BUREAU VERITAS CMA CGM PSA ONET

The role of nuclear in shipping decarbonization

Main conclusions of the study carried out by our dedicated working group

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NEW ENERGIES

The energies coalition for transport & logistics

Preamble

The present whitepaper provides a summary of the analysis as to why nuclear power would make sense in the maritime sector, covering propulsion, coastal near-shore nuclear power plants and on-land installation using SMR (small modular reactor) technologies within port premises. It assesses the available and under-development technologies that are applicable for different purposes and the applicable regulatory contexts. It concludes with a plausible timeline if all the identified main challenges are addressed for the large-scale industrial deployment of nuclear power in the maritime industry.

This extensive study has been carried out by the New Energies Coalition, as part of one of its working groups led by Bureau Veritas, with the valuable contribution of CMA CGM, PSA International, and ONET, and in collaboration with one of the major global consultancies.

It is intended to provide decision-makers with objective information on one of the possible zero-emission technologies for the future of maritime.

For those interested in diving deeper, further analysis subjects have been identified for a comprehensive assessment of the viability of nuclear energy in the maritime sector.

About New Energies

The NEW ENERGIES Coalition, initiated in 2019 by CMA CGM, is a consortium of key players in international supply chains, working across various sectors and industries.

Through a collaborative approach, they aim to develop innovative technologies and energy solutions to decarbonize maritime, air, and road activities worldwide.

Additionally, to address the need for a regulatory framework that encourages the recognition and development of new energies and low-carbon and renewable fuels, the members of the NEW ENERGIES Coalition produce studies and manifestos for public and private representatives in the transportation and logistics sector.

NEW ENERGIES thus operates on two levels: solutions and mobilization.

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Executive summary

The maritime industry stands at a critical juncture in its pursuit of decarbonization and environmental sustainability. This whitepaper has explored the potential of nuclear power as a viable solution for marine propulsion, coastal power generation, and port-based energy production.

- **Technological readiness**: Both Generation III+ and emerging Generation IV small modular reactors (SMRs) show promise for maritime applications. While some designs are already operational or nearing commercialization, others are advancing rapidly through development stages.
- **Environmental benefits**: Nuclear propulsion and power generation offer a carbon-free alternative that aligns with stringent emission regulations and global decarbonization goals. This technology could significantly reduce the maritime sector's environmental footprint.
- **Regulatory landscape**: While existing international conventions provide a foundation, there is a clear need for updated and harmonized regulations. Ongoing efforts by organizations such as the IAEA, IMO, and national regulators will be crucial in creating a comprehensive framework for maritime nuclear applications.
- **Economic viability**: As alternative fuel production may struggle to meet demand, nuclear energy could become an economically competitive option and bring additional business benefits, especially as SMR designs reach industrial-scale production.
- **First movers and pilot projects**: Several ports and shipping routes could be considered as potential early adopters. Pilot projects and state-sponsored initiatives will be essential in demonstrating the feasibility and safety of maritime nuclear applications.
- **Challenges and opportunities**: Key challenges include regulatory harmonization, supply chain development, and public acceptance. However, these challenges also present opportunities for innovation, international cooperation, and industry leadership.
- **Timeline for deployment**: A plausible timeline suggests that with concerted effort, we could see commercial deployment of nuclear-powered vessels by 2040-2045, with earlier projects for port-based SMRs and near-shore floating nuclear plants.

Nuclear power has the potential to play a significant role in the future of maritime transportation and port operations. However, realizing this potential will require coordinated efforts from industry stakeholders, regulatory bodies, and governments. The next decade will be crucial in setting the stage for the integration of nuclear technology into the maritime sector.

As the industry moves forward, continued research, pilot projects, and international dialogue will be essential to address remaining technical, regulatory, and social challenges.

A such, the following areas require further analysis and development:

- **Radioactive waste management**: There is a pressing need to develop comprehensive safety guidelines for the management of radioactive waste and spent fuel from SMRs. This aspect is crucial for the long-term sustainability and public acceptance of maritime nuclear applications.
- **Crew training and qualifications**: Developing specific training programs and qualification standards for crew members operating nuclear-powered vessels is essential. This will ensure the safe operation of these advanced technologies and compliance with radiological protection standards.
- **Cybersecurity**: Given the prevalent threat of industrial espionage and cyberattacks, it is imperative to integrate robust cybersecurity requirements within the international nuclear security framework. This integration is crucial for protecting nuclear assets in the maritime sector.
- **Insurance and shared liability**: The current lack of standardized maritime insurance covering nuclear material transport and nuclear risks poses a significant challenge. There is a need to adapt conventional liability frameworks to accommodate the unique aspects of maritime nuclear applications, potentially involving shared responsibility among ship operators, owners, and SMR developers. Similarly, further analysis is required concerning financing structures that could support the supply chain and developers.

Addressing these additional challenges will be crucial in creating a comprehensive and secure framework for the implementation of nuclear technology in the maritime sector.

The following milestones have been identified as key indicators to keep an eye on the future of nuclear in the maritime.

- **The IAEA** official launch of **ATLAS** with a clear support from state members and industry, and in collaboration with IMO
- **IMO resolution** to review and update the Nuclear Code
- **The** i**nsurance community**, through its associations, reopening the 1962 Brussels Convention
- **The financial institutions and agencies** recognizing nuclear energy as a clean source, on par with renewable energies.

The next decade will be pivotal in determining the role of nuclear power in the maritime industry. With concerted efforts from all stakeholders, nuclear energy has the potential to significantly contribute to the decarbonization of shipping and port operations, marking a new era in sustainable maritime transportation.

Learning from the past and new promises

Nuclear can play a role in maritime by providing carbon free energy 24/7

- Technology has proved feasible and reliable, providing power to ports and ships for decades, driven by the US, French and Russian military as well as Russian Arctic civil applications. Since the1950s, +770 nuclear reactors (mostly PWRs), have been operated at sea. As of 2024, ~160 nuclear-powered vessels are operated (mostly submarines)
- Four nuclear merchant ships have operated in the past as well as one FNPP. Another FNPP has been operating in Siberia since 2020. See Figure 1
- A fleet of nuclear icebreakers has continued to operate in Siberian waters since the 1950s.

Latest technological advances have sparked a renewed interest in nuclear

- Thanks to nuclear power's specific characteristics and new technological developments, the EU has officially labelled it as "strategic" for decarbonization. Specific characteristics include large-scale, sovereign and low-carbon energy production, which meet today's requirements in the context of global warming (and the need to decarbonize the shipping sector), growing demand for electricity, and geopolitical instability (e.g., Russian war in Ukraine). New technology developments include improved reactor passive safety, higher operational efficiency (e.g., long refueling time), and greater market acceptance (e.g., spent fuel recycling capability).

This whitepaper focuses on the small modular reactors (SMRs) some of which fall within the category of advanced modular reactors (AMRs).

Table 1 provides a summary of their main differences with the conventional on-land reactors currently operating or being built.

	Large reactors	Small modular nuclear reactors
Size	*1,000MW+*	*~10-300MW*
RPV layout	*Large and complex design*	*Compacted, encapsulated and standardized design*
Size	*> 10 m2 / Mwe*	*5 to 10 m2 / MWe*
Siting	*10 km*	*Potentially EPZ at site perimeter (pending regulatory approval)*
Fuel type	*Conventional Low Enriched Uranium (LEU)*	*LEU, next generation fuel HALEU - with spent fuel recycling capability*
Fuel enrichment	*LEU < 5%*	*LEU <5% and HALEU [5%-to-20%]*
Applicability	*Land: fixed siting location and requires access to established grid*	*Land: flexible siting location without existing grid infrastructure* *Sea: marine propulsion*
Time for construction	*[5-15+] years, with a median of ~7.5 years*	*[3-4] years – Limited information on median*
Power output	*Electricity*	*Electricity and Heat*
Refueling frequency	*12 to 18 months*	*+24 months up to no refueling*

TABLE 1: MAIN CHARACTERISTICS OF CONVENTIONAL REACTORS AND GEN.III+, GEN.IV OF SMRS

Sources: ANSTO [Link]; Nuward [Link]; Press [Link]; Westinghouse [Link]; Nuscale [Link]; IAEA [Link]; Monitor Deloitte Research & Analysis

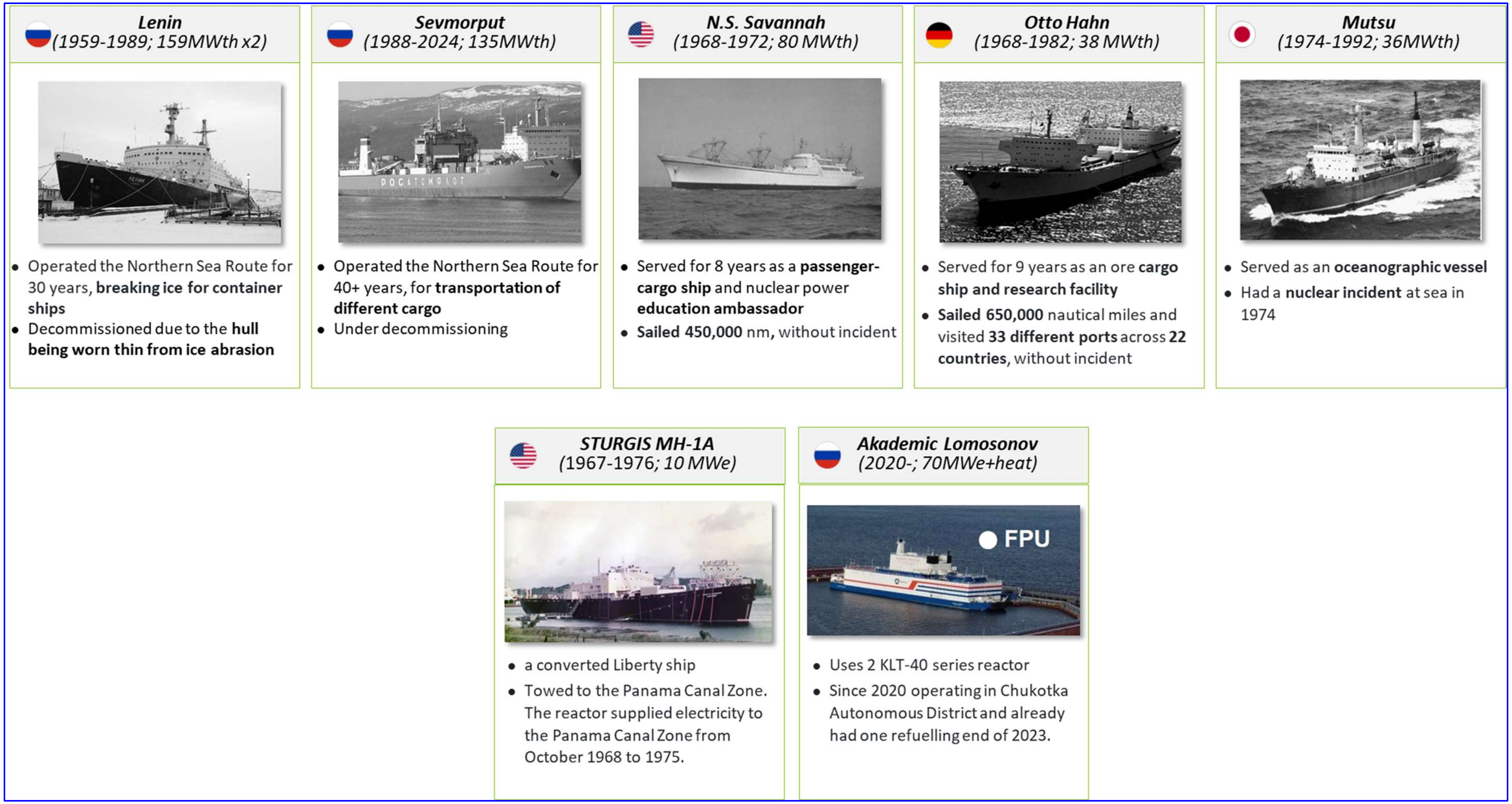


FIGURE 1: PAST CIVIL NUCLEAR VESSELS AND PAST AND CURRENT FLOATING NUCLEAR POWER PLANTS

Sources : https://en.wikipedia.org/wiki/MH-1A; https://www.usace.army.mil/About/History/Exhibits/Nuclear-Power-Program/Sturgis/; Rosatom and Afrikantov OKBM JSC presentation at IAEA FNPP Forum November 2023

Key driver: Marine environmental footprint

Although maritime transport is the most efficient means of transport and has the lowest share of CO2 emissions (less than 3%) of all the transport industries, the transition to cleaner fuels is not only about CO2 and decarbonization. The different regulations that have been enacted since the second half of the 2000s, with the first appearances of the ECA (Emission Control Areas) imposed limits not on CO2 but on sulfur oxides (SOx), with the Baltic and the North Seas being the first, as shown in Figure 2. Nitrogen oxides (NOx) limitations started a few years later with the Tier I definition in 2008. The regulatory trend for environmental and health considerations continued with several new ECA appearing and a more stringent limit to sulfur content in marine fuels, which was the origin to very low sulfur fuels and the appearance of scrubbers on board of vessels.

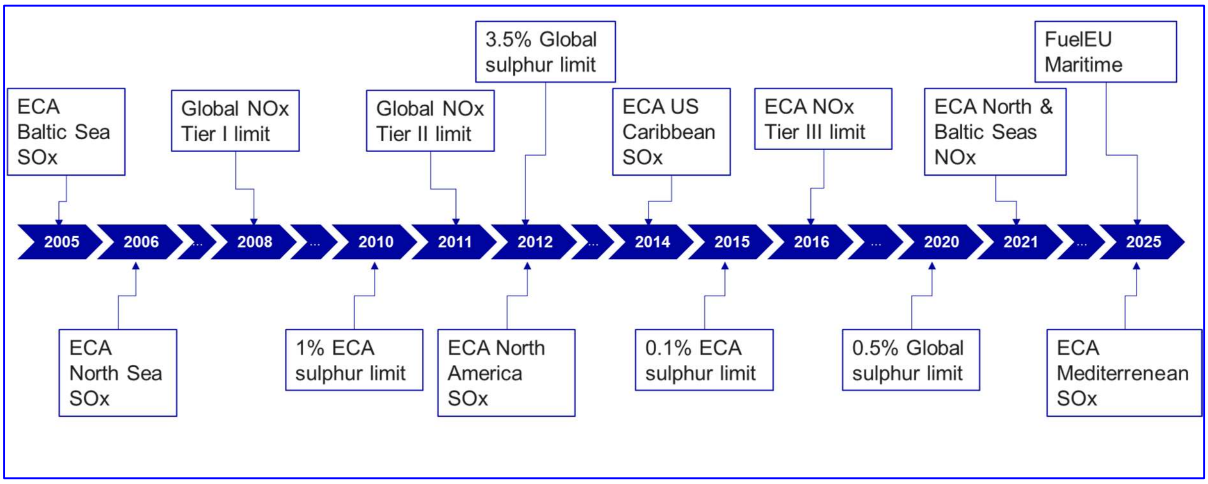


FIGURE 2: MARINE EMISSIONS LIMITATION REGULATIONS ENTRY INTO APPLICATION

Replacing current fossil-based fuels with new ones, electrification and nuclear propulsion can then be seen as the logical continuation of transforming the maritime fleet with as minimal an environmental footprint as possible.

Can nuclear propulsion have a sizable share of new-build vessels by 2050?

From a fuel cost perspective, when brought down to the expected cost to obtain a unit of energy (1MWh), current analysis tends to think that by the time environmentally friendly fuels are available in scale, SMRs should be starting to be fabricated industrially (Nth-of-a-kind) leading to a comparable cost per energy unit to that expected from low-carbon fuels, making nuclear propulsion worthy of consideration.

Where the environmental regulations become relaxed (either in scope or in time of application), traditional fuels would remain the lowest cost option. See Figure 3

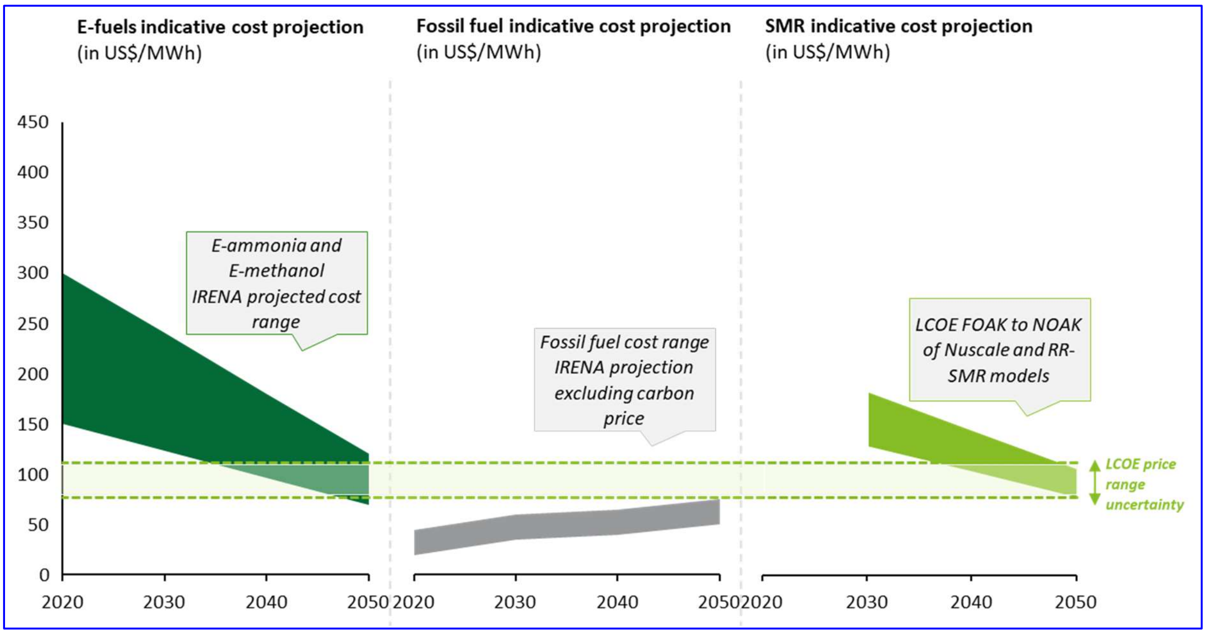


FIGURE 3: OVERVIEW OF COST PROJECTIONS TO GENERATE 1MWH OF ENERGY

The next question, assuming the production costs mentioned above materialize, is whether there would be enough production of alternative fuels to drive the green transformation of the maritime fleet, as per the net-zero scenarios (see Figure 4). If the marine fuel was the only hard-to-abate industry, having not only greenhouse emissions to tackle but SOx and NOx too, then most probably there would be enough production of greener fuels to replace the 230-250MT of fuel consumed by the vessels worldwide. However, that is not the case, and the ship managers would compete with other industries to have access to the new fuels.

Based on current expectations of production and current fuel consumption, the fleet would be demanding for one third of the overall production capacity, when it nowadays represents 3% of the energy use (see Figure 5). Less demanding decarbonization pathways, such as the conservative scenario by Deloitte would still mean 15% of the overall alternative fuel production.

This leads to conclude that pursuing other decarbonization options, such as nuclear energy, makes sense from several points of view: environmental, economic and risk management.

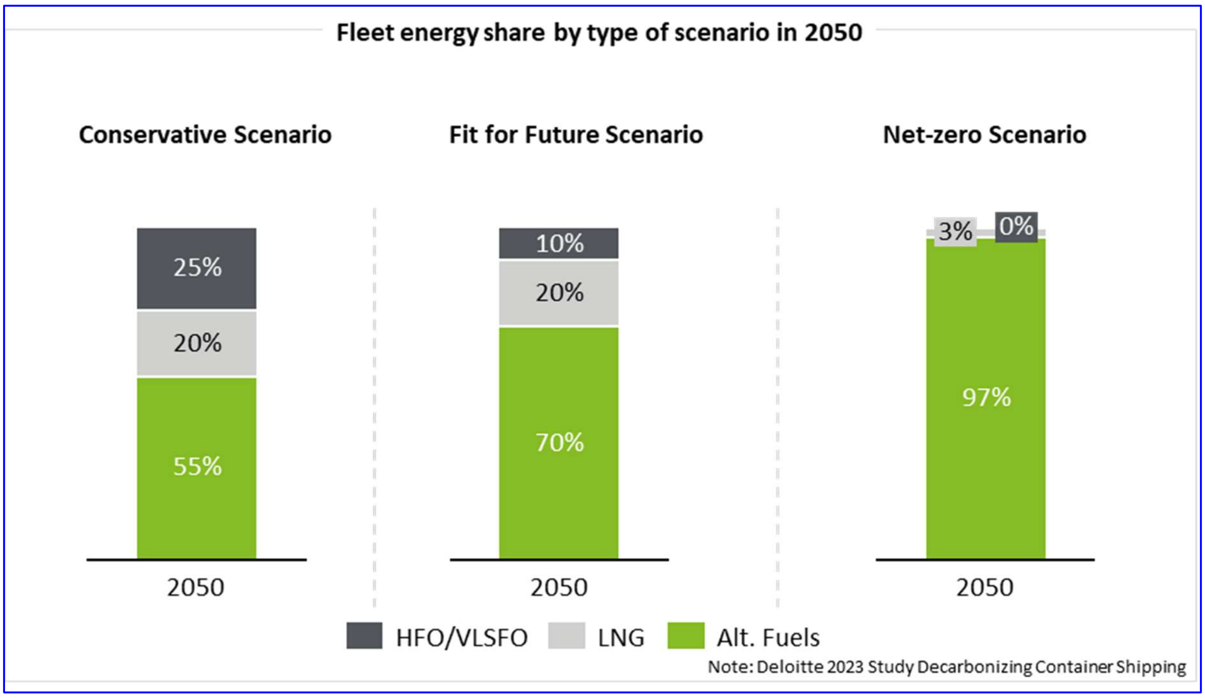


FIGURE 4: SEVERAL SCENARIOS OF CO2 ESTIMATE BY 2050 BASED ON ALTERNATIVE FUEL ADOPTION[1]

Sources: Deloitte shipping reports; DNV Maritime Forecast 2050 [Link]; Statista; Monitor Deloitte Research & Analysis

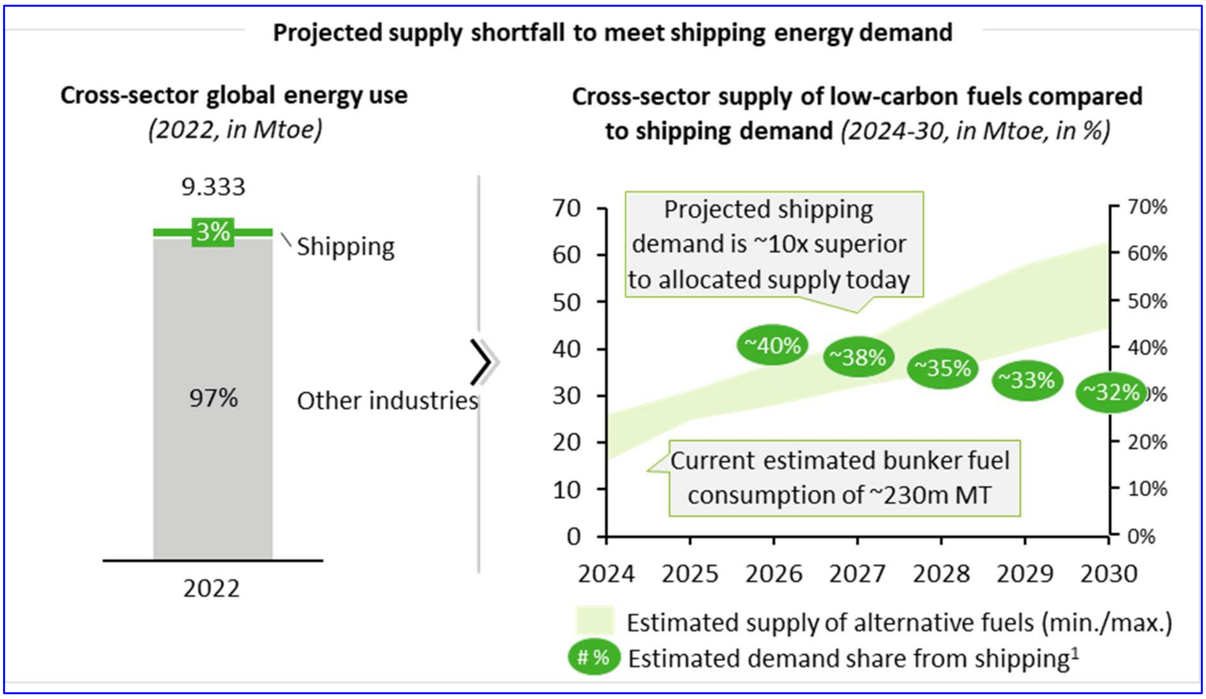


FIGURE 5: PROJECTED ALTERNATIVE FUELS SUPPLY SHORTFALL FOR SHIPPING ENERGY DEMAND

[1] *Estimated demand share calculated based on the average on alternative fuels min./max. project supply available*

Alignment with ports

Ports are also feeling the pressure to transition to a carbon-free activity and their Scope 3 emissions include the emissions from vessels at berth. So here the interest of nuclear propulsion aligns with those of the receiving port. In addition, FuelEU requires ports to provide cold ironing (power from shore) to vessels berthed, which although would only represent 10% of the port total power (see Table 2), could lead to significant infrastructure works in the port and several hundred of MW contracted from the grid.

Typical emitters	Share of electricity demand for decarbonization (%)[4]
Scope 1: ***Port Direct Sources*** *(Direct emissions from port-owned and controlled assets)*	
- Diesel-powered cargo handling equipment (e.g., cranes, forklifts) - Diesel-powered port fleet vehicles (trucks, maintenance vehicles) - Service vessels (e.g., tugboats, pilot boats)	***~23%*** *(freight handling 20%, service vessels 3%)*
Scope 2: ***Port Indirect Sources[2]*** *(Indirect emissions from non-renewable electricity consumption by the port's operational activities)*	
- Port buildings (e.g., offices, warehouses) - Port infrastructure (e.g., lighting, sensors, gates)	*Variable*
Scope 3: ***Other Indirect Sources[3]*** *(All other emissions associated with tenant operations not directly owned or controlled by the port)*	
- Third-party ships at berth (using cold ironing) - Inbound/outbound transportation (e.g., trucks, trains) - Tenant operations	***~77%*** *(cold ironing 10%, service inbound/outbound transportation 67%)*

TABLE 2: OVERVIEW OF PORT EMISSIONS ACROSS THE THREE GHG SCOPES[2]

Sources: DNV [Link]; Deloitte Port Report [Link]; World Resources Institute (WRI) and World Business Council for Sustainable Development (WBCSD) [Link]; Monitor Deloitte Research & Analysis

Nuclear powered vessels could then help ports achieve their emissions targets, allowing them to invest first in the electrification of their own activities and even deploy their own SMRs within the premises, not only for their own electricity demand but possibly also for the production of low-carbon fuels to power the smaller vessels.

The European Commission estimates the investment in alternative fuel infrastructure between 2025-2025 at €9.9 billion, with €2.5 billion allocated for hydrogen infrastructure and €7.4 billion for OPS. Sources: (European Sea Ports Organization (ESPO) [Link];)

[2] Notes: 1) The methodology for the scopes is given by the World Ports Climate Initiative (WPCI) guideline, established to raise awareness in the port and maritime community about the need for action regarding GHG emissions; 2) Assuming the electricity is sourced from the grid and not generated on-site from renewable sources; Tenant power and energy purchases are not included in this scope; 3) For a port with a large number of tenants, this will likely be the largest source of greenhouse gas emissions; 4) Based on EU outlook electricity demand in GWh by 2050 [Link]

What vessels?

If nuclear energy is then one of the options from which shipbuilders and shipowners can choose for an environmentally friendly propulsion, what vessels should be the first targets for

its deployment? Two different considerations can be made then, based on installed power or highest impact on achieving emissions targets.

With regards to power and based on the power output capacities of the different SMR designs publicly available, vessels with an installed power above 30MW would be good candidates to have nuclear propulsion. This would mean containerships above 10000 TEU, cruise ships, the largest LNG carriers and the largest oil tankers (see Figure 6).

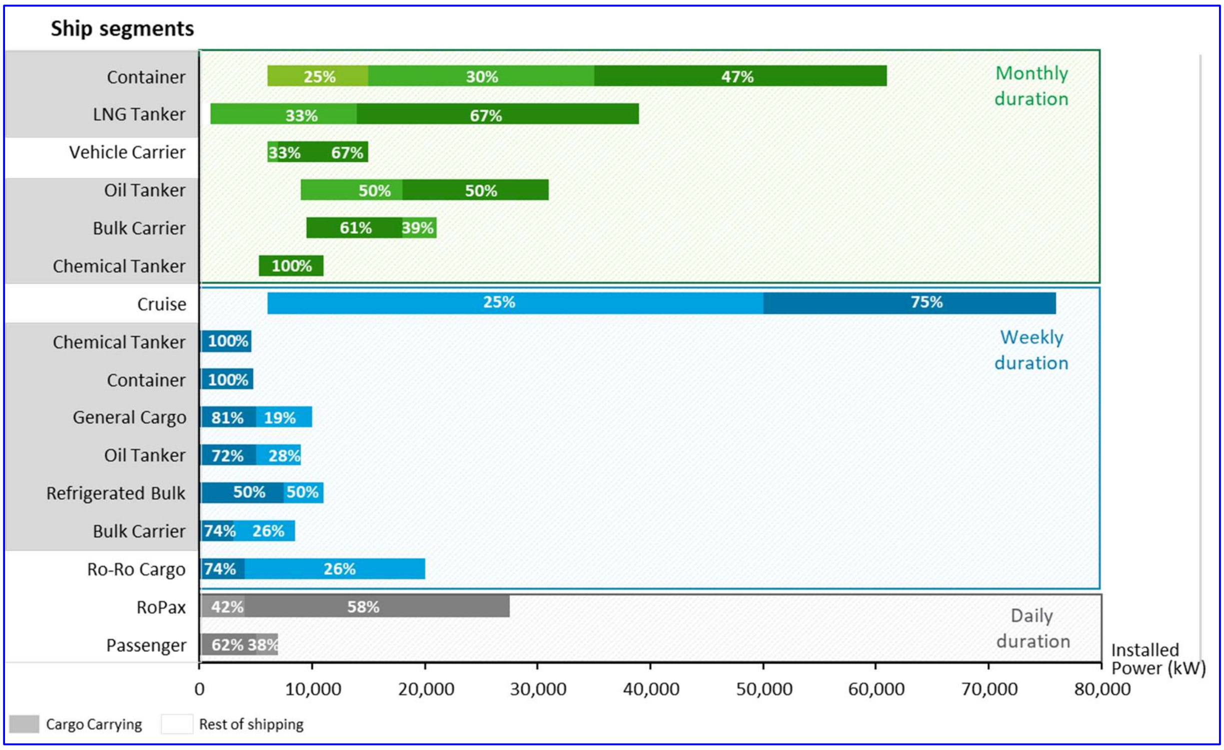


FIGURE 6: OVERVIEW OF SHIPS PER INSTALLED POWER, TYPE, NUMBER AND VOYAGE DURATION
Sources: RINA [Link]; Monitor Deloitte Research & Analysis

From an emissions impact point of view, the cargo carrying fleet would best be served by nuclear energy, and within it those vessels engaged in monthly international voyages, as they would represent 4/5 of the total maritime emission (see Figure 7). Cruise vessels could also be added here given that they navigate in ECA zones and are being required to have zero emissions while in port (FuelEU regulations).

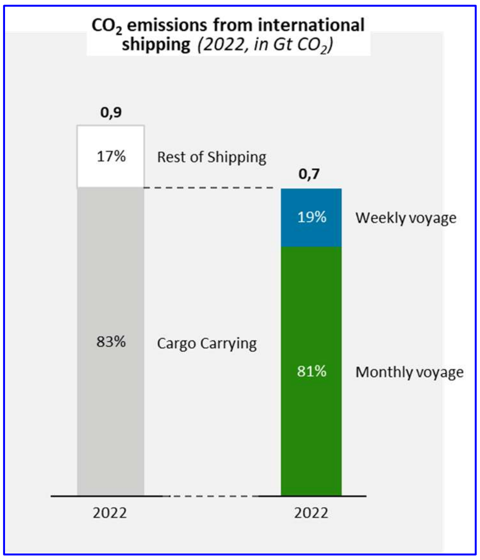


FIGURE 7: CO2 EMISSIONS FROM INTERNATIONAL SHIPPING (2022 FIGURES)

The fourth IMO GHG study of 2020 illustrated very well those vessels that consume the most and therefore emit the most, and even if per ton transported, they are the most efficient (see Figure 8). We see here bulk carriers, the containerships and oil tankers that stand out from the rest.

It is not surprising then to see a bulk carrier, a containership and, once again, a cruise ship, given as illustrations of potential nuclear vessels in the latest EMSA report on Potential Use of Nuclear Power for Shipping, published in Nov. 2024.

Going into some detail, and using Clarksons' estimations, the older steam turbines LNG carriers have the highest average emissions (close to 300t of CO2 per day). These vessels are however starting to leave the fleet. The newer LNGCs have close to half their predecessors' average CO2 emission per day.

According to Clarksons' figures, the largest oil tankers (VLCCs) are then the greatest emitters, followed closely by large containerships (10000 TEU and above) with 160-180 t of CO2 per day. Large bulk carriers (VLOCs) are next, hand in hand with the first generation of 174k LNG carriers, just below the 160 t of CO2 per day.

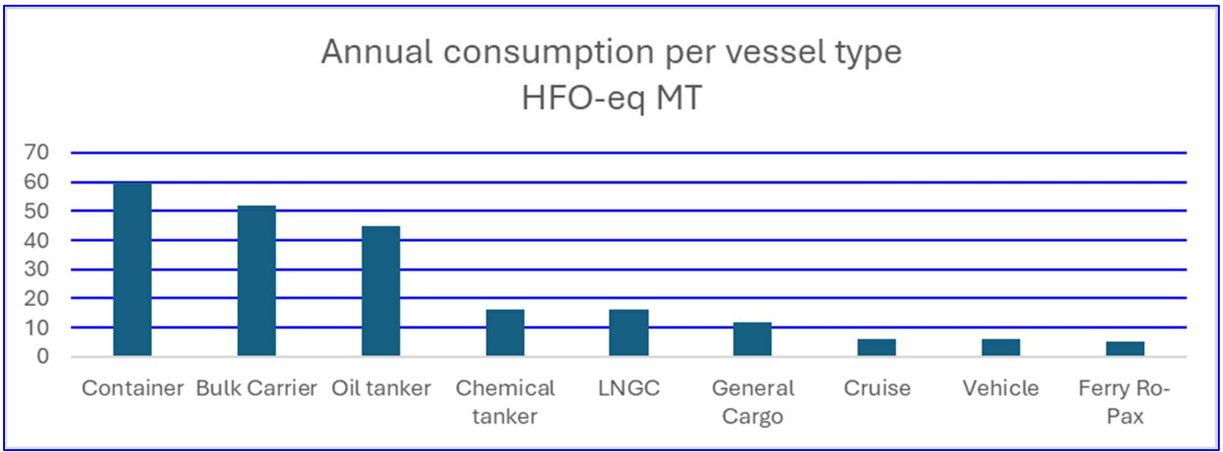


FIGURE 8: AVERAGE ANNUAL FUEL CONSUMPTION PER SHIP TYPE, ACCORDING TO THE VOYAGE BASED ALLOCATION OF INTERNATIONAL EMISSIONS (IMO GHG STUDY 2020)

Regulatory context

The deployment of nuclear propulsion or nuclear power within port premises already counts with a comprehensive legal basis although uneven coverage for SMRs. The only maritime convention that outlines the safety norms for nuclear ships (Code of Safety for Nuclear Merchant Ships under SOLAS chapter VIII) is related to the pressurized water reactors' design. Meanwhile, existing nuclear regulations focus mainly on traditional land-based nuclear power plants and the transport of radioactive materials[3]. Regulatory bodies must also clarify the applicability of land-based nuclear conventions to permanently installed units that might have been built elsewhere, as such is the case for floating nuclear power plants or transportable nuclear power plants (FNPPs & TNPPs) and attached to the shore.

To develop a comprehensive regulatory framework for maritime applications of SMRs, there is a need to align the ongoing efforts of the IAEA (which is tackling the points mentioned in previous paragraph) and the IMO (which is starting to consider updating the Nuclear Code) at a global scale. Prioritizing and addressing critical regulatory areas in the first place is fundamental for the integration of SMRs into maritime applications. These critical regulatory areas are the following:

- **Emergency and exclusion zones**: Current IAEA safety standards are tailored to water-cooled, land-based SMRs and do not address adequate emergency arrangements' design. An important challenge is to develop and justify the size of the emergency planning zones (EPZs).

- **Radioactive waste and spent fuel**: So far, most SMR developers have devoted little detailed attention to the management of radioactive waste and spent fuel from SMRs. It is necessary to develop the safety guidance in several areas, including for the processing, storage of spent fuel, and the disposal of entire reactors.

- **Training and qualifications of crew**: Maritime conventions lack specific provisions for training personnel on nuclear-powered ships, which is critical for safety and radiological protection (note: there are no requirements on this specific topic in the STCW Convention).

- **Nuclear cyber security**: The integration of cybersecurity requirements within the binding international nuclear security framework is imperative, given the prevalent threat of corporate espionage and cyber-attacks against industrial assets. The monitoring of the NIS 2 Directive (2023) and the upcoming Cyber Resilience Act is required.

- **Export control and recognition between national nuclear safety regulators**: Export control regulations may be of extraterritorial application, meaning that the use, incorporation, supply, transfer, etc. of goods and technologies of one country can be subject to restrictions at a further stage within international waters or on the soil of a foreign country. These rules can limit SMR exports.

- **Insurance requirements**: There is currently no standard maritime insurance covering transport of nuclear materials and nuclear risks are generally excluded from maritime insurance policies. SMRs' application for ship propulsion would require time for insurers to be ready and discussions with insurers are necessary to raise awareness.

- **Shared liability**: The principle of strict absolute liability of the shipowner finds its echo in the nuclear industry with the nuclear licensed operator. But how these will translate in maritime SMR applications will require particular attention. The conventional liability frameworks need to be adapted through specific services agreements between them. A particular tricky point is the responsibility of the nuclear reactor operator and its relation to the shipowner, the ship operator and the ship captain.

[3] Not including irradiated nuclear reactors and radioactive materials part of a means of transport. Currently not covered by any regulation.

Local regulatory evolutions are also needed to enable nuclear ship propulsion.

While countries with nuclear installations have comprehensive national frameworks, local regulations mainly address the transport and docking of packaged radioactive materials.

There is a clear need for new local regulations for the safe, secure navigation and docking of such nuclear ship and mobile FNPPs/TNPPs within ports.

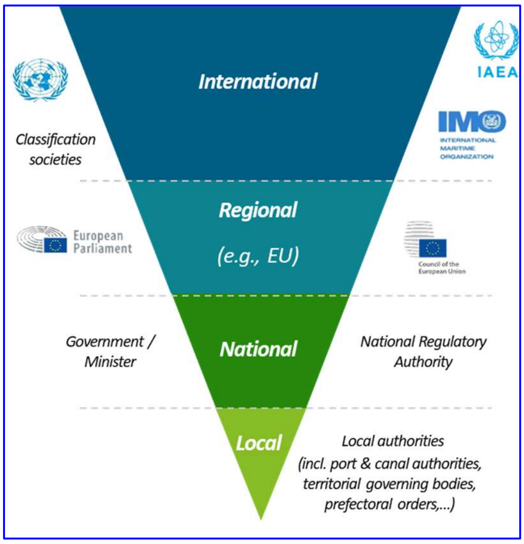


FIGURE 9: REGULATION LEVELS

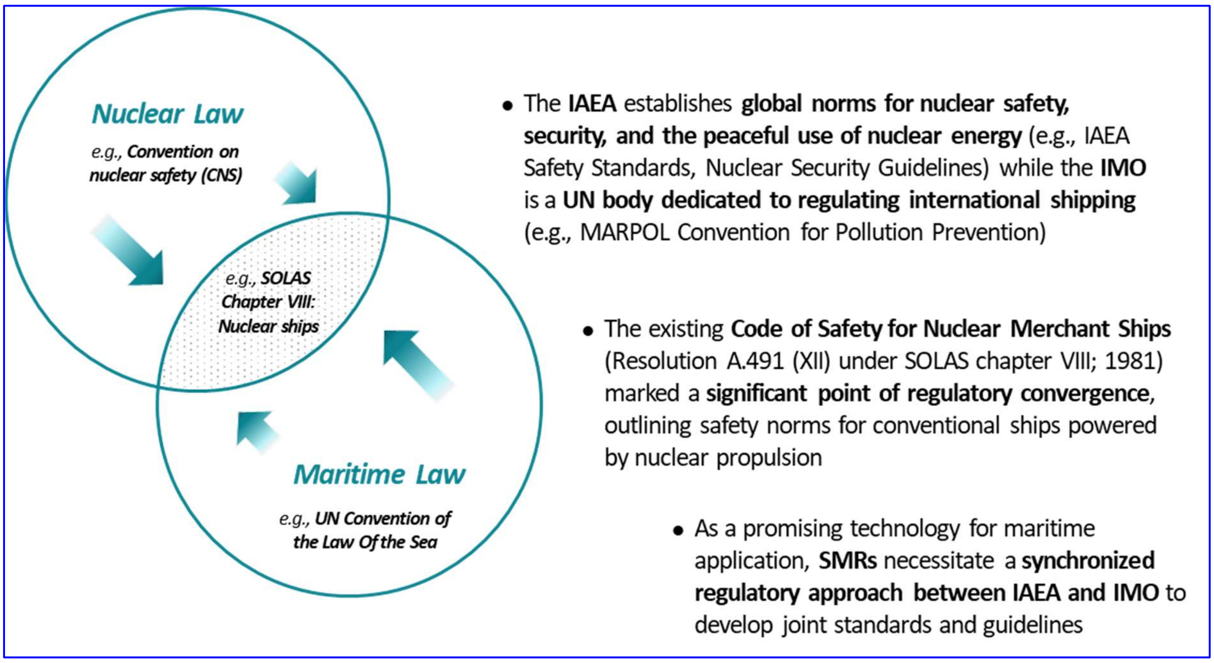


FIGURE 10: ALIGNMENT BETWEEN THE IMO AND THE IAEA

Sources: Monitor Deloitte & Deloitte Société d'Avocats Research & Analysis

National and local regulations are often derived from international standards, so initiatives at the IAEA and IMO would lead the way. Concerning ratification of international nuclear codes, around 50 out of 120 countries with national nuclear regulatory bodies feature well-developed nuclear regulatory frameworks that comply with key international conventions on nuclear safety, security and liability (see Figure 11). Since COP28, 30 countries have committed to increase by three the nuclear power in their territories, leading to a certain optimism of seeing cooperative disposition at the international agencies. There still are seven countries that have legally banned nuclear power use: Austria (since 1978), Denmark (since 1985), Italy (since 1987), New-Zealand (since 1987), Australia (since 1999), Ireland (since 1999), and Germany (since 2022), but a comeback is being considered in some of them, as recently seen in announcements by the Government in Italy, the future German Chancellor and the opposition party in Australia.

To note that the USA and Canada have not ratified either the 1960 Paris Convention or the 1963 Vienna Convention, both of which address international nuclear liability and for any transportable nuclear reactor (be it for propulsion purposes or within a FNPP/TNPP), they will need to consider their position.

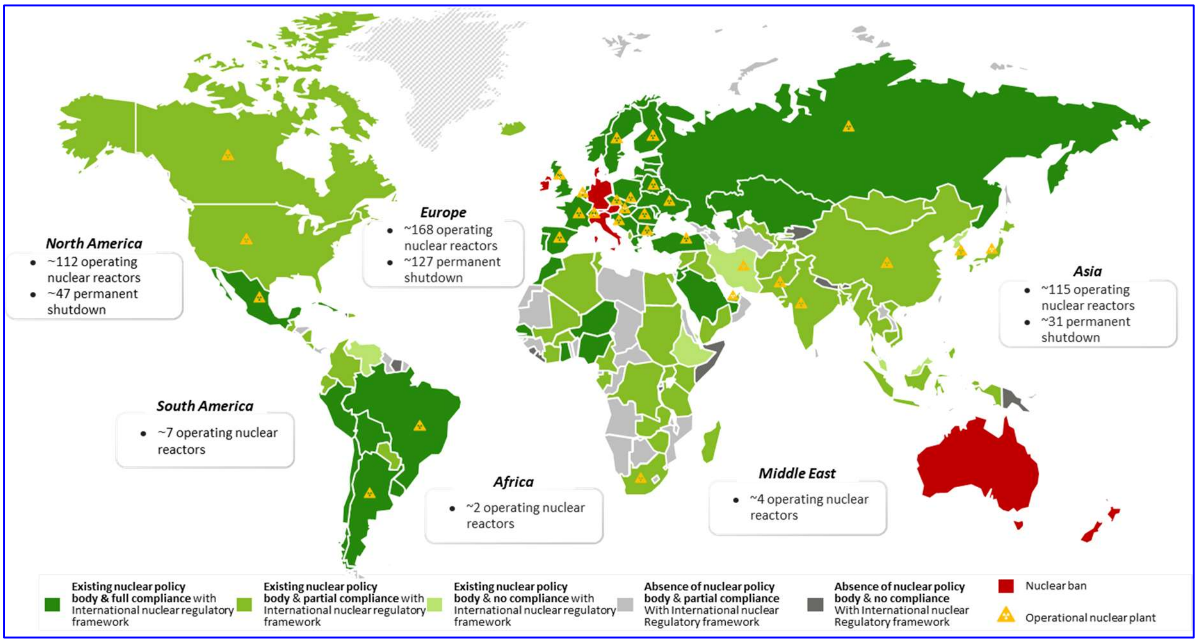


FIGURE 11: OVERVIEW OF COUNTRY COMPLIANCE WITH INTERNATIONAL NUCLEAR REGULATORY FRAMEWORK

Although the 1981 ratified Nuclear Code is rather prescriptive and was developed considering only pressure light water reactors (PLWRs), it allows designing and building nuclear propelled vessels for international trade. To do so, however, these vessels would need to be insured, which is extremely improbable without an equivalent to the Vienna and Paris liability conventions for on-land NPPs (Vienna Convention on Civil Liability for Nuclear Damage, Paris Convention on Third Part Liability in the Field of Nuclear Energy) that put a cap on the liability covered by the insurer (usually a pool) and above which national funds would kick in. The Paris Convention excludes the radioactive materials that form an integral part of a means of transport. The attempt, in 1962 through the Brussels Convention (1962) – IMO Convention on the Liability of Operators of Nuclear Ships – was not successful and makes it extremely uncertain for insurers to cover civilian propelled vessels. But if, as it happened with the pilot vessels in the 1960s and 1970s, states would step in, civil nuclear merchant vessels could navigate under the surveillance of the Nuclear Code ratifying Flags.

FNPPs and TNPPs can be, and de facto are, using the actual example of the Akademik Lomonosov before the conflict in Ukraine, covered by a pool of nuclear insurers under the Vienna or the Paris conventions. The only challenge with these units, when intended to be moved outside of national waters, is that after being fueled or irradiated they have no code or regulation to cover their transport. The IAEA SSR-6 (Safety regulations for the Transport of Radioactive Material) and the IMO INF Codes (International Code for the Safe Carriage of Packaged Irradiated Nuclear Fuel, Plutonium and High-Level Radioactive Wastes on Board Ships) do not cover such case, that is, transporting a whole irradiated reactor or the transport of fuel without proper packaging according to the aforementioned codes. Not to mention the considerations for application of the IAEAs' Security of Radioactive Material in Transport and Security of Nuclear material in transport.

Reactors technology

A final common challenge to both nuclear propelled vessels and deployable SMRs (on-land or with FNPPs/TNPPs) are the current prescriptive guidelines concerning emergency planning zones or distances, as set out in IAEA's DS 453, in GSR Part 3 and GSR Part 7, and succinctly illustrated in Figure 12, that are followed by most national nuclear safety regulators. By default, they would apply to the PWRs covered by the SOLAS Ch. VIII and would mean that the surrounding port and populated areas around the reactor would need to prepare and file emergency contingency plans accordingly.

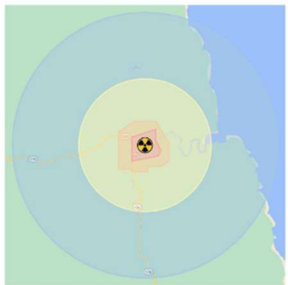
Some Generation III+ and most, if not all, Gen IV SMRs (including AMRs) promise being able to demonstrate and be recognized by regulators having EPZs limited to the site boundaries. At the time of this report, some designers have initiated such demonstration process with their national nuclear regulator.

Countries are not obliged to follow the IAEA recommendations concerning EPZ and EPD and Canada is an example of not doing so, choosing to follow a Safety Case approach where it is the nuclear operator to demonstrate the EPZ it considers necessary based on pre-defined terms.

IAEA RECOMMENDED EMERGENCY ZONES AND DISTANCES

Precautionary Action Zone (PAZ)	Designated area for urgent protective and response actions before a significant radioactive release
Urgent Protective action planning Zone (UPZ)	Designated area for urgent protective and response actions before or after a significant radioactive release.
Extended Planning Distance (EPD)	Area beyond the UPZ for monitoring and assessment of the radiological situation off-site
Ingestion and Commodities Planning Distance (ICPD)	Area beyond the EPD for response actions to protect the food chain, water supply, and public from contamination.

IAEA Suggested emergency zones



Reactor Power 100 to 1000MWth:

EPZ *(in km)*	3km	30km
EPD *(in km)*	50km	100km

FIGURE 12 : IAEA RECOMMENDED EMERGENCY ZONES AND DISTANCES[4]

The Advanced Reactors Information System (ARIS) database includes technical information about advanced reactor designs that is provided by the responsible design organizations and/or reactor plant vendors. According to the definitions established by the International Atomic Energy Agency (IAEA), an advanced reactor design consists of both evolutionary and innovative reactor technologies. Evolutionary reactor designs improve on existing designs through small or moderate modifications with a strong emphasis on maintaining proven design features to minimize technological risk. Innovative reactor designs incorporate radical changes in the use of materials and/or fuels, operating environments and conditions, and system configurations. Advanced reactors can be classified in terms of coolant, neutron spectrum, temperature or purpose. With regards to purpose, the reactors can be sorted in terms of experimental or prototype, demonstration and commercial. The NEA SMR Dashboard: Second Edition from the OECD Nuclear Energy Agency (NEA) also provides insight on the current reactor designs based in publicly verifiable sources (www.oecd-nea.org/dashboard-edition2-ref).

[4] https://nucleus.iaea.org/sites/orpnet/training/orphighexposure/Shared%20Documents/6-Preparedness%20and%20Action%20in%20Emergency.pdf

Table 3 provides a summary of the different technologies being considered and a proposed division line between Gen. III+ (commercially proven, with running demonstrators or on the last phases of design and construction) and the upcoming Gen. IV designs (most at early design and licensing stages)

Our analysis uses these two sources as basis (IAEA, NEA) and it adds privately held discussions with less publicized projects and reactor designers.

Nearly half of the 150+ SMR projects under development are Generation III+ water reactors,

Three SMR reactor technologies are commercially operating today, including Chinese land-based Gen III+ GCR (HTR-PM), Russian coastal-based Gen II PW (KLT-40S), and Russian nuclear propulsion Gen II IPWR (RITM-200).

Gen III+ reactors are the most developed technology type for naval propulsion, benefiting from Gen II IPWR operation today by Russian icebreakers. Gen IV SFR technology is expected to be available from 2035

Gen III+ reactors are the most developed technology type for coastal-based energy generation, benefiting from Russian Gen II floating power plant experience and Chinese Gen III+ GCR. Gen IV LFR is expected to be available from 2030

Gen III+ GCR is the most developed technology type for land-based energy generation, benefiting from operational Chinese reactor. Gen IV SFR is expected to be available from 2035 and other technologies from 2040.

Table 4 summarizes the most relevant features, as a quick overview not intended to be precise, for the different technologies presented, indicating on a green background those that represent a positive feature for the parameter considered. It is to be noted that for Gen IV technologies most of these features are theoretical and the constraints to practical application at industrial scale have not been considered.

Nearly half of the SMR projects are Generation III+ water reactors, with Gen. III+ gas-cooled reactors (GCRs) being the second most deployed technology covered by our analysis (see Table 5)

What technologies for what purposes

Three key criteria were considered in this study for the selection of SMR designs based on their deployment purpose:

- Technical performance requirement
- Compatibility requirements
- Operations requirements

Plus, other considerations that can be common to all three purposes covered (see Table 6).

Based on these criteria, from the 160 technologies considered, only a selected few have been retained for a deeper analysis of their prospects for consideration in the different purposes analyzed in this whitepaper:

- **20 designs are shortlisted for marine propulsion**
- **25 designs are shortlisted for coastal-based power generation**
- **25 designs are shortlisted for land-based power generation**

They are summarized in Figure 13, indicating the assessed Technical Readiness Level, going from TRL 1-2 for conceptual stage, to TRL 9 for proven commercial operations and with TRL 5 concerning Technology validated in a lab, in between.

Time to commercialization

Based on the information publicly available from designers, IAEA, NEA and privately held discussions, the expected time to move from a particular TRL to commercialization (TRL 8 & 9) was estimated as a min-max range, under current regulatory known pathways.

- **TRL 3 to TRL 8:** 10 to 23 years (longer timeline for Gen IV most innovative designs, shorter timeline for Gen III+ water cooled newer designs)
- **TRL 4 to TRL 8**: 8 to 18 years
- **TRL 5 to TRL 8**: 5 to 6 years
- **TRL 6 to TRL 8 (Gen IV case only)**: 6 to 9 years

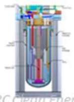
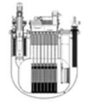
GENERATION	Generation III+					Generation IV				
SPECTRUM	Thermal *(fission chain reaction is sustained by moderated neutrons)*						Fast *(fission chain reaction is sustained by fast neutrons[1])*			
TECHNOLOGY TYPE	Water Cooled				Gas Cooled	Molten Salt	Molten Metal		Molten Salt	Gas Cooled
REACTOR TYPE	PWR	IPWR	BWR	Heavy Water	GCR	MSR	SFR	LFR	MSFR	GCFR
FUEL TYPE	Oxides	Oxides	Oxides	Oxides	TRISO	Molten salts	TRISO	MOX	Molten salts	GCFR
FUTURE ALTERNATIVE FUELS		Thorium		Thorium	Thorium	Thorium	Thorium/ liquid metals	Nitride/ Metal	Thorium	Ceramic/ thorium
DESCRIPTION	*Light water-cooled graphite moderated reactor*  Last Energy, Open20	*Compact PWR design with primary circuit (e.g., pressurizer, coolant pumps, steam generators) encapsulated in the reactor vessel*  OKBM, RITM200-N	*Boiling light water-cooled and moderated reactor*  NIKIET, KARAT-45	*Heavy water (deuterium oxide D2O) -cooled and moderated reactor*  UWB Pilsen, TEPLATOR	*Gas-cooled reactor that uses graphite as a neutron moderator and carbon dioxide or helium as coolant*  X-energy, Xe-100	*Molten salt mixture-cooled reactor*  Seaborg, CMSR	*Liquid sodium-cooled reactor. First adapted for nuclear submarine*  ARC Clean Energy, ARC-100	*Liquid lead-cooled reactor. First adapted for nuclear submarine*  Newcleo, LFR-AS-30	*Molten salt mixture-cooled reactor*  TerraPower, MCFR	*Gas-cooled reactor*  General Atomics, EM2

TABLE 3: SUMMARY TABLE OF SMR TECHNOLOGIES CONSIDERED[5]

Sources: IAEA ARIS [Link]; IAEA SMR Book [2020; 2022]; INL [Link]; Monitor Deloitte Research & Analysis

[5] Notes: 1) Fast reactors offer i) enhanced fuel efficiency (i.e., increased energy yield from natural uranium compared to thermal reactors), ii) closed fuel cycle (i.e., reprocessing and recycling their own fuel), and iii) waste reduction (i.e., burning nuclear waste)

		PWR	IPHWR	BWR	Heavy Water	GCR	MSR	SFR	LFR	MSFR	GCFR
	GENERATION	Generation III+					Generation IV				
	SPECTRUM	Thermal						Fast			
	TECHNOLOGY TYPE	Water Cooled				Gas Cooled	Molten Salt	Molten Metal		Molten Salt	Gas Cooled
	REACTOR TYPE	PWR	IPHWR	BWR	Heavy Water	GCR	MSR	SFR	LFR	MSFR	GCFR
SAFETY BY DESIGN	Low Pressure	*Plume exposure EPZ (100-150MPa)*					*Limited exposure reducing EPZ (up to 40-50MPa)*				
SAFETY BY DESIGN	Liquid Fuel	*Risk of fuel melting*					*No risk of fuel melting*	*Low risk of fuel melting*		*No risk of fuel melting*	*Low risk of fuel melting (e.g., Triso)*
SAFETY BY DESIGN	Air/Water Chemical Reactivity	*Low*						*High*	*Low*		
SAFETY BY DESIGN	Coolant Boiling Point	*Low (~300°C)*				*Low (less than 0°C)*	*(1400°C)*	*High (900°C)*	*(1300-1900°C)*	*(1400°C)*	*Low (less than 0°C)*
OPERATIONAL EFFICIENCY	Coolant solidification	*Low risk of reactor poisoning*					*High risk of reactor poisoning*				*Low risk of reactor poisoning*
OPERATIONAL EFFICIENCY	Net efficiency	*Conventional efficiency (30% electricity & heat)*				*High thermal efficiency (30% electricity - 50% heat)*					
OPERATIONAL EFFICIENCY	Online Refueling	*Shutdown required for refueling (18-24months)*				*Pebble bed allow online refueling*	*Molten salt allow 10Y-to-online refueling*	*Shutdown required for refueling (at least 24months)*		*Molten salt allow 10Y-to-online refueling*	*Pebble bed allow online refueling*
OPERATIONAL EFFICIENCY	RPV & Energy Transf. System Size Compacity	*Large occupied volume*	*Low occupied volume*								
MARKET ACCEPTANCE	Closed-fuel cycle	*Partial spent fuel recycling capability (MOX). Note: Triso fuel recyclability under investigation*									
MARKET ACCEPTANCE	Proliferation Resistance[1]	*Gen III+ reactors conventionally use Low Enriched Uranium (LEU), i.e., <5% enrichment level*					*Gen IV reactors conventionally use High Assay Low Enriched Uranium (HALEU), i.e., [5-20]% enrichment level*				
MARKET ACCEPTANCE	Commercially proven	*Operated design (from 1950's to current)*					*Under development[2]*	*Operated & Decommissioned (Superphénix France[3])*	*Under development*	*Under development*	

Applicable / Not applicable

TABLE 4: OVERVIEW OF RELEVANT FEATURES OF SMR DESIGNS[6]

Sources: IAEA ARIS [Link]; IAEA SMR Book [2020; 2022]; INL [Link]; Monitor Deloitte Research & Analysis

[6] Notes: 1) Overall, limited risk of plutonium diversion during the operation of Gen III+ and IV reactors. Pending further clarification/study on reactor state under sub-criticality; 2) The Oak Ridge National Laboratory (ORNL) Molten Salt Reactor Experiment (MSRE) ran successfully for five years until December 19694; 3) France Superphénix reactor decommissioned in 1997

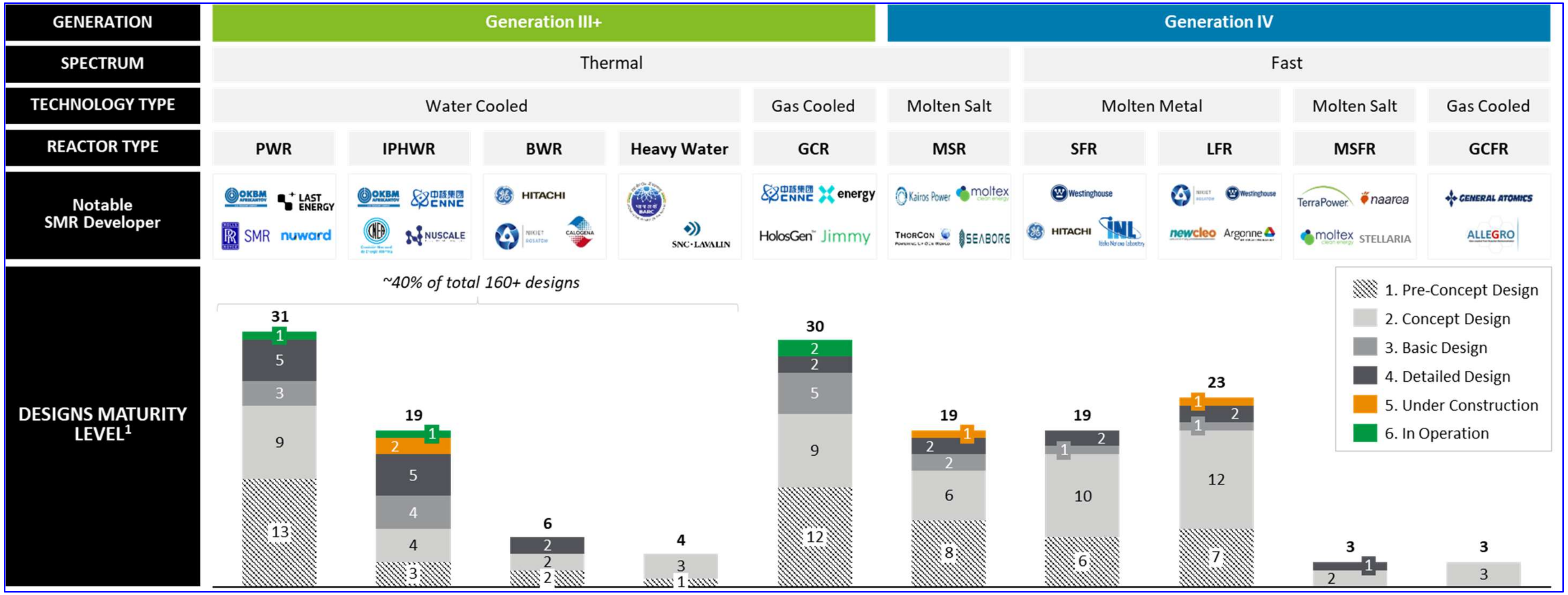


TABLE 5: OVERVIEW OF GLOBAL SMR DESIGNS PROJECTS PHASE STATUS (2024)[7]

[7] Notes: 1) Includes commercial and demonstrator designs. Commercial operating designs include KLT 40S, RITM-200 and HTR-PM. Demonstrator operating include HTR-10. *(Note: For simplicity RITM-200 and KLT-40S are included in Gen III+ but technically should be referred to as Gen II type reactors)*

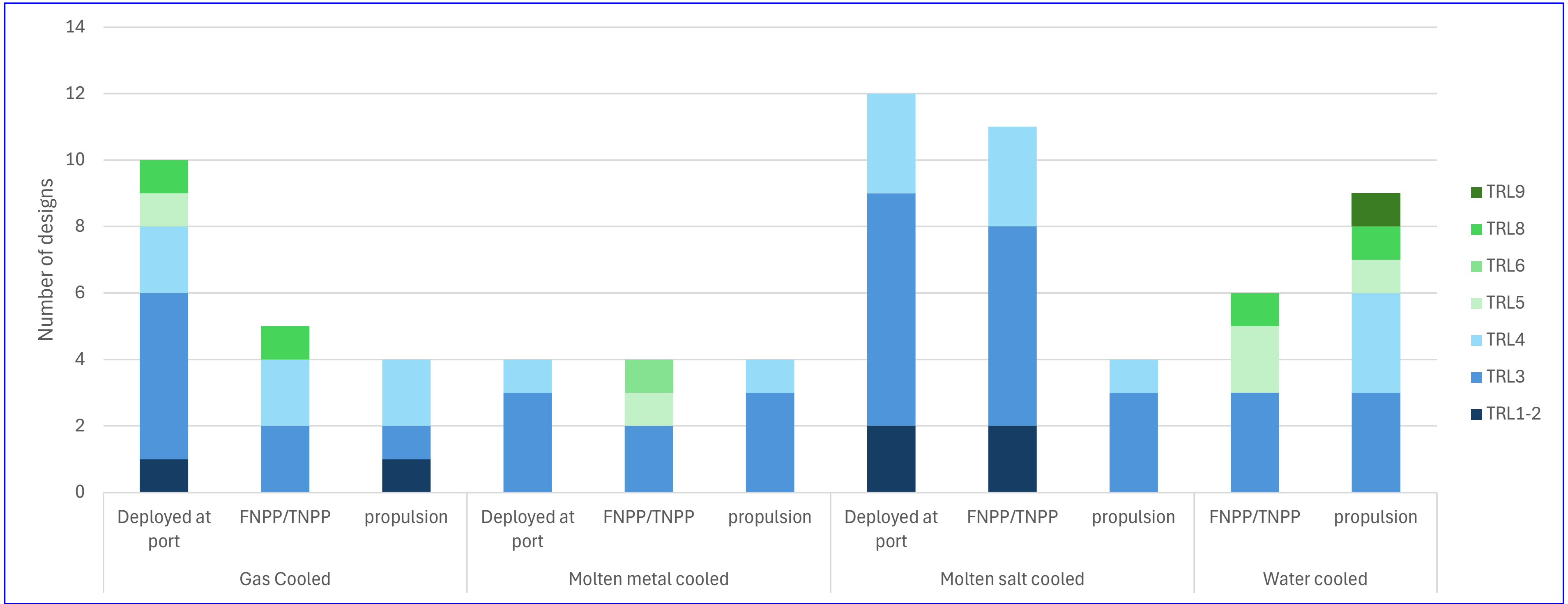


Figure 13: Selected designs by reactor type, purpose and TRL stage

SMR Design Criteria	Ship propulsion	Coastal-based energy generation	Ports & Terminals energy generation
Technical performance	Power generation range between 10MWe to 90MWe *(i.e., ~**30MWth** to **270MWth**)*	Min **50MWe**	Hybrid SMR reactor (i.e., producing heat and power), with core temperature of **minimum 600°C** and **Min 50MWe** *Note: Gen III+ reactors are consequently deprioritized*
Compatibility	RPV weight up to **600 tons**	*Not applicable*	*Not applicable*
Operation	Refueling cycle as a multiple of IMO drydocking requirements **(5 years)**	Refueling cycle minimum every **4 years** **(**to reduce the number of fissile material transport and operations**)**	Refueling cycle minimum every **2 years** **(**to reduce the number of fissile material transport and operations but easier logistics than coastal-based**)**
Other	*i) Minimum EPZ;* *ii) crew/operator training requirements,* *iii) passive safety features,* *iv) autonomous operation*		

TABLE 6: KEY CRITERIA CONSIDERED FOR SMR PURPOSE TARGETED

First movers ports and routes

With such technology and regulatory considerations, there are a number of routes that could be considered viable in the medium term (see Figure 14):

- 1 & 3: There are local or regional routes within national waters of one or several states having a ratifying Flag of the Nuclear Code and an active nuclear safety regulator and ready to act as warrant in case of accident. They would also need to have dedicated ports legally recognized for berthing nuclear propelled vessels, particularly with EPZs following the IAEA recommendations. These routes shown in China and Europe are only for illustration purposes and similar routes are feasible in other regions such as North America.
- 2: A bilateral trading route, through international waters, setup by two ratifying Flag states with, once again, dedicated ports at each country and with the states providing the liability warranties. Such could be the case between an Asian country and the US West Coast.

At a medium term an international route (4) from Asia to Europe could be considered for nuclear propelled vessels given that through most of the routes there would be countries with a favorable regulatory environment to nuclear, that could allow pre-defining emergency port of calls. However, longer routes would not be a fuel cost issue anymore and navigating around the Cape of Good Hope becomes a viable option.

In parallel, it is possible to identify ports that could be interested in acting as « first movers » given the positive positioning of their countries to nuclear, their size and the industrial hubs that surround them that could benefit from the deployment of SMRs and the berthing of nuclear propelled vessels. See Figure 15.

As an illustration, the Port in Le Havre, France, seems well suited as the French regulatory framework for nuclear safety is reasonably well developed:

A recent law (Law no. 2023-491) enables the acceleration of procedures for the construction of new nuclear facilities to speed up the development of nuclear energy and applies specifically to the construction of EPR2 reactors including SMRs. It also refers to cyber security which should be taken into account more thoroughly.

Chapter VIII of the SOLAS Convention was incorporated into French law in 1987. It is worthwhile mentioning that the decree applies to all nuclear ships, without specifying the type of reactor.

Nevertheless, changes to the rules governing the authorization to dock in the Port of Le Havre would need modification as they currently seem to concern only packaged dangerous goods (SSR-6, IMDG and INF Code), with no specific reference to nuclear-powered vessels.

The US ports also seem well suited for a « first movers » recognition. In addition to the positive signals sent on updating the licensing process in the final year of the Biden administration, the federal regulations on nuclear safety are broad enough and are not restricted to land-based reactors and may apply to SMR-type of reactors. Another positive element is the Price-Anderson Act limits liability in case of nuclear damage, the scope of which is broad enough and may cover mobile / transportable nuclear power plants as well as fixed nuclear installations. The act applies to reactors with at least 100 MW.

Otherwise, as for Le Havre, the laws of California and the Los Angeles Port Authority do not specifically cover a nuclear reactor in operation.

The other ports indicated in the map have additional constraints to those mentioned for Le Havre, such as specifically only covering conventional reactors in their application of the Solas Ch. VIII (Felixstove), without having similar favorable (at least not yet) elements. China has a positive disposition and would probably move very fast if it saw the interest of having nuclear civilian ports, given that it is currently deploying new nuclear plants at a rate only seen in the 1970s and 80s by France and the USA.

Singapore is mentioned here given its relevance as an international shipping and maritime bunkering hub. With its long-term planning horizons for infrastructure the Singapore government may consider implementing new regulations to support the development of SMR.

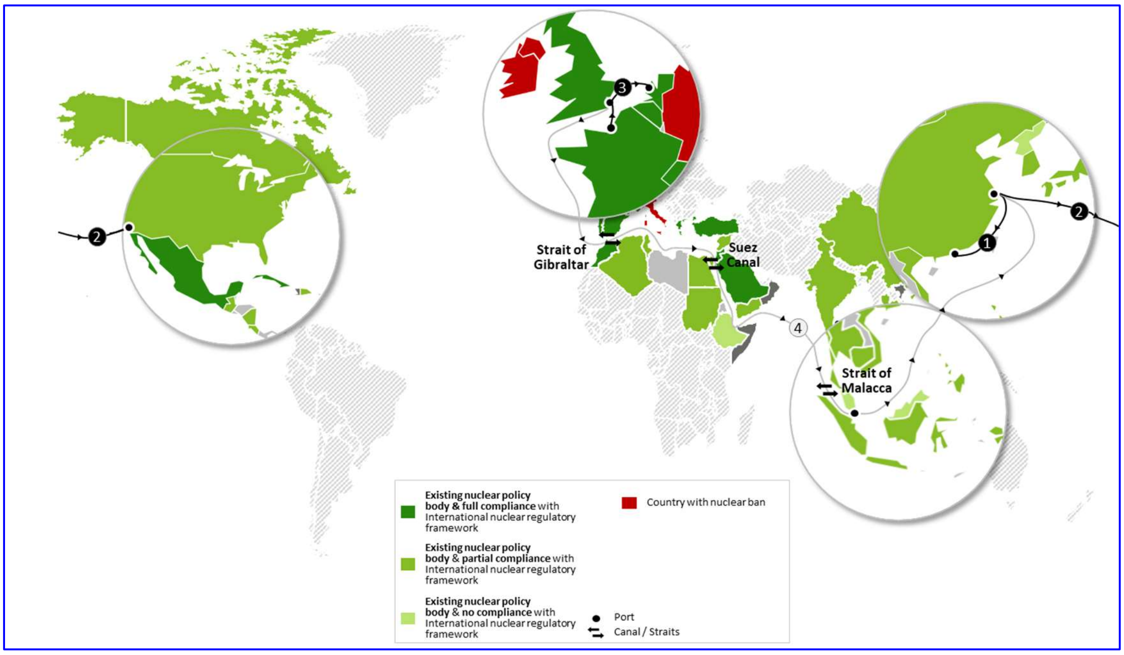


FIGURE 14: ROUTES CONSIDERED FOR FIRST MOVERS IN NUCLEAR PROPULSION

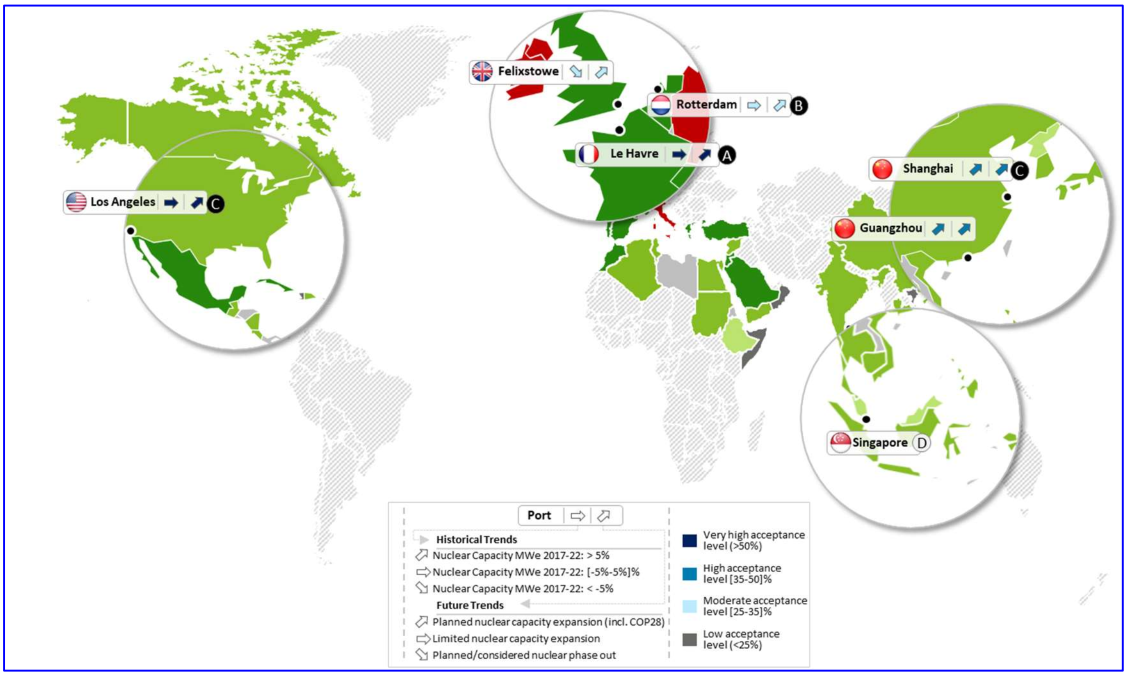


FIGURE 15: PORTS CONSIDERED AS FIRST MOVERS FOR SMR DEPLOYMENT AT THEIR PREMISES AND RECEIVING NUCLEAR-POWERED VESSELS

Assessed plausible timeline, way forward and challenges

Given the current alignment concerning nuclear power at different international agencies levels (IMO, IAEA) as well as commitments and backslapping by governments, a plausible timeline for the deployment of nuclear propulsion, coastal-based and port-on-premises deployment of SMRs is given in Table 7.

If in 2025 the different international agencies, insurers and government started the overhauling of the necessary codes and liability conventions, first drafts from votes should be expected five years later, based on past experience, with final ratification and implementation by 2035.

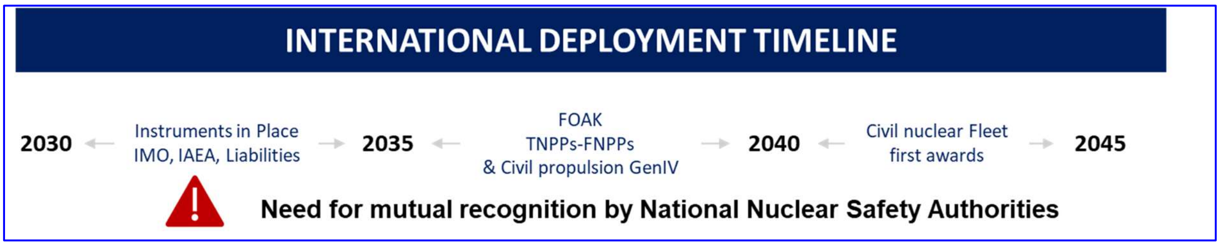


TABLE 7 : ASSESSED PLAUSIBLE TIMELINE FOR DEPLOYMENT OF NUCLEAR IN THE MARITIME

The fact of having such initiatives kick-started would send a positive signal to the industry and the investment communities, therefore making it plausible that most of Gen.III+ and some of the Gen IV designs would move forward and reach TRL 7 or 8 by then.

This would allow deploying first-of-a kind versions (FOAK) of such innovative technologies on TNPPs and FNPPs since 2035 and within the next five years the construction and operation under state-sponsoring of pilot nuclear-powered civil vessels using Gen.III+ and Gen IV designs.

Allowing two to five years of return of experience for such pilot cases, it could be plausible to have the first orders of nuclear propelled privately-owned vessels.

This would mean that, under such premises, by 2045 there should already be ports with on-site nuclear power production, nuclear civil vessels sailing international waters commercially and several FNPPs and TNPPs deployed in remote areas.

Common challenges for this timeline are:

- the mutual recognition by national nuclear safety regulators on licensing of nuclear design and an international agreement concerning technology exports control
- a robust and resilient supply chain in time to provide the components and support all project lifecycles
- development of reliable business cases that may mean a paradigm shift compared to what is being done nowadays.

In the particular case of nuclear propulsion, the management of the complete lifecycle of the vessel means that shipbuilding and the commissioning of the nuclear reactors will require specific licenses for organization changes to existing shipyards or the development of entirely new yards. See Figure 16

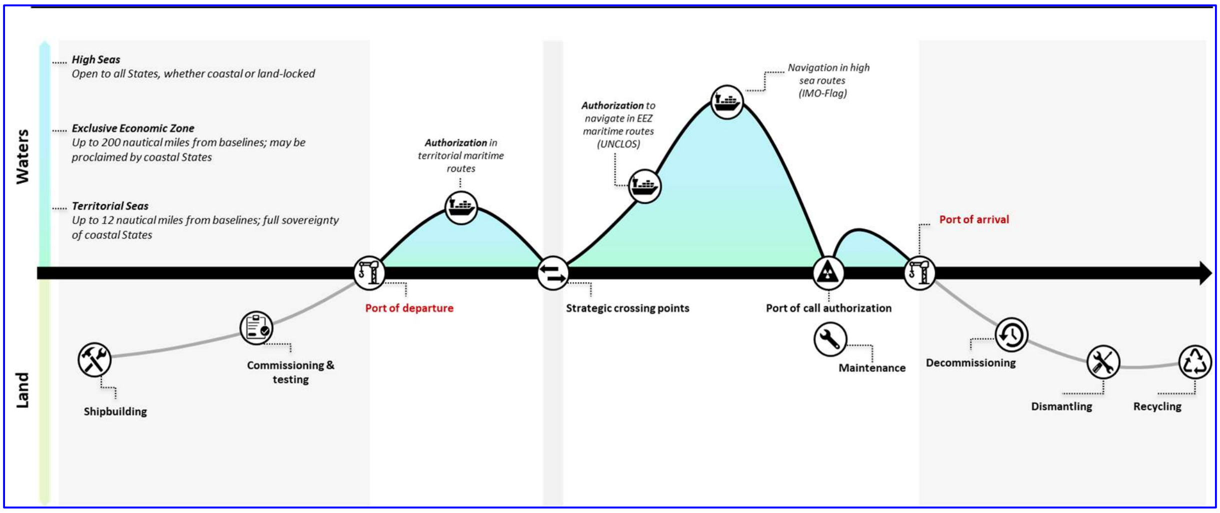


FIGURE 16: CONSIDERATIONS FOR MARINE PROPULSION

At the other end it would require dedicated locations for the decommissioning, dismantling and recycling of the vessels. New industrial sites might appear to remove the nuclear island and manage according to international regulations the spent fuel and nuclear waste for safe disposal, before sending the vessel to conventional vessel recycling sites.

In between the actual design life of the vessels might be extended to match that of the nuclear reactor, which could mean design lives of 40 or 50 years instead of the 20 usually considered nowadays. As a bonus this would also align with global sustainability goals.

Whether ports of call for loading/unloading will require specific organizational and infrastructure would depend on the safety, security and safeguard regulations that will be developed in the coming years, but ports that would have deployed SMRs for their own use will most probably have an advantage over those that would not have.

With regards to mandatory dry-docking for inspections and maintenance yards that would want to service nuclear-propelled vessels, they will certainly need dedicated organizational skills and infrastructure investment and probably have a close-at-hand nuclear-related value chain.

Finally, the nuclear propulsion will have to deal with a specific challenge concerning line-of-command when it comes to the nuclear reactor. Will the nuclear reactor operator have a final decision capability in what concerns the reactor, or will the vessel Captain maintain full decision making?

Encouraging initiatives and industry announcements

There are several press-releases and announcements concerning concepts and approvals in principle for nuclear-powered vessels, but these are at conceptual stage, except when it relates to Gen.II and Gen.III PWRs icebreakers, or for naval purposes which might be at a more advanced stage.

Table 8 shows a selection of such announcements with more making the news in the last months.

Concerning FNPPs and TNPPs, there are also a considerable number of concepts being presented featuring different Gen.III+ and Gen IV designs. Canada and Indonesia seem to be the only countries, apart from Russia, that have identified locations where such units would be deployed. Nevertheless, it is understood that at most such projects are at basic design stage (TRL 3)

Table 9 illustrates a selection of such projects.

Finally, land-based options are in a more advanced level; however, their application on ports is understood to still be at feasibility stage given the regulatory and insurability consideration in multi-industry locations.

Table 10 illustrates a selection of such projects.

In parallel to these private-driven announcements there have been a number of encouraging initiatives at international agencies, industrial associations and regional discussion groups. They highlight the change in public perception and the consideration that policymakers give to nuclear in general and its application in the maritime domain in particular:

- The IAEA (International Atomic Energy Agency) Symposium on Floating Nuclear Power Plants
- The IAEA International Conference on SMRs and their applications with dedicated sessions on marine applications
- The IMO (International Maritime Organization) Director General recognizing that Nuclear Propulsion is very much on the table, after that at the MSC (Maritime Safety Committee) 108 an information paper was submitted by WNTI (World Nuclear Transport Institute) on a gap analysis of the Nuclear Code with regards to new technologies
- The IAEA DG announcing the creation of the ATLAS (Atomic Technology License at Sea) initiative, the launch of which is expected in 2025
- A French joint Marine & Nuclear Associations dedicated collaboration day
- The growing relevance of the recently founded NEMO (Nuclear Energy Maritime Organization) association and the interest in its working groups concerning Marine Regulations, Nuclear Safety and Insurance
- EMSA (European Maritime Safety Authority) Nuclear Report and presentation at its 3rd Workshop on Alternative Fuels and Power Solutions
- NuclearDrive project in the Netherlands (https://kvnr.nl/en/news/nuclear-propulsion-in-house-of-representatives)
- NuProShip project in Norway (https://www.vard.com/articles/nuproship-exploring-advanced-nuclear-propulsion-in-shipping).

All of this draws a rosy picture of the nuclear in the maritime, which could become an industrial reality if the following green lights turn on:

- The IAEA officially launches ATLAS with a clear support from state members and industry, and in collaboration with IMO
- IMO agrees to review and update the Nuclear Code
- The insurance community, through its associations, openly launch the reopening of the 1962 Brussels Convention
- The financial institutions and agencies recognize nuclear energy as a clean source, on par with renewable energies.

These milestones would be sending very powerful messages to regulators, policymakers, and industry and investment firms that nuclear in the maritime has a solid backing to become an industrial reality.

	Italy-based	Norwegian-based[1] (NuProShip)	UK-based	China-based	South Korea-based	South Korea-based
	Visualization not available	Visualization not available			Visualization not available	Visualization not available
Nuclear Technology Developer	newcleo *Gen IV - 30MWe Lead-cooled Fast Reactor*	USNC, Kairos Power, LeadCold *3 Gen IV technologies shortlisted (LFR, MSR, GCR)*	TerraPower *Gen IV – MSFR co-development*	*Little information on reactor possibly linked to military applications* *Thorium-based Generation IV molten salt reactor*	KEPCO *Little information on reactor*	*Little information on technology developer* *Gen IV molten salt reactor*
Shipbuilding Company	FINCANTIERI *Italy-based ship building company*	Knutsen OAS Shipping, VARD *Global shuttle tanker / offshore shipbuilding*	CORE-POWER, KSOE, Imabari *CorePower: UK TNPP developer Imabiri & KSOE: shareholders*	CSSC Jiangnan Shipyard *Subsidiary of China Shipbuilding Industry Corp.*	Zodiac Maritime, KSOE *UK-based operator / South-Korea-based offshore Engineering*	H-Line Shipping, HMM, Sinokor *South Korea-based shipping companies*
Mentioned Classification Society	RINA *Italy-based classification society*	DNV·GL *Norway-based classification society*	LR *UK-based classification society*	DNV·GL *Norway-based classification society*	LR *UK-based classification society*	KR *South Korea Register of Shipping*
Nuclear Research Agency	*Limited information*	*Limited information*	*Limited information*	*Limited information*	*Limited information*	KRISO, KAERI Korea Atomic Energy Research Institute *South Korea nuclear Energy Agency*
Comments	*Feasibility study to assess the practicality of deploying a 30-megawatt reactor on naval vessels*	*Target prototype at seas early 2030's, and demonstrator from 2035*	*Target demonstrator at seas early 2030's*	*Received in-principle approval from certification agency Det Norske Veritas at the Marintec China (Dec'23)*	*MOU signed for a joint development project of nuclear-propelled ship designs, including bulk carriers and containerships (Jan'24)*	*MOUs signed between 9 organizations for a demonstration of SMR technology for propulsion of large ships (Feb'23)*

TABLE 8: OVERVIEW OF NOTABLE NUCLEAR SHIPPING PROPULSION PROJECTS ANNOUNCED[8]

Sources: Italy-based [Press]; Norwegian-based [Press1; Press2; Press3; Press4]; UK-based [Link1; Link2; Link3]; China-based [Link]; Korea-based [Link1; Link2; Link3]

[8] Notes: 1) Other Norwegian design concepts include Ulstein shipbuilder "Thor" mobile/power charging stations for EV ships

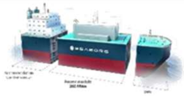
	US-based	Denmark-based	UK-based	Indonesia-based	South Korea-based	Russia-based	China-based
							
Nuclear Technology Developer	NUSCALE, Westinghouse *Gen III+ & Gen IV SFR*	SEABORG *Gen IV - MSR CMSR*	TerraPower *Gen IV – MSFR co-development*	ThorCon Powering Up Our World *Gen IV – MSR*	KEPCO *Gen III+ - PWR Bandi-60S 60MWe*	*Gen III+ IPWR, RITM-200S, 200M, 400M*	中国核工业集团有限公司 China National Nuclear Corporation *Gen III+ IPWR, ACP100S*
Shipbuilding Company	Prodigy Clean Energy *Canadian TNPP developer*	Samsung Heavy Industries *1 of the 'big 3' shipbuilders of South Korea*	Core-Power, Imabari Shipbuilding Co. Ltd *CorePower (UK TNPP devp.) Imabiri (shareholder)*	*Limited information*	KSOE Korea Shipbuilding & Offshore Engineering *South-Korea-based offshore Engineering*	Baltic Shipyard *St Petersburg Shipyard*	CSSC Jiangnan Shipyard *Subsidiary of China Shipbuilding Industry Corp*
Mentioned Classification Society	*Limited information*	ABS *US-based classification society*	LR *UK-based classification society*	Bureau Veritas *French-based classification society*	ABS *US-based classification society*	*Certification Association Russian Register*	*Limited information*
Nuclear Research Agency	*Limited information*	*Limited information*	*Limited information*	BRIN, Bapeten *National Research and Innovation Agency & Nuclear Energy Regulatory Agency*	*Limited information*	Rosatom *ROSATOM[1] State Corporation*	*Limited information*
Comments	*Conceptual design for a plug-and-play access to electricity and heat supply (Jan'24)*	*Secured approval in principle from the U.S.-bassed ABS classification society (Jan'23) Target commercialization by 2028*	*Target demonstrator at seas early 2030's. Secured 3-year grant from US DOE for research (Aug'22)*	*Target building a demonstrator on the Gelasa island (Indonesia) and start commercial operation in 2031*	*Received approval in principle (AiP) from the classification society ABS for a new design of a floating offshore nuclear power barge (Oct'23)*	*Development of a floating power unit for foreign markets*	*China suspends plans to build floating NPP after Nord Stream explosions (May'23)*

TABLE 9: OVERVIEW OF NOTABLE COASTAL-BASED NUCLEAR POWER PLANT PROJECTS ANNOUNCED[9]

Sources: US-based [Press1; Press2; Press3]; Denmark-based [Link]; UK-based [Link]; Indonesia-based [Link]; South Korea-based [Link]; Russia-based [Link]; China-based [Link1; Link2]

[99] Notes: 1) Afrikantov OKBM JSC is a Scientific and Production Center for Nuclear Engineering in the ROSATOM State Corporation

	US-based	US-based	US-based	US-based	France-based	UK-based
						
Nuclear Technology Developer	NUSCALE *Gen III+ IPWR*	Westinghouse *Gen IV SFR & LFR*	GE HITACHI *Gen III+ BWR*	X energy *Gen III+ GCR*	nuward EDF GROUP *Gen III+ PWR*	Rolls-Royce SMR *Gen III+ PWR*
Industry Partners	FLUOR, NUCOR, framatome, Ultra Electronics, DOOSAN, Sarens	ansaldo nucleare, Southern Company	Ontario Power Generation, TVA Tennessee Valley Authority	Zachry, Amsted, Burns McDonnell, Ontario Power Generation, Day & Zimmermann, Doosan, SIMSA, cavendish nuclear, Kinectrics, Southern Nuclear	EDF, Naval Group, TA TechnicAtome, framatome, Tractebel engie	Jacobs, Atkins, bam nuttall, assystem, Keppel FELS, TWI, Nuclear AMRC
Nuclear Research Agency	Oak Ridge National Laboratory	ENEA, INL Idaho National Laboratory	*Limited information*	*Limited information*	cea	National Nuclear Laboratory
Comments	*Best fitted market uses include: 1) clean electricity 2) Process heat*	*Best fitted market uses include: 1) clean electricity 2) H2 production 3) Process heat 4) Desalination*	*Best fitted market uses include: 1) clean electricity 2) H2 production 3) District heating*	*Best fitted market uses include: 1) clean electricity 2) Process heat 3) Desalination*	*Best fitted market uses include: 1) clean electricity 2) H2 production, 3) CO_2 Carbon Capture 4) desalination*	*Best fitted market uses include: 1) clean electricity 2) H2 & synthetic fuels production, 3) district heating/cooling; 4) desalination*

TABLE 10: OVERVIEW OF NOTABLE LAND-BASED NUCLEAR POWER PLANT PROJECTS ANNOUNCED

Sources: US-based [Link1; Link2; Link3]; France-based [Link1; Link2]; UK-based [Link1; Link2]

Conclusion

The maritime industry is at a critical juncture in its pursuit of decarbonization and environmental sustainability, within a context of expected growth. This whitepaper has explored the potential of nuclear power for marine propulsion, coastal power generation, and port-based energy production. The key findings indicate that nuclear power could play a significant role in the future of maritime transportation and port operations, offering an emissions-free reliable alternative that aligns with stringent emission regulations and global decarbonization goals.

While technological readiness, especially in SMRs, shows promise, several challenges remain. The regulatory landscape requires updating and harmonization, and economic viability needs to be demonstrated as SMR designs reach industrial-scale production. Pilot projects and state-sponsored initiatives will be essential in demonstrating feasibility and safety.

Moving forward, four critical areas require further analysis and development:

- **Radioactive waste management**: There is a pressing need to develop comprehensive safety guidelines for the management of radioactive waste and spent fuel from SMRs. This aspect is crucial for the long-term sustainability and public acceptance of maritime nuclear applications.
- **Crew training and qualifications**: Developing specific training programs and qualification standards for crew members operating nuclear-powered vessels is essential. This will ensure the safe operation of these advanced technologies and compliance with radiological protection standards.
- **Cybersecurity**: Given the prevalent threat of industrial espionage and cyberattacks, it is imperative to integrate robust cybersecurity requirements within the international nuclear security framework. This integration is crucial for protecting nuclear assets in the maritime sector.
- **Insurance and shared liability**: The current lack of standardized maritime insurance covering nuclear material transport and nuclear risks poses a significant challenge. There is a need to adapt conventional liability frameworks to accommodate the unique aspects of maritime nuclear applications, potentially involving shared responsibility among ship operators, owners, and SMR developers. Similarly, further analysis is required on financing structures that could support the supply chain and developers.

Addressing these challenges will be crucial in creating a comprehensive and secure framework for implementing nuclear technology in the maritime sector. The industry must work closely with regulators, insurers, and international bodies to develop solutions that ensure safety, security, and economic viability of nuclear-powered maritime operations.

The next decade will be pivotal in determining the role of nuclear power in the maritime industry. With concerted efforts from all stakeholders, nuclear energy has the potential to significantly contribute to the decarbonization of shipping and port operations, marking a new era in sustainable maritime transportation.

Glossary

AMR	advanced modular reactor
ARIS	Advanced Reactors Information System
ATLAS	Atomic Technology License at Sea
CO2	carbon dioxide
ECA	emission control area
EMSA	European Maritime Safety Agency
EPD	emergency preparedness distance
EPZ	emergency planning zone
ESPO	European Sea Ports Organization
FNPP	floating nuclear power plant
FOAK	first-of-a-kind
GCR	gas-cooled reactor
Gen III+	Generation III+ (reactor technology)
Gen IV	Generation IV (reactor technology)
IAEA	International Atomic Energy Agency
IMDG Code	International Maritime Dangerous Goods Code
IMO	International Maritime Organization
INF Code	International Code for the Safe Carriage of Packaged Irradiated Nuclear Fuel, Plutonium and High-Level Radioactive Wastes on Board Ships
IPWR	integral pressurized water reactor
LFR	lead-cooled fast reactor
LNGC	liquefied natural gas carrier
MSC	Maritime Safety Committee
NEA	Nuclear Energy Agency
NEMO	Nuclear Energy Maritime Organization
NIS 2 Directive	Network and Information Security Directive
NOx	nitrogen oxides
OECD	Organization for Economic Co-operation and Development
OPS	onshore power supply (also known as "cold ironing")
PLWR	pressure light water reactor
PWR	pressurized water reactor
SFR	sodium-cooled fast reactor
SMR	small modular reactor
SOLAS	Safety of Life at Sea (Convention)
SOx	sulfur oxides
SSR-6	Specific Safety Requirements for the Transport of Radioactive Material
STCW	Standards of Training, Certification and Watchkeeping
TEU	twenty-foot equivalent unit
TNPP	transportable nuclear power plant
TRL	technology readiness level
VLCC	very large crude carrier
VLOC	very large ore carrier
WNTI	World Nuclear Transport Institute

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