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# Challenges and Opportunities with Floating Nuclear Power Plants

A Study on Floating and Offshore NPPs

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Högskoleingenjörprogrammet i kärnkraftteknik



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### **Abstract**

As the global energy sector works toward net-zero emissions by 2050, nuclear energy is expected to play an increasingly important role. Floating Nuclear Power Plants (FNPPs), which use Small Modular Reactors (SMRs) on marine platforms, present a promising solution for supplying electricity and heat to remote or coastal areas where land-based infrastructure is limited. This thesis explores the challenges and opportunities associated with FNPPs through a literature review and a case study of the Faroe Islands.

Key focus areas include reactor technology, legal and regulatory frameworks and alternative uses other than supplying electricity to the grid, such as hydrogen production and desalination. The study investigates various FNPP concepts, including barge-based and offshore rigs and evaluates their suitability for different applications.

Findings suggest that FNPPs can enhance energy security and support decarbonization in isolated regions. However, significant challenges remain, including unclear regulatory standards, complex security and safeguard requirements and potential public resistance. The case study illustrates both the potential benefits and the practical limitations of deploying FNPPs in real-world settings.

The report concludes that while FNPPs offer strategic and technological advantages, their development requires further research and regulatory adaptation. Recommendations are made to support future deployment, including international collaboration and clearer legal frameworks.

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# Sammanfattning

För att världen ska klara klimatmålen enligt Parisavtalet krävs att utsläppen av växthusgaser minskar drastiskt, särskilt för energisektorn som står för cirka tre fjärdedelar av de globala utsläppen. Vikten av att minska koldioxidutsläppen mycket och i hög takt har gjort att kärnkraften som energikälla åter blivit ett alternativ. Kärnkraft ger inte upphov till koldioxidutsläpp under drift och är oberoende av väder, till skillnad från exempelvis vindkraft och solceller. Ett nytt och växande område inom kärnkraften är så kallade flytande kärnkraftverk eller Floating Nuclear Power Plants (FNPPs) där små kärnreaktorer installeras på flytande plattformar.

Detta examensarbete undersöker möjligheter och utmaningar kopplade till FNPPs ur tekniska, juridiska och praktiska perspektiv. Fokus ligger på att kartlägga hur tekniken fungerar och vilka reaktortyper som är mest lämpliga. Arbetet omfattar även olika typer av frågor om säkerhet, avfallshantering och drift som FNPPer medför. Dessutom undersöks hur dagens lagstiftning förhåller sig till denna typ av anläggningar samt om det finns behov av kompletterande reglering. Arbetet baseras på en omfattande litteraturstudie samt en fallstudie med Färöarna som exempel.

En fördel med FNPPs är deras flexibilitet och skalbarhet. De kan byggas i varv med hög kvalitet, sedan transporteras till avlägsna platser och tas i drift snabbt. Eftersom de använder sig av små modulära reaktorer (SMR:er) kan de vara enklare att standardisera och massproducera. Många av dessa moderna reaktorer är dessutom konstruerade med passiva säkerhetssystem vilket innebär att de inte är lika beroende av personalinsatser eller elförsörjning för att kunna kylas vid en incident.

Med den ökade kapaciteten att producera el som FNPPs tillhandahåller, möjliggörs elanvändning till andra ändamål som är energikrävande. Ett exempel är avsaltning av havsvatten, vilket kan vara livsavgörande i torra kustområden med brist på färskvatten. FNPPs kan också bidra till att producera vätgas och ammoniak, två ämnen som spås få en nyckelroll som bland annat fossilfria bränslen i framtidens industri och transporter.

Dock medför tekniken betydande utmaningar. Många internationella lagar och konventioner är skapade för landbaserad kärnkraft och omfattar inte applikationer såsom kärnkraftsdrivna fartyg eller havsbaserade kärnkraftverk. Det saknas en tydlig reglering av ansvar vid olyckor, säkerhetszoner, tillstånd att angöra hamnar eller skydd mot terrorism. Inom konventionell kärnkraft är kraven höga på strålsäkerhet, säkerhetsskydd och icke-spridning vilket är särskilt komplicerat till havs där flera länders jurisdiktioner kan överlappa vilket komplicerar licensieringen av FNPPs ytterligare.

Fallstudien om Färöarna visar att flytande kärnkraftverk kan vara ett intressant alternativ för samhällen som idag är beroende av fossila bränslen. Samhällen som har begränsade möjligheter att importera el eller bygga stora kraftverk på land på grund av exempelvis platsbrist skulle kunna gynnas av ett flytande kärnkraftverk. Samtidigt krävs en bred politisk vilja, rättsliga anpassningar och en bred förståelse i samhället för att tekniken ska kunna bli verklighet.

Sammanfattningsvis visar examensarbetet att flytande kärnkraftverk är ett framtidskoncept med stor potential, inte minst för att bidra till klimatomställningen och öka tillgången till ren energi globalt. Men för att tekniken ska kunna förverkligas krävs fortsatt forskning, internationellt

samarbete och tydligare regleringar. FNPPs är inte en universallösning, men de kan spela en viktig roll i den mångfald av tekniker som behövs för att skapa ett hållbart energisystem.

# Acknowledgments

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Uppsala, May  
 Anton Buske  
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Distribution of responsibilities (X) = Large contribution, (O) = Less contribution, (-) = No contribution			
Chapter		Anton Buske	Jonathan Forssten
1 Introduction	1.1	-	X
	1.2	O	X
	1.3	O	X
2 Method	2.1	X	O
	2.2	X	O
	2.3	X	-
3 Reactor systems and applications	3.1	O	X
	3.2	-	X
	3.3	X	-
	3.4	X	-
	3.5	X	-
4 Governance of nuclear safety, security and safeguards	4.1	O	X
	4.2	-	X
5 Case-study: The Faroe Islands	5.1	-	X
	5.2	X	-
	5.3	X	O
6 Results and Discussion	6.1	X	O
	6.2	X	O
	6.3	O	X
	6.4	O	X
	6.5	X	O
7 Conclusion	7	X	X
	7.1	X	X

# Table of contents

1	INTRODUCTION.....	1
1.1	Background .....	1
1.2	Purpose .....	1
1.3	Limitations .....	2
2	METHOD.....	3
2.1	Overall approach for the study .....	3
2.2	Information collection method .....	3
2.3	Ethical positions and use of AI .....	3
3	REACTOR SYSTEMS AND APPLICATIONS .....	5
3.1	Advanced reactors .....	5
3.2	Small Modular Reactors.....	6
3.3	Floating Nuclear Power Plants and icebreakers .....	7
3.3.1	Akademik Lomonosov .....	7
3.3.2	Icebreakers .....	9
3.3.3	Reactors in development for floating nuclear power purposes .....	11
3.4	Alternative uses .....	13
3.4.1	Hydrogen and ammonia production.....	13
3.4.2	Desalination.....	14
3.5	Types of floating maritime platforms.....	14
3.5.1	Barge .....	14
3.5.2	Offshore.....	15
4	GOVERNANCE OF NUCLEAR SAFETY, SECURITY AND SAFEGUARDS.....	17
4.1	Safety, security & safeguards.....	17
4.1.1	Safety.....	17
4.1.2	Security.....	20
4.1.3	Safeguards .....	20
4.2	Regulations and organizations relevant to maritime nuclear power .....	21
4.2.1	The International Atomic Energy Agency and its treaties and conventions ....	21
4.2.2	The International Maritime Organization .....	23
4.2.3	Summary table of conventions and treaties.....	24
4.2.4	Atomic Technology Licensed for Applications at Sea.....	25
4.2.5	Nuclear Energy Maritime Organization.....	25
5	CASE-STUDY: THE FAROE ISLANDS .....	26
5.1	Geographical position and international relations.....	26

5.2	The Faroe Islands current situation and goals .....	26
5.2.1	Renewable energy ambitions .....	29
5.3	Nuclear power options .....	29
5.3.1	Option 1.....	30
5.3.2	Option 2.....	31
6	RESULTS AND DISCUSSION .....	33
6.1	Design and possibilities.....	33
6.2	Challenges and areas for improvement .....	34
6.3	Operation, decommissioning and waste management .....	34
6.4	The 3Ss – possibilities and issues .....	36
6.5	Case-study findings .....	36
7	CONCLUSION .....	38
7.1	Further studies .....	39
8	REFERENCES.....	41

# List of tables

Table 1 List of Gen IV reactors, their abbreviation, neutron spectrum and coolant type. Adapted from [14]. .....	6
Table 2 List of all icebreakers, when they were deployed, their reactor type, class and operational status.....	10
Table 3 List of SMRs in development that lists company, reactor, type of platform, power and additional comments. ....	11
Table 4 Overview of key international treaties and conventions relevant to nuclear safety, security, safeguards and liability, including applicability to Floating Nuclear Power Plants (FNPPs).....	24

# List of figures

Figure 1 An overview of methods used in the project. .... 3

Figure 2 General cross-section view of the FPU [17]. .... 8

Figure 3 Illustration of a KLT-40S reactor [17]. .... 9

Figure 4 The 3Ss, Safety, Security and Safeguards are closely linked together and dependent on each other. .... 17

Figure 5 The five levels of protection in defense-in-depth. Adapted from [32]. .... 18

Figure 6 The five physical barriers of defense-in-depth to limit radiological release. Illustration from [33]. .... 19

Figure 7 Graph showing power output from different energy sources [65]. .... 27

Figure 8 A map of The Faroe Islands showing where the different energy sources are and the red line divides the two different grids, which are not connected [65]. .... 28

Figure 9 Graph over effect demand of the two grids [65]. .... 29

Figure 10 Graph showing the change of ammonia production and power delivered to the grid from option 1. .... 31

Figure 11 Graph showing the change of ammonia production and power delivered to the grid from option 2. .... 32

# Abbreviations

3S	Safety, Security and Safeguards
3SBD	Safety, Security and Safeguards by Design
ATLAS	Atomic Technology Licensed for Applications at Sea
CNS	Convention on Nuclear Safety
CPPNM	Convention on the Physical Protection of Nuclear Material
EPZ	Emergency Planning Zone
EU	(the) European Union
FNP	Floating Nuclear Power
FNPP	Floating Nuclear Power Plant
FNR	Fast Neutron Reactor
GFR	Gas-cooled Fast Reactor
IAEA	International Atomic Energy Agency
IMO	International Maritime Organization
INIR	Integrated Nuclear Infrastructure Review
LFR	Lead-cooled Fast Reactor
LSR	Large Scale Reactor
LWR	Light-Water Reactor
MoU	Memorandum of Understanding
MSF	Multi-Stage Flash
MSR	Molten Salt Reactor
MWe	Megawatts electric
MWt	Megawatts thermal
NEMO	Nuclear Energy Maritime Organization
NPT	Treaty on the Non-Proliferation of Nuclear Weapons
OFNP	Offshore Floating Nuclear Power Plant
OFPU	Optimized Floating Power Unit
PWR	Pressurized Water Reactor
R&D	Research and Development

RO	Reverse Osmosis
SBD	Safeguards by Design
SbD	Safety by Design
SCWR	Supercritical-Water-cooled Reactor
SeBD	Security by Design
SFR	Sodium-cooled Fast Reactor
SHI	Samsung Heavy Industries
SMR	Small Modular Reactor
SOEC	Solid Oxide Electrolysis Cell
SOLAS	Safety of Life at Sea
SSAC	State System of Accounting for and Control of Nuclear Material
TFI	The Faroe Islands
TRL	Technology Readiness Level
UN	(the) United Nations
VCCLND	Vienna Convention on Civil Liability for Nuclear Damage
VHTR	Very-High-Temperature Reactor
VRE	Variable Renewable Energy
WCR	Water Cooled Reactor

# 1 INTRODUCTION

*The first chapter briefly introduces the content of the study and its purpose and objectives. It also presents the question formulation used to fulfill the goals and the boundaries of the work.*

## 1.1 Background

As agreed, in the Paris Agreement [1], carbon emissions must reach net zero by 2050. Since the energy sector accounts for about three quarters of global emissions, they need to make a big transformation to fossil-free production in the coming years [2]. The nuclear industry can play a vital part in the transformation as it is, in most cases, more reliable and cheaper than other fossil free energy sources, such as wind- or solar power [3]. The International Energy Agency (IEA) states that a possible route to achieve net zero by 2050 could include doubling the capacity of nuclear power by 2050 [4].

Considering this, the emergence of small modular reactors (SMRs) has begun. What is attractive about SMRs is that they are proposed to be prefabricated, anticipated to make them faster and easier to install and cheaper upfront. In addition, they are smaller than large-scale reactors (LSRs), possibly meaning they could be sited where a larger one cannot [6]. Since they have been around since the 1950's, there is nothing new about small reactors. Nevertheless, there are only a handful of operational SMRs worldwide as of early 2025 - for both research and commercial purposes. Additionally, there are a few more reactors currently under construction [7]. Bearing this in mind, there is still a need to prove their economic competitiveness [6].

One of the SMRs in operation is *Akademik Lomonosov*, owned by Russian state corporation Rosatom. Akademik Lomonosov is the world's only operational floating nuclear power plant (FNPP), and it is docked in the Pevek harbor in the far northeast of Russia. An FNPP is a nuclear-powered energy generation system with one or several reactors built on a floating platform, such as a barge or an offshore rig. These plants are being designed to supply electricity and heat for additional services such as hydrogen production and desalination to coastal or isolated regions, especially where land-based infrastructure is limited or impractical [8].

## 1.2 Purpose

The purpose of this bachelor project is to identify the challenges and opportunities the nuclear industry faces regarding FNPPs, and to compile and present this information in a structured and comprehensive manner. Additionally, the study aims to analyze the challenges and opportunities, which include evaluating the possible reactor types and procurement strategies and assessing the impact of existing laws and regulations on development. To fulfill the purpose of this thesis, four research questions have been formulated:

1. What are the advantages of FNPPs over land-based NPPs?
2. What reactor types are being considered for FNPPs?
3. What are the potential options for the procurement, operation, decommissioning and waste management of FNPPs?
4. How well-adjusted are current legal and regulatory frameworks to the deployment of FNPPs, and where are they lacking?

### **1.3 Limitations**

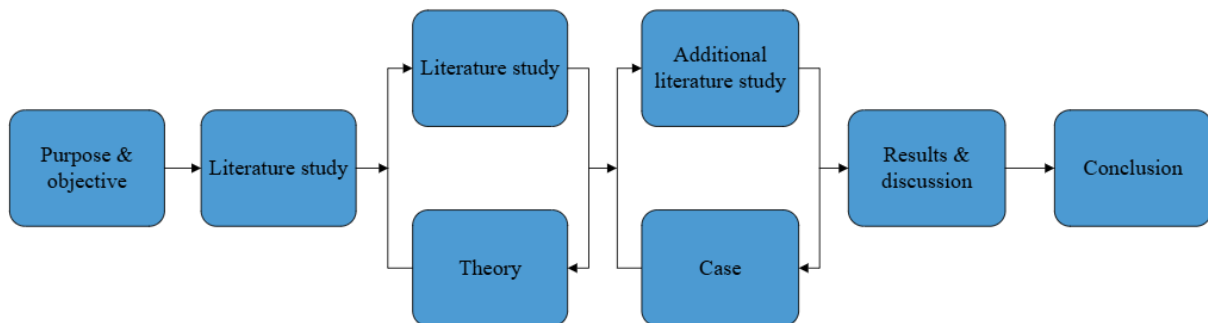
Due to the limited timeframe of this thesis, two key restrictions were made. Firstly, the investigations were restricted to a literature review and a basic case study, thus no interviews or laboratory work were conducted. Secondly, all information used was drawn from publicly available sources to ensure accessibility. This is in line with the overarching aim of the thesis - to compile and present information on FNPPs in a way that is open to all interested readers.

## 2 METHOD

*This chapter presents the method used for this study, along with some ethical positions.*

### 2.1 Overall approach for the study

To assess the obstacles and opportunities with floating nuclear power plants, the method shown in Figure 1 was used. The project started with establishing a baseline for the questions of interest alongside a comprehensive literature study surveying the field. When the questions had taken a more mature form, the literature study continued to establish background and theory to the thesis. To showcase opportunities of deploying an FNPP, a case study was performed. The case study and its findings are presented in the result section and later analyzed and discussed. By following this process, it was possible to address the questions and formulate a conclusion with suggested areas for future investigations.



*Figure 1 An overview of methods used in the project.*

### 2.2 Information collection method

The information used in the study was collected from publicly available sources, including reports and publications from companies and organizations with a focus on nuclear or other areas relevant to the thesis. This approach was chosen to ensure that the information was both credible and relevant to the research questions. The selection of sources was made by criteria such as technical relevance, transparency and credibility. Priority was given to well-established institutions with a focus on nuclear technology, floating energy systems or energy infrastructure in remote regions. Examples include the IAEA, World Nuclear Association (WNA) and national energy authorities.

The method has certain limitations. Since no primary information or data was collected through interviews or surveys, conclusions heavily rely on the accuracy and objectivity of the source material. Some sources may have commercial or political interests that could influence how information is presented. Areas where data is scarce or inconsistently reported could be more challenging to draw fully comprehensive conclusions from. Despite this, the use of secondary data provided a solid foundation for analysis and enabled the identification of knowledge gaps which informed the conclusions and suggestions for future research.

### 2.3 Ethical positions and use of AI

When looking at innovative solutions in a sensitive subject such as nuclear power, it is important to objectively assess the information presented and to also be aware of subjective perspectives.

Since English is not our first language, AI tools [9] were used to translate and improve formulations in the text.

# 3 REACTOR SYSTEMS AND APPLICATIONS

*This chapter explores reactor systems and their diverse applications, beginning with small modular reactors extending to past and present experiences with maritime nuclear power, including reactors that are currently being developed. It also examines alternative uses such as hydrogen production and desalination, alongside different types of floating maritime platforms.*

## 3.1 Advanced reactors

In nuclear reactor research and development (R&D), reactors are often categorized by a generation (Gen), ranging from Gen I to Gen IV. Almost all currently operating reactors belong to Gen II, with only a few Gen III or Gen III+ reactors in service. Gen I reactors were the first reactors to be constructed in the 1950-60s and they were phased out by 2015 [10]. Although R&D on reactors potentially classifiable as Generation IV has been ongoing since the 1950s, no reactor to date has fully met all the criteria established by the Generation IV International Forum (GIF) (see list of criteria below) [11]. The classification criteria for these generations are somewhat arbitrary and can vary between sources, leading to differences in how many reactors are considered part of each generation [10].

Typically, Gen III reactors are classified as evolutionary light-water reactor (LWR) designs and Gen IV reactors as innovative designs, which are terms defined by The International Atomic Energy Agency (IAEA). Evolutionary designs are defined as achieving “[...] improvements over current designs through small to moderate modifications, with a strong emphasis on maintaining proven design elements to minimize technological risks”. These improvements often focus on enhanced safety and cost reduction through simplified systems and better maintainability, amongst other things. In contrast, innovative designs involve fundamental conceptual changes compared to current reactors, requiring extensive research and development, testing and often the construction of demonstration reactors. However, focus still lies on improving current designs in varying aspects [12].

Both evolutionary and innovative designs are sub-categories to the term advanced designs. While most existing reactors are water cooled reactors (WCRs), and more specifically LWRs, advanced reactor development is not confined to this design. It also includes reactors that use other coolants such as liquid metals, fluoride salts or gases. These alternatives can support closed fuel cycles, enable more compact designs and achieve higher outlet temperatures compared to conventional LWRs [12]. In an IAEA publication about advanced reactor designs Professor Matthew Fisher states:

Some distinguishing features of advanced reactors include enhanced thermal efficiency, waste minimization, optimized use of natural resources and the ability to address both electricity production and non-electric applications of nuclear power, such as hydrogen production. These features expand operating potential and vastly improve nuclear power plant economics.

These are some examples of what R&D of advanced reactors aim to achieve. Fisher also explains that advanced reactors have the potential to make nuclear power a more accessible, sustainable and affordable source of low-carbon energy, which is why they are important to reach the global climate goals [13].

The GIF has established a set of criteria that a reactor design must meet to be considered a Gen IV reactor. These criteria were evaluated by approximately 100 experts, who identified six promising reactor concepts capable of fulfilling the requirements, presented in Table 1. A reactor operating in the fast neutron spectrum can potentially enable a more advanced fuel cycle by burning long-lived actinides or breeding new fissile material, thereby contributing to closing the nuclear fuel cycle.

**Table 1** List of Gen IV reactors, their abbreviation, neutron spectrum and coolant type. Adapted from [14].

Gen IV system	Neutron spectrum	Coolant
<b>Very-High-Temperature Reactor (VHTR)</b>	Thermal	Helium
<b>Sodium-cooled Fast Reactor (SFR)</b>	Fast	Sodium
<b>Supercritical-Water-cooled Reactor (SCWR)</b>	Thermal/fast	Water
<b>Gas-cooled Fast Reactor (GFR)</b>	Fast	Helium
<b>Lead-cooled Fast Reactor (LFR)</b>	Fast	Lead
<b>Molten salt reactor (MSR)</b>	Thermal/fast	Fluoride Salts

The key criteria for Gen IV reactors are as follows:

- Sustainable by effective fuel utilization and long-term availability,
- Minimize and manage nuclear waste,
- Low life-cycle cost compared to other energies,
- Low financial risk compared to other energy projects,
- Excel in safety and reliability,
- Very low likelihood of reactor core damage,
- Eliminate offsite emergency response need,
- Offer a very unattractive and the least desirable route for diversion or theft of weapons-usable materials,
- High physical protection against acts of terrorism.

### 3.2 Small Modular Reactors

According to the World Nuclear Association [7] and the IAEA [6], SMRs are defined by two key principles: they have a maximum capacity of 300 MWe and they are modular, meaning they are prefabricated then shipped to the site. Additionally, they can be physically smaller than LSRs, which could make the required land use smaller than normal. Because they are standardized, prefabricated and serially produced, costs are predictably lower upfront and the time before the power plant is operational is reduced. Furthermore, construction efficiency and quality can be improved due to the factory setting. LSRs are at times faced with construction delays because they are custom designed for the location where it is being built, which can be mitigated by prefabrication [6].

Some developing countries and remote industries and communities are currently looking at purchasing SMRs to reach net zero by 2050, amongst other things. There are over 80 commercial designs in development and about two thirds of them are non-WCR [5]. Some of the developing reactors are being designed to be deployed underwater or underground (sub-grade), which can increase protection from external threats like tsunamis, earthquakes or sabotage [7].

The possibly smaller size and reduced need for cooling water of SMRs make them well suited for deployment in remote locations where LSRs would be impractical. In such settings, SMRs can support alternative applications such as hydrogen and ammonia production or desalination. As part of the category of advanced reactor designs, SMRs often incorporate passive safety systems, which minimize the need for operator intervention and reduce reliance on active components like pumps or external power supplies. This typically results in simpler construction, potentially lowering costs and improving maintainability [7].

### 3.3 Floating Nuclear Power Plants and icebreakers

Two distinct applications of nuclear reactors in maritime contexts have been identified in this thesis. The majority of operational experience stems from their use in military propulsion systems, such as in submarines, aircraft carriers or other naval vessels. In contrast, the use of nuclear reactors for civilian power generation aboard stationery or semi-mobile platforms, supplying electricity to shore, remains limited and relatively unexplored.

Usage of nuclear power to propel marine vessels has been researched since the 1940s, with the first submarine put to sea in 1955. Following this, multiple applications of nuclear power in nuclear vessels have arisen, mainly for military purposes. Apart from submarines, other nuclear-powered vessels such as naval surface ships, icebreakers and aircraft carriers have been designed and deployed over the years. It is approximated that over 14,000 reactor years have been accumulated from some 700 reactors since the 1950s. The popularity is mainly due to the time between refueling is significantly longer compared to other fuels [15].

Civil use of nuclear propulsion is limited, with almost all experience coming from Russia. Currently, Russia operates the only nuclear-powered fleet of icebreakers in the world. On 28 December 2024, the deployment of *Yakutia* brought the total number operational icebreakers to eight [16]. Other attempts to use nuclear propulsion for other applications, such as in merchant ships, are few and largely unsuccessful. Japan, Germany and the United States have all built, operated and later decommissioned nuclear-powered merchant ships. While Germany's *Otto Hahn* and United States' *NS Savannah* were technically successful, they proved economically unviable, because it was cheaper to use traditional fuel. Japan's *Mutsu* was deemed an embarrassing failure due to its technical and political problems. Only Russia still operates a nuclear-powered merchant ship, the *NS Sevmorput* [15].

#### 3.3.1 Akademik Lomonosov

The Russian FNPP Akademik Lomonosov is the world's only operational mobile small-scale nuclear power plant, designed to provide stable and sustainable electricity to remote areas with harsh arctic environments. This FNPP consists of a reactor vessel and a floating power unit (FPU), designed by Rosatom. The vessel measures 144 meters in length, 30 meters in width and has a displacement of 21,000 tons. The reactor plant (RP) is in the middle of the vessel and the steam turbine plant (STP) is positioned further toward the front (Figure 2).

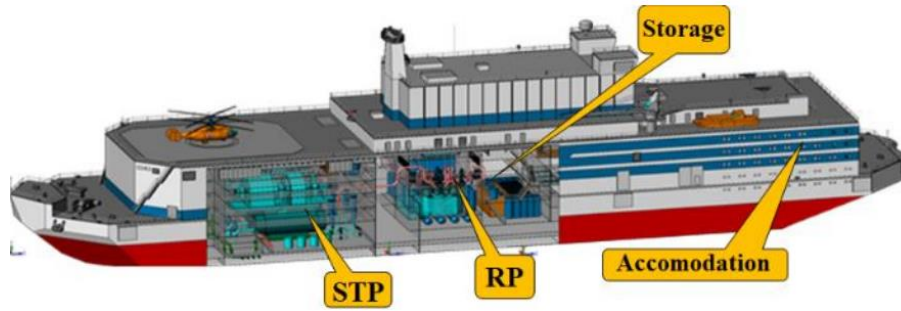


Figure 2 General cross-section view of the FPU [17].

The initial concept of FNPPs dates back to early Russian nuclear development projects when Rosatom initially planned to construct up to seven or eight FNPPs by 2015, with the first one expected to be completed in 2010 and stationed at Severodvinsk. However, the construction of the Akademik Lomonosov faced multiple delays due to financial and logistical challenges. The keel was originally laid in 2007 at Sevmash, but due to the military workload, the contract was transferred to Baltiysky Zavod Shipyard in St. Petersburg in 2008. In 2012 the United Shipbuilding Corporation acquired the shipyard and thus revived the project. The reactors were installed in October 2013 and onshore infrastructure work began in 2016. After a series of mooring tests in 2016, the FNPP was towed to Murmansk for fuel loading in 2018. The plant was transported to the city Pevek and commenced operation in December 2019 and was fully integrated into the regional grid by May 2020 [18].

Akademik Lomonosov plays a crucial role in the energy stability and security of Chukotka one of Russia's most remote and extreme weather regions. It replaced the aging Bilibino Nuclear Power Plant and the Chaunsk coal-fired power plant, significantly reducing CO<sub>2</sub> emissions by approximately 50,000 tonnes per year in the region. Its deployment supports key industries and economic development in the region [8].

Akademik Lomonosov is equipped with two KLT-40S PWRs (Figure 3), each with a capacity of 35 MWe. These reactors are adapted from those used in Russian icebreakers, ensuring a robust and tested design. The reactor fuel consists of UO<sub>2</sub> pellets in a silumin matrix with an 18.6% enrichment level. The plant follows a 30-36 month refueling cycle with all fuel assemblies being replaced simultaneously. The operational lifetime of the FNPP is projected at 40 years. Spent nuclear fuel is stored onboard and later transported to the mainland, ensuring minimal environmental impact in remote regions [8, 18]. The primary cooling circuit operates at a pressure of 127 bar, with an inlet temperature of 280°C and an outlet temperature of 316°C. The FNPP employs a four-loop cooling system, allowing both forced and natural circulation in emergency scenarios. The safety system includes both active and passive protection measures, featuring an emergency cooling system and multiple physical containment barriers to prevent radioactive release [17].

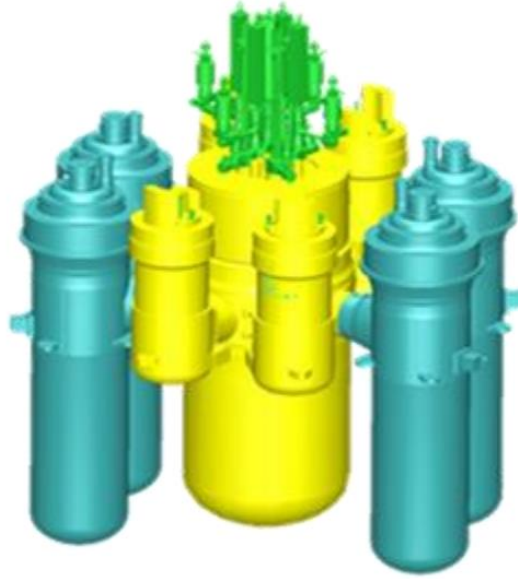


Figure 3 Illustration of a KLT-40S reactor [17].

Following the success of Akademik Lomonosov, Rosatom has proposed second-generation Optimized Floating Power Units (OFPU) which would use RITM-200M reactors with higher power output (50 MWe per reactor) and a longer refueling cycle (10–12 years). These improvements reduce operational costs and environmental impact. There are plans to use OFPUs for a domestic copper mining project and possibly for international applications, with interest from countries such as China, Indonesia and Guinea [18].

### 3.3.2 Icebreakers

Nuclear powered icebreakers are a unique and strategically valuable application of nuclear propulsion, and they are especially suited for operations in the harsh Arctic environment. Unlike conventional ships, these vessels can operate for extended periods without the need for refueling, offering an unparalleled operational efficiency. This is particularly important for maintaining an all-year-round access to the Northern Sea Route (NSR) which is a key for maritime passage through the Russian Arctic. The NSR significantly shortens the journey between Europe and Asia compared to other routes [15].

Russia was the pioneer in this field, launching the world's first nuclear powered surface ship, *Lenin*, in 1959. It was originally fitted with three OK-150 PWRs but was later refitted with two OK-900 PWRs and remained in service until 1989. This vessel laid the foundation for future nuclear icebreaker designs by showcasing the viability of nuclear propulsion for sustained Arctic missions. Following *Lenin*, a series of more powerful icebreakers, so called Arktika-class vessels, entered service. These ships were equipped with two OK-900A reactors and could break through ice up to 2.8 meters thick. Notably Arktika became the first surface ship to reach the North Pole in 1977. Many of these vessels were dual-purpose, supporting both commercial navigation and scientific or strategic missions [15].

Russia is currently operating a new generation of nuclear icebreakers under the name *Project 22220* which includes ships like *Arktika* (2017), *Sibir* (2022) and *Ural* (2024). The vessels are powered by two RITM-200 reactors, each producing 175 MWt enabling them to break through ice up to 2.8 meters thick. They are also dual-draft, allowing for operations in both deep and shallow waters, increasing their navigational flexibility. In addition to the three vessels named

above, *Yakutia* has just recently been deployed but is not yet in full operation. Furthermore, *Chukotka* is under construction and is expected to be completed by the end of 2026, and two more are planned to be deployed by the end of 2028 and 2030 as well. This will bring the number of Projekt 22220 vessels to seven in operation. In writing moment, the total number of active nuclear icebreakers are eight, presented along with those that are decommissioned in Table 2 [15].

In addition to the Project 22220 series, Russia has initiated the Leader-class (Project 10510) icebreaker program with the first vessel, *Rossiya*, under construction and expected to enter service around 2030. These next-generation ships will be the most powerful yet, using RITM-400 reactors and being capable of breaking through ice with a thickness over 4 meters and also carving a broader path to accommodate larger vessels [15].

**Table 2 List of all icebreakers, when they were deployed, their reactor type, class and operational status.**

<b>Name</b>	<b>Deployed</b>	<b>Reactor (PWR)</b>	<b>Class</b>	<b>Operational status</b>
<b>Lenin</b>	1959	3 OK-150 / 2 OK-900	N/A	Decommissioned 1989
<b>Arktika</b>	1975	2 OK-900A	Arktika	Decommissioned 2008
<b>Sibir</b>	1977	2 OK-900A	Arktika	Decommissioned 1992
<b>Rossiya</b>	1985	2 OK-900A	Arktika	Decommissioned 2013
<b>Sovetskiy Soyuz</b>	1990	2 OK-900A	Arktika	Decommissioned 2014
<b>Yamal</b>	1993	2 OK-900A	Arktika	In service
<b>50 Let Pobedy</b>	2007	2 OK-900A	Arktika	In service
<b>Taymyr</b>	1989	1 KLT-40M	Taymyr	In service
<b>Vaygach</b>	1990	1 KLT-40M	Taymyr	In service
<b>Arktika</b>	2017	2 RITM-200	Project 22220	In service
<b>Sibir</b>	2021	2 RITM-200	Project 22220	In service
<b>Ural</b>	2022	2 RITM-200	Project 22220	In service
<b>Yakutiya</b>	2024	2 RITM-200	Project 22220	In service
<b>Chukotka</b>	(2026)	2 RITM-200	Project 22220	Under construction

<b>Leningrad</b>	(2028)	2 RITM-200	Project 22220	Under construction
<b>Stalingrad</b>	(2030)	2 RITM-200	Project 22220	Under construction
<b>Rossiya</b>	(2030)	2 RITM-400	Project 10510	Under construction

The development of nuclear icebreakers has evolved from early cold war-era experimentation into a core component of the arctic maritime strategy. As climate change opens more northern sea lanes, the importance of these vessels, both from a commercial and geopolitical standpoint, is only expected to grow [15].

### 3.3.3 Reactors in development for floating nuclear power purposes

Several SMRs are currently in development for potential use on FNPPs. While a few are specifically designed for integration with FNPPs, others are land-based concepts that are merely being considered for adaptation to maritime platforms. The reactors are at varying stages of development and their current statuses differ depending on the source. Most of the reactors listed in Table 3 are included in the IAEA’s unofficial 2024 SMR catalogue [17]. The table compiles all reactor designs that have been referenced in [6] as being intended, or potentially adaptable, for use in FNPPs. Additionally, if a reactor is listed in the IAEA’s *Advanced Reactor Information System (ARIS)*, a database that provides up-to-date information on advanced reactor designs, its development status is also indicated [19].

**Table 3 List of SMRs in development that lists company, reactor, type of platform, power and additional comments.**

<b>Company, Country</b>	<b>Reactor</b>	<b>Platform (intended for)</b>	<b>Power [MWe]</b>	<b>Development status (from ARIS [19])</b>	<b>Comment</b>
<b>CORE POWER, UK</b>	Molten Chloride Fast Reactor (MCFR) (MSR)	Barge	N/A	N/A	Developed by a consortium including TerraPower, CORE POWER, Southern Co and HD KSOE. Closed fuel cycle and continuous operation when refueling.
<b>Saltfoss (Seaborg), Denmark</b>	Compact Molten Salt Reactor (CMSR) (MSR)	Barge	110	Conceptual Design	FNPPs will be built in Samsung Heavy Industries’ shipyards. Power output is 200 MWe per module, with up to 4 modules installed on a single barge
<b>Rosatom, Russia</b>	KLT-40s (PWR)	Barge	35	Operational	“Akademik Lomonosov”, the only FNPP in operation (since 2020)
<b>Rosatom, Russia</b>	RITM-200M (PWR)	Barge	57 (for RITM-200, not	Conceptual Design	Rosatom is planning three OFPUs each with twin RITM-200M reactors at Cape Nagloynyn

			specified for RITM- 200M)		
<b>Rosatom, Russia</b>	VBER-300 (PWR)	Barge	295	Under Regulatory Review	More powerful sister- reactor to the KLT-40s
<b>Rosatom, Russia</b>	ABV-6M (PWR)	Barge	11	Detailed Design	
<b>NuScale, USA</b>	NuScale Power Modules (MPS) (PWR)	Barge	77	Under Regulatory Review	NuScale, in cooperation with Prodigy Clean Energy, is developing an FNPP version of the MPS. Power output is 77 MWe per module, with up to 12 modules installed on a single barge
<b>Westingho use, USA</b>	eVinci microreact or (Heatpipe FNR)	Barge	5	Detailed Design	In agreement with CORE POWER to use the eVinci microreactor on their barges
<b>Kepeco E&amp;C, South Korea</b>	BANDI- 60S (PWR)	Barge	60	Conceptual Design	In September 2020 Kepeco signed an agreement with Daewoo Shipbuilding & Engineering to develop offshore nuclear power plants using the reactor
<b>China National Nuclear Corporati on (CNNC), China</b>	ACP25S/ ACP100S (PWR)	Barge	28 / 125	Basic Design (only ACP100S mentioned)	Passive safety features. CNNC signed an agreement in July 2016 with China Shipbuilding Industry Corporation (CSIC) to prepare for building its ACP100S demonstration floating nuclear plant.
<b>State Power Investmen t Corporati on (SPIC), China</b>	CAP200/ OceanStar- V (PWR)	Barge	200	N/A	OceanStar-V is the FNPP version of the LandStar-V.
<b>China General Nuclear Group</b>	ACPR50S (PWR)	Barge	50	N/A	Passive cooling for decay heat. CGN announced the construction start on the first FNPP at Bohai Shipyards in Huludao,

(CGN), China					southwestern Liaoning province, in November 2016. No further announcements on the project have since been made.
<b>China Shipbuilding Industry Corporation (CSIC),</b>	HHP25 (PWR)	Barge	25	N/A	
<b>Westinghouse, USA</b>	AP1000 / AP300 (PWR)	Offshore rig	1110 / 330	Operational / Basic Design	MIT has concepts of OFNPs utilizing Westinghouse's reactors

### 3.4 Alternative uses

FNPPs and SMRs have a range of potential alternative uses beyond heat and electricity production, and this chapter will introduce some of them. These uses can be a key to reaching the goal of net zero by 2050.

#### 3.4.1 Hydrogen and ammonia production

The production of hydrogen or ammonia, or both, presents a viable solution to electricity overproduction by allowing surplus energy to be converted into chemical products, which can be stored and transported more efficiently compared to electricity [20].

Instead of curtailing excess power, FNPPs could channel their surplus energy into a power-to-ammonia plant. One way to do that is to apply the solid oxide electrolysis cell (SOEC) [20] to produce hydrogen from water. Hydrogen can be further utilized to synthesis ammonia by combining it with nitrogen which is separated from air. The resulting ammonia is a more stable and easily transportable chemical compared to hydrogen. Ammonia can be used as a carbon-free fuel, a key component in fertilizer production and as an energy carrier for long-term storage and transport [20].

This approach enables FNPPs to integrate into fossil-free hydrogen economies, supporting decarbonization efforts in remote and industrial regions. By leveraging FNPPs alongside variable renewable energy (VRE) like solar and wind for hydrogen and ammonia production, energy can be stored and redistributed efficiently, reducing dependency on fossil fuels and enhancing energy security in isolated locations. The process is called *Power-to-X* where renewable energy is transformed into a spectrum of energy carriers like green hydrogen, green ammonia or eMethanol [20]. In 2023, about 95% of the hydrogen production capacity in Europe was based on fossil fuels. Using *Power-to-X* could reduce the carbon footprint from production of hydrogen [21].

Producing green hydrogen by electrolysis is energy intensive where the chosen method greatly influences its overall efficiency. SOEC requires less energy than traditional alkaline and PEM technologies by operating at high temperatures (675–825°C). SOEC utilizes both electricity and thermal energy, allowing it to function at lower voltages and achieve higher efficiency. This

leads to a 20% energy savings per unit of hydrogen produced compared to low-temperature alternatives, which can increase up to 30% if steam is provided. A key advantage of SOEC is the potential ability to integrate waste heat from industrial processes such as ammonia synthesis, NPPs, or steel production. By utilizing approximately 70% of the required thermal energy from what is typically considered low-value waste heat and reusing steam internally for the remaining 30%, SOECs can significantly reduce their electricity demand. This integration has the potential to lower electricity consumption from about 4.0 to 3.5 kWh per normal cubic meter (Nm<sup>3</sup>) of hydrogen produced. This will not only cut energy costs but also minimize low grade heat losses, which are otherwise wasted in alkaline and PEM systems that require 5 kWh per Nm<sup>3</sup> of hydrogen produced [22].

A standard 100 MW SOEC plant can generate approximately 28,600 Nm<sup>3</sup>/h of green hydrogen with steam integration, equivalent to 2,570 kg/h. This output can support downstream production of ammonia by an additional 3.26 MW for an air-separation unit and 5.43 MW for synthesis of ammonia. Bringing the total electricity consumption to 108.69 MW to produce 330 metric tons per day of green ammonia, highlighting the potential of SOEC in decarbonization at scale [22].

### **3.4.2 Desalination**

Knowledge of desalination is vast since about 19,000 desalination plants are in operation worldwide, with almost half of the capacity installed in the middle east. The most common feedwater is seawater, with about 60 % of the plants using it. As most plants today are being powered by fossil fuels, there is great potential to reduce carbon dioxide emission should they instead be powered by nuclear power. Desalination is a very energy-demanding process that can use both electricity and heat, which makes nuclear power a viable option [23]. Desalination plants exist on land and at sea, where they have been used on nuclear powered icebreakers and freight carriers. The maritime experience comes from Russian ships where the capacity has ranged from 60-120 m<sup>3</sup> per day [24].

In addition to maritime use, nuclear-powered desalination has been explored as a sustainable solution for freshwater production in coastal and arid regions. The integration of nuclear reactors with desalination technology allows for continuous large-scale water production while reducing reliance on fossil fuels [23]. The IAEA has assessed various reactor types including PWRs and SMRs as viable sources of energy for desalination. Some projects have demonstrated the feasibility of coupling nuclear reactors with reverse osmosis (RO) or multi-stage flash (MSF) desalination processes to maximize efficiency [24]. RO needs about 6 kWh of electricity per cubic meter of water while MSF uses about 38 kWh/m<sup>3</sup> thermal input plus 3,5 kWh/m<sup>3</sup> of electricity to produce the same amount. [23].

## **3.5 Types of floating maritime platforms**

FNPPs can be deployed on different structures and in different vessels. One option is to place a reactor on a barge, combining nuclear reactor engineering with maritime architecture. The other option is to place a reactor on an offshore rig, which combines two well-meditated principles of nuclear reactors and offshore platforms like oil and gas rigs, possibly allowing use of larger reactors than on barges.

### **3.5.1 Barge**

Barges are very similar to large ships, both in design and construction. The difference is that a barge cannot propel itself, which means it can be designed more freely from a hydrodynamic

perspective. A common feature among barge designs intended for FNPPs is the plan to construct them in existing shipyards. This is primarily due to the need for prefabrication with marine expertise and the logistical and large-scale infrastructure that is already available at such places.

Modern concepts by companies like Saltfoss Energy (formerly Seaborg Technologies) and Core Power continue the trend from Akademik Lomonosov, but with unique design philosophies. Saltfoss is developing a Compact Molten Salt Reactor (CMSR) which is designed to be deployed on modular barges. These barges will be constructed in shipyards and collaboration agreements are in place with Samsung Heavy Industries (SHI) in South Korea, leveraging their existing marine manufacturing infrastructure. Highlights of Saltfoss' design include small size, passive safety and proliferation resistance, making it highly adaptable for deployment in remote or underserved regions. The CMSR barge is intended to be mass-produced, fully tested and commissioned in the shipyard for easy deployment to coastal sites. The capacity ranges from 200 to 800 MWe, depending on the number of modules. Each module increases the barge's length by 70 meters, resulting in a total length of 115 meters for 200 MWe, 185 meters for 400 MWe, 255 meters for 600 MWe and 325 meters for 800 MWe [25]. Each module is designed to accommodate four reactors, with two installed and operating during the first 12 years, followed by the remaining two for the subsequent 12 years. This staged operation results in an overall operational lifespan of 24 years before the barge is towed to a central shipyard for decommissioning. [26]

Core Power has presented their *Liberty program*, which is a barge concept that would be 160 meters long and 35 meters wide with a draft between six and seven meters, weighing in at 25,000 tons. The barge would be capable of delivering about 70-80 MWe and is marketed as one solution to target the approximately 300 ports in the US that need to be electrified. It could also be used to supply electricity to other facilities that are near waterways or the shore. They also plan on using shipyards to construct their barges, making it possible to deliver them on time and on budget [27]. This corresponds to what Mikal Bøe, Chairman and CEO at CORE POWER, mentioned about how the entire barge should be modular, not only the reactor [28].

### 3.5.2 Offshore

The development of offshore platforms has traditionally been dominated by the oil and gas industry, although offshore wind and solar energy parks have gained increased attention in recent years. An innovative concept on this topic is the Offshore Floating Nuclear Power Plant (OFNP), which is a marine based nuclear power system on a floating platform. This concept combines two well-established technologies, nuclear reactors and the engineering principles from offshore oil and gas rigs, forming a new form of safe, flexible and scalable power generation [29].

Two OFNP configurations have been proposed by Massachusetts Institute of Technology (MIT), one of them being the OFNP-1100 deploying the full-scale Westinghouse AP1000 PWR. The rig would be designed with a draft/height of 66/106 meters, a diameter of 75 meters and a displacement of 368,000 tons, capable of producing 1100 MWe. The second configuration proposed is the OFNP-300, which is a smaller, more compact, design. The OFNP-300 would have an integral PWR where all primary system components are housed within a single pressure vessel. This type is smaller than OFNP-1100 with a draft/height of 49/73 meters, a diameter of 45 meters and a displacement of 72,000 tons, capable of producing 300 MWe [29].

OFNPs are designed with high safety margins by incorporating multiple defense in depth features beyond those in conventional land based nuclear facilities. The platforms feature a double hull structure with watertight compartments and elevated reactor buildings to minimize intrusion risk. The spent reactor fuel is stored on the platform in passively cooled pools designed to accommodate all the fuel from the entire lifetime of the plant. Construction of the OFNP is based on the idea of constructing the entire plant at a centralized shipyard. Shipyard based construction offers several advantages like improved quality control, shorter construction times and significantly lower capital costs as the need for extensive site excavation and concrete structures is eliminated. At the end of the plant's service life, the plant would be towed back to a shipyard for rapid decommissioning and minimal environmental impact [29].

The completed platform of spar-buoy design is then towed to a predetermined site approximately 10–20 kilometers offshore in about 100 meters deep waters. The positioning offers natural protection against seismic and tsunami events, critical considerations following the Fukushima Daiichi incident in 2011. The ocean essentially serves as an infinite heat sink, which allows for passive cooling of the reactor and containment over an unlimited duration, even under severe accident conditions. Compared to land-based plants, there is a lower requirement for the Emergency Planning Zone (EPZ) on land for OFNPs, since they are located far from population centers [29].

# 4 GOVERNANCE OF NUCLEAR SAFETY, SECURITY AND SAFEGUARDS

*This section introduces some treaties and conventions that regulate the use of nuclear power and marine activities to promote safe, secure and proliferation proof operations.*

## 4.1 Safety, security & safeguards

Peaceful use of nuclear power has its basis in the 3Ss: safety, safeguards and security (Figure 4). Together, they shape the solutions, design principles and regulations that ensure that nuclear energy remains safe and reliable. Although they are sometimes treated separately, they are closely related. This means that changes in one area can affect something, either positively or negatively, in another [30].



*Figure 4 The 3Ss, Safety, Security and Safeguards are closely linked together and dependent on each other.*

### 4.1.1 Safety

In the nuclear field, safety aims to prevent unintentional events leading to radiological release. Safety has been a central concern to the industry since the beginning, and even more so following major accidents such as Three Mile Island, Chernobyl and Fukushima Daiichi. Optimal safety, in all nuclear facilities but especially in NPPs, is achieved through *defense-in-depth*, in which *protection* (Figure 5) and *physical barriers* (Figure 6) is a part [31].

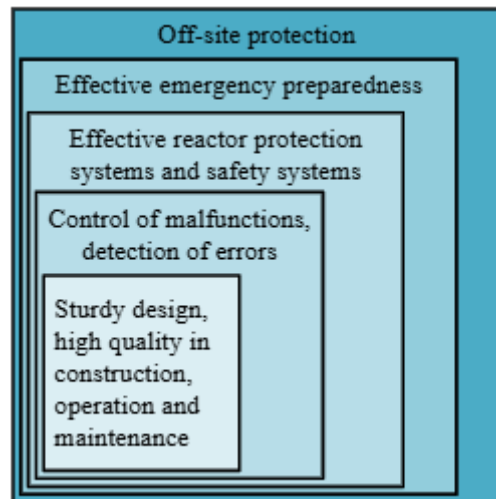


Figure 5 The five levels of protection in defense-in-depth. Adapted from [32].

As presented in Figure 5, defense-in-depth consists of five levels of protection, where each lower level aims to prevent the next from occurring. The goal is to operate the plant with as few errors as possible, as accidents can have catastrophic consequences and every day that they are shut down leads to big economic losses [32].

- **Level 1:** High quality in design, construction, operation and maintenance ensures smooth operation with few failing components,
- **Level 2:** If a component fails, rely on robust detection and control systems, such as radiation monitoring systems, emergency shutdown systems, situation management training etcetera,
- **Level 3:** Minimize the consequences and prevent damage to the core through safety systems and routines for situation management,
- **Level 4:** Minimize radiological release and limit further accident progression through a well prepared and effective response team,
- **Level 5:** Limit radiological release off-site through robust construction design, planning and routines.

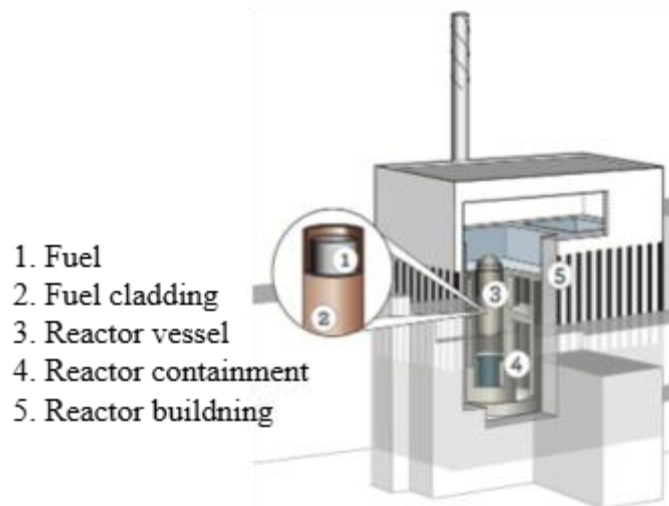


Figure 6 The five physical barriers of defense-in-depth to limit radiological release. Illustration from [33].

The five physical barriers (Figure 6) of defense-in-depth are designed to prevent radioactive material being dispersed into the environment. With a few exceptions, the first three barriers - *fuel*, *fuel cladding* and *reactor vessel* - are present in all NPP types, regardless of coolant or design. The fourth and fifth barriers – *reactor containment* and *reactor building* - can vary in form for different reactor types [34, 33]. As previously mentioned, some SMRs in development are designed to be placed underwater or underground, which would then act as the reactor building in the context of the fifth barrier [7].

- **Barrier 1:** The fuel itself is made with e.g. ceramics or metals to withstand high temperatures, so as not to melt,
- **Barrier 2:** The fuel cladding prevents damaged fuel or fission products, that are not contained in the matrix, from contaminating the coolant,
- **Barrier 3:** The reactor vessel and associated piping systems are designed to withstand high temperature and pressure to enclose the radioactive coolant and core securely,
- **Barrier 4:** If all three previous barriers fail, the containment structure is designed, usually with thick concrete, to contain any radioactive material or gas,
- **Barrier 5:** The reactor building (potentially sub-grade) is designed to withstand external threats like tsunamis, earthquakes, sabotage or attacks.

Most FNPP designs in development feature SMRs, mainly for their modularity and the potential for large scale production [35, 36]. Apart from being modular, SMRs are designed to enhance safety, compared to outdated Gen II reactors, through smart, modern technology and passive safety systems [37, 38]. While some of the offshore platforms are being designed to accommodate LSRs, these designs are also expected to include advanced reactors with enhanced safety features [29].

FNPPs introduce unique challenges, particularly due to their long-term deployment in dynamic maritime environments. Central to these challenges is the Emergency Planning Zone (EPZ), which addresses radiological safety. The EPZ is defined as the area around a nuclear facility within which emergency preparedness measures are developed to mitigate public exposure in the event of a radiological release. Unlike traditional land-based nuclear power plants with EPZs extending up to 80 km, emerging SMR technologies, including those used in FNPPs, may allow significantly smaller EPZs, potentially limited to the immediate vicinity of the plant [39].

Weather and environmental conditions are critical factors in EPZ planning for FNPPs. As floating vessels, these reactors must account for marine-specific hazards such as high winds, waves, storm surges and variable current patterns. These conditions influence dispersion modeling for radioactive releases and affect emergency response logistics. Directional factors, such as wind-driven “keyhole” shaped evacuation zones, are essential to planning, particularly in coastal or offshore deployments [39].

#### 4.1.2 Security

Since sabotage of a nuclear facility or theft of nuclear material can cause catastrophic consequences, much effort is put into preventing, detecting and responding to potential threats. Normally, responsibility for security lies with national governments and the operators of the facility. High-level security is maintained through a combination of physical and technological measures, including physical barriers, restricted access zones, identification protocols, radiation detectors and surveillance systems. With the increasing digitalization of the nuclear industry, cybersecurity has become an essential component of nuclear security. A successful cyberattack could disrupt or disable digitally controlled safety and security systems or potentially compromise sensitive information such as construction plans or 3D models of the facility [40].

Nowadays, nuclear facilities have various areas, for example waste storage and the control room, that are restricted to all but some. This conflicts with the SOLAS Convention (section 4.2.2), which states that in the event of an emergency, unrestricted access to escape routes is required on all vessels. Similarly, shipyards used for construction will have to consider their security in ways not previously thought of. This becomes especially problematic for companies that plan to use already existing shipyards to build their FNPPs. Using existing shipyards may include renovating the facility to incorporate security measures, which can become costly and time consuming [41].

#### 4.1.3 Safeguards

Safeguards are the measures used to ensure that a state only uses nuclear materials for peaceful purposes, and that it is not dispersed too states with unlawful intent. To achieve this, the IAEA regularly inspects nuclear facilities, tracks material flow, installs seals, monitors movement with cameras and samples nuclear material, amongst other things. Countries that fail to comply with the agreement cannot be subjected to technical countermeasures, such as military action or shutting down facilities, by the IAEA or any other country. If the IAEA discovers noncompliance however, it is reported to the United Nations (UN) whose responses are political and could include sanctions and trade bans [42].

One safeguard tool that the IAEA requires each member state to establish is the *State System of Accounting for and Control of Nuclear Material* (SSAC), which serves both national and international functions. Internationally, the SSAC provides the IAEA with accurate data on the state's nuclear material inventory and grants inspectors access to verify compliance with safeguards. Nationally, it helps the state monitor and manage its nuclear materials, detect any losses and prevent unauthorized use or removal [43].

## 4.2 Regulations and organizations relevant to maritime nuclear power

### 4.2.1 *The International Atomic Energy Agency and its treaties and conventions*

The International Atomic Energy Agency (IAEA) was created on 29 July 1957, after *The Statute of the IAEA* was approved in 1956. The second article of The Statute states the IAEA's objectives:

The [International Atomic Energy] Agency shall seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world. It shall ensure, so far as it is able, that assistance provided by it or at its request or under its supervision or control is not used in such a way as to further any military purpose.

Among other things, the statute outlines the IAEA's rights and responsibilities concerning nuclear safeguards, the procedures for the supply and control of nuclear materials, the process by which a state becomes a member and the measures the IAEA can take if a member state fails to comply with its obligations [44].

One of the IAEA's missions is the implementation and monitoring of the 3Ss in established nuclear facilities, but also in states developing new nuclear programs. To promote more effective and efficient safeguarding of nuclear facilities, the IAEA advocates for early integration of safeguards in their designs, a concept is known as *Safeguards by Design* (SBD). Since one of the IAEA's core missions is to ensure that nuclear material is not diverted for military purposes, effective safeguards are important. The IAEA, operators, stakeholders, regulatory authorities and so on have realized the potential cost and time saving by also integrating safety and security into the *by Design* concept. Integrating all 3Ss: Safety by Design (SbD), Security by Design (SeBD) and SBD, could then be called 3SBD [45].

The *by Design* concept essentially involves incorporating the 3Ss directly into the facility's design from the beginning, thus minimizing the need for costly modifications or regulatory adjustments after construction. As said, the 3Ss have a lot in common and integrating them early in the design, and synergistically, could lead to a competitive advantage on the market. For example, strategically planning where to install video surveillance cameras can aid in detecting unauthorized access to the facility while at the same time monitoring for any attempts to remove nuclear material. Another example could be that it is common to take the same measurement twice, one for safeguard verification and one for operator quality control, relating to safety. Designing this to be synergized from the beginning could reduce the personnel exposure to radiation and lower the time and resources required to perform the measurement [45].

To support countries in establishing NPPs, either additional plants or for the first time, the IAEA offers technical expertise, training and practical tools, amongst other things. One key example is the Integrated Nuclear Infrastructure Review (INIR), which assesses a country's infrastructure in relation to the development of NPPs. These reviews help identify gaps in the infrastructure and receive tailored guidance to ensure the safe, secure and sustainable implementation of nuclear power [46].

To ensure that countries operate nuclear power responsibly and peacefully, the IAEA has developed a range of treaties and conventions, a few of which will be presented here. If a country chooses not to sign, it cannot benefit from the rights, protections, or support the treaty

provides. Moreover, it cannot be held accountable under its framework and is not obligated to follow its rules, even if the country is a member of the IAEA [47].

### ***The Treaty on the Non-Proliferation of Nuclear Weapons***

Following the atomic bombings of Hiroshima and Nagasaki in 1945, it became evident that action was needed to prevent the proliferation of nuclear weapons. As a result, the Treaty on the Non-Proliferation of Nuclear Weapons, the Non-Proliferation Treaty for short (NPT), was established on 5 March 1970 by members of the IAEA. Since the NPT is an international treaty between states, the IAEA is not a party to it. Instead, the Agency is entrusted with verifying that states comply with its conditions [48].

The NPT has limited the number of Nuclear Weapons States (NWSs) to eight, instead of the predicted 30-35. Knowing the catastrophic consequences a nuclear war would entitle, the objective of the NPT is to deter from and prevent the spread of nuclear weapons, provide security to non-NWSs and promote disarmament of nuclear weapons. However, the NPT also affirms the possible benefits of nuclear technology and therefore encourages continued peaceful use of nuclear energy and technological development through international cooperation [49, 48].

### ***Convention on the Physical Protection of Nuclear Material***

To set legal standards for the protection of nuclear material, the IAEA adopted the *Convention on the Physical Protection of Nuclear Material* (CPPNM) in 1979, with an amendment in 2005. The convention requires member states to establish national laws to ensure the physical protection of nuclear material during international and domestic transport, as well as during its use and storage. Since the convention is defined to apply to nuclear material, it is applicable to usage of FNPPs. According to Article 7, paragraph 1, any act that causes, or could cause, harm to people, property or the environment, as well as any attempt to acquire nuclear material unlawfully, must be made punishable by law [50, 51].

Although physical protection focuses on the security of a nuclear facility, as all three Ss are closely related and depend on each other, measures to strengthen security indirectly leads to a higher level of nuclear safety and safeguards in many cases. For example, Article 5 §2 of the CPPNM states that in case of theft of nuclear material, member nations should aid in the recovery and protection of the material to the maximum feasible extent. In doing so, proliferation of nuclear material is limited. Likewise, protection from sabotage that could lead to radiological release is a question of both nuclear security and safety [50, 51].

### ***Vienna Convention on Civil Liability for Nuclear Damage***

To provide financial protection against damage resulting from peaceful use of nuclear power, the IAEA established the *Vienna Convention on Civil Liability for Nuclear Damage* (VCCLND) on 23 November 1977. The convention aims to ensure that compensation is available for damage caused by a nuclear incident at a “nuclear installation”. The convention establishes that the operator is responsible for any damage caused by nuclear incidents, unless it can be proven that it was not their fault. Article 1, paragraph 1, subparagraph (j), item (i) of the convention defines “nuclear installation” as any reactor, except those used at sea or in the air. In other words, the convention is not applicable to FNPPs. However, article XVII states that the convention does not affect the application of other international agreements. That means that bilateral agreements that apply to maritime use of nuclear installations can be reached [52].

### ***Convention on Nuclear Safety***

Through the *Convention on Nuclear Safety* (CNS), the IAEA established principles to maintain a high level of safety during operation of NPPs. The convention entered into force on 24 October 1996, and it aims to prevent radiological accidents through effective defenses and international cooperation. Similarly to the VCCLND, the CNS does not apply to FNPPs. According to Article 2, the convention only applies to nuclear installations, which in this convention are defined as a land-based civil nuclear power plant, including related storage, handling and treatment facilities [53].

### ***Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management***

In the *Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management*, it is specified that handling nuclear waste is a national responsibility. In short, it means that IAEA member states are required to establish national laws for managing the nuclear waste they produce. Paragraph 11 of the convention's preamble states:

Convinced that radioactive waste should, as far as is compatible with the safety of the management of such material, be disposed of in the State in which it was generated, whilst recognizing that, in certain circumstances, safe and efficient management of spent fuel and radioactive waste might be fostered through agreements among Contracting Parties to use facilities in one of them for the benefit of the other Parties, particularly where waste originates from joint projects

This implies that nuclear waste can be imported and disposed of in another state than the one in which it was generated. However, this must be stated in the national laws of both supplier and host states, as well as in a bilateral agreement between them [54].

#### ***4.2.2 The International Maritime Organization***

To promote and facilitate maritime safety, the United Nations (UN) established the International Maritime Organization (IMO) in 1948. One of the IMO's key instruments is the *International Convention for the Safety of Life at Sea* (SOLAS), which outlines minimum standards for the construction, equipment and operation of ships to ensure their safety [55].

Recognizing that nuclear-powered vessels require different and more substantial safety standards, the IMO adopted the *Code of Safety for Nuclear Merchant Ships* (CSNMS) in 1981. This code, much like SOLAS, sets standards for the design, construction, operation and maintenance of nuclear-powered ships. It also addresses procedures for their decommissioning and disposal. Notably, the code excludes FNPPs and ships propelled by reactors that are not PWRs from its scope. Paragraph 4 of the preamble reads [55]:

While development of the Code has been based upon established and accepted ship-building, marine and nuclear engineering principles, it is recognized that review will be necessary as technology progresses. Initial application of the Code is restricted to conventional types of ships propelled by nuclear propulsion plants with pressurized light water type reactors.

Due to the stringent requirements outlined in the CSNMS, particularly those related to the EPZ, PWRs are rarely used on civil merchant vessels today as they face significant challenges in securing permission to enter ports and insurance coverage. For these reasons, among others, a proposal has been put forward for the IMO to initiate a revision of the CSNMS. Following the advancements on nuclear technology since 1981 and the will to use commercial nuclear ships,

Republic of Korea and United States, along with five organizations associated with the nuclear and maritime sectors, submitted the proposal on 9 April 2025 [55].

#### 4.2.3 Summary table of conventions and treaties

In Table 4, the treaties and conventions mentioned in sections 4.2.1 and 4.2.2 are summarized for an easy overview.

**Table 4 Overview of key international treaties and conventions relevant to nuclear safety, security, safeguards and liability, including applicability to Floating Nuclear Power Plants (FNPPs).**

<b>Name of Treaty/ Convention</b>	<b>Adopted (Entered into force)</b>	<b>Latest amendment entered into force</b>	<b>Applies to FNPPs?</b>	<b>Category</b>
<b>Statute of the IAEA</b>	1956 (1957)	1989	Yes (General Framework)	Mixed (Safety, Security, Safeguards)
<b>Treaty on the Non-Proliferation of Nuclear Weapons (NPT)</b>	1968 (1970)	Extended indefinitely in 1995	Yes (Indirectly, via safeguards)	Safeguards, Security
<b>Convention on the Physical Protection of Nuclear Material (CPPNM)</b>	1979 (1987)	2016	Yes	Security
<b>Vienna Convention on Civil Liability for Nuclear Damage (VCCLND)</b>	1963 (1977)	2003	No (Excludes sea/air-based reactors)	Liability
<b>Convention on Nuclear Safety (CNS)</b>	1994 (1996)	N/A	No (Only land-based NPPs)	Safety
<b>Joint Convention on the Safety of Spent Fuel Management and Radioactive Waste Management</b>	1997 (2001)	N/A	Potentially (requires additional agreements)	Safety
<b>International Convention for the Safety of Life at Sea (SOLAS)</b>	1974 (1980)	Regular updates	Indirectly, as applies to ships	Safety
<b>Code of Safety for Nuclear Merchant Ships (CSNMS)</b>	1981 (Non-binding code (applies upon state adoption))	N/A	No (Excludes FNPPs & non-PWR reactors)	Safety

#### 4.2.4 Atomic Technology Licensed for Applications at Sea

Currently, the IAEA has well-established regulatory frameworks in place for the transport of nuclear material by sea. Simultaneously, the IMO's regulations regarding operation of reactors at sea have not been updated since the 1980's. The CSNMS, adopted on 19 November 1981, was based on the reactor designs used at the time for nuclear propulsion, primarily those in submarines and warships [28, 56]. However, modern FNPP designs are not covered by the code, wherefore a new regulatory framework on sea-based reactor operation is needed. Considering this, a group within the IAEA has initiated the *Atomic Technology Licensed for Applications at Sea* (ATLAS) project. ATLAS was announced on 21 August 2024 and will be launched in 2025 [28, 57].

To enable safe and secure deployment for nuclear operation at sea, the ATLAS project aims to establish a regulatory framework through cooperation between both the IAEA and the IMO [57]. Through this, an updated liability convention is expected to emerge. There was a convention that would apply to maritime nuclear installations drafted in Brussels in 1962, but it was ultimately abandoned by all states due to a lack of agreement between the United States and the Soviet Union [28].

This type of convention is also partly necessary to enable companies to insure nuclear propelled ships and FNPPs. The area an owner must insure is determined by the size of the EPZ. Ideally, the EPZ for an FNPP or nuclear propelled ship is contained within the ship's hull. Insuring areas beyond the hull is challenging since that could limit the transportability of the plant [28].

#### 4.2.5 Nuclear Energy Maritime Organization

In early 2024, the Nuclear Energy Maritime Organization (NEMO) launched. NEMO's goal is to help regulators create standards and rules for the deployment, operation and decommissioning of floating nuclear power, both power plants and nuclear propelled ships in other words. They will provide the IAEA and the IMO with guidance to bridge the gap between the nuclear and maritime industries [58].

NEMO held a workshop together with the IAEA, reactor vendors, regulatory bodies and supporting industry sectors to discuss nuclear safeguards on 21 March 2025. The main topic of discussion was that current safeguard instruments and regulations are not suitable for potential maritime uses. Reactor vendors showcased that future reactor designs, including heat-pipe micro-reactors, MSRs and VHTGs, face unique challenges and opportunities for safeguard implementation [59].

## 5 CASE-STUDY: THE FAROE ISLANDS

*The Faroe Islands, hereinafter referred to as “TFI”, are a great example where an FNPP could be very useful and beneficial. TFI aims to have 100% clean energy by 2030 and currently their electricity production based on about 45% fossil fuels sources. Since they are a small territory, their electricity demand is not that high and a single FNPP with a capacity around 30 MWe could completely replace all production from fossil fuels. Excess energy could be used to produce hydrogen which could fuel their vessels or be sold to others.*

### 5.1 Geographical position and international relations

TFI, located in the North Atlantic Ocean, are a self-governing territory under the Kingdom of Denmark. There are 17 inhabited islands, and the population is just under 55,000 (2024 estimate). Over 90% of the islands’ export value consists of fish and fish products, making TFI the biggest producer per capita in the world. Through their experience and rich seafaring culture, TFI can provide extensive knowledge and skills, along with advanced port facilities and robust transport infrastructure to the international market [60].

TFI are not part of the European Union (EU) but maintain formal relations through three separate bilateral agreements covering fisheries, trade in goods, and scientific and technological cooperation. A Memorandum of Understanding (MoU) between the EU and TFI was signed in March 2024: “*The MoU recognises shared values, principles and commitments to democracy, rule of law and respect for human rights, peace and stability, international law, and sustainable development.*” Furthermore, TFI and the EU “[...] welcome the deepening and steady increase of their long-standing cooperation ties” [61]. Although Denmark is a member of the UN, TFI are not. Consequently, TFI are not a member of the IAEA nor the IMO. However, they are associate members of three UN agencies, including the IMO. They have adopted all IMO conventions despite not holding full membership [62].

Denmark currently has no operating nuclear facilities, aside from a nuclear research laboratory, following the closure of its three research reactors and fuel fabrication facilities in the early 2000s. Greenland, another self-governing territory under Denmark, has previously engaged in mining and export of nuclear material, placing it under the regulatory framework of the IAEA and the NPT. Notably, it is Denmark, rather than Greenland itself, that is a member of the IAEA, with both governments having reached a mutual agreement on the application of international obligations [63].

### 5.2 The Faroe Islands current situation and goals

In 2024, the total electricity production forecast was to reach 481.8 GWh, according to TFI’s electricity provider “Sev”. This is an increase of about 5% from the previous year, which approximately reflects the annual growth since 2019. This growth stems from increased consumption as well as improvements in infrastructure and grid capacity. The energy mix is divided between fossil fuels and renewables, with green energy sources accounting for 55% of total production and thermal (oil-based) energy comprising the remaining 45%. The green energy segment is dominated by wind power (31.6%), followed by hydropower (21.8%), and a small but growing contribution from biogas, tidal and solar (1.6%). The oil-based energy share remains significant due to lower output from hydro and wind than expected, caused by renovations and weather variability [64]. The numbers above reflect the total amount of energy

supplied to the grid in 2024. In Figure 7, the power output from the different energy sources on a monthly basis is presented, showing the peak production depending on the time of year [65].

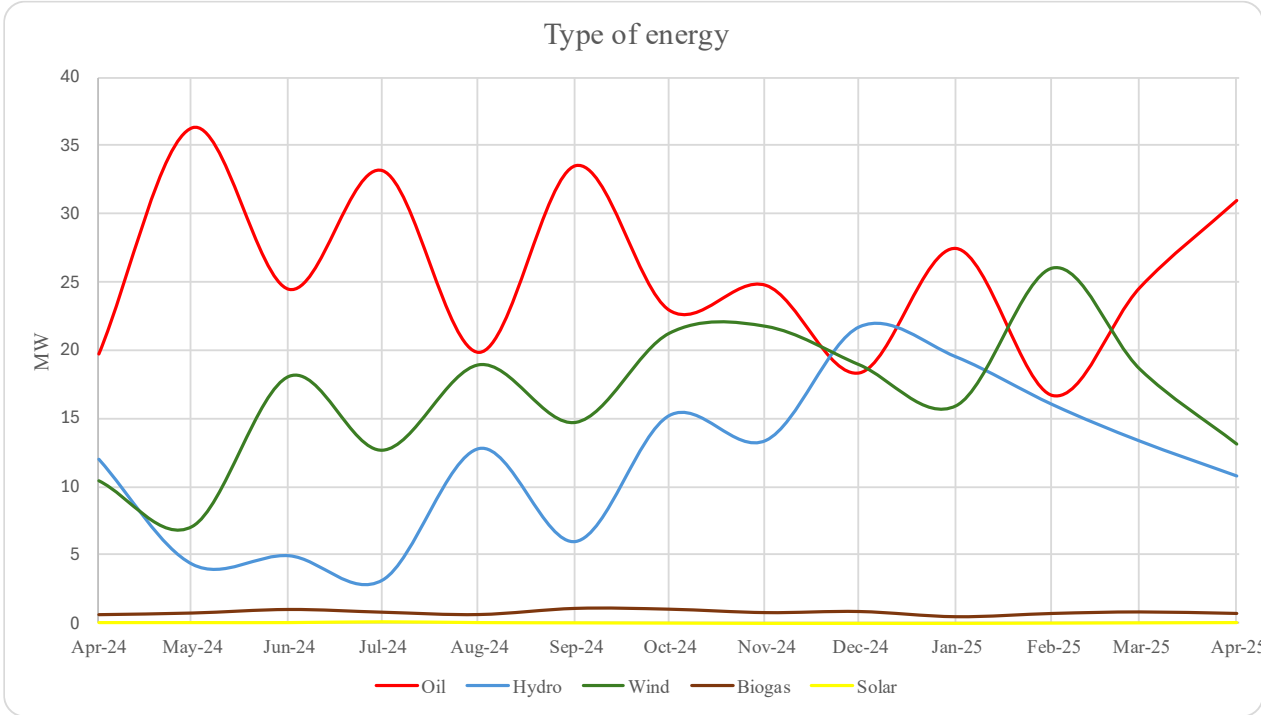


Figure 7 Graph showing power output from different energy sources [65].

The power grid on TFI is divided into two sections, the main northern area and the southern island, which increases the demand for additional energy sources. The type and locations of the power stations are illustrated in Figure 8, and those highlighted with stars are the three largest facilities, which supplies the majority of TFI’s electricity.

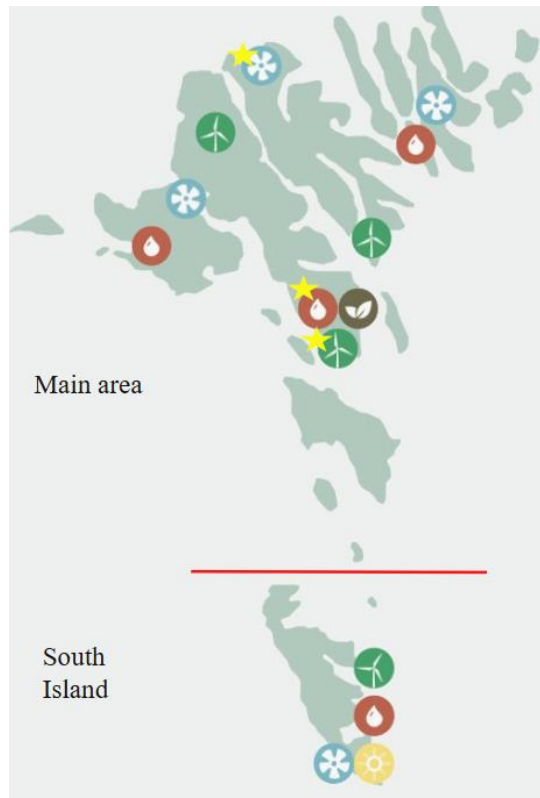


Figure 8 A map of The Faroe Islands showing where the different energy sources are and the red line divides the two different grids, which are not connected [65].

The consequence of having two power grids is that it creates two different power demands which cannot solely be solved by one power plant. In Figure 9, the total and the two different power consumptions are displayed for the main area which has the higher power consumption, and the South Island which has a significantly lower consumption. The main area consumes around 45-60 MW, depending on the time of year, while the South Island only consumes between 3-6 MW during the same period [65].

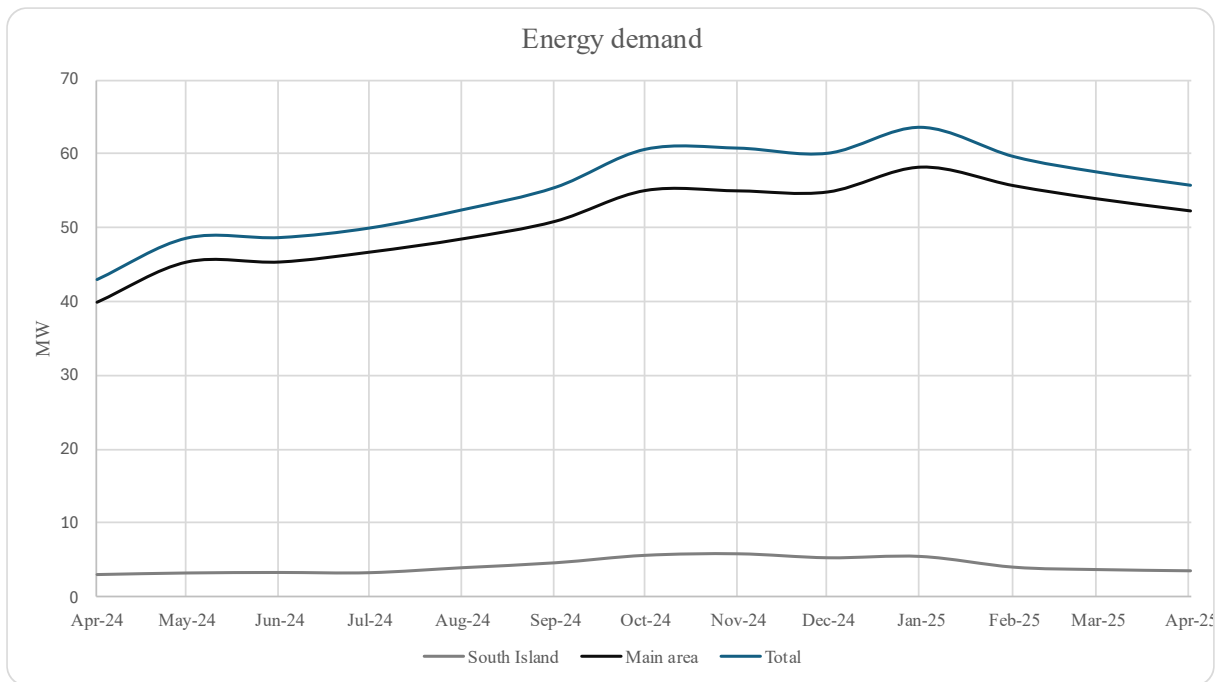


Figure 9 Graph over effect demand of the two grids [65].

### 5.2.1 Renewable energy ambitions

TFI and Sev have set an ambitious goal to achieve 100% renewable electricity production by 2030, known as the “100by2030” strategy. This target is closely monitored by financing institutions, as green energy quotas are tied to loan conditions. For 2024, Sev was required to reach a 57% green share but is forecast to fall short by 2 percentage points. Despite this setback, Sev continues to expand its renewable capacity. Key initiatives include upgrades to wind farms in Neshaga and Porkeri, new solar projects in Sumba, and tidal developments in Vestmanna. In addition, the recent deployment of battery stations and synchronous compensators, such as the major installation in Sund, has strengthened Sev’s ability to stabilize the grid and absorb more intermittent renewable power [64].

## 5.3 Nuclear power options

An alternative solution to what Sev has presented to reach 100by2030 could be to achieve carbon free energy by usage of one or multiple FNPPs. By using nuclear power, they would not become 100% renewable (according to the goal of 100by2030), but they would not be relying on fossil fuels for their power production. Depending on whether the goal is to just cover the electricity demand or use excess power to, for example, produce hydrogen, ammonia or desalination of sea water, the options could be different.

Two potential FNPP options are considered for integration into TFI’s power grid in this study. The first is based on a sister vessel to Akademik Lomonosov, currently the only operational FNPP. The second option is a conceptual FNPP being developed by the Danish company Saltfoss, which has a larger capacity but is still in the design phase and has not been deployed yet.

Both scenarios involve supplying electricity to the whole territory of TFI by constructing a submarine cable to connect the main and southern grids, creating one unified power grid. The baseline capacity that needs to be replaced has been estimated at 30 MW. This is based on production data indicating an average required output of 25 MW [64]. However, as shown in

Figure 7, monthly peak consumption has exceeded 35 MW at times. To account for this variability, a conservative annual average replacement demand of 30 MW is used. In periods of higher consumption, supplemental energy may be provided by an ammonia-fueled power plant, using ammonia produced locally as a form of energy storage.

To calculate an estimate on the production of ammonia, Equation 1 was used. The equation is based on the power demand of the SOEC technology introduced in section 3.4.1. In the equation,  $p$  is the power capacity of the FNPP and  $x$  is the power supplied to the power grid. The excess is the power that can be used for ammonia production.

$$\frac{(p - x)}{108,69} \times 330 = \text{tons/day} \quad (1)$$

Based on historical trends of approximately 5% annual growth in power consumption [64], Equation 2 was used to estimate the time over which the FNPP would be capable of covering the increasing power demand on its own.

$$(60 + x) = 1,05^y \times 60 \Rightarrow y = \frac{\log \frac{(60 + x)}{60}}{\log 1,05} = \text{years} \quad (2)$$

### 5.3.1 Option 1

Option one is to deploy a sister vessel to Akademik Lomonosov, which could deliver 70 MWe to the power grid. After meeting the 30 MWe required to replace oil-based electricity generation, a surplus of 40 MWe remains. This excess energy could be directed toward the production of ammonia, shown in Equation 1, serving as an energy storage medium or as a clean fuel alternative for ships.

In addition to enabling ammonia production, this surplus could provide a buffer for future increases in electricity consumption. The added capacity from this FNPP would be sufficient to meet demand for approximately ten years, according to Equation 2. This makes it a viable medium-term solution, offering both decarbonization benefits and a degree of futureproofing for the Faroe Islands' power system, illustrated in Figure 10.

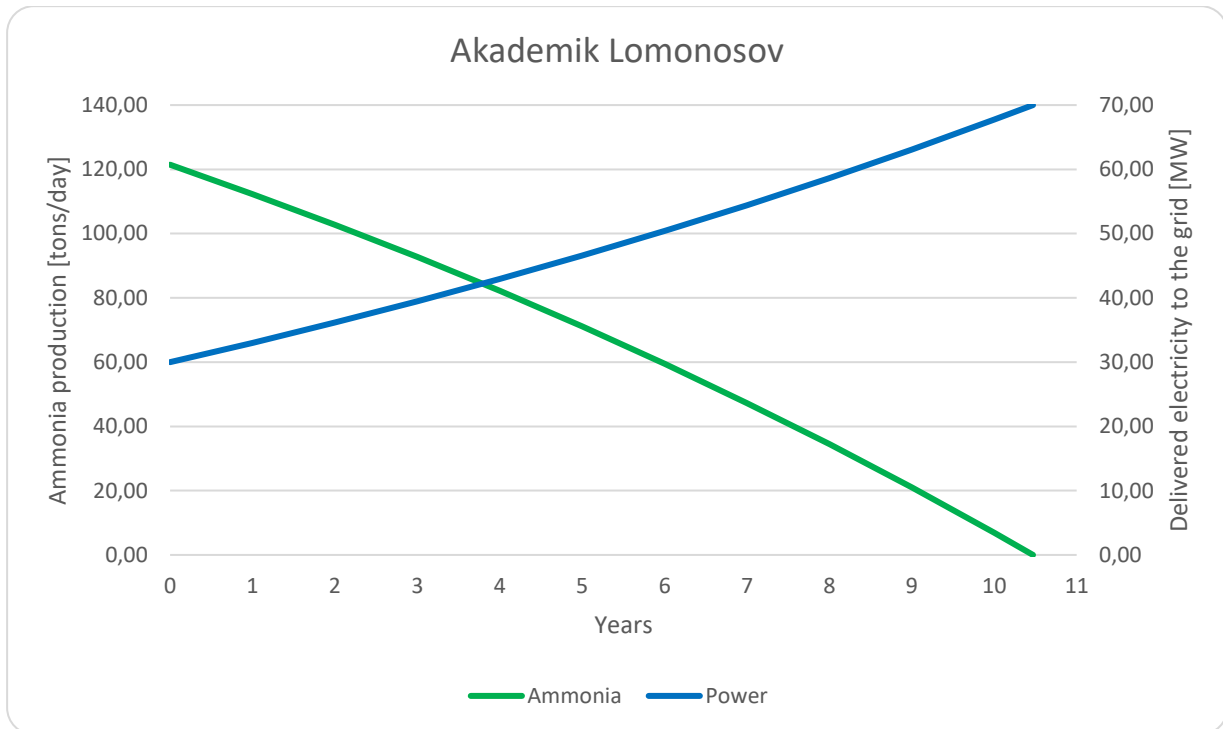


Figure 10 Graph showing the change of ammonia production and power delivered to the grid from option 1.

### 5.3.2 Option 2

The second option is Saltfoss' FNPP barge fitted with their CMSR, which is designed to generate 200 MWe. After meeting the 30 MWe needed to replace the current oil-based generation, this leaves a substantial surplus of 170 MWe. This additional capacity allows for significant production of ammonia according to Equation 1, providing a valuable resource for energy storage or use as a clean fuel.

In terms of future energy needs, the higher output also means that Saltfoss' FNPP could meet TFI's projected electricity consumption growth for a long period according to Equation 2. This solution would cover rising power consumption for more than 27.5 years. This is 3.5 years longer than the expected 24-year operational lifespan of the FNPP, which adds an additional margin for unforeseen increases in electricity consumption. See Figure 11 to see the change in production of ammonia with a higher power consumption.

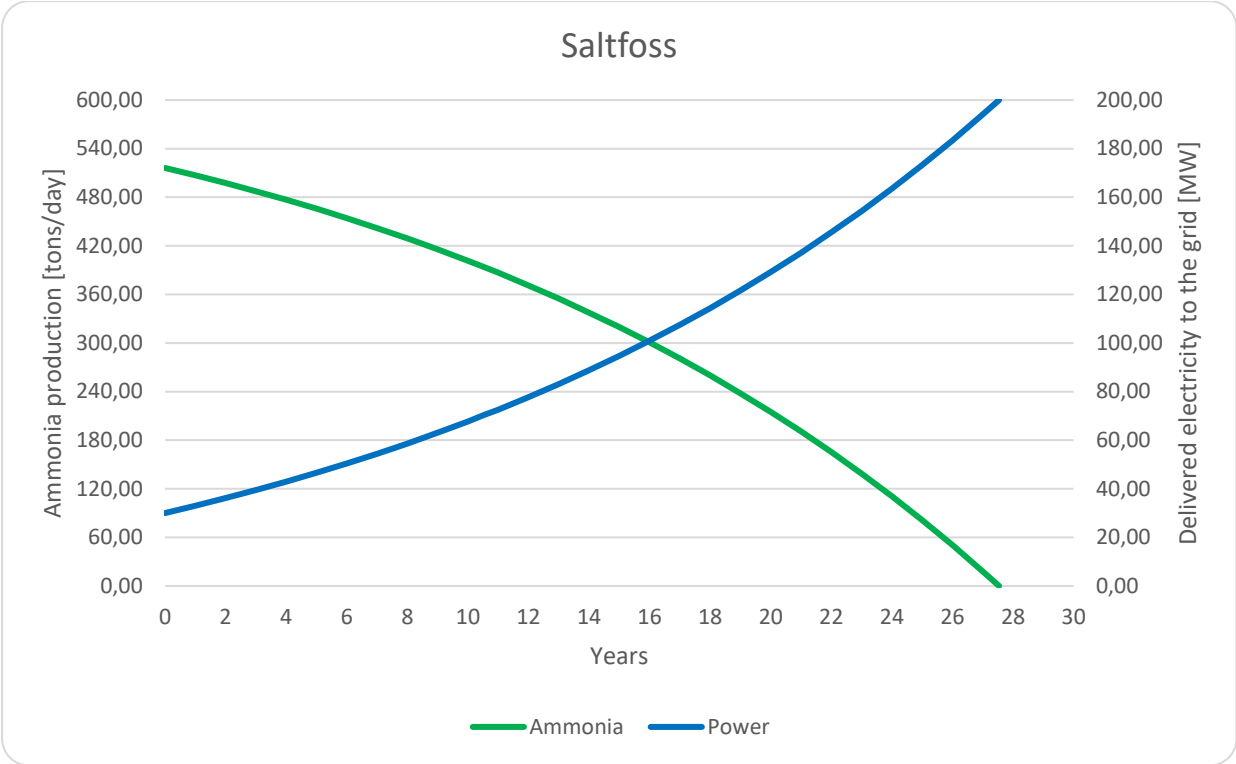


Figure 11 Graph showing the change of ammonia production and power delivered to the grid from option 2.

## 6 RESULTS AND DISCUSSION

The growing interest in transforming the energy sector stems from increasing global environmental awareness, with nuclear power emerging as a promising alternative to fossil fuels in the pursuit of Net Zero by 2050. In this context, there is rising interest in the civil use of maritime nuclear power for electricity generation and alternative applications such as hydrogen production. While nuclear propulsion for maritime vessels has gained a renewed interest, it has not been covered in this thesis.

Currently only one FNPP is in operation, Russia's Akademik Lomonosov, which supplies electricity to the Chukotka region. However, given its relatively recent deployment in 2020, the long-term impacts of FNPPs remain unknown. While several companies have expressed interest in developing FNPPs, many of these projects are still in early stages and detailed information about their implementation and operational plans is limited. Most available material focuses on high-level concepts like the intended power output, reactor type and general construction plans, often highlighting the use of existing shipyards. However, information about the full lifecycle, particularly what happens before commissioning and after decommissioning is scarce. Some companies have stated that decommissioned FNPPs would be towed back to a central shipyard for dismantling, which suggests at least some consideration for end-of-life management. Yet, details regarding the decommissioning process, radioactive waste handling and final disposal are often vague or missing entirely. It also remains unclear whether it is the manufacturing company or the host state who will bear responsibility for nuclear waste. This presents a major regulatory and logistical challenge that must be addressed before FNPPs can be widely accepted or deployed.

### 6.1 Design and possibilities

Barges and offshore rigs are the two main types of platforms that have been considered for FNPPs, each targeting different locations and differing in power output. Most FNPP concepts, along with the only one currently in operation, are barge-type designs, whose construction closely resembles that of conventional large vessels. The alternative is a larger platform design, similar to modern offshore oil rigs. The main differences between these two types lie in their size and placement: offshore rigs are predictably larger, capable of housing full-scale reactors, while barges typically accommodate one or more SMRs. Additionally, barges are generally stationed near the shoreline, whereas offshore rigs are intended to be located approximately 20 kilometers offshore.

The ability to deploy FNPPs close to the shore without occupying large amounts of coastal land, unlike traditional nuclear power plants, offers a valuable solution for delivering energy to coastal populations. Since many major cities are located near coastlines, FNPPs could enable localized power production closer to where the demand is highest. Offshore nuclear power plants can reduce the size of the EPZ while still maintaining proximity to urban centers. Some FNPP concepts even include onboard substations, allowing the barge to connect directly to the grid with minimal onshore infrastructure. This makes FNPPs ideal for covering temporary power needs, such as during large construction projects, industrial expansions or while building new permanent power plants. In such cases, FNPPs can be deployed as flexible, mobile power sources, for example while an aging power plant is being decommissioned before a replacement is operational. This mobility also makes FNPPs a viable option for smaller island nations or remote regions with limited or unstable electricity infrastructure. In these locations, FNPPs

can serve as a primary power provider and be replaced or rotated as needed, minimizing environmental impact and preserving the natural character of sensitive areas.

Alternatives to electricity production to the grid are hydrogen and ammonium production or electricity generation for desalination purposes. Hydrogen can be a way to store energy for later use, while ammonium can be used both as an alternative fuel for boats and in fertilizer production. Additionally, the ability to power desalination plants makes FNPPs suitable for regions where freshwater availability is limited. Since an FNPP brings most of its own infrastructure, it can operate independently of local utilities, making it ideal for deployment in remote or underdeveloped areas.

## **6.2 Challenges and areas for improvement**

Political instability and international tensions can significantly hinder the development and deployment of FNPPs. Regulatory approval, cross-border collaboration and public acceptance are tied to national policies and geopolitical relations. Sanctions, shifts in government priorities or conflicts in coastal regions could delay projects, restrict access to critical technologies or raise concerns about nuclear safety and security. An example of this is the sanctions imposed on Russia after the escalation of the war in Ukraine in 2022. These measures have placed the only country currently operating an FNPP in a position where international collaboration and business opportunities are severely limited or effectively blocked. To ensure continued international cooperation with Russia on FNPP development, alternative frameworks or multilateral agreements may be needed. However, even with such mechanisms in place, geopolitical developments and public opinion could still jeopardize cooperation at any time.

An additional source of uncertainty regarding FNPPs is the proposed use of reactor types that are not yet in widespread commercial use. This raises questions about the feasibility of large-scale production of reactor components and fuel, and whether existing infrastructure can support industrial scale deployment. Furthermore, the use of less established technologies introduces additional complexity in terms of decommissioning and long-term waste management. The associated supply chains for these technologies may also be tied to geopolitical factors, making both the scalability and sourcing of critical components subjected to political influence and international relations.

Current Regulatory frameworks and standards are ill fitted for FNPP application in most cases. They are either outdated or completely lacking. International organizations, such as the IAEA or the IMO, currently seem to lack necessary cooperation to accommodate operation and transportation of energy-producing power plants. There are organizations, like NEMO and subdivisions of organizations, like ATLAS, that are currently in the beginning of the process of creating or amending regulations and standards relating to FNPPs, but much work is left to be done.

## **6.3 Operation, decommissioning and waste management**

Some companies developing FNPPs plan to either utilize existing shipyards or construct new ones, aiming to establish a factory-like environment that streamlines production. As mentioned, if the entire barge is modular, streamlined production could reduce capital costs compared to traditional land-based NPPs, since it eliminates the need for extensive site preparation and customized construction. However, the host nation may still need to invest in port facilities and supporting infrastructure to accommodate the FNPP.

Based on the findings of this study, no companies currently have plans to integrate propulsion with electricity production. As a result, once construction of the barge is complete, the FNPP will be towed from the shipyard to the host destination. Towing the FNPP through the territories of the host and supplier states is unlikely to present significant regulatory challenges, especially if there is no nuclear fuel in the reactor. However, passage through third-party states may become problematic if nations either withhold their approval or require new regulatory frameworks. Establishing such regulations can be a time-consuming process, potentially delaying the FNPP's transit through their territory.

As mentioned in section 4.2.4, the IAEA's framework on nuclear security during transport and land-based operation of nuclear material is well-established. The CPPNM in its current form does not prohibit a business model where a state other than the host state or a national company manages operation, decommissioning or waste handling. However, the framework is unclear on how a nuclear reactor loaded with fuel can be classified, which may cause a problem. The study identified three options in this matter:

- 1) Transfer the FNPP with fuel on the barge – classified as nuclear material transport
- 2) Transfer the FNPP and fuel separately
- 3) Transfer the FNPP with fuel in the reactor – classified as an operating nuclear reactor

The first option suggests that the reactor vessel, or any of the containment barriers in Figure 6, could serve as a compliant transport vessel. This option would be comparable to transporting nuclear fuel assemblies, for which the regulatory frameworks are well-established by the IAEA and the IMO. Similarly, transporting the fuel separately, as in option two, would not raise any regulatory concerns. However, this option introduces other potential challenges. For example, if the FNPP encounters unforeseen issues during fuel loading or testing, it may need to be returned to the shipyard, resulting in delays and additional costs.

If the FNPP were to be classified as an operating reactor, as in option three, appropriate regulatory frameworks are currently lacking. Alternatively, if this classification would suggest that the FNPP is comparable to a nuclear-propelled vessel, a relevant framework does exist through the CSNMS. It is, however, outdated and not compatible with modern reactor designs, particularly those designed for commercial electricity production. In any case, the framework needs to be amended.

There are two main approaches to how an FNPP could be commissioned, operated, decommissioned and have its waste managed, as presented in [66]. Either the host state assumes responsibility for all aspects except constructing the FNPP, or they purchase a full-service package in which the supplier manages operation, decommissioning and waste handling. A full-service package is likely the more attractive option for states that lack current or historical experience from nuclear power. For states with nuclear experience that already have, or plans to build, facilities for decommissioning and waste storage, it is likely more cost-effective and regulatory straightforward to avoid purchasing a full-service package. However, this assumption would need to be confirmed through detailed, case-by-case analyses.

The fuel cycle and maintenance schedule will depend on the type of reactor used. Since most FNPP designs feature PWRs, their timelines will be similar to those used today. For example, Russia has used a fuel leasing concept to take back spent nuclear fuel from NPPs they have built in other states for reprocessing, recycling and later disposal. In the context of FNPPs, this

means that the supplier state can take back the entire FNPP for decommissioning and waste storage. A possible solution to manage spent fuel before the FNPP is decommissioned would be an intermediate storage unit integrated in the barge or platform.

## **6.4 The 3Ss – possibilities and issues**

Several factors must be considered when assessing the safety, security and safeguards of FNPPs, including reactor type and design, platform configuration, placement, accessibility and more. Many FNPP designs incorporate passively safe reactors, which theoretically enhance overall plant safety. However, in the event of a radiological release significant concerns remain, particularly because FNPPs are expected to be located near populated coastal areas. This placement considerably shortens the available evacuation time compared to traditional nuclear facilities, which are typically sited in less densely populated areas. Current international regulation does not explicitly address marine-based reactor deployments, creating ambiguity in defining and implementing EPZs for FNPPs. Effective EPZ implementation requires coordination between nuclear regulators, maritime authorities and emergency management bodies.

Experience with the civilian operation of water-based nuclear reactors is limited, especially when compared to land-based installations. Ensuring the non-proliferation of nuclear material and maintaining high levels of security will demand considerable investment in the development and deployment of specialized technologies and protocols.

The transportable nature of FNPPs introduces added complexity across all three Ss. While FNPPs are generally expected to operate while stationary in a port, the possibility of relocation during their service life raises concerns about how to maintain consistent operational standards in new environments. Unlike land-based reactors, where sites can be custom designed to meet the requirements, FNPPs will often dock in pre-existing ports or near already developed areas. These sites may not be optimized for nuclear operations, requiring the FNPP to adapt to varying infrastructure conditions. This challenge also applies during the initial installation. Standardized FNPPs may face complications due to differing local conditions, making it harder to streamline deployment and ensure consistent implementation of the 3Ss across all locations.

## **6.5 Case-study findings**

The results of the case study highlight the potential to replace the current fossil fuel-based energy sources on TFI with an FNPP, while also enabling the production of hydrogen and ammonia using surplus electricity. The hydrogen can be used to power hydrogen-based energy plants, allowing energy storage that can be dispatched when needed.

Two FNPP deployment options were considered. Option 1, based on a sister vessel to Akademik Lomonosov, would provide enough capacity to meet projected demand growth for approximately 10 years. Option 2, based on the Saltfoss CMSR concept would exceed that period and reach 27 years. During this time, any surplus electricity that is not consumed by the growing power demand would be used for ammonia production, reaching a peak of 120 tons/day for Option 1 and 516 tons/day for Option 2. As the power demand increases over time, the surplus energy available for hydrogen and ammonia production will decrease, eventually reaching zero when power production matches the demand. Despite being temporary, the installation of hydrogen production facilities offers long-term benefits, such as providing a backup to oil-based power plants and creating a domestic alternative fuel source for TFI's maritime fleet.

Overall, deploying an FNPP would not only support TFI's transition away from fossil fuels but also provide a buffer period for the development and scaling of renewable energy technologies. Additionally, investing in hydrogen and ammonia infrastructure enables effective energy storage, helping to offset one of the primary limitations of weather-dependent renewable sources and contributing to a more reliable and resilient energy grid.

While the use of a FNPP could effectively meet the TFI's energy demand, it would not align with their stated goal of achieving 100% renewable energy by 2030 (100by2030). However, it would allow them to achieve carbon-free electricity production. Given that fossil fuels still make up 45% of their energy production, the feasibility of reaching the 100by2030 target seems unlikely as there are only five years remaining. Although an FNPP does not qualify as a renewable source, its integration alongside wind, hydro and solar significantly enhances the overall sustainability of the energy system. This is particularly important because wind, hydro and solar generation are highly weather-dependent, meanwhile nuclear power provides consistent and reliable baseload power.

Considering their lack of nuclear experience, the most fitting alternative for TFI is to purchase a full-service package that includes operation, decommissioning and waste managing of a FNPP. In doing so, they would significantly reduce their need for establishing relevant education and on-land facilities for decommissioning and waste storage. They would still need to establish their own regulatory frameworks in some capacity, but seeing as Denmark has nuclear experience, much of theirs can probably be adopted. Furthermore, TFI will have to negotiate with Denmark to be included in their IAEA- and IMO-memberships.

## 7 CONCLUSION

The potential of maritime nuclear power has been acknowledged globally, mainly for power generation with FNPPs and for propulsion of vessels such as icebreakers and cargo ships, but very few are currently in active use. Although some companies have presented FNPP concepts, showing their interest in developing this type of power plant, only one FNPP is operating today.

This study identifies three key advantages of FNPPs over land-based large-scale NPPs. First, FNPPs can be fully modular, meaning the entire platform, including the reactor, can be constructed in a shipyard. This allows for streamlined production that reduces construction time and costs compared to large-scale reactors. Second, FNPPs offer improved accessibility to remote or hard-to-reach areas, where they can supply electricity, desalination, hydrogen and so on more easily than conventional infrastructure. Third, FNPPs can support nuclear energy adoption in countries without existing nuclear programs, especially if offered with full-service packages that simplify deployment by reducing the need for local infrastructure, workforce training and site preparation. Keeping in mind the need for a national regulator still exists.

However, these advantages could all be achieved with a land based SMR, there are still some unique aspects of FNPPs. Firstly, there is a reduced need for invasive procedures on the ground on land. Deploying power plants in water only requires a port and infrastructure to connect to the grid. Secondly, FNPPs represent an additional opportunity to install nuclear power plants in places where there is no space or geological possibilities to place a plant on land.

Several challenging aspects have been identified in this thesis. One issue is the limited availability of knowledge and data on FNPPs for civilian use, as much of the existing expertise originates from military maritime nuclear applications. Critical considerations include how marine conditions, such as wave impact and seawater exposure, affect system performance and reliability, as well as the development of effective emergency response strategies. Natural disasters, such as tsunamis and earthquakes, also impose high requirements on the structural integrity and resilience of FNPPs. Moreover, scenarios involving accidents raise questions regarding cleanup processes, evacuation planning and methods for containing the spread of radionuclides, especially given the potential proximity to densely populated coastal areas. These factors underline the need for continued research, robust design strategies and clearly defined safety protocols to ensure responsible deployment of FNPPs.

Based on the findings of this study, PWRs appear to be the most common choice in FNPP designs under development, followed by MSR. A notable distinction is that MSRs tend to be favored by companies aiming to export FNPPs internationally, whereas PWRs are more often intended for domestic use. This may be because MSRs are being designed with inherent safety features and simplified systems, making them more attractive to international buyers. Furthermore, since regulatory frameworks for MSRs are still lacking, along with technical solutions for both the front- and backend of the fuel cycle, there is an opportunity to develop these technologies in parallel with regulatory progress. In contrast, PWRs have a more mature design status, enabling quicker deployment. Countries currently exploring FNPPs also tend to have prior nuclear experience, which may contribute to the preference for reactors similar to what they currently have.

This study has identified two main options for how an FNPP could be operated, decommissioned and have its waste managed. The first is the traditional model, in which the host state has full responsibility for all aspects. The second involves purchasing a full-service

package from a supplier, where these responsibilities are included. While this model can take many forms through various agreements and arrangements, the core idea is to simplify the process for the customer by minimizing the need for them to establish their own facilities and education programs and so on. While no existing regulations explicitly prohibit this model, there is currently an absence of a defined regulatory framework to support or guide its implementation. To implement this model, the host and supplier state, along with the IAEA and the IMO, need to reach coordinated agreements. The first option is generally more viable for countries with prior nuclear experience, while the second is better suited to those without established nuclear infrastructure.

Regardless of which operational model is pursued, both approaches must navigate a regulatory landscape that is still evolving. The conventions and standards reviewed in this study represent only a fraction of the IAEA's and IMO's current publications. The selected publications provide a foundational understanding of current expectations of conventions and standards relating to nuclear safety, security, safeguards and liability. At present, most existing regulatory frameworks and standards from both the IAEA and IMO are not adapted to accommodate the deployment of FNPPs. Significant work remains, and initiatives such as ATLAS and NEMO have only recently begun efforts to revise and expand the relevant conventions and standards.

Although it is technically possible to deploy FNPPs under current conditions, doing so would require the supplier and host states, as well as all involved third-party states, to establish specific international agreements or rely on national legislation. Considering this, it is in the shared interest of international regulatory bodies, national governments and industry stakeholders to develop harmonized international frameworks. Doing so would simplify, or at least clarify, the legal aspects surrounding FNPP deployment, operation and transportation.

## **7.1 Further studies**

As this study takes a broad approach to the topic of FNPPs, several areas are unexplored or only briefly touched upon. Furthermore, some specific questions have not yet been fully addressed in international discourse, highlighting the need for continued research.

One such area is the architectural design and visual integration of FNPPs. Since barge-type FNPPs are likely to be docked in ports near populated areas, their appearance may influence public acceptance. Future studies could therefore focus on how FNPPs can be aesthetically adapted to different environments and landscapes to minimize visual intrusion and increase local support.

Another important topic is the overall safety assessment of FNPPs, with particular attention to the risks of radiological release into the marine environment or the potential for barge capsizing. These concerns warrant careful analysis, drawing lessons from historical nuclear submarine accidents.

In terms of reactor technology, comparative studies between MSR and other non-WCRs could clarify their compatibility with offshore use, particularly regarding safety, cooling and regulatory requirements. Additionally, as FNPP technologies mature it is important to monitor developments in their Technology Readiness Level (TRL) as well as progress in regulatory frameworks and standardization efforts. Keeping such information up to date will support both feasibility assessments and public communication.

One important area not addressed in this report is the nuclear fuel cycle and its associated frontend and backend activities. While the focus has been on reactor technologies and deployment strategies, a comprehensive evaluation of FNPPs should also consider the broader implications of fuel fabrication, transportation, interim storage, final disposal and potential reprocessing or recycling. Each of these stages presents its own technical, logistical and regulatory challenges. Therefore, a recommended continuation of this work would involve an in-depth analysis of the entire nuclear fuel cycle, including an assessment of supply chain reliability.

Further case studies focused on actual implementation scenarios would be valuable, especially those that consider national laws and site-specific suitability. Although deployment in places like the Faroe Islands may be unlikely in the near term, deep dives into local legal contexts can still offer critical insights for more realistic applications.

Economic analysis also remains a key area for further exploration. A comparison between land-based LSRs, land-based SMRs and FNPPs would help clarify trade-offs. While FNPPs offer advantages such as mobility and service-based deployment, they also carry the cost of newer, less-established technology. In contrast, land-based reactors benefit from established infrastructure, but may require additional facilities.

Lastly, it would be relevant to examine the feasibility of deploying FNPPs in large inland water bodies, such as lakes, since not all cities are located near the sea. This could broaden the applicability of FNPPs as a flexible power solution for various geographic contexts.

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