

Subsection 4.1: Economic Considerations

Nuclear-powered commercial vessels present a different economic reality compared to conventional or innovative low- or zero-carbon fuel solutions. High-level economic tradeoffs involve high capital expenses (CAPEX) for a new build or retrofitted vessel and potentially lower operational expenses (OPEX) due to reduced need for frequent refueling. However, many uncertainties exist regarding the exact CAPEX required or the potential OPEX savings.

CAPEX will depend on the specific reactor arrangement and the integration of thermoelectric energy conversion equipment onboard. Considerations for system redundancy and separation to protect continuous power in case of primary system failure may significantly increase CAPEX. The CAPEX is strongly related to the propulsion plant's specific arrangements.

OPEX may be reduced by eliminating or significantly decreasing the need to bunker liquid or gaseous fuels, with nuclear power plants needing servicing or refueling once every few years, compared to conventional ships refueling every few weeks or months. This extended period without bunkering is expected to result in significant savings and more revenues due to less downtime, though the potentially higher costs of less frequent nuclear propulsion plant servicing and refueling must be considered. Specific refueling or nuclear servicing arrangements differ between thermal- and fast reactors, with fast reactors known for higher fuel efficiency and longer refueling cycles.

Another major consideration is the development of carbon taxes, carbon trading, or other economic incentives or disincentives to reduce carbon fuel use for transport. A nuclear-powered commercial vessel that achieves zero-carbon emissions may realize substantial economic benefits in the near and long term.

These economic considerations must also be seen in combination with the various ship types. Different ship types have different operational profiles and therefore different reactor requirements. With the large number of different types of SMRs and microreactors being developed, it is very likely that some reactor types will be more suitable for some ship types. For example, ships that run mostly in transit across the world's oceans can use steam turbines and will therefore benefit from reactor types that work best with steam turbines, while ships using multiple thrusters for dynamic positioning will probably benefit more from electric drives and hence another type of reactors. In addition, the effect output of the reactor will obviously be a part of this consideration. Basically, one size does not fit all ships.

Subsection 4.2: Regulatory Considerations

Commercial ships are subject to different regulatory oversight and requirements than naval or government-owned vessels. Existing international regulations for merchant nuclear vessels include the International Maritime Organization (IMO) Convention for the Safety of Life at Sea (SOLAS) Chapter VIII for Nuclear Ships (1961) and the subsequent Resolution A.491(XII) Code of Safety for Nuclear Merchant Ships (1981). However, these mechanisms are to some extent outdated and applicable only to PWR systems, which were the only reactor type considered at the time of publication.

These regulations require significant updates to modernize requirements and accommodate other reactor technologies. IMO regulations are adopted by member state flag authorities to standardize engineering and safety practices for international ships. It may be possible for a merchant vessel to operate between nations if agreements are made regarding maritime and nuclear engineering standards and operations.

The primary regulatory challenge is the slow pace of regulatory development, acceptance, and implementation compared to the rapid pace of technology development. A secondary challenge is implementing the regulatory regime internationally and at all ports where the vessel may call for cargo, provisions, service, maintenance, or shelter. A third challenge is the insurance of nuclear ships, which rests upon successful settlement of the two aforementioned issues. Otherwise, it is very unlikely that a commercial insurance market for nuclear shipping will be established.

Subsection 4.3: Licensing Considerations

Modern land-based nuclear licensing arrangements are designed for large power plant reactors, typically PWRs at unique sites. Nuclear regulators are independent national authorities responsible for approving the design, construction, and in-service operation of nuclear reactors and related safety systems.

Licensing commercial nuclear-powered vessels complicates the existing system and may require updates to current licensing requirements or the creation of new procedures. National nuclear regulators may not have extensive experience with maritime applications and may need to dedicate resources to develop new licensing requirements for floating applications.

The primary licensing challenge is approving reactor design and operations in a floating environment, transitioning from stationary land sites to vessels transiting national and international waters under dynamic forces. Licensing the operations of maritime reactors is also challenging, as training and qualification scopes are currently unknown, security risks in the international marine environment are not well understood, and manufacturing facilities may require different safety standards for producing transportable reactor units or installing reactors on ships. A secondary licensing challenge is that different countries have different systems, which means that some level of international harmonization will be key in order to establish nuclear merchant shipping.

Nuclear licensors, similar to other regulatory authorities, may move slower to change than technology development and demonstration activities can.

Subsection 4.4: Safety and Security Considerations

Integrating nuclear technology on commercial vessels introduces additional unknowns. Regulatory and licensing regimes may be slow to adjust to new technologies or applications until safety and security hazards are well understood and minimized.

Specific safety considerations for nuclear reactors on ships include reducing the emergency planning zone (EPZ) to minimize potential impact in case of an incident, managing radiological hazards in maritime and port environments, and addressing collision, grounding, or sinking risks.

Security is also a primary concern for maritime nuclear applications, considering the mobility of vessels and international trade. Security hazards include piracy, attacks, or malicious intent involving nuclear material proliferation. Consistently providing defenses against security threats while traveling through international waters and foreign ports presents significant challenges.

Conclusions

This article examines various types of Small Modular Reactors (SMRs), detailing their characteristics, advantages, and limitations as prime movers for all-electric maritime vessels. Additionally, it discusses the technical modeling of essential components for these vessels, including the power network, the SMR, and energy storage units. This modeling is versatile and applicable to different simulation levels from short-term dynamic studies to long-term component sizing and planning.

Nuclear technology has been successfully powering Navy submarines and aircraft carriers for decades, demonstrating its reliability and efficiency. Historical implementations, such as the NS Savannah in the 1960s, provide a promising precedent for utilizing nuclear energy to decarbonize commercial shipping.

While applying commercial nuclear technology to merchant shipping involves complex technology transfer challenges, it also offers the potential for substantial advancements. Efforts to adapt SMRs for maritime use are progressing and targeted research and development activities are enhancing our understanding of the associated economic, regulatory, licensing, safety, and security considerations.

To fully realize the potential of this technology, it is imperative to expand current research and initiate new studies that involve a wider range of stakeholders. This includes addressing economic, regulatory, licensing, and safety/security aspects. Furthermore, additional research is necessary to inform and educate the public about the opportunities and benefits of this transition, fostering support and cultivating committed markets for nuclear-powered commercial shipping.

For Further Reading

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