10-31-2022

The role of generation IV nuclear reactors in decarbonising international shipping: a multi-criteria decision making (MCDM) framework for matching potential decarbonisation pathways to different ship types and size

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Recommended Citation

Kunze, Claudianus David, "The role of generation IV nuclear reactors in decarbonising international shipping: a multi-criteria decision making (MCDM) framework for matching potential decarbonisation pathways to different ship types and size" (2022). *World Maritime University Dissertations*. 2071.
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WORLD MARITIME UNIVERSITY
Malmö, Sweden

THE ROLE OF GENERATION IV NUCLEAR REACTORS IN DECARBONISING INTERNATIONAL SHIPPING

A Multi-Criteria Decision Making (MCDM) framework for matching potential decarbonisation pathways to different ship types and sizes

By

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A dissertation submitted to the World Maritime University in partial
fulfilment of the requirements for the award of the degree of

MASTER OF SCIENCE
in
MARITIME AFFARS

(MARITIME ENERGY MANAGEMENT)

2022

Declaration

I certify that all the material in this dissertation that is not my own work has been identified, and that no material is included for which a degree has previously been conferred on me.

The contents of this dissertation reflect my own personal views, and are not necessarily endorsed by the University.

(Signature):

(Date): **20-09-2022**

Supervised by: **Professor Dr. Aykut Ölçer**

Supervisor's affiliation**: Head of Maritime Energy Management Specialization**

Acknowledgements

First and foremost, I would like to extend my sincere gratitude to the Government of Norway through the Norwegian Development Agency (NORAD) for sponsoring my Master’s Degree at the World Maritime University (WMU), I will forever be indebted to the Government of Norway for offering me this rare opportunity. Secondly, I would like to thank my dissertation supervisor, Professor Dr. Aykut Ölçer on behalf of the Maritime Energy Management Specialisation, his invaluable insights and guidance has been instrumental in making this study a success. Similarly, I would like to extend my gratitude to Professor Dr. Jan Emblemsvåg from the Department of Ocean Operations and Civil Engineering at the Norwegian University of Science and Technology (NTNU) for his contribution to the study. Lastly, I would like to thank my family for their emotional support and encouragement.

Abstract

Title of Dissertation: The Role of Generation IV Nuclear Reactors in Decarbonising International Shipping: A MCDM framework for matching potential decarbonisation pathways to different ship types and sizes

Degree: Master of Science

According to the United Nations Economic Commission for Europe (UNECE), Nuclear Energy will eclipse fossil fuels as the biggest source of energy by 2050 under supportive policy intervention. The new generation of nuclear reactors (Generation IV) whose design philosophy is rooted in sustainability offers great opportunity for "hard to abate" sectors particularly International Shipping now that recent findings claim only a maximum of 14% overall savings in fuel demand can be achieved through deployment of technical and operational energy efficiency measures.

This study makes use of the Multi-Criteria Decision Making (MCDM) model in matching two decarbonisation pathways to three vessel classes, containerships, bulk carriers and tankers of small, medium and large sizes that are in essence based on electrification. Pathway A is referred to as direct electrification by using Generation IV shipboard nuclear reactors. 1While Pathway B is referred to as indirect electrification of seagoing vessels achieved through feeding shipboard PEM-fuel cells by using electro-ammonia as nuclear energy carrier generated through Nuclear Power-to-X arrangement. The results show that Pathway A is a suitable decarbonisation option for medium and large vessels with the decarbonisation potential of 23%, while on the other hand, Pathway B is a suitable for small vessels with the decarbonisation potential of 15% regardless of ship type under study. This study concludes that with proper policy intervention the combination of Generation IV nuclear Power, Electro-Fuels and Fuel cells holds potential as a candidate for the 4th propulsion revolution (the new propulsion S-Curve).

KEYWORDS: Electrification, e-Fuels, Generation IV Nuclear Reactors, MCDM, Power-to-X

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Abbreviations

CAPEX	Capital Expenditure
DNV	Det Norske Veritas
DOE	Department of Energy
EEDI	Energy Efficiency Design Index
EPZ	Emergency Planning Zone
FMADM	Fuzzy Multiple Attribute Decision Making
FMAGDM	Fuzzy Multiple Attribute Group Decision Making
FNPP	Floating Nuclear Power Plant
GFR	Gas-cooled Fast Reactor
GHG	Green House Gases
GIF	Generation IV International Forum
IAEA	International Atomic Energy Agency
IC	Internal Combustion
IFO 380	Intermediate Fuel Oil 380
IGC	International Gas Carrier Code
IGF	International Code of Safety for Ship using Gases or Other Low-flashpoint
IMCO	Inter-Governmental Maritime Consultative Organisation
IMO	International Maritime Organisation
IPCC	Intergovernmental Panel on Climate Change
LCOE	Levelised Cost of Electricity
LFR	Lead-cooled Fast Reactor
LR	Lloyd's Register
MARPOL	International Convention for Prevention of Pollution from Ships
MBM	Market Based Measures
MCDM	Multi-Criteria Decision Making
MCR	Maximum Continuous Rating
MEPC	Marine Environment Protection Committee
MeV	Megaelectron-volt
MSRE	Molten Salt Reactor Experiment
NPT	Non-Proliferation Treaty
NPV	Net Present Value
NS	Nuclear Ship

O&M	Operation and Maintenance
OECD	Organisation for Economic Co-operation and Development
O-KPI	Operational Key Performance Indicator
ORNL	Oak Ridge National Laboratory
PEM	Proton Exchange Membrane
PEMFC	Proton Exchange Membrane Fuel Cell
PtX	Power-to-X
PWR	Pressurised Water Reactor
RCP	Representative Concentration Pathway
REG	Regulatory Complexity
SCWR	Supercritical Water-cooled Reactor
SEEMP	Ship Energy Efficiency Management Plan
SFOC	Specific Fuel Oil Consumption
SFR	Sodium-cooled Fast Reactor
SMR	Small Modular Reactor
SOFC	Solid Oxide Fuel Cell
SOLAS	International Convention for the Safety of Life at Sea
SSP	Shared Socio-economic Pathway
TOPSIS	Technique for Order Preference by Similarity to the Ideal Solution
TRL	Technological Readiness Level
TRU	Trans-uranium
UNECE	United Nations Economic Commission for Europe
UNSDG	United Nations Sustainable Development Goals
VHTR	Very High Temperature Reactor
WACC	Weighted Average Cost of Capital

Chapter 1-Introduction

1.1 Background information

It has been revealed in the most recent report from the Intergovernmental Panel on Climate Change (IPCC) that meeting both the 1.5°C (2.7°F) and 2°C (3.6°F) global temperature targets set by the Paris Agreement is now highly unlikely. This is because new findings estimate that achieving the agreed temperature targets requires emission reduction to peak before 2025 at the latest followed by emission reduction by 43% by 2030 (IPCC, 2022). As a custodian of emission reduction from International shipping, the IMO has put in place a strategy for reduction of carbon intensity per transport work by 40% by 2030 while pursuing efforts towards 70% which corresponds to 50% emission reduction as compared to the level of 2008 by 2050 through a combination of short term, medium term and long term measures (J. Faber et al., 2020). However, the ambitions set by the Initial IMO GHG Strategy have been found to be inconsistent with those of the Paris Agreement to an extent that, emission reduction by up to 50% by 2030 and 100% by 2040 relative to 2008 needs to be pursued in order for the maritime transport sector to be in line with the Paris agreement (Comer, 2021). Again, this is also highly unlikely in the existing business as usual scenario, therefore turning things around requires deliberate effort to make much bigger steps than anticipated now or never.

On the other note, despite disruptions that have happened in the past as well as those that are bound to happen, statistics show that international shipping will continue to grow in volume from the current contribution of 80% of global trade (UNCTAD, 2021). Projections from IPCC and OECD suggest that the growth of international shipping by volume will heavily be influenced by the projected growth in GDP (IMO, 2020). In that regard, based on the business as usual scenario as per the IPCC-SSP2_RCP2.6_L in the Fourth IMO GHG Study, emissions from international shipping are expected to grow from 1,000 Mt CO_2 in 2018 to 1,000 Mt - 1,500 Mt CO_2 in 2050 which is equivalent to an increase of 0% - 50% of the 2018 level and 90% - 130% of the 2008 level (J. Faber et al., 2020).

Up until this point it is evident that the existing policy interventions particularly the

Paris Agreement and the Initial IMO GHG strategy are facing a lot of uncertainties in realising their principal objectives. This calls for deliberate efforts to review existing policies in order to get back on track towards a net zero future. In the case of the IMO, review of the Initial strategy is scheduled to take place in 2023(IMO, 2022). Considering the existing technical and operational measures that are fuel consumption-centric, new findings find them insufficient to reach the set levels of ambition. In that regard, in the research work by (Masodzadeh et al., 2022) a new paradigm shift from a conventional fuel consumption-centric approach is proposed which is centred on operational performance through establishment of the new operational performance indicator (O-KPI) which among other things is expected to form the basis for establishment of hybrid Market Based Measures(MBM) as it links all the contributing factors of total ship energy efficiency. In the face of new findings, it remains to be seen on whether or not the IMO will adopt them in the forthcoming review of the Initial GHG Strategy in 2023.

1.2 Problem statement

Renewable Energy Sources as the main sources of sustainable energy powering production of cleaner Maritime Fuels by using the Power-to-X (PtX) arrangement (Bicer & Dincer, 2017) particularly electro-Fuels (e-Fuels) such as Hydrogen, Ammonia and Methanol are known to have a low-capacity factor. This means production of e-fuels by using Renewables require more space, materials and energy to generate a modest output. Approximately 10MWh (36GJ) of renewable electricity is required to produce one metric ton of ammonia (Grundt & Christiansen, 1982; IRENA & AEA, 2022; McKinlay et al., 2021). To put it in perspective, Jan Emblemsvåg, a professor at Norwegian Technical University estimates that 580 big container ships sailing 80% of the time with 12 return voyages per year will consume the amount of green ammonia equivalent to 1300TWh of green electricity per year which is almost half of Europe's combined electricity generation in the year 2019 which amounted to 2780TWh (Kristiansen, 2022).

In this regard, scaling up the uptake of e-Fuels in the maritime industry becomes unsustainable from the point of view of Resource Utilisation, Energy Efficiency, and Economics. A number of recent literary sources such as the one conducted by IRENA as depicted in figure 1 along with the works of (Emblemsvåg, 2021; Furfari & Mund, 2022) suggest incorporation of Nuclear Energy amongst not only sources of electricity powering e-fuel production but also direct shipboard application of advanced nuclear reactors as a possible solution to the aforementioned sustainability problem.

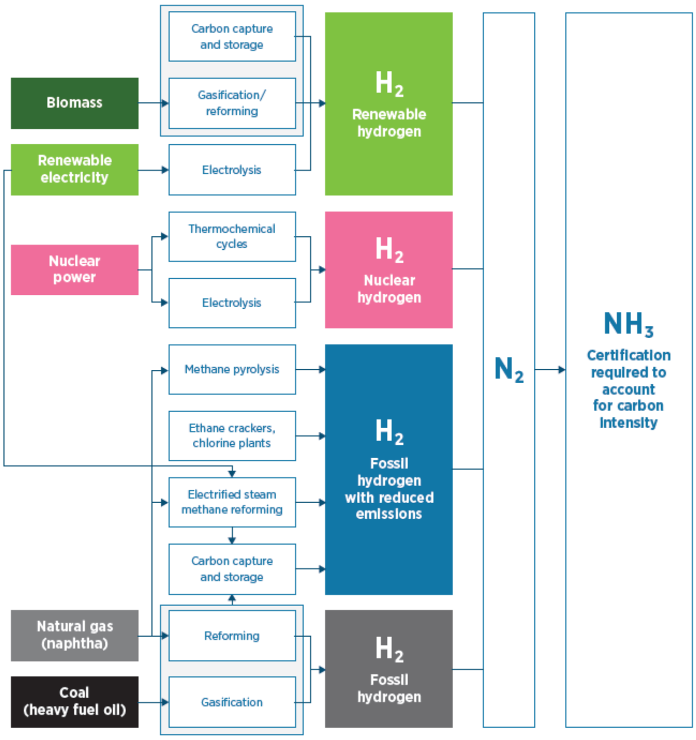


Figure 1: Ammonia Production Pathways (IRENA & AEA, 2022)

The pathway involving Nuclear Power in generation of ammonia as seen in figure 1, along with shipboard application of nuclear reactors become an attractive option due to its huge potential for scalability which is contributed by its highest capacity factor of all means of energy production (Deutch et al., 2003) as well as the immense energy density of nuclear fuel which is approximately 3,900,000MJ/kg for uranium at 3-5% enrichment levels as compared to conventional marine diesel at 42-46MJ/kg (World Nuclear Association, 2022a). In that regard, this work examines the use of the new generation of Nuclear Reactors (Generation IV) in the marine environment because of their superior properties to traditional Pressurised Water Reactors (PWR) in use today such as resource efficiency, energy efficiency, cleanliness, manageable waste generation, competitive economics, secure nuclear energy systems and materials, high degree of safety performance as well as miniaturisation potential which is ideal for the marine environment due to the relatively modest power capacity required by marine power plants (DoE, 2002; Emblemsvåg, 2021).

1.3 Motivations

From the point of view of energy efficiency as an element of sustainability, Electric Propulsion is arguably a superior ship propulsion arrangement to the mechanical one due to its higher propulsor efficiency, flexibility in arrangement of equipment especially due to the lack of a mechanical transmission, less vibration and so on (Nuchturee et al., 2020). However, in order for electric propulsion to function it must be complemented by shipboard prime-movers such as Internal Combustion (IC) engines, turbo-machineries or energy storage and conversion devices such as batteries, fuel cells, super-capacitors and so on. However, with the efficiency of approximately 43%, 2-stroke marine IC engines are considered to be a mature technology (Buhaug et al., 2009), this means newer innovations in the technology only results in marginal improvements. In addition to that, the challenges facing application of fossil fuels in IC engines particularly, emission of Green House Gases (GHGs) and air pollutants, fuel price volatility and supply chain constraints resulting from geopolitical tensions are worth mentioning (Furfari & Mund, 2022). On the other hand, energy storage and conversion devices are not immune to drawbacks. Batteries are characterised by higher weight and volume requirements, longer recharging time, short life span, low power density and so on. While, supercapacitors can provide a high amount of power for only a short time (Reusser & Pérez Osses, 2021). Although there are no significant challenges in electricity generation capabilities of fuel cells (Nuchturee et al., 2020), making it the most efficient way of energy extraction from e-Fuels such as Hydrogen, Ammonia and Methanol (McKinlay et al., 2021), however, shipboard storage of the required fuel for powering fuel cells is considered to be one of its biggest challenges.

On the other hand, from the point of view of resource efficiency as an element of sustainability, nuclear fuel is known to be the superior fuel in terms of energy density at approximately 3,900,000MJ/kg for uranium at 3-5% enrichment levels as compared to marine diesel al 42-46MJ/kg (World Nuclear Association, 2022a).The immense energy density of nuclear fuel contributes in making nuclear power plants to achieve the highest capacity factor of all means of energy generation (Deutch et al., 2003).

However, the technology for harnessing energy in nuclear power plants available today is based on older and less efficient Light Water Reactors/ Pressurised Water Reactors (LWR/PWR) that only convert 1% of mined uranium resources into energy, expensive to build, they have bad public image associated with nuclear accidents that occurred in the past, they require active safety features, also they are vulnerable to proliferation risks. As firstly introduced in section 1.2, a new breed of nuclear reactors referred to as Generation IV have been under development since 2001 as part of the Generation IV Initiative(DoE, 2002), these reactors have been designed to meet the need for sustainable utilisation of nuclear resources while having enhanced capabilities to generate manageable nuclear waste, competitive economics, secure nuclear energy systems and materials, high degree of safety performance(DoE, 2002).

Lastly, from the point of view of energy transition as an element of sustainability, there have been three major propulsion revolutions in shipping over the years initiated by the combination of human and wind power which is regarded as the first revolution, steam power propulsion as the second, and the internal combustion power revolution as the third (Wijnolst et al., 2009). In view of the above, this study is motivated by the prospect of a combination of Generation IV Nuclear Reactors, Fuel cells and e-Fuels forming the sustainable 4th ship propulsion revolution (4th ship propulsion S-Curve) as a way to transcend the limitations of energy dependence on fossil fuels as discussed in previous paragraphs. In the proposed S-Curve, electrification is regarded as the common denominator across the technologies involved, whereby nuclear generated electricity is either used directly in the form of a shipboard power plant or stored in the form of electro-fuels through the electrolysis process and then it gets converted back to electricity by using shipboard fuel cells whenever necessary (Power-to-X-to-Power).

1.4 Aims and objectives

Development of the decision-making framework for ranking the decarbonisation pathways based on the deployment of Nuclear Energy in the Marine Environment with regards to ship types and sizes, focusing on three key criteria, Technological

Readiness Level (TRL), Life Cycle Cost (NPV), and the complexity of the involved regulatory framework (REG).

1.5 Research questions

i. Which decarbonisation pathway is suitable for what ship type and size?

ii. What is the most influential amongst criteria under study, Technological Readiness Level (TRL), Life Cycle Cost (NPV), and the complexity of the involved regulatory framework?

iii. Which decarbonisation pathway is more likely to be the candidate for the 4th propulsion revolution (S-Curve)?

1.6 Scope of the study

This study focuses on the two pathways that the introduction of nuclear power to the marine environment could take designated as Pathways A and B. Pathway A focuses on direct electrification through deployment of a shipboard MSR type nuclear reactor, while Pathway B focuses on the indirect electrification through the usage of e-Fuels (Power-to-Ammonia-to-Power). The nuclear technology under discussion is the new generation of nuclear reactors as part of the Generation IV initiative. The Generation IV Initiative contains 6 key types of reactor technologies, however this study focuses only on Molten Salt Reactor (MSR) mainly due to some of their friendly features to the marine environment such as their capacity to be miniaturised to meet relatively modest power requirement of marine installations as compared to their land based counterparts, low operating pressure (near ambient pressure) and weight requirements making it require less nuclear safety materials (de Freitas Neto et al., 2021). On the other hand, the type of Fuel cell discussed in this study is Proton Exchange Membrane Fuel Cell (PEMFC), fuel cells have been chosen instead of IC engines because they are considered to be the most effective means of energy extraction from electro-fuels (McKinlay et al., 2021) as discussed in previous sections. Furthermore, the type of e-Fuels used discussed in this study is Ammonia due to its zero carbon content, less complex shipboard storage arrangement, accumulated experience in handling it as a transported cargo in ships and at ports, well established supply chain (Kim et al., 2020; McKinlay et al., 2020). Moreover, 7MW for Small ships, 15MW for Medium-sized ships, 30MW for Large ships have been chosen as representative Maximum Continuous Rating (MCR) values for this study.

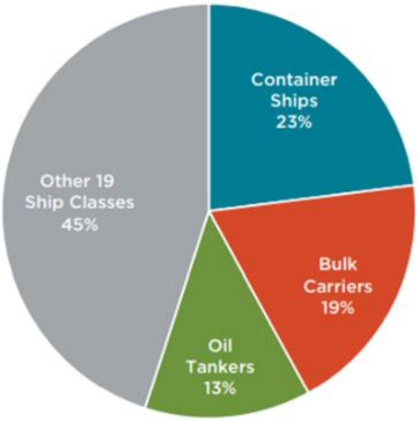


Figure 2: Share of GHG emissions by ship type (Olmer et al., 2017)

In addition to that, Container ships (at 23%), bulk carriers (at 19%), and oil tankers (at 13%) accounts for 55% of total GHG emissions from shipping, which is equivalent to 84% of emissions originated from total shipping transport work measured in deadweight ton-nautical mile or ton-mile (Olmer et al., 2017),therefore this study is focused on these three vessel classes considering they are the most polluting of all.

1.7 Organisation of the Study

This study is organised in six Chapters. Chapter 2 introduces the literature review, from which this study is organised as shown in figure 3 below.

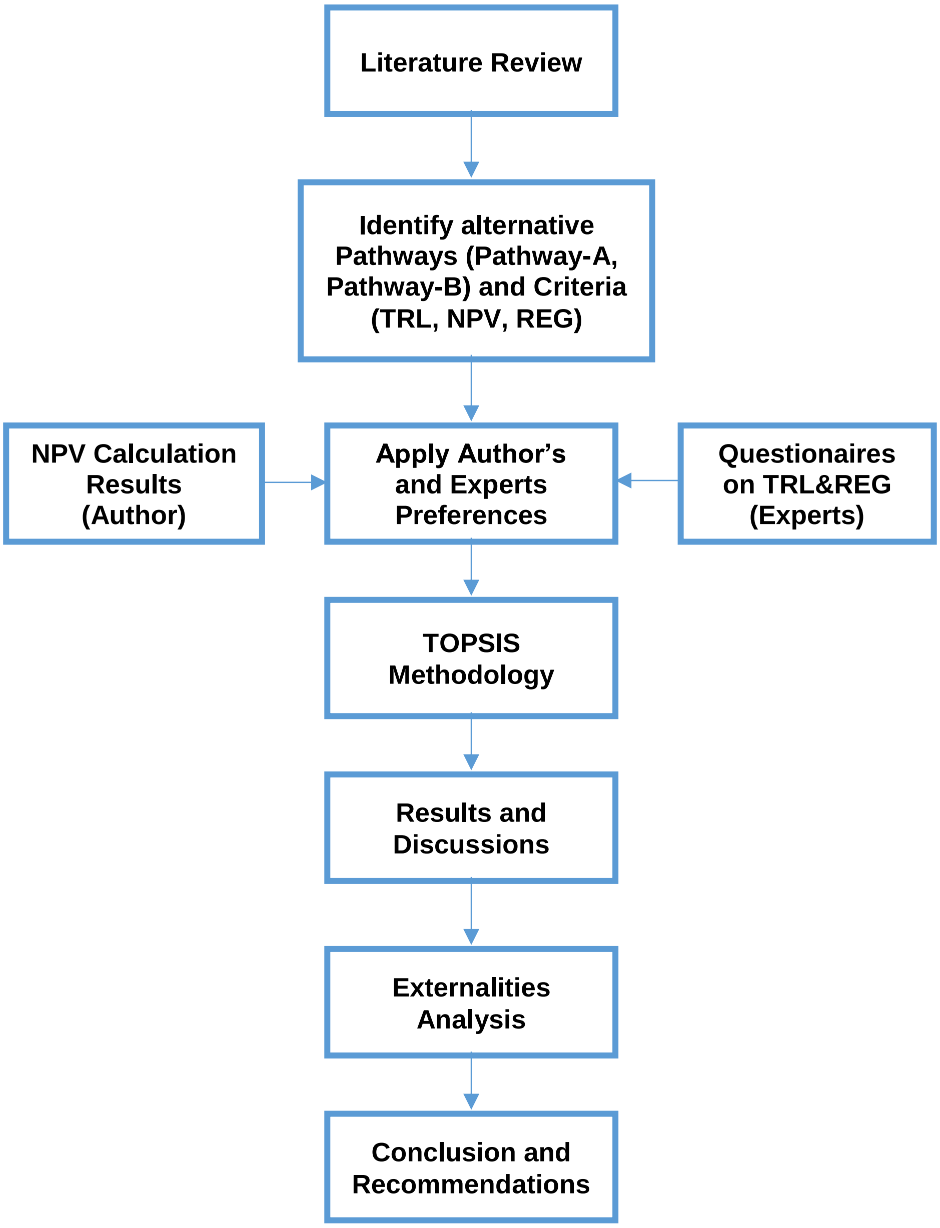


Figure 3: Organisation of the Study (Author)

CHAPTER 2- Literature Review

2.1 Introduction

This chapter is organised into four main parts starting with the introduction, existing regulatory instruments for clean maritime transport, a deep discussion on the nuclear option as the alternative maritime fuel source and finally it ends with the chapter summary.

2.2 Existing Regulations, Strategies and Policies for Clean and Sustainable Maritime Transport

The Kyoto protocol in 1997 remains to be the most important milestone in global climate action because as a result of which the IMO was given the mandate to come up with a plan to reduce GHG emission in international shipping. The IMO responded to the resolutions reached during the Kyoto protocol by conducting the First IMO GHG study in the year 2000, the second in 2009, the third in 2014 and the most recent fourth in 2020. In between the year 2000 and 2020 a significant milestone in reduction of GHG emissions was achieved by adoption of the Paris Agreement in 2015 (Doelle & Chircop, 2019). In the wake of the Paris Agreement, it was imperative that the IMO had to take concrete steps towards GHG emission in international shipping. In that regard, the IMO commissioned the Initial GHG Strategy in 2018 with the aim of revising it in 2023 (Joung et al., 2020).

Table 1: IMO Regulatory milestones (IMO, 2022)

Key timeline	**MEPC meeting**	**The IMO actions**	**Remarks**
Sept.1997		Resolution.8 of the 1997 MARPOL Conference on CO2 from ships (The First adoption of MARPOL Annex VI)	The first IMO actions on reduction of GHG from shipping
June 2000	MEPC 45	First IMO GHG study 2000	
May 2005		Entry into force of MARPOL Annex VI	
July 2009	MEPC 59	Second IMO GHG study 2009	

July 2011	MEPC 62	Resolution.MEPC.203(62): Amendments to MARPOL Annex VI (set up of Chapter 4 and related amendments to other chapters)	The first binding regulation on reduction of GHG emissions in shipping
1 Jan.2013		Regulations on Ships’ Energy Efficiency (Res. MEPC.203(62)) came into force	
Oct. 2014	MEPC 67	Third IMO GHG study 2014	
Spring 2018	MEPC 72	Adoption of the Initial IMO GHG Strategy	
Autumn 2020	MEPC 76	Fourth IMO GHG study 2020	
Spring 2023	MEPC 80	Adoption of the revised IMO GHG Strategy	

The IMO addresses air pollution through the International Convention for the Prevention of Pollution from Ships (MARPOL), particularly its Annex VI which regulates air emissions from ships, including nitrogen oxides, sulphur oxides, volatile organic compounds, and ozone-depleting substances. In an effort to address carbon intensity per transport work, amendments were done to MARPOL Annex VI Chapter 4 in 2011, including mandatory requirements such as the Ship Energy Efficiency Management Plan (SEEMP) and Energy Efficiency Design Index (EEDI) which entered into force on 1st January 2013 for the purpose of enforcing enhanced energy efficiency in future ships as shown in the graphic representation shown in figure 4 (Ölçer et al., 2018; Van Dokkum, 2013).

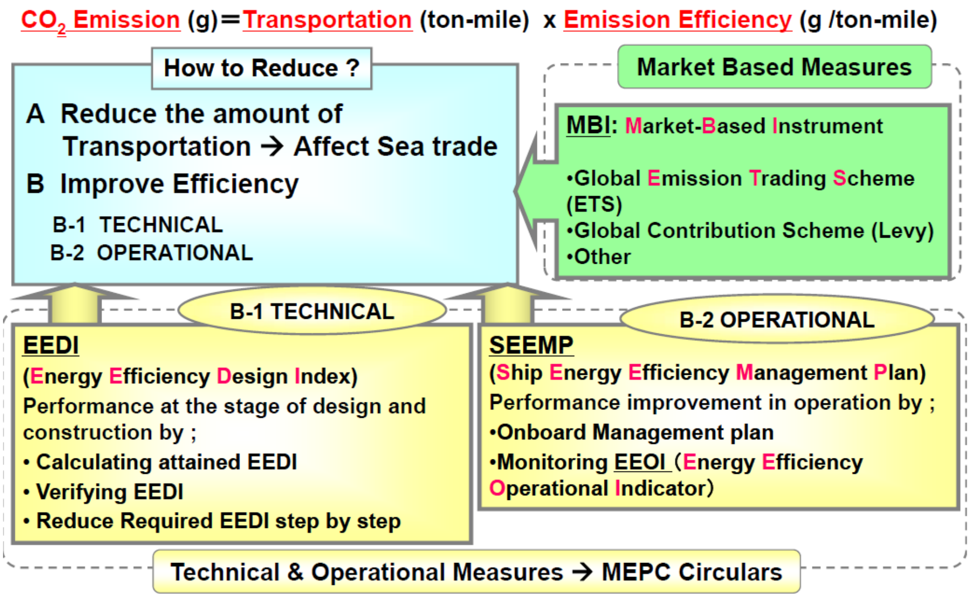


Figure 4: IMO Approach to Energy Efficiency in Ships(WMU Lecture notes by Prof. Aykut Ölçer)

Furthermore, as depicted in figure 5, the Initial IMO GHG strategy aims at reducing total annual emissions in international shipping by 50% by 2050 as compared to the level of 2008 while aiming at phasing them out by the end of the century. In terms of energy intensity per transport work, the strategy pursues 40% reduction by 2030 and 70% reduction by 2050 respectively. The strategy put forward candidate measures to be adopted in the short-term (2018-2023), mid-term (2023-2030), and long term (2030-onwards).

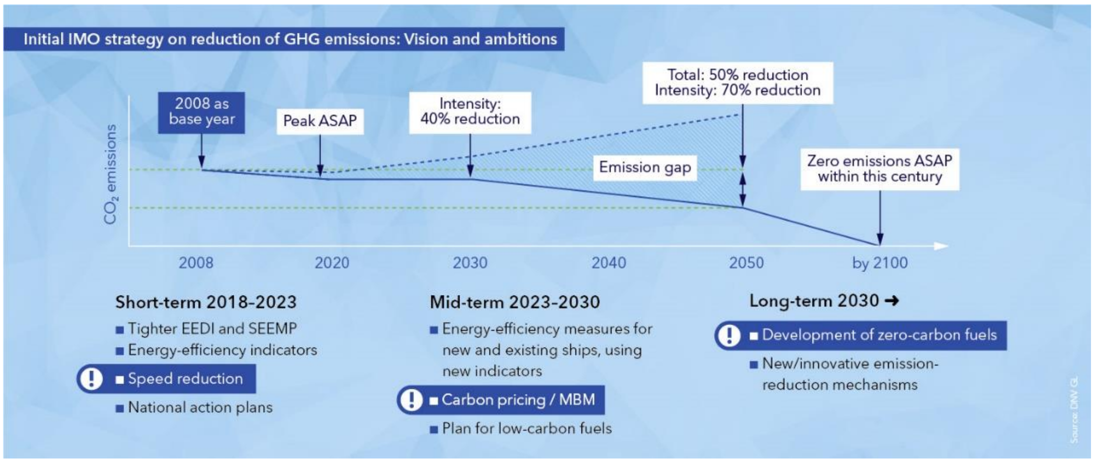


Figure 5: The initial IMO GHG Strategy(DNV GL, 2022)

This strategy is set up in a way that requires GHG emissions from international shipping to peak as soon as possible in order to be in line with temperature goals set by the Paris Agreement. However, recent findings reveal inconsistencies between the targets of the Initial IMO GHG Strategy and those of the Paris Agreement in a way that, emission reduction by up to 50% by 2030 and 100% by 2040 relative to 2008 needs to be pursued in order to be in line with the Paris agreement (Comer, 2021; IPCC, 2022). This implies, peaking of GHG emission before declining is now a matter of urgency, failure to do that say until 2030 will lead to the need for unrealistically steeper reduction trajectory in order to comply with the Paris Agreement as depicted by a dotted blue line on figure 6.

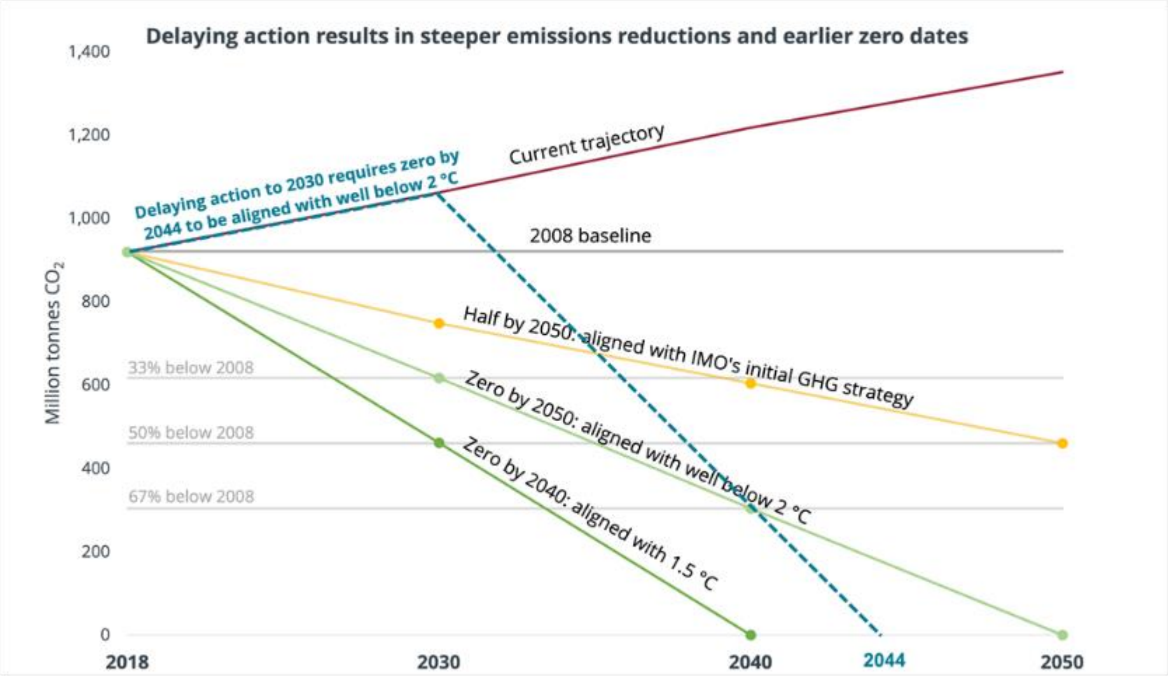


Figure 6: Steeper emission reduction trajectory for compliance to the Paris Agreement(Comer, 2021)

The primary focus of this study is to assess the prospect of zero-carbon alternative fuels as the only viable option to enable the IMO GHG strategy to align with temperature goals set by the Paris Agreement. This is because, it has recently been revealed that only a maximum of 14% overall savings in fuel demand can be achieved through deployment of technical and operational energy saving measures as part of candidate short term measures(Buckingham, 2020; McKinlay et al., 2021). Similarly, deployment of Market Based Measures (MBM) in international shipping as part of candidate mid-term measures still faces uncertainties. Most importantly, seaborne transportation will continue to grow along with world trade as a result of future economic and energy development (IMO, 2020; Ölçer et al., 2018), hence demanding more fossil fuels in the process.

2.3 Nuclear Power as one of Existing Cleaner Options as Alternative Maritime Energy Sources

With the current level of technology Renewables do not have the required energy density that would enable propulsion of a modern day international commercial vessel without major operational changes, instead they hold a great potential to be used in tandem with conventional means of propulsion or as auxiliary onboard power sources(Carlton et al., 2013). Another pathway that would enable renewable energy sources such as wind, solar, hydro-electricity to enable propulsion of modern day international commercial vessels is through powering production of e-Fuels such as hydrogen and ammonia via Power-to-X. However, this pathway as well faces the serious challenge of scalability challenges as discussed in the previous sections.

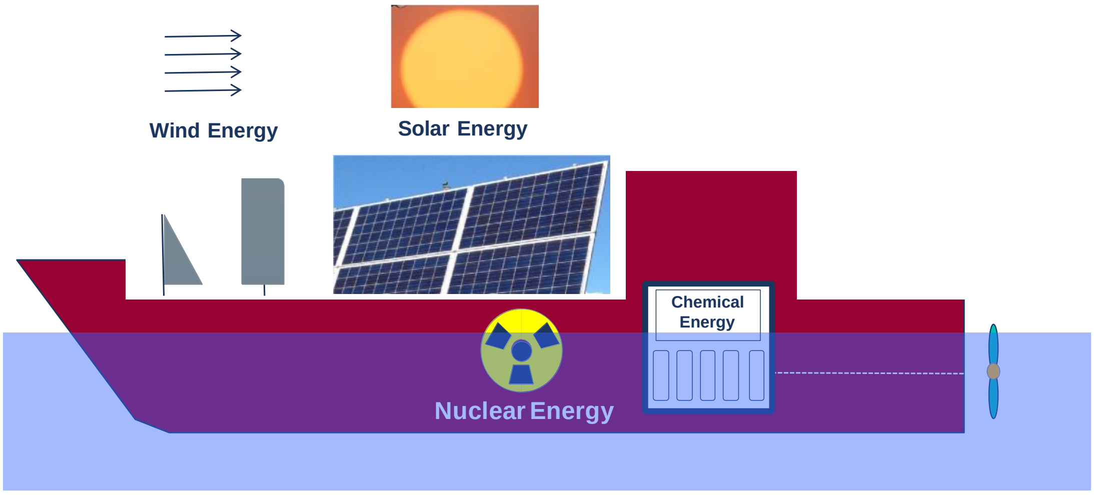


Figure 7: Ship powering options (Ölçer et al., 2018)

In the quest for the future maritime energy source, this study shed light on the renewed interest in Nuclear energy for shipping especially after inauguration of the Generation IV (GIF) Initiative by the United States Department of Energy (DOE) in 2001 as part of the solutions. In addition to that, Nuclear Power is projected to eclipse fossil fuels as the biggest source of energy by 2050 under supportive policy intervention (UNECE, 2022).

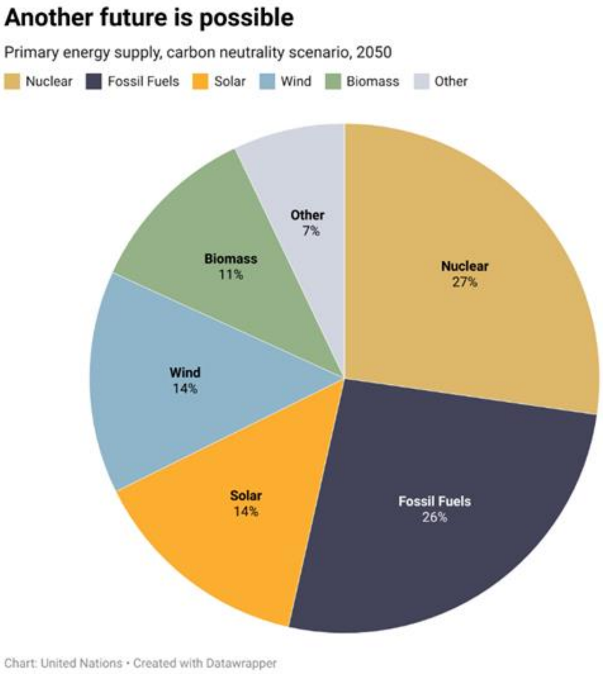


Figure 8: 2050 Global Energy Scenario(UNECE, 2022)

Therefore, maritime transport like all other sectors is also likely to adopt nuclear power as per the projected 2050 energy scenario. However, energy production by using nuclear power has evolved over the years from the first generation of nuclear reactors to the IV generation under development which is the main focus of the Generation IV Initiative.

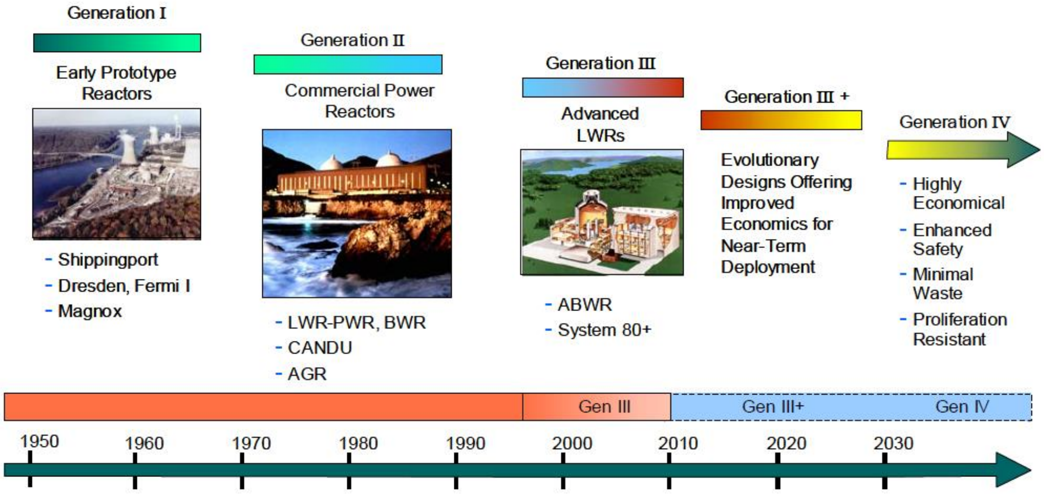


Figure 9: Technological Roadmap of Generation IV Nuclear Energy Systems (DoE, 2002)

Generation IV nuclear reactors marks a significant departure from the conventional Pressurised Water Reactor (PWR/LWR) technology that has dominated both Marine and Land-based applications over the past 60 years by identifying the new design approach to six key technologies for the purpose of meeting future energy demands through new innovations in the existing reactor concepts on the basis of enhanced cleanliness, proliferation resistance, cost-effectiveness, and safety (DoE, 2002; Hirdaris et al., 2014). The six technologies considered to be part of the Gen IV initiative includes Molten Salt Reactor (MSR), Gas-cooled Fast Reactor (GFR), Supercritical Water-cooled Reactor (SCWR), Lead-cooled Fast Reactor (LFR), Very High Temperature Reactor (VHTR), and Sodium-cooled Fast Reactor (SFR) respectively (Furfari & Mund, 2022; GEN IV International Forum, 2022).

2.4 Generation II-III Pressurized Water Reactors (PWR)

Before further discussing Generation IV of Nuclear reactors which is the focus of this work, it is crucial to provide introduction to the physics of the conventional Generation II-III PWR type reactors for convenience purposes. A nuclear reactor is a piece of equipment designed to initiate and control a sustained chain reaction of a nuclear fuel such as Uranium-235 or Uranium-233 (Krivit & Lehr, 2011). A sustained nuclear fission reaction occurs when a fissile heavy atom such as Uranium-235, Uranium-233 and Plutonium-239 absorbs a neutron causing vibrations in its internal structure which makes it unstable to an extent where it breaks apart under mutual electrostatic repulsion of its parts generating immense amount of heat energy in the process. A typical fissile material would split into Ce-140 and Rb-93 as well as emitting three additional neutrons that would go ahead and split more fissile nuclei, hence a sustained chain reaction(Carlton et al., 2011; Cengel et al., 2011; Hirdaris et al., 2014).

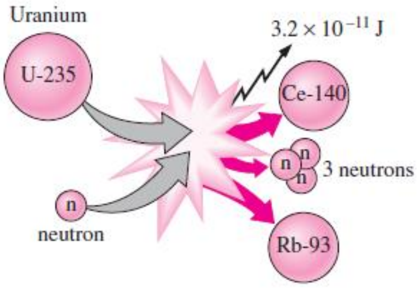


Figure 10 :Chain reaction(Cengel et al., 2011)

A nuclear reactor is made up of a number of components, three main ones being the nuclear fuel, control rods, and moderator. Initiation of nuclear chain reaction in the reactor is facilitated by the moderator (graphite, water, deuterium in heavy water) whose function is to maximise the probability of neutron absorption by the fissile nucleus by slowing down the neutrons to thermal energies. While the control function of the reactor is performed by control rods through adjustment of the level of reactivity inside the reactor core because they are made up of materials that facilitate absorption of thermo-neutrons such as Cadmium and Boron.

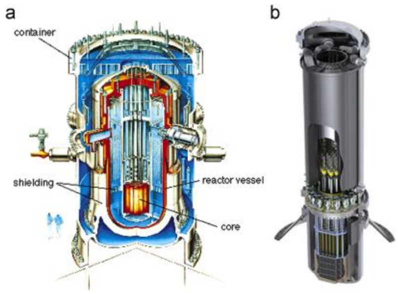


Figure 11: Marine Nuclear Reactors (a) MRX,100MWt and (b) mPowerreactor (Aspelund et al., 2006)

Furthermore, a set-up consisting of a nuclear reactor as the heat source and energy conversion equipment such as turbo-machinery arrangement as depicted by a simplified layout in figure 12 constitute a nuclear power plant. A nuclear power plant is typically a thermal power plant whose source of heat is a nuclear reactor instead of a conventional fossil fuel burner.

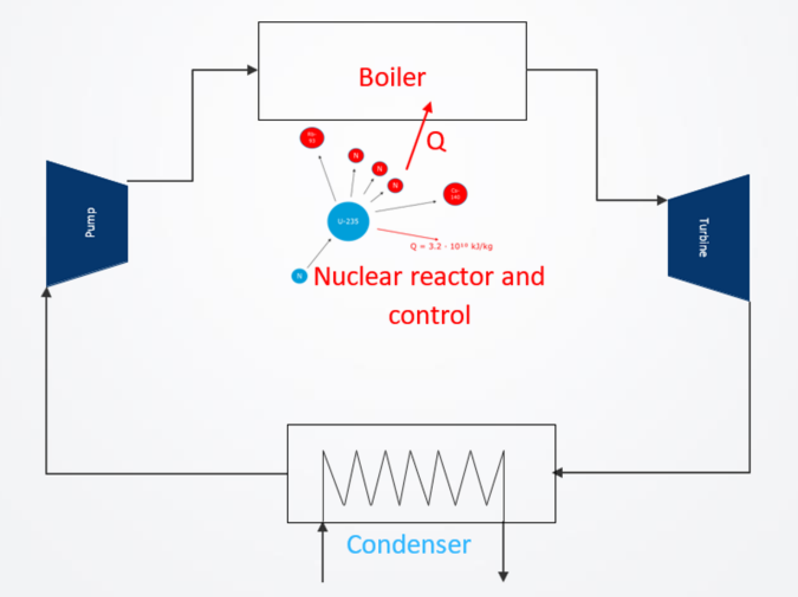


Figure 12:WMU lecture notes by Prof. Alessandro Schönborn

The nuclear power plant can be used for a variety of purposes depending on the type of additional equipment coupled to the turbo-machinery. When coupled with the electric generator it becomes a power station. On the other hand, nuclear power plants are capable of powering ship propulsion when coupled with propulsion units.

2.4.1 PWR-based Nuclear Marine Propulsion

Nuclear powered marine propulsion consists of two main parts, the reactor compartment and the propulsion compartment. The reactor compartment is responsible for generation of high temperature steam for running the turbines (Namikawa et al., 2011). On the other hand, the propulsion compartment consists of either a steam turbine directly coupled to the propeller shaft through a reduction gear as seen in the figure 13 or a turbo-electric arrangement coupled with electric propulsors(Carlton et al., 2011).

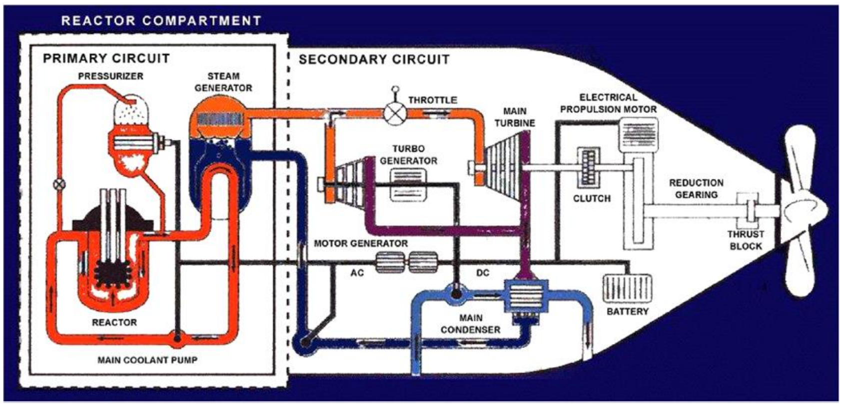


Figure 13: PWR-based Nuclear Marine Propulsion (Hirdaris et al., 2014)

Following conceptual and experimental studies by the pioneers of nuclear reactor technology, particularly the work of Enrico Fermi in 1944, the first practical application of nuclear power was in the marine environment for propulsion of navy submarines. The first vessel equipped with a PWR type nuclear reactor was the US submarine, Nautilus in 1954 by Admiral Hyman Rickover who was in charge of the US submarine fleet (Furfari & Mund, 2022).

However, from 1950 to present day, four nuclear powered civilian vessels have been commissioned in the US (NS Savannah), Germany (NS Otto Hahn), Japan (NS Mutsu) and Russia (NS Sevmorput). NS Savannah (Container vessel, 80MW) and NS Otto Hahn (Ore carrier, 38MW) had excellent technical reliability record, unlike NS Mutsu (General cargo vessel, 36MW) which is said to have had a number of technical problems. However, the abovementioned civilian vessels were deemed to be expensive to run (Hirdaris et al., 2014). NS Sevmorput (Barge carrier and container vessel, 135MW) commissioned in 1988 is the only nuclear-powered commercial vessel that is still in service to this day.

Figure 14:Historic civilian nuclear powered vessels (a) Ice breaker Lenin (Russia) – 1959, (b) NS Savannah (USA) – 1962, (c) NS Otto Hahn (Germany) – 1964, (d) NS Mutsu (Japan) – 1970, (e) NS Sevmorput – 1988, and (e) NS 50 Let Povbedy – 2007: Source (Hirdaris et al., 2014)

2.4.2 PWR-based Floating Nuclear Power Station (FNPP)

A nuclear power plant can as well be designed as a floating electric power station mainly for the purpose of supplying electricity to remote locations that are not connected to the main grid, in such arrangement the facility is referred to as a Floating Nuclear Power Plant (Yuan & Nian, 2020). Sturgis which was later renamed as SS Green Port commissioned in 1962 pioneered FNPPs as it was used to generate electricity at one of the US military base in antarctica and later a site in the Panama canal (Orr & Dotson, 1973).The most recent and the only operating FNPP to this day is the Akademik Lomonosov based in Russia (Subki, 2020).

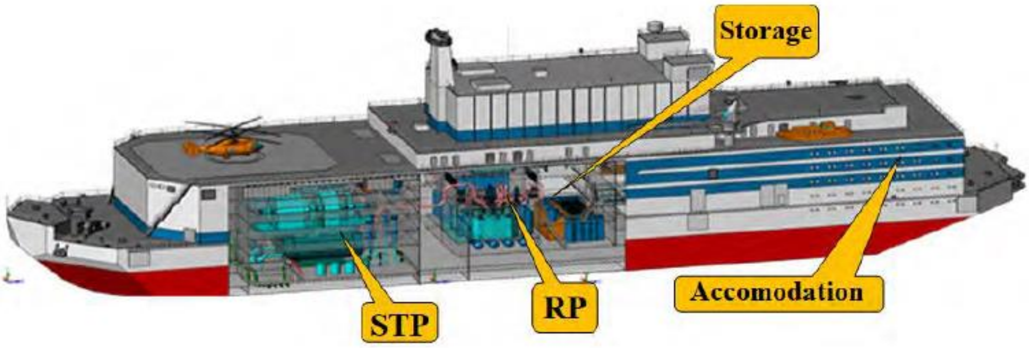


Figure 15: The Akademik Lomonosov

Akademik Lomonosov was commissioned in May 2020 in the remote coastal town of Pevek. The power plant is powered by KLT-40S PWR marine reactors with the capacity of 35MW per module capable of producing the cogeneration of electricity and process heat. According to the International Atomic Energy Agency (IAEA), KLT-40S is the first Small Modular Reactor (SMR) in operation after finalising construction to this day. This reactor type achieves longer refuelling cycles of up to 30-36 months due to high enrichment levels of its fuel, up to 19% (Subki, 2020).

2.5 Limitations of Generation II-III Pressurised Water Reactors (PWR)

2.5.1 Safety

Marine nuclear reactors are known to have an incredible safety record as compared to any other marine propulsion and power generation technology. However, the higher operating pressure inside the reactor core of a PWR type reactor is vulnerable to the risk of expulsion of harmful radio toxins to the environment under accident conditions. Furthermore, the use of water inside the reactor core runs the risk of loss of coolant (due to evaporation or any other loss) leading to overheating and finally core meltdown like what happened at Three Miles Island power plant. Moreover, the use of water inside the reactor is liable to the risk of hydrogen explosion when extremely hot metal (Zirconium) comes into contact with water like what happened at Fukushima power plant. On the other note, a PWR reactor a requires long term reactivity margin which runs the risk of reactor criticality accidents like what happened at the Chernobyl power plant (Furfari & Mund, 2022).

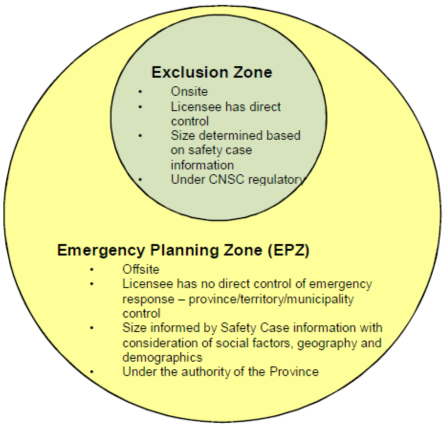


Figure 16: Emergency Planning Zone (IAEA, 2018)

Therefore, the aforementioned technical and operational-intricacies necessitate the PWR type asset to require establishment of a bigger Emergency Planning Zone (EPZ). An Emergency Planning Zone is referred to as the area in which implementation of protective and operational actions might be required in the occurrence of a nuclear emergency (IAEA, 2018). In the context of advanced emergency planning, IAEA reiterates provision for mitigation of consequences of the accident at its source in order to prevent or minimise associated severe deterministic effects or reasonably reduce stochastic effects.

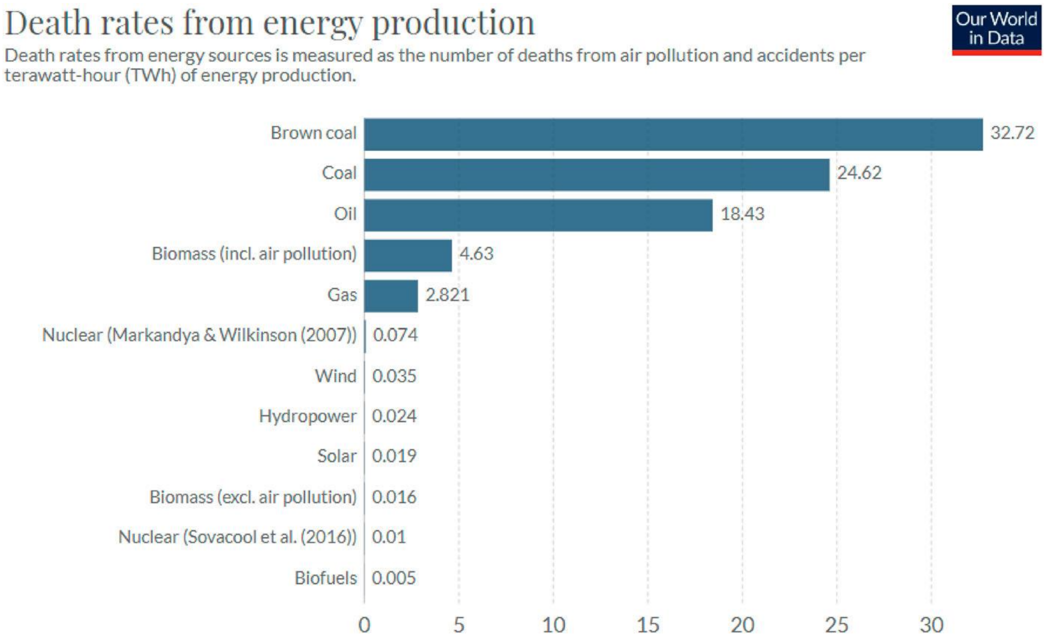


Figure 17:Loss of life cases from energy production (Markandya & Wilkinson, 2007; Sovacool et al., 2016)

Despite the delicacy of conventional nuclear power plants, they still maintain an excellent safety record due to the exacting safety culture in all facets of the nuclear industry from design, construction, operation, ownership, inspection, regulation, licensing, insurance and so on (Namikawa et al., 2011).

2.5.2 Security

Nuclear proliferation risk is a concern for PWR type reactors (Emblemsvåg, 2022). According to the International Atomic Energy Agency (IAEA) nuclear proliferation is defined as the action of weaponizing nuclear facilities licensed as civilian-grade (meant for civilian applications such as clean energy generation, medical application, and research) which is against the Non Proliferation Treaty (NPT) of 1968 (IAEA, 2022). During operation of PWR type reactor weapons-grade Plutonium-239 is generated as a by-product when Uranium-238 absorbs a neutron during the chain reaction.

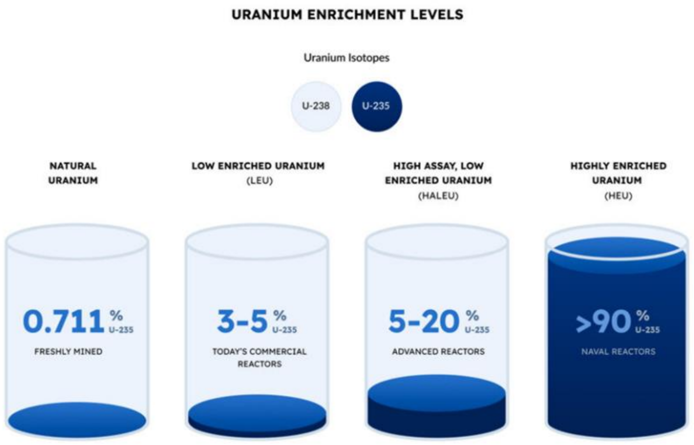


Figure 18: Uranium Enrichment Levels(Centrus Energy, 2022)

Plutonium is an isotope used in creation of nuclear weapons, hence it is in most cases an unwanted isotope in civilian-grade nuclear installation because it is a target for proliferation. Apart from Plutonium, enrichment levels beyond 20% is also considered weapons-grade hence the Non-Proliferation Treaty (NPT) allows export of civilian reactors provided that the level of enrichment of nuclear fuel is less than 20% as a mitigation measure (Furfari & Mund, 2022).See Figure 18.

2.5.3 Radioactive Waste

In a PWR type reactor, only 5% of the nuclear fuel is utilized for power generation while the rest goes to waste as fission by-products due to radiation damage such as Trans-uranium (TRU) material like americium and curium (Greaves et al., 2012). Nuclear waste can be classified as high-level waste, intermediate-level waste and low-level waste respectively (Carlton et al., 2011). High level waste is referred to as spent nuclear fuel or by-product of nuclear fission from the reactor core. Intermediate-level waste is the less radioactive category made up of sludge formed during reprocessing of spent nuclear fuel and fuel cladding. Intermediate-level waste is the least radioactive category consisting of components of the nuclear facility contaminated by neutron irradiation such as reactor water treatment residues. Nuclear waste from PWR reactors remain radioactive for many years. Without reprocessing spent nuclear fuel, It is estimated that it takes about a million years to lose its radioactivity, even with reprocessing it still takes about 100,000 years(Kamei, 2011).

2.5.4 Economics

A comparative study on life cycle costing when using HFO, gas and nuclear as fuel for a 400,000DWT Ore carrier, and a 10,0000DWT Container vessel was conducted by (Namikawa et al., 2011). In the study, the cost of a new build was extracted from a report from Drewry, the cost differences between gas and nuclear were evaluated according to published studies and reports. Installation cost of a nuclear reactor, the cost for five-year interval dry-docking for refuelling, decommissioning as well as scrapping were included in the study. Based on the extracted cost data, Net Present Value (NPV) was calculated at the discount rate of 8% and the annual inflation rate of 2% for 25 years.

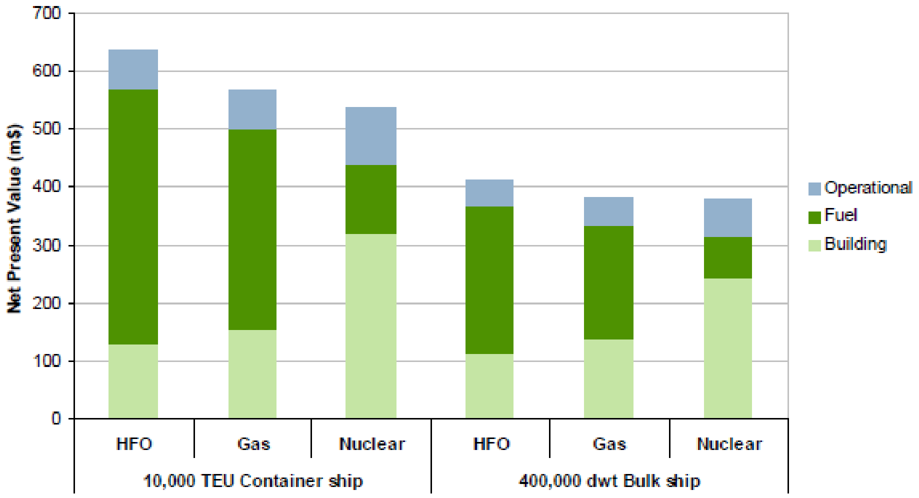


Figure 19: Financial performance of the Nuclear option as compared to conventional fuels (Namikawa et al., 2011)

As shown in figure 19, the nuclear option attains better NPV than the rest of the fuels. The results of the study also concluded, the nuclear option remains competitive when uncertainties concerning future fuel prices are factored in because unlike other fuel options, nuclear fuel price has almost negligible effect on life-cycle cost because its contribution is much smaller as compared to other cost elements. Despite being cheaper than coal, HFO and Gas even in terms of the Levelized Cost of Electricity (LCOE), it was revealed by the research work by (Kamei, 2010) that the total cost of running the PWR type power plant at 4.11cents/kWh is still 30% more expensive than newer generation of Molten Salt Reactors (MSR).

2.6 Generation IV Molten Salt Reactors (MSR)

In order to mitigate the limitations of PWR type reactor technology, generation IV of nuclear reactors have been under development. The GIF Initiative was inaugurated by the U.S Department of Energy by identifying six key technologies for the purpose of meeting future energy demands through new innovations in the existing reactor concepts on the basis of cleanliness, proliferation resistance, cost-effectiveness, and safety.

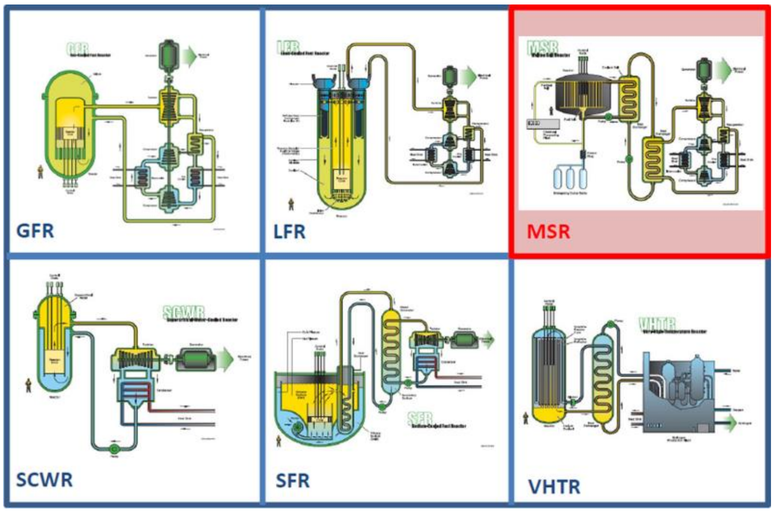


Figure 20: Generation IV Reactors Technologies(Furfari & Mund, 2022)

Of all six Gen IV designs, Molten Salt Reactor (MSR) technology is considered by multiple researchers as ideal for the marine environment due to its potential to be miniaturised to meet the requirement for modest power capacities required by vessels and floating platforms (Emblemsvåg, 2021), less requirement for establishment of a bigger Emergency Planning Zone(Genaro, 2021), manageable nuclear waste, competitive economics, secure nuclear energy systems and materials, high degree of safety performance (DoE, 2002).

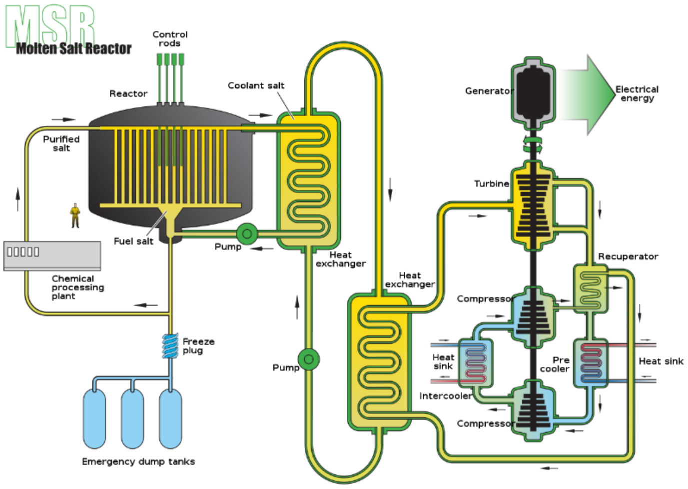


Figure 21: Molten Salt Reactor(DoE, 2002)

Molten Salt Reactors have been studied since 1950s, however, the first experimental reactor was developed in 1965 by Oak Ridge National Laboratory (ORNL) as Molten Salt Reactor Experiment (MSRE) which operated successfully for four years (World Nuclear Association, 2022b). Despite the experimental project being a success, further development was shut down in 1978 because PWR reactors and Sodium Cooled Fast Breeders (SFB) were a priority (Furfari & Mund, 2022).

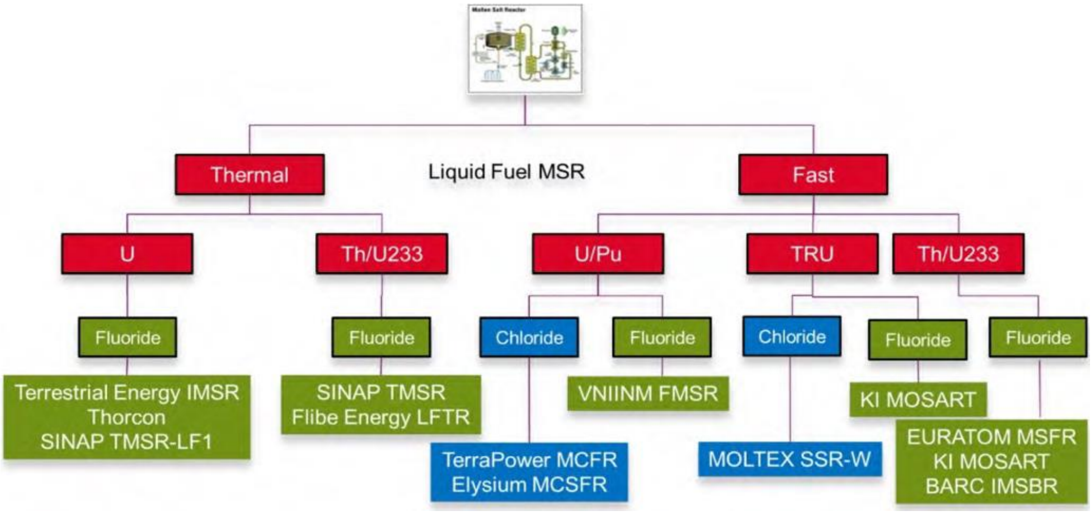


Figure 22: MSR Family tree (GEN IV International Forum, 2022)

MSR type reactors are characterised by superior properties such as passive safety features, sustainable fuel cycle, high temperature holding capacity of molten salt at near atmospheric pressure (lowers the risk of expulsion of radio-toxins to the environment under accident condition), high temperature operation (around 700°C) which offers higher thermal energy conversion efficiencies to electricity, proliferation resistance, reduced nuclear waste and economic advantages over not only conventional nuclear power plants but also two stroke marine engines run on HFO (Emblemsvåg, 2021; Mignacca & Locatelli, 2020).

2.7 Merits of Generation IV MSR type reactors

2.7.1 Safety

Having fuel in a molten state, MSR type reactors are equipped with passive safety features that makes them safer than conventional PWR type reactors(World Nuclear Association, 2022b). Their negative temperature coefficient suppresses reactivity when core temperatures get out of control, hence, prevents the possibility of core meltdown. Similarly, the absence of water inside the reactor core prevents the risk of loss of coolant (due to evaporation or any other loss) leading to overheating and finally core meltdown like what happened at Three Miles Island power plant. On the other hand, the absence of water inside the reactor prevents the risk of hydrogen explosion when extremely hot metal (Zirconium) comes into contact with water, in addition to that, MSR reactor does not require long term reactivity margin which prevents the risk of reactor criticality accident like what happened at Fukushima and Chernobyl power plants as discussed in earlier sections(Furfari & Mund, 2022).

2.7.2 Security

There is two main ways in which MSR type reactors achieve proliferation resistance better than conventional PWR type achieved by its ability to accept because. The type of reactors that use the uranium fuel cycle achieve proliferation resistance by running fuel with not more than 20% level of enrichment as per the NPT treaty (IAEA, 2022). In addition to lower enrichment levels, uranium fuelled generation IV reactors are designed to close the nuclear fuel cycle by consuming isotopes that a target for proliferation such as Plutonium generated by PWR type reactors. While the reactors that use the thorium fuel cycle generate Uranium-232 with penetrating gamma radiation (2.6 MeV) inside the reactor which complicates diversion of fuel for proliferation(Hargraves & Moir, 2010; Moir & Teller, 2005)

2.7.3 Radioactive Waste

MSR type reactors run on Uranium-238 or Thorium-232 as fertile material requires fissile Uranium-235 or Plutonium-239 in order to initiate a sustained chain reaction. Nuclear waste from conventional PWR/LWR type reactors can also be used as fissile material for MSR type reactors. This offers the prospect of fully closing the through life cycle of nuclear fuel remaining with minimal inventory of high level-waste such as Pu-242 being the dominant Pu isotope, hence shorter-lived radioactivity(Emblemsvåg, 2022; World Nuclear Association, 2021b).

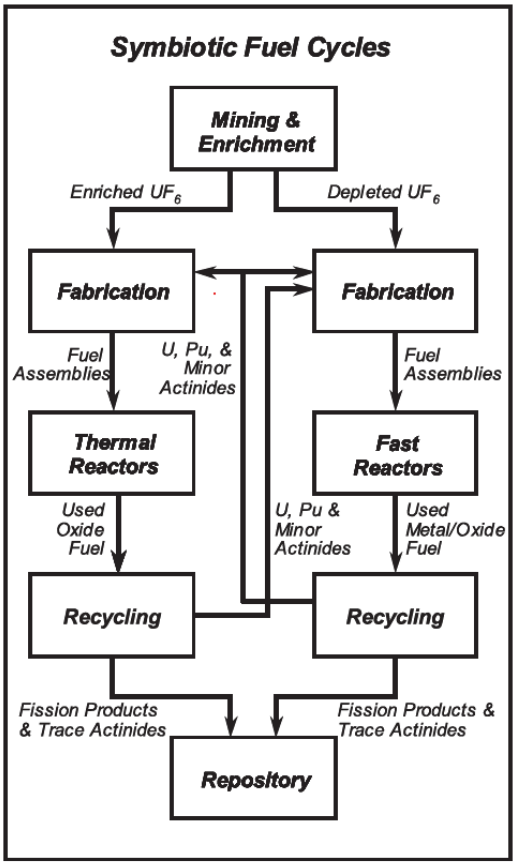


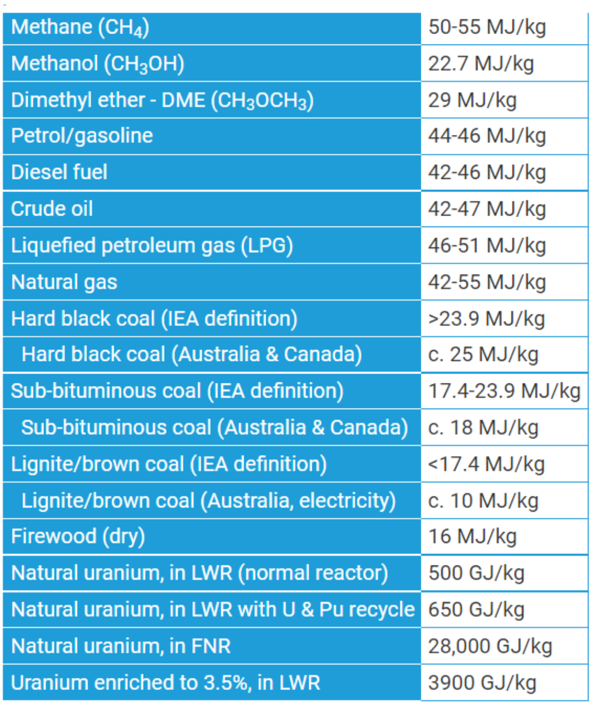
Figure 23: Circularity in Nuclear Fuel Utilisation(DoE, 2002)

It is evident from the figure 23 that fully closing the fuel cycle through deployment of MSR type reactors forming symbiosis between conventional and MSR type reactors may shorten the radiotoxicity of nuclear waste up to about 300 years (this means, it would take only about 300 years for the radio toxicity of spent nuclear fuel to be the same as that of the natural uranium ore instead of tens of millions of years in the once through cycle(Taylor et al., 2022).

2.7.4 Fuel Utilisation

Fuel Utilisation of PWR type reactors is very low. Only 1% of mined uranium resources is converted to useful energy causing the rest of the fuel to add up to nuclear waste. Even with enrichment, between 3%-5% the achieved fuel conversion (Fuel burnup) is approximately 3900GJ/kg (World Nuclear Association, 2022a).

Table 2: Low Heating Values of Fuels (World Nuclear Association, 2022a)



Methane (CH_4)	50-55 MJ/kg
Methanol (CH_3OH)	22.7 MJ/kg
Dimethyl ether - DME (CH_3OCH_3)	29 MJ/kg
Petrol/gasoline	44-46 MJ/kg
Diesel fuel	42-46 MJ/kg
Crude oil	42-47 MJ/kg
Liquefied petroleum gas (LPG)	46-51 MJ/kg
Natural gas	42-55 MJ/kg
Hard black coal (IEA definition)	>23.9 MJ/kg
Hard black coal (Australia & Canada)	c. 25 MJ/kg
Sub-bituminous coal (IEA definition)	17.4-23.9 MJ/kg
Sub-bituminous coal (Australia & Canada)	c. 18 MJ/kg
Lignite/brown coal (IEA definition)	<17.4 MJ/kg
Lignite/brown coal (Australia, electricity)	c. 10 MJ/kg
Firewood (dry)	16 MJ/kg
Natural uranium, in LWR (normal reactor)	500 GJ/kg
Natural uranium, in LWR with U & Pu recycle	650 GJ/kg
Natural uranium, in FNR	28,000 GJ/kg
Uranium enriched to 3.5%, in LWR	3900 GJ/kg

However, with the deployment of thorium fuel cycle in thermal spectrum reactors, MSR type reactors have potential to breed more fissile materials than they consume when operating as breeder reactors thereby improving the energy conversion of mined thorium resources significantly which as a result leads not only to less mining requirements but also eliminates the need for fuel enrichment(Dolan, 2017; Hargraves, 2012). Molten Salt variant of the original Fast Neutron Reactors (FNR) run on Uranium/Plutonium fuel cycle is 60 times more efficient in converting mined uranium resources to energy than a conventional PWR/LWR type reactor as shown by energy conversion figures in the table 2 (World Nuclear Association, 2021b).

2.7.5 Economics

In the context of land based PWR type nuclear power plants, overnight capital costs at the beginning of the project are very high as compared to other alternatives (coal, oil and gas fired plants) for the same capacity, but running costs are much lower for nuclear power plants(Moir, 2002). Similarly, for a PWR type nuclear powered merchant vessel, the most significant portion of the through life-cycle cost is concentrated at the initial capital, unlike conventional merchant vessels whose costs are spread-out throughout their life(Carlton et al., 2010). This implies that, if the comparison is made with regards to through-life total cost, the nuclear option becomes the more attractive option from the life cycle perspective (Carlton et al., 2010). In the nuclear power industry, through-lifecycle costs are divided in four main categories, capital cost, operation and maintenance cost (O&M), fuel cost and decommissioning cost (Mignacca & Locatelli, 2020). In a study by (Samalova et al., 2017), through-lifecycle cost of a PWR type reactor model AP1000 was compared to three reactor models of the MSR type, IMSR 600, IMSR 300, and IMSR 80.

Table 3: Comparative costs between Conventional and Generation IV power plants (Mignacca & Locatelli, 2020)

Case	MWe	Total overnight cost	Overnight cost per kWe($/kWe)
AP1000	1000	3249.105	2972.57
IMSR 600	291	829.456	2850.37
IMSR 300	141	524.450	3719.51
IMSR 80	32.5	297.840	9164.31

From table 3, estimated total overnight cost of IMSR 600 per kWe was observed to be slightly lower than that of AP1000. However, the Levelized Cost of Energy for IMSR 600 was observed to be higher than that of AP1000, see table 4.

Table 4: Cost Comparison of Nuclear Power Plants with reference to main cost elements (Mignacca & Locatelli, 2020)

Components($/MWh)	AP1000	IMSR 600	IMSR 300	IMSR 80
Capital cost	20.27	21.92	28.60	70.48
Operational cost	9.23	13.85	17.15	44.73
Fuel cycle-Front end	7.95	7.01	7.44	9.25
Fuel cycle-Back end	1.24	1.20	1.21	1.24
D&D sinking fund	0.16	0.15	0.17	0.35
Total ($/MWh)	**39.38**	**44.13**	**54.58**	**126.05**

This is because AP1000 has much higher installed capacity(1000MW) as compared to IMSR 600 (291MW) hence, AP1000 gets favoured by the rule of economies of scale(Mignacca & Locatelli, 2020; Samalova et al., 2017).

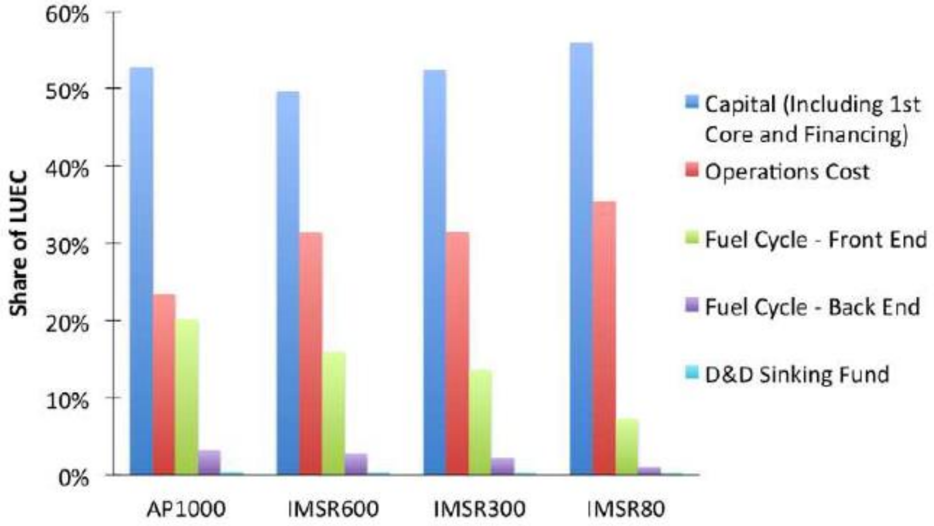
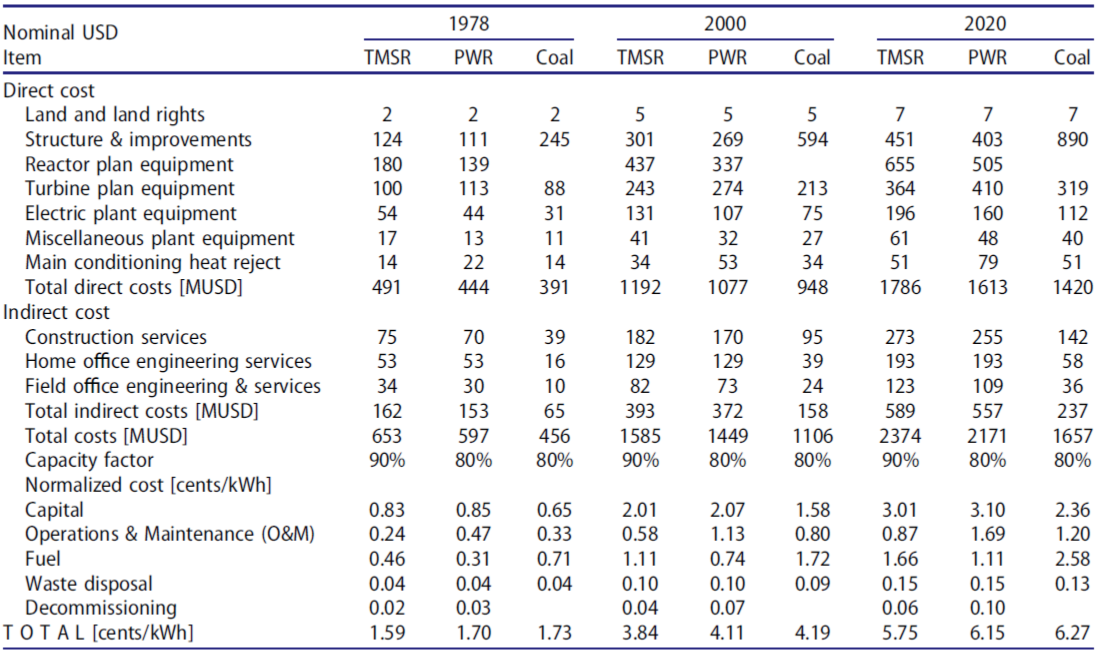


Figure 24: Source(Samalova et al., 2017)

Therefore, it was concluded that replacing PWR/LWR type reactor with MSR type reactor would result in an overall cost reduction of up to 10%. However, the updated calculation in 2020 by (Emblemsvåg, 2022) stands as an upgrade to earlier cost estimates of the MSR type reactors including the works of (Delene, 1994; Moir, 2002) published in 1978 and 2000 respectively based on the most recent safety, licensing and regulatory requirements provides a more conservative cost estimation as shown in table 5.

Table 5: Cost figures for a 1000 MWe reference power plant as analysed in 1978, by sourcing information from (Delene 1994; Engel et al. 1980; Moir 2002; Emblemsvåg 2022) for 1978 , 2000 and 2022 respectively.



Nominal USD	1978			2000			2020		
Item	TMSR	PWR	Coal	TMSR	PWR	Coal	TMSR	PWR	Coal
Direct cost									
Land and land rights	2	2	2	5	5	5	7	7	7
Structure & improvements	124	111	245	301	269	594	451	403	890
Reactor plan equipment	180	139		437	337		655	505	
Turbine plan equipment	100	113	88	243	274	213	364	410	319
Electric plant equipment	54	44	31	131	107	75	196	160	112
Miscellaneous plant equipment	17	13	11	41	32	27	61	48	40
Main conditioning heat reject	14	22	14	34	53	34	51	79	51
Total direct costs [MUSD]	491	444	391	1192	1077	948	1786	1613	1420
Indirect cost									
Construction services	75	70	39	182	170	95	273	255	142
Home office engineering services	53	53	16	129	129	39	193	193	58
Field office engineering & services	34	30	10	82	73	24	123	109	36
Total indirect costs [MUSD]	162	153	65	393	372	158	589	557	237
Total costs [MUSD]	653	597	456	1585	1449	1106	2374	2171	1657
Capacity factor	90%	80%	80%	90%	80%	80%	90%	80%	80%
Normalized cost [cents/kWh]									
Capital	0.83	0.85	0.65	2.01	2.07	1.58	3.01	3.10	2.36
Operations & Maintenance (O&M)	0.24	0.47	0.33	0.58	1.13	0.80	0.87	1.69	1.20
Fuel	0.46	0.31	0.71	1.11	0.74	1.72	1.66	1.11	2.58
Waste disposal	0.04	0.04	0.04	0.10	0.10	0.09	0.15	0.15	0.13
Decommissioning	0.02	0.03		0.04	0.07		0.06	0.10	
TOTAL [cents/kWh]	1.59	1.70	1.73	3.84	4.11	4.19	5.75	6.15	6.27

2.8 Decarbonisation Pathways for MSR type reactors deployment in Marine Environment

This study draws inspiration from marine deployment of Generation II-III PWR reactors as both mobile and stationary assets namely, Nuclear Ships (NS) and stationary Floating Nuclear Power Plants (FNPPs) discussed in earlier sections in order to make the case for potential deployment of Generation IV MSR reactors in the form of two different Pathways A and B analysed by considering three main criteria namely, technological readiness level (TRL), economic requirements (NPV), and the involved regulatory framework (REG).

2.9 Pathway A: Shipboard Nuclear Reactor

In the context of this study, Pathway A is referred to as direct electrification by using Shipboard Generation IV Nuclear Reactors (Emblemsvåg, 2021; Furfari & Mund, 2022).

2.9.1 Technological Readiness Level (TRL)

The concept of Technological Readiness Level (TRL) was originally developed by NASA and later adopted by the U.S department of defence as a means to evaluate complex technologies that were designed to operate under extremely harsh environments such as warfare and space-flight (Mankins, 1995; Sowder, 2015). In essence TRL is meant to measure the level of maturity of a particular technology in the scale of 1 to 9, 1 being on paper initial descriptions of the engineering and scientific principles while 9 being full maturity particularly commercial deployment (DoD, 2011). Considering nuclear propulsion has been in application in the marine environment for over the past 60 years in both naval and civilian applications, therefore system integration is already matured from the Naval Architecture point of view as shown in figures 25 and 26.

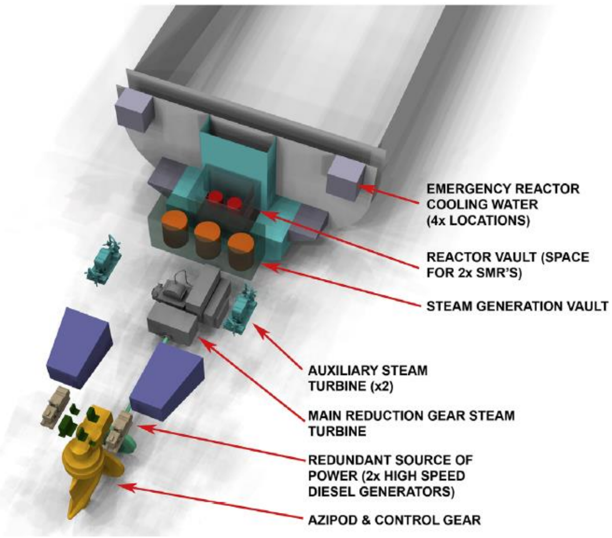


Figure 25: Planar Layout of Electric Propulsion Powered by Generation IV Shipboard Nuclear Reactor (Hirdaris et al., 2014)

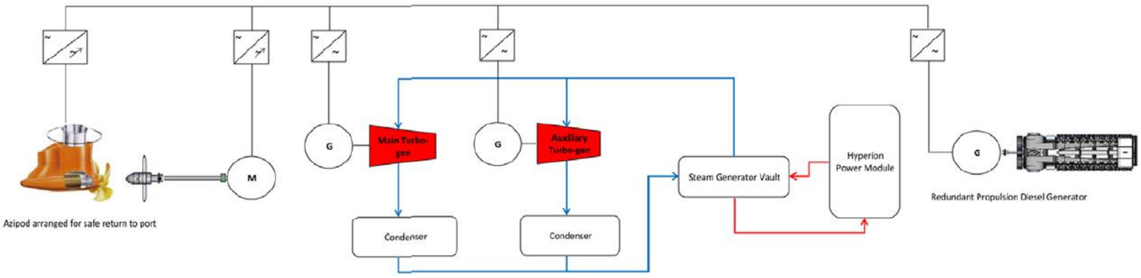
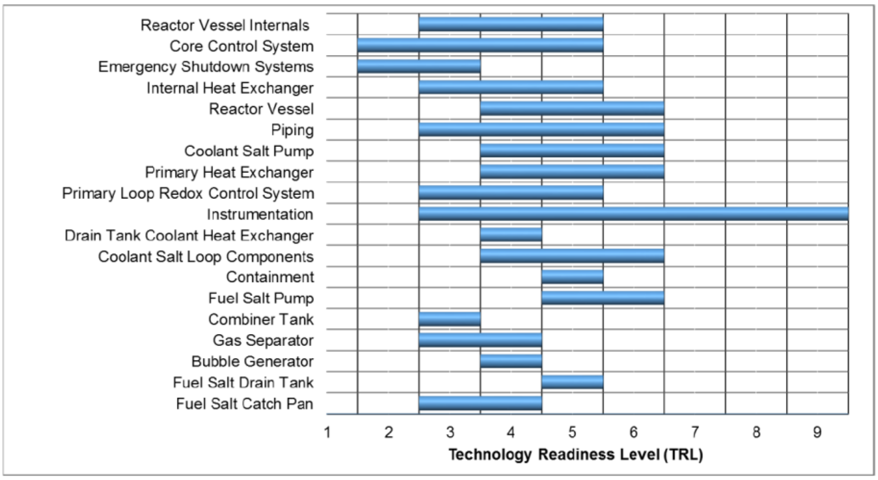


Figure 26: Schematic Layout of Electric Propulsion Powered by Generation IV Shipboard Nuclear Reactor (Hirdaris et al., 2014)

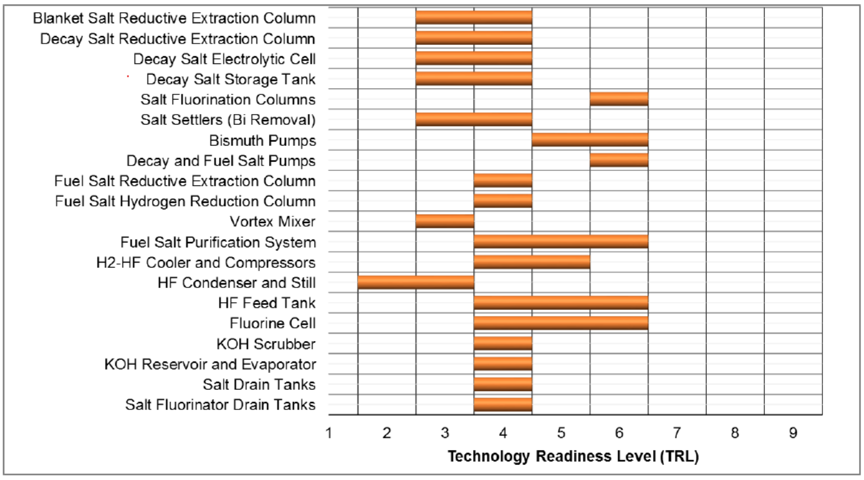
However, the Generation IV MSR reactor technology is the key component that is still in the late stage of development or the early demonstration stage (Emblemsvåg, 2021; Sowder, 2015). Therefore, in this study TRL will only be assessed based on the reactor technology. Using the Liquid Fuelled Thorium Reactor model as case study, four main elements are identified in the study on TRL published by (Sowder, 2015) namely reactor cell (along with the reactor vessel as well as other primary loop components such as supporting pumps, primary heat exchanger, and containment), Chemical processing system, Off-gas handling system and Power conversion system. Of the aforementioned four elements, the power conversion system is already a matured technology, hence it is not part of the TRL assessment. Also, Off-gas handling system is not analysed at a component level therefore it is as well not included in the TRL assessment.

Table 6: Technological Readiness of the Reactor cell (Sowder, 2015)



However, the reactor cell forms the key part of TRL assessment as most of its components are not matured yet. As seen in the table 6 above all components except for instrumentation systems which fall under the category of matured technologies do not perform beyond TRL 6, instead they score TRL between 3 and 6 which means late development to early demonstration stages.

Table 7: Technological Readiness of the Chemical processing system (Sowder, 2015)



Similarly, in the case of the Chemical processing system as shown in table 7 all components are observed to perform not more than TRL 6, instead they score TRL between 3 and 6 which also means late development to early demonstration stages (Sowder, 2015).

2.9.2 Life Cycle Cost (NPV)

A number of studies have been conducted on the financial performance of seagoing ships powered by PWR type nuclear reactors in comparison with those powered by Two stroke HFO engines. Despite higher capital costs of the nuclear option, the consensus amongst researchers is that the nuclear option has superior financial performance over 2 stroke HFO engines from the life cycle perspective(Carlton et al., 2010; Namikawa et al., 2011). By using the Net Present Value (NPV) financial indicator as a measure of life cycle costing, (Namikawa et al., 2011) estimates the total cost of operating a nuclear powered containership as 16% less than the HFO fuelled ship with the reactor cost of $4000 per KW and HFO price of $350 (in the year 2010) per ton as assumptions. On the other hand, the nuclear option on bulk ships (Bulkers and Tankers) was found to be 8% less than the HFO fuelled ship with the reactor cost of $4500 per kW and HFO price of $400 per ton as assumptions (Namikawa et al., 2011). The conclusions to be made from the aforementioned study is that deployment of PWR type reactors in seagoing vessels is more cost effective for containerships than bulk carriers and tankers. However, the purpose of this study is to analyse financial implications of a different type of reactor technology (MSR type reactor) to different ship types and sizes. Therefore, the above-mentioned financial performance of PWR type reactors will only be used to provide guidelines on cost elements for the detailed financial analysis of shipboard MSR type reactors in the Chapter 5.

2.9.3 Regulatory Framework

The regulatory framework for nuclear powered merchant vessels comprises of a variety of regulatory stakeholders such as the International Maritime Organization (IMO), the International Atomic Energy Agency (IAEA), Classification societies, Local Maritime Administrations, Local Nuclear Regulatory Authorities, Port state, Flag states and so on. In the context of International regulatory on the use of Nuclear energy at sea, the IAEA in association with the IMO (then IMCO) published guidelines on safety considerations in the use of Ports and Approaches by Nuclear Merchant Ships in 1968(IAEA, 1968). Moreover, In the context of international shipping regulation, the IMO regulatory regime for nuclear powered merchant vessels powered by onboard PWR type reactors is already in place since 1974 in the form of comprehensive routines for daily inspection and maintenance that have been outlined in the Chapter VIII of the SOLAS convention(Carlton et al., 2010; Namikawa et al., 2011).

Table 8: Regulatory Framework of Nuclear-powered merchant vessels(Namikawa et al., 2011)

	Government		**Flag/ IMO**	**Class**	**Port Authority**
	national nuclear	international nuclear	SOLAS		ISPS
Design & Construction	X	X	X	X	
Operation		X	X	X	X
Decommission	X	X			
Disposal	X	X			

As a supplement to Chapter VIII of the SOLAS convention, the detailed IMO Resolution A.491 (XII) CODE OF SAFETY FOR NUCLEAR MERCHANT SHIPS was adopted in 1981. On the other hand, classification societies particularly Det Norske Veritas (DNV) and Lloyd's Register (LR) have also published regulatory frameworks on nuclear powered merchant vessels. Both DNV and LR published a comprehensive high level set of rules for nuclear propulsion (in 2010) focusing on safety in integrating a licensed reactor into a ship to be applied when the industry is ready to uptake nuclear propulsion (Jenkins, 2021; Namikawa et al., 2011). More recently, the United Kingdom has paved the way on regulatory readiness for Port and Flag-states through approval of the Merchant Shipping (Nuclear Ships) Regulations by the parliament in 2021. It should be noted that the existing regulatory framework was tailored to serve the regulatory requirements of conventional PWR type reactors in the marine environment. In that regard, deployment of Generation IV MSR type reactors would require amendments of the existing regulations with regards to operation, safety, and licensing in order to accommodate unconventional features of new reactors such as higher operating temperatures which requires different materials for reactor construction, the use of molten salts that comes with corrosion problems, as well as online fuel processing with complex chemistry (DoE, 2002; Sowder, 2015).

2.10 Pathway B: e-Ammonia as Nuclear Energy Carrier

In the context of this study, this is the indirect electrification pathway involving the Power-to-Ammonia-to-Power fuel cycle. Under this pathway, shipboard Proton Exchange Membrane Fuel Cells (PEMFC) are fed with e-Ammonia produced in offshore nuclear powered ammonia generation platforms that use sea water and air as feedstock for electrolysis and haber-bosch processes respectively. For the purpose of powering ships, Ammonia as hydrogen carrier for running PEMFC has been chosen because of its 100% emission reduction potential from the tank to wake perspective(Gore et al., 2022), along with other attractive features such as less complex storage requirements due to its relatively high volumetric energy density as well as its well established world supply chain(Kim et al., 2020; Mallouppas & Yfantis, 2021).

2.10.1 Technological Readiness Level (TRL)

TRL assessment in this section is divided in two main categories the first one being nuclear powered offshore green ammonia production as shown in figure 27, and the second category being systems level configuration of a green ammonia powered ship propulsion system as seen in figure 28. Nuclear powered offshore green ammonia production requires a floating installation equipped with a MSR type nuclear reactor for generation of electricity. Electricity powers the electrolysis process for hydrogen generation by using sea water as feedstock. By using the Haber-Bosch process hydrogen is combined with nitrogen extracted from air to form Ammonia(Mallouppas & Yfantis, 2021). Both the electrolysis process by using PEM electrolysers and haber-bosch process are mature technologies(Megginson, 2022), therefore they are not covered in the TRL assessment. Furthermore, it should be noted that the MSR type reactor to be deployed in Pathway B is required to be of Gigawatt-scale (in excess of 1000MWe) in order to take advantage of the concept of economies of scale in fuel synthesis.

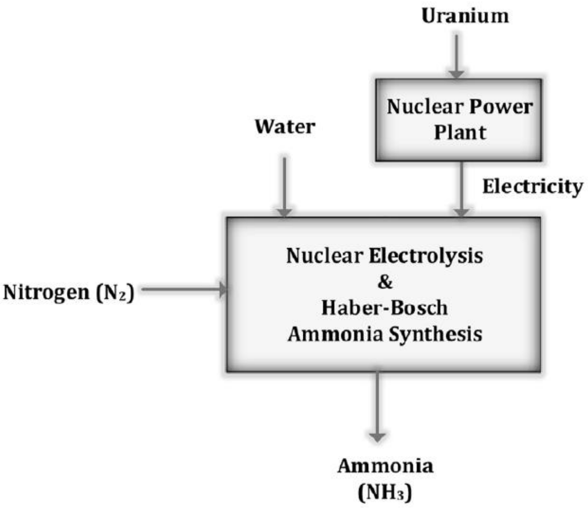


Figure 27: Nuclear Powered e-Ammonia Production (Bicer & Dincer, 2017)

However, the reactor technology in this Pathway is the same as that of Pathway A, hence the TRL ratings are considered to be the same for both pathways A and B.

On the other hand, this study has chosen green ammonia powered electric propulsion for TRL assessment in order to limit the number of externalities of ammonia when used in Internal Combustion engines, particularly NOx emission. This study adopts the setup proposed in the research works by (Kim et al., 2020; Perčić et al., 2022) with main components of the ammonia powered electric propulsion being the fuel tank, cracker, purifier, PEMFC, power electronic converters, and propulsion motors.

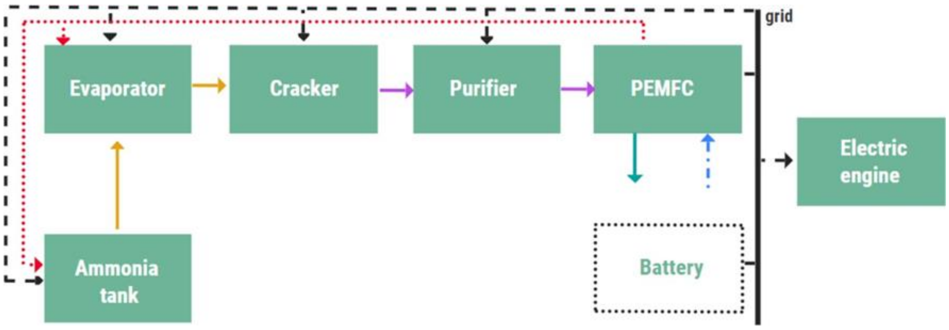


Figure 28: Ammonia powered electric propulsion with PEM Fuel cell (Perčić et al., 2022)

In this setup all the components are technologically matured (TRL score 9) therefore, they are not included in the TRL assessment. Liquefied Ammonia has a well-established supply chain especially for the fertiliser industry. Partly because it has a relatively high volumetric energy density than hydrogen, relatively easy to handle also it has less demanding storage requirements at -33°C in storage tanks, therefore the shipping industry has accumulated adequate experience in transporting ammonia world-wide (Foretich et al., 2021). Similarly, unlike the most energy efficient Solid-oxide Fuel Cells (SOFC) fuel cells currently under development, PEMFC in the Electric propulsion arrangement is a matured technology in shipping(Kim et al., 2020; Mallouppas & Yfantis, 2021), that is why it has been preferred in this study.

2.10.2 Life Cycle Cost (NPV)

This section will be limited to the financial performance of ammonia powered electric propulsion. A study was recently conducted aimed at analysing the cost of deploying four alternative fuel technologies i.e Methanol, LNG, Green Hydrogen, and Green Ammonia on Irish ports for 20 most frequently calling ships in the year 2019. Despite its 100% emission reduction (tank to wake) which ranks first amongst the given alternatives, the Green Ammonia in combination with PEMFC (as hydrogen carrier) was observed to have a Negative NPV(Gore et al., 2022).

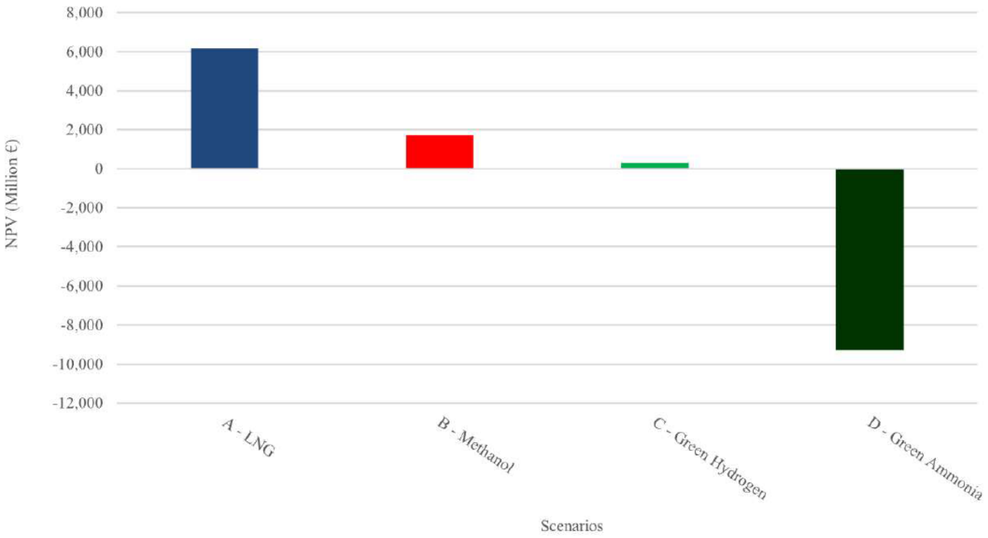


Figure 29: NPV Comparison of Alternative Fuels(Gore et al., 2022)

One of the reasons for the negative NPV is higher prices of green ammonia produced by renewable electricity. Since fuel price is one of the most sensitive factors in NPV calculations, lower green ammonia prices would mean better NPV. In that regard, the methodology section of this study employs a detailed financial analysis of atomically generated green ammonia as fuel in combination with PEMFC.

2.10.3 Regulatory Framework

The regulatory framework for using ammonia as maritime fuel is rooted in two key regulatory instruments, the first on being the International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels (IGF Code).In the context of IGF, (Kim et al., 2020) argues that the code is not compatible with deployment of ammonia as maritime fuel hence, partial amendments needs to be done. Similarly, amendments need to be done with regards to the International Gas Carrier Code (IGC Code) in order to allow ammonia to be used as maritime fuel. On the other hand, despite non-existence of classification rules for using ammonia as a fuel for ships, classification societies have already formulated class rules for ammonia carrier ships such as ammonia tankers, and refrigerated ships using ammonia, hence these can be used as a starting point for developing rules for ammonia as a fuel(Kim et al., 2020).

2.11 Chapter Summary

In this chapter, the existing instruments for the sustainable maritime industry set by the IMO have been examined and found to be insufficient to meet agreed sustainability goals in the international shipping segment out of the overall targets that are in line with the Paris Agreement and Sustainable Development Goals (SDG 2030). Hence, the proposition of incorporation of the primordial energy source (Nuclear Power) into the mix, of which, the existing Generation II-III technology has been observed to be not sustainable. In that respect, Generation IV MSR reactors deployment in two Pathways based in fleet-electrification, Shipboard Generation IV Nuclear Reactors as Pathway A, and Shipboard PEMFC fuelled by e-ammonia as nuclear energy carrier as Pathway B. In the next chapter (Chapter 3), TOPSIS decision making model is proposed for ranking two decarbonisation Pathways with respect to ship types and sizes.

CHAPTER 3-Methodology

3.1 Introduction

This chapter discusses the approach taken to answer research questions and objectives set in section 1.5. This study employs a Multi-Criteria Decision Making (MCDM) scheme for matching the most promising technological pathways of MSR type nuclear reactors deployment in the marine environment for powering different oceangoing vessel types and sizes. In the context of this work, Pathway A refers to as the decarbonization pathway that requires Shipboard Nuclear reactor as the source of propulsion power, while on the other hand, Pathway B refers to as the decarbonization pathway that requires e-Ammonia as Nuclear energy carrier in combination with PEMFC as the source of propulsion power. Amongst available alternatives, TOPSIS methodology has been chosen to implement a MCDM scheme in this study.

3.2 Topsis Methodology

The Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS) as developed by (Hwang & Yoon, 1981) is a Multi Criteria Decision Making (MCDM) technique for selecting the closest alternative to the ideal solution and farthest from the negative ideal solution. The classical TOPSIS method is based on known data represented by crisp numbers on attributes from a single decision maker or a group of decision makers (Roszkowska, 2011). With regards to the complexity of most real-world problems, a number of extensions to the classical TOPSIS methodology such as Fuzzy Multiple Attribute Decision Making (FMADM), Fuzzy Multiple Attribute Group Decision Making (FMAGDM) and many others have been developed in order to deal with real life imprecision, lack of information or vagueness (Ölçer & Ballini, 2015).

In order to identify criteria and alternatives involved, this study consulted peer reviewed journal articles, technical reports, databases, and other valuable literary sources. After establishment of alternatives and criteria, expert opinions were sought in order to provide ratings of alternatives based on given criteria through questionnaires. Given the above-mentioned inputs, steps to complete the TOPSIS model were taken as outlined in figure 30.

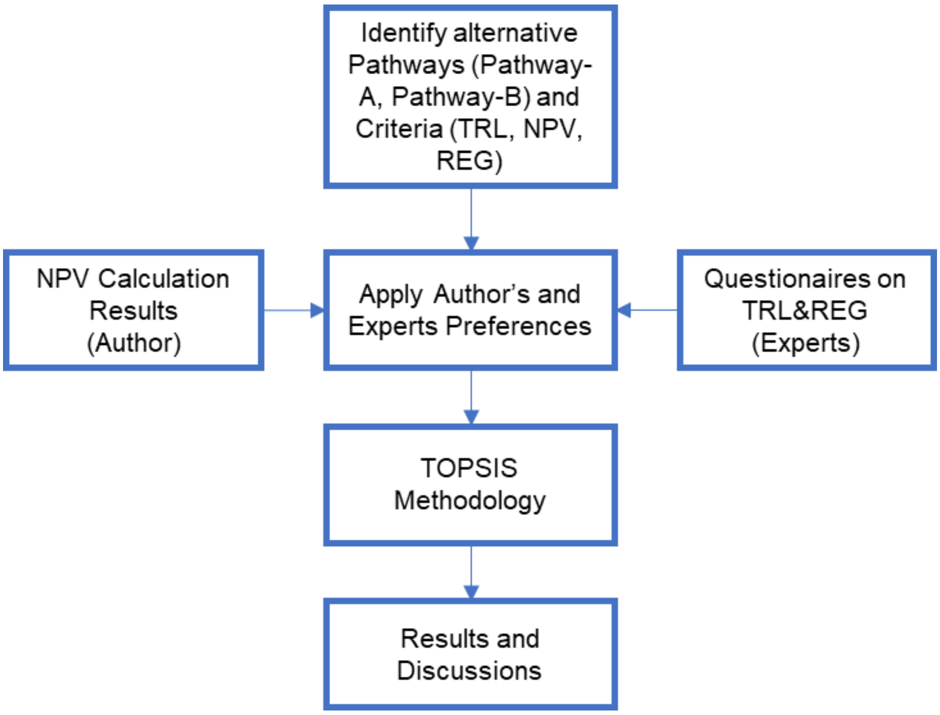


Figure 30: Methodology Roadmap (Author)

In the context of vessel types and sizes at the core of this work, two alternative decarbonization pathways to be taken by MSR type reactors are assessed against three criteria, Technological Readiness Level (TRL), Life cycle cost (NPV), and Complexity of the involved regulatory framework (REG) respectively. A detailed NPV analysis was conducted in this chapter with the help of excel modelling tools which was then used to establish performance rating for life cycle costing of energy and fuel for the two pathways under study. On the other hand, performance ratings for the remaining two criteria (Technological Readiness Level and Regulatory Complexity) were established based on expert opinions from questionnaires.

3.3 Life Cycle Cost (Net Present Value)

As a useful decision-making tool for measuring economic performance of different projects, Net Present Value (NPV) is referred to as the financial technique for conversion of cost or benefit streams occurring at different points in times over life cycle of the project to their present value equivalent and aggregating them to calculate the net value of the said cost of benefit streams(Bhattacharyya, 2019).

$$NPV = \sum_{t=1}^{N} \frac{R_t - C_t}{(1+r)^t} - I_O \quad \text{.......(1)}$$

Where, $\boldsymbol{R_t}$ = Revenue at time t, $\boldsymbol{C_t}$ = Costs in year t **,** $\boldsymbol{I_O}$ = Initial investment $\boldsymbol{t}$ = time

However, this research work is limited to the cost streams only of the chosen decarbonisation pathways because benefit streams are difficult to estimate, hence, they are ignored in the NPV analysis. NPV analysis involving cost streams only is calculated by using the modified equation 2.

$$NPV = \sum_{t=1}^{N} \frac{C_t}{(1+r)^t} + I_O \quad \text{.......(2)}$$

Moreover, in order to perform NPV calculations in the context of this work, total annual cost of ownership (annual energy generation cost) of each pathway was estimated before it got spread out over the vessel's lifetime. Calculation of total annual cost requires ships' energy cost to be established, which is the function of ship's energy consumption which is also a function of ship's fuel consumption as discussed in section 3.3.1 through 3.3.3.

3.3.1 Ship's Energy Cost

Since the second oil crisis in 1979, fuel cost has become the biggest cost item in the running of ships (Wijnolst et al., 2009). Drewry Shipping Consultants Ltd estimates that bunker fuel costs represent between 45% and 50% of ships operating costs (Rodrigue, 2020). Furthermore, a ship's fuel cost is equal to the product of fuel consumption and fuel price. Ship's fuel consumption is affected by a number of factors such as ship size, ship's hull, ships loading condition (full or ballast), weather condition (currents, waves, wind), ship's speed, fuel type, fuel quality, type and capacity of the main and auxiliary engines and so on (Wijnolst et al., 2009).

3.3.2 Ship's energy consumption

Energy in generic terms, energy is the product of power and duration. In that regard, the ship's energy consumption is given by multiplying engine power by operational time. However, in shipping only 75-85% percent of the engine's Maximum Continuous Rating (MCR) referred to as the manufacturer's tested engine power (Moreno-Gutiérrez et al., 2015) is involved in energy consumption computations as shown in equation 3 adapted from a research work by (Schrooten et al., 2008).

$$Energy\ Consumption\ (kWh) = \%\ of\ MCR\ x\ Maximum\ Installed\ Power\ (kW)\ x\ Duration\ ..(3)$$

However, the ship's load factor as an important factor affecting energy consumption as outlined in the research work by (Moreno-Gutiérrez et al., 2015) has been ignored in equation 3. However, load factor is an essential factor in ship's energy consumption, hence its inclusion in equation 7 from a research work by (Perčić et al., 2022) which is utilised in this work.

3.3.3 Ship's fuel consumption

Although the scope of this work is limited to electric-propulsion powered by PEMFC as analysed in details on section 3.6.2, it is crucial to make the conventional case of internal combustion engines for comparison purposes. In order to establish an equation for ship's fuel consumption, equation 3 is used as an input to equation 4 adapted from a research work by (Schrooten et al., 2008). Specific Fuel Oil Consumption (SFOC) is usually provided by the engine manufacturer, however in instances where SFOC is unknown, guidelines in the MEPC document by (IMO, 2021) allows approximated values to be used as 190gkWh^{-1} for the main engine and 215gkWh^{-1} respectively.

$$FOC\ (Ton) = Energy\ Consumption\ (kWh)\ x\ SFOC\ (gkWh^{-1})\ x\ 1.1\ x\ 10^{-6} \ldots\ldots(4)$$

3.4 Classical TOPSIS ranking of decarbonisation pathways under study

As introduced in section 3.2, this work employs a Classical TOPSIS approach which in this case involves a combination of performance ratings of the decarbonisation Pathways in linguistic form from two experts in the subject under study having different priorities. The first expert is both a University Professor and Researcher from the academic background, while the second expert is a Technology Provider from the industrial background. Furthermore, the Classical TOPSIS model developed in chapter 4 uses the results of the NPV analysis developed by using the methodology presented in section 3.3 as performance ratings for the Life Cycle Cost criteria. Moreover, the following list of steps were utilised in establishing a Classical TOPSIS model, as adapted from a research work by (Roszkowska, 2011) with references to previous works by (Chen & Hwang, 1992; Jahanshahloo et al., 2006).

1.Establish a decision matrix consisting of proper performance ratings (PR) and criteria weights (W)

Let X =$\left(X_{ij}\right)$ be a decision matrix for a single decision maker,

However, for problems involving multiple decision makers, equation () is used,

$$X_{ij} = \frac{1}{K}\left[X_{ij}^{1} + X_{ij}^{2} + \cdots + X_{ij}^{K}\right] \ldots..(9)$$

W = $[\mathrm{w}_1, \mathrm{w}_2, \ldots.., \mathrm{w}_n]$ be a weight vector

Where,

$K =$ the n^{th} decision-maker, also $X_{ij} \in \mathbb{R}$, $\mathrm{w}_j \in \mathbb{R}$ and $\mathrm{w}_1 + \mathrm{w}_2 + \cdots + \mathrm{w}_n = 1$

A benefit criteria (0) means more of it is better, while a cost criteria (1) means less of it is better.

2.Normalise the decision matrix

$$n_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{m} X_{ij}^{2}}}$$

$$n_{ij} = \frac{X_{ij}}{max_i\, X_{ij}}$$

$$n_{ij} = \begin{cases} \dfrac{X_{ij} - min_i\, X_{ij}}{max_i\, X_{ij} - min_i\, X_{ij}} & if\ C_i\ is\ a\ benefit\ criterion \\ \dfrac{min_i\, X_{ij} - X_{ij}}{max_i\, X_{ij} - min_i\, X_{ij}} & if\ C_i\ is\ a\ cost\ criterion \end{cases}$$

For i = 1,…,m; j = 1,…, n

3.Set up a weighted normalised decision matrix (WNR)

$$\vartheta_{ij} = \mathrm{w}_j n_{ij} \text{ for } i = 1,\ldots,m;\ j = 1,\ \ldots,\ n.$$

Where, w_j is the weight of $j - th$ criterion, $\sum_{j=1}^{n} \mathrm{w}_j = 1$.

4. Calculate the Positive Ideal Solution (PI) and Negative Ideal Solution (NI)

Where Positive Ideal Solution is given by,

$$A^+ = (\vartheta_1^+, \vartheta_2^+, \dots., \vartheta_n^+) = \big((max_{ij} \mid j \in I), (min_{ij} \mid j \in J)\big)$$

Where Negative Ideal Solution is given by,

$$A^- = (\vartheta_1^-, \vartheta_2^-, \dots., \vartheta_n^-) = \big((max_{ij} \mid j \in I), (min_{ij} \mid j \in J)\big)$$

For I relates to the benefit criteria, and J relates to the cost criteria, while i = 1,…,m; j = 1, …, n.

5. Compute separation measures from PI (PI-ϑ_{ij}) and NI (NI-ϑ_{ij})

$$d_i^+ = \sum_{j=1}^{n}((\vartheta_{ij} - \vartheta_j^+)^p)^{1/p}\ ,\ i = 1,2, \dots, m.$$

$$d_i^- = \sum_{j=1}^{n}((\vartheta_{ij} - \vartheta_j^-)^p)^{1/p}\ ,\ i = 1,2, \dots, m.$$

Where $p =\geq 1$.

however, the most used traditional n-dimensional Euclidean metric is computed

For $p = 2$ as shown below,

The separation of alternatives from Positive Ideal Solution,

$$\boldsymbol{S}_i^+ = \sqrt{\sum_{j=1}^{n}(\vartheta_{ij} - \vartheta_j^+)^2},\ i = 1,2, \dots, m.$$

The separation of alternatives from Negative Ideal Solution,

$$\boldsymbol{S}_i^- = \sqrt{\sum_{j=1}^{n}(\vartheta_{ij} - \vartheta_j^-)^2},\ i = 1,2, \dots, m.$$

6. Compute relative closeness to the Positive Ideal Solution (OAR)

$$R_i = \frac{\boldsymbol{S}_i^-}{\boldsymbol{S}_i^- + \boldsymbol{S}_i^+}$$

Where $0 \leq R_i \leq 1, i = 1,2, \dots, m$

7. Rank the order of preferences of alternatives,

The alternatives are ranked in a descending order of R_i

3.5 Chapter Summary

This chapter has presented the chosen methodology which lays the groundwork for data collection, MCDM model formulation, data analysis, presentation, and analyses in Chapter 4. Chapter 4 as well presents the chosen Case Study, Results and Discussions.

Chapter 4 - Case Study: Containership, Bulker and Tanker

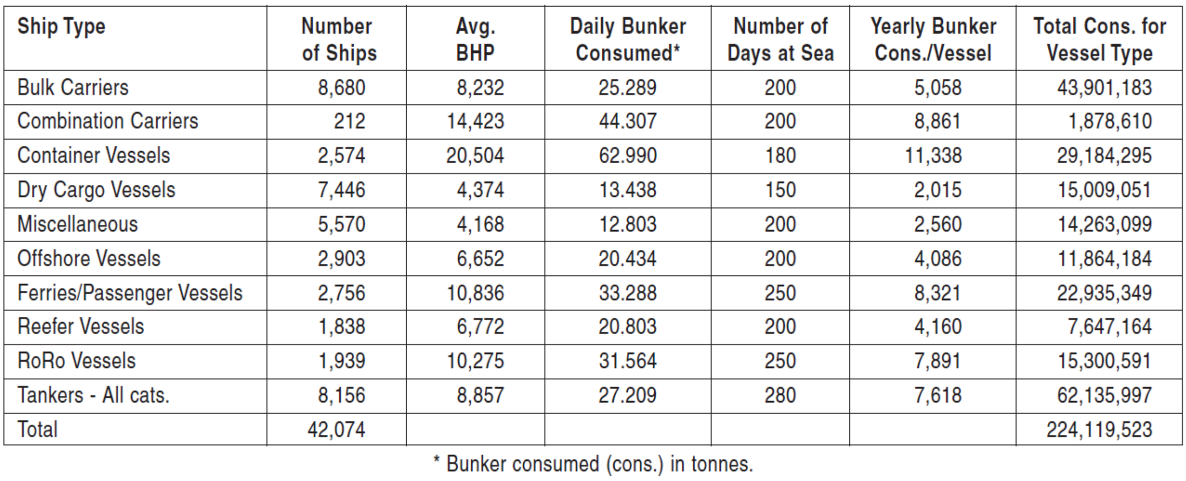
4.1 Introduction

This study focuses on three of the most polluting seagoing vessels namely, container ships (at 23%), bulk carriers (at 19%), and oil tankers (at 13%) accounts for 55% of total GHG emissions from shipping, which is equivalent to 84% of emissions originated from total shipping transport work measured in deadweight ton-nautical mile or ton-mile (Olmer et al., 2017). This study assesses small sized, medium sized and large sized vessels under appropriate assumptions as discussed in sections.

4.2 Assumptions on targeted ship types under study

For the purpose of this study, the engine's installed capacity (engine's MCR) is regarded as the only parameter differentiating vessel sizes. Therefore, representative MCR values for a small vessel are assumed to be rated at 7MW, medium sized vessel at 15MW, and large sized vessel at 30MW respectively. On the other hand, ship's operational profile is assumed to be the sole differentiating factor between different ship types of the same MCR, of which the number of operational days at sea as shown in table 9 also as updated in the Fourth GHG Study by (S. Faber et al., 2020) is assumed to be differentiating factor between ship types.

Table 9: The operational profile of ships types under study(GESAMP, 2007)



Ship Type	Number of Ships	Avg. BHP	Daily Bunker Consumed*	Number of Days at Sea	Yearly Bunker Cons./Vessel	Total Cons. for Vessel Type
Bulk Carriers	8,680	8,232	25.289	200	5,058	43,901,183
Combination Carriers	212	14,423	44.307	200	8,861	1,878,610
Container Vessels	2,574	20,504	62.990	180	11,338	29,184,295
Dry Cargo Vessels	7,446	4,374	13.438	150	2,015	15,009,051
Miscellaneous	5,570	4,168	12.803	200	2,560	14,263,099
Offshore Vessels	2,903	6,652	20.434	200	4,086	11,864,184
Ferries/Passenger Vessels	2,756	10,836	33.288	250	8,321	22,935,349
Reefer Vessels	1,838	6,772	20.803	200	4,160	7,647,164
RoRo Vessels	1,939	10,275	31.564	250	7,891	15,300,591
Tankers - All cats.	8,156	8,857	27.209	280	7,618	62,135,997
Total	42,074					224,119,523

* Bunker consumed (cons.) in tonnes.

4.3 Assumptions on financial calculations under study

For Pathway-A, discount rate is assumed to be 6.5% which originates from averaging Weighted Average Cost of Capital (WACC) across 19 countries under appropriate financial assumptions(Emblemsvåg, 2021), this figure is as well echoed by (world Nuclear Association, 2021a) at 7% respectively. Since the cost elements of an experimental 1000MW MSR type plant as shown in table 10 sourced from the research work by (Emblemsvåg, 2022) are used as the baseline for establishment of cost figures for Pathway A, the cost to capacity method (power law) as represented by equation 7 is employed for extrapolation of cost figures from the 1000MW experimental plant to 7MW, 15MW, and 30MW plants under study.

Table 10: Baseline cost figures for 1000MW MSR type power plant (Emblemsvåg, 2022)

S/N	Cost element	Cent/kWh
1.	Capital	3.01
2.	O&M	0.87
3.	Fuel	1.66
4.	Waste disposal	0.15
5.	Decommissioning	0.06
	Total cost	5.75

Furthermore, given information in table 10, annual cost of running the plants at 7MW, 15MW and 30MW is calculated by using equation 5,

$$Annual\ cost = Total\ cost/kWh\ \ x\ annual\ operational\ hours\ x\ plant\ capacity \ldots\ldots (5)$$

Where,

$Total\ cost/kWh$ = standardised total plant's cost per kWh from table 10,

$Annual\ operational\ hours$ = ship specific plant's annual operational hours derived from ships' operational profiles as shown in table 9,

$Plant\ capacity$ = the installed capacity of the plant (7MW, 15MW and 30MW).

See further assumptions along with the detailed analysis for Pathway-A in section section 4.4.1

On the other hand, for Pathway-B, the discount rate was assumed to be the same as the one sourced from one of the most recent research works by (Gore et al., 2022) relevant to this study at 4%. Furthermore, cost elements per kW referred to as the base case under this study were also adapted from the same research work except for cost element No.4 in table 11 (Fuel Cost), the cost of atomically generated ammonia is sourced from the financial model by Core Power, a UK based company that is currently working on deployment of new generation of Nuclear reactors in the marine environment, see (CORE-POWER, 2021)

Table 11: Baseline cost figures for Green Ammonia Fuelled PEM Fuelcell Propulsion System (Gore et al., 2022).

S/N	**Cost element**	**$/kW**
1	PEM Fuel cells installation (Including fuelcell replacement once in the ship's lifetime)	371
2	Cracker and Purifier Installation	111.3
3	Fuel Tank Installation	540
4	Fuel	1175 per MT

See further assumptions along with the detailed analysis for Pathway-B in section 4.4.2

4.4 Net Present Value Analysis for the Two Pathways

Molten Salt Reactors are still in their late development to early demonstration stages (Emblemsvåg, 2021; Sowder, 2015) which means they are currently not commercially available hence, for Pathway A, cost estimates per unit energy output are sourced from the 1000MWe experimental plant operated by the Oak Ridge National Laboratory (ORNL) between 1960s and 1970s as upgraded in 1994 (Delene, 1994), 2000 (Moir, 2002), 2021 (Emblemsvåg, 2021) and 2022 (Emblemsvåg, 2022) respectively in order to account for the most recent safety, licensing and regulatory requirements. On the other hand, for Pathway B, price of atomically generated green ammonia from a model developed by Core Power (UK) together with estimated ship's green ammonia consumption given by equation 5 above were used as a basis for estimating annual energy cost for the three ship types and sizes.

4.4.1 Pathway A: Shipboard Nuclear Reactor

Considering the assumptions made on sections 4.2 and 4.3 above particularly on ship types and sizes, ships' operational profiles, and cost elements of the base case, the estimated annual cost of running MSR type ship propulsion plants at 7MW, 15MW and 30MW respectively were calculated through the extrapolation of the baseline cost of the 1000MW experimental plant. The extrapolation methodology that was adopted by this study is the Power law technique represented as equation 7.

$$\frac{C_2}{C_1} = \left(\frac{Q_2}{Q_2}\right)^x \dots\dots\dots\dots\dots\dots (7)$$

Where,

C_2 = unknown cost of facility to be estimated

C_1 = known cost of a facility

Q_2 = known capacity of a facility, associated with C_2

Q_1 = known capacity of a facility, associated with C_2

X = Scaling factor for a common technology of the two facilities, 1 and 2.

The power law technique which is also referred to as the cost-to-capacity method was originally developed by (Williams, 1947) for establishing equipment cost estimates, the rationale behind it being costs of mechanical equipment or facilities of similar technology but with different sizes vary exponentially (Baumann, 2014). Furthermore, (Baumann & Lopatnikov, 2017) argues that power laws are essential in establishing cost estimates for industrial plants and equipment in cases of uncertainties concerning specific design or configuration involved. In a practical case, the scaling factor "X" as shown in equation 7 for thermal power systems with steam turbines is given in the range between 0.70 and 0.72 as per the quality guidelines for energy system studies provided by the U.S. Department of Energy (Turner & Pinkerton, 2013). For the purpose of this work, 0.71 has been used as the scaling factor as it has as well been used in the research work on shipboard MSR type power plants by (Emblemsvåg, 2021).

After establishing annual cost of running MSR type ship propulsion plants at 7MW, 15MW and 30MW for ship types under study, their respective NPVs were calculated by using equation 2, assuming the ships' life time to be 30 years at the discount rate of 6.5% as stated in the financial assumptions section (4.3). Finally, the results were summarised and tabulated in table 12. See the appendix section for detailed calculations.

Table 12: Life cycle cost of a Shipboard Nuclear reactor, Source (Author, 2022)

Plant cost	**Ship size**	**Container ship**	**Bulk carrier**	**Tanker ship**
Life cycle cost, NPV ($)	Small (7 MW)	99,531,948.93	110,591,054.37	154,827,476.11
	Medium (15MW)	170,988,811.47	189,987,568.30	265,982,595.62
	Large (30MW)	279,704,201.78	310,782,446.43	435,095,425.00

Table 9

4.4.2 Pathway B: e-Ammonia as Nuclear Energy Carrier in combination with PEM Fuel cells

Considering the assumptions made on sections 4.2 and 4.3 above particularly on ship types and sizes, ships' operational profiles, and cost elements of the base case, the annual cost of running the e-Ammonia fuelled PEMFC propulsion plants is estimated independently at 7MW, 15MW and 30MW respectively.

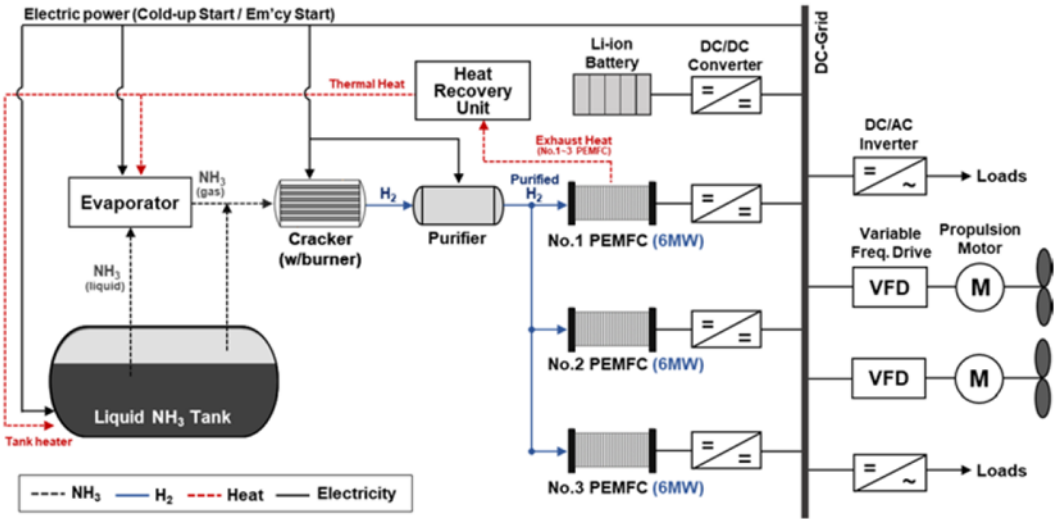


Figure 31: Green Ammonia fuelled PEM Fuel cell-electric propulsion plant (Kim et al., 2020)

In this ship propulsion arrangement as shown in figure 31, ammonia from the fuel tank is passed through the cracker where it is decomposed into Hydrogen and Nitrogen and then passed through the purifier which filters out Nitrogen and allowing only Hydrogen to be fed to fuel cells as shown equation 7 for calculating ammonia consumption (in metric tonnes) adapted from (Gore et al., 2022; Perčić et al., 2022).

$$Fuel\ Consumption\ (Ton) = \sum_i \left(\frac{T\ x\ P_{CL}\ x\ L_{CL}}{\eta_{CL}\ x\ \eta_{CR}\ x\ \eta_{PR}\ x\ NCV} \right) x10^{-3} \ldots\ldots\ldots\ldots(7)$$

Where, $\boldsymbol{T}$ = Time spent at sea, $\boldsymbol{P_{CL}}$ = Power output of fuel cell (MW), $\boldsymbol{L_{CL}}$ = Load factor of the fuel cell (%) **,** $\boldsymbol{\eta_{CL}}$ = Efficiency of fuel cells (%), η_{CR} = Efficiency of cracker (%), η_{PR} = Efficiency of purifier (%), NCV= Net Calorific Value of Ammonia.

For the purpose of this study, Time spent at sea ($\boldsymbol{T}$) is assumed to be equal to ship specific plant's annual operational hours derived from ships' operational profiles as shown in table 6, Power output of fuel cells ($\boldsymbol{P_{CL}}$) is assumed to be the same as the installed capacity of ships' power plants (at 7MW, 15MW and 30MW). On the other hand, Load factor of the fuel cells propulsion plant ($\boldsymbol{L_{CL}}$), Efficiency of fuel cells (η_{CL}), Efficiency of the cracker (η_{CR}) and Efficiency of the purifier (η_{PR}) were assumed to be 75%, 48%, 80%, and 90% respectively (Perčić et al., 2022).

On the other hand, the NCV or low heating value (LHV) of ammonia at 5.17 kWh/kg as used in equation 7 is sourced from values shown in table 10 adapted from the research works by (Foretich et al., 2021; Kim et al., 2020).

Table 13: Calorific Values of Fuels (Kim et al., 2020)

Fuel Property	Unit	HFO	Compressed Hydrogen (350 bar)	Liquid Hydrogen	Liquid Ammonia
Low heating value	MJ/kg (kWh/kg)	40.2 (11.17)	120.00 (33.33)	120.00 (33.33)	18.6 (5.17)
Volumetric energy density	MJ/m^3 (kWh/m^3)	39,564–42,036 (10,990–11,677)	5040 (1400)	8500 (2361)	14,100 (3917)
Min. auto-ignition temperature	°C	250	500–577	500–577	650–657
Boiling temperature at 1atm	°C	N/A	N/A	$^{-}253$	$^{-}33.4$
Condensation pressure at 25 °C	Atm	N/A	N/A	N/A	9.90
Hydrogen content	% by mass	N/A	100.0	100.0	17.8

Furthermore, for the case of the price of atomically generated green ammonia, the UK based company, Core Power (UK) models the price of atomically generated green ammonia as shipping fuel after factoring in all costs associated with its production in offshore floating installations and supply bunkering stations as 2.35 times higher than the current price of Intermediate Fuel Oil (IFO) 380 (CORE-POWER, 2021). Assuming the price of IFO 380 to be approximately $500 per metric ton, the price of atomically powered green ammonia at bunkering stations was estimated to be $1,175 per metric ton. At this price, atomically generated ammonia is more than 50% cheaper than the current price of green ammonia generated from renewable energy sources at $ 2,697 per metric ton as retrieved in February 2022 (Argus, 2022).

Having established the price of atomically generated green ammonia per metric tonne, total annual cost for running green ammonia on PEMFC propulsion plants for ships of types and sizes under study was calculated by using a combination of equation 5 and equation 8 below adapted from (Wijnolst et al., 2009).

$$Ship's\ fuel\ cost(\$) = Fuel\ consumption\ x\ Fuel\ price\ldots\ldots(8)$$

Again, after establishing annual cost of running the Green Ammonia fuelled PEMFC propulsion plants at 7MW, 15MW and 30MW for ship types under study, their respective NPVs were calculated by using equation 2, assuming the ships' life time to be 30 years at the discount rate of 4% as stated in the financial assumptions section (4.3). Finally, the results were summarised and tabulated in table 14. See the appendix section for detailed calculations.

Table 14: Life Cycle Cost of Green Ammonia as Nuclear energy carrier in combination with PEM Fuel cells, Source (Author, 2022)

Plant cost	**Ship size**	**Container ship**	**Bulk carrier**	**Tanker ship**
NH_3**Cost per MT ($)**	All ship sizes	1,175		
Life cycle cost, NPV ($)	Small (7 MW)	147,007,862.87	148,702,917.37	155,483,135.41
	Medium (15 MW)	315,016,849.00	318,649,108.66	333,178,147.30
	Large (30MW)	579,908,514.70	637,298,217.32	666,356,294.60

4.5 Establish a decision matrix consisting of proper performance ratings (PR) and criteria weights (W)

By using questionaires, expert opinions were sought from two types of well-established experts in the topic under study having distinct priorities, the academic expert (ER1) as well as the industrial expert (ER2). The collected expert opinions in the form of linguistic terms were converted to their equivalent crisp values by using the conversion scale shown on table 15,

Table 15: Conversion of linguistic terms into crisp values (Author)

Scale	**Rating**
Very Low (VL)	1
Low (L)	3
Average (A)	5
High (H)	7
Very High (VH)	9
Intermediate values between the two adjacent judgments	2,4,6,8

The equivalent crisp values representing expert opinions were properly summarised and tabulated as observed in table 16. In line with that, criteria weights as seen in table 14 were assigned by the author of this work where by REG is assigned more overall weight (50%), followed by NPV (30%) and finally TRL (20%) as informed by peer reviewed journal articles, technical reports, databases, and other valuable literal sources on the subject under study, refer to chapter 2.

Table 16: Expert Ratings (ER1 from the Academic Expert, ER2 from the Industrial Expert), criteria weight (Author)

		Pathway-A						**Pathway-B**					
		Container ship		**Bulk carrier**		**Tanker ship**		**Container ship**		**Bulk carrier**		**Tanker ship**	
Criteria	**Ship sizes**	ER1	ER2	ER1	ER2	ER1	ER2	ER1	ER2	ER1	ER2	ER1	ER2
TRL	Small	5	5	5	3	5	3	7	5	7	5	7	3
	Medium	5	5	5	3	5	3	7	5	7	5	7	3
	Large	5	3	5	1	5	1	7	5	7	3	7	3
NPV	Small	7	3	7	5	7	5	7	7	7	7	7	7
	Medium	5	3	5	5	5	5	7	7	7	7	5	7
	Large	3	1	3	3	3	3	5	9	7	9	3	9
REG	Small	7	9	7	9	7	9	5	5	5	5	5	5
	Medium	7	9	7	9	7	9	5	5	5	5	5	5
	Large	7	9	7	9	7	9	5	5	5	5	5	5

Expert ratings from two different experts as seen in table 16 were combined in order to form a set of aggregated expert ratings by using equation 9 and the results are presented in table 17.

Table 17: Aggregated Expert Ratings (AER), criteria weight (Author)

Criteria	**Ship sizes**	**Pathway-A**			**Pathway-B**			**Criteria Weights (Author)**
		Container Ship	**Bulk carrier**	**Tanker Ship**	**Container Ship**	**Bulk carrier**	**Tanker Ship**	
		AER	AER	AER	AER	AER	AER	
TRL	Small	5	4	4	6	6	5	0.2
	Medium	5	4	4	6	6	5	
	Large	4	3	3	6	5	5	
NPV	Small	5	6	6	7	7	7	0.3
	Medium	4	5	5	7	7	6	
	Large	2	3	3	7	8	6	
REG	Small	8	8	8	5	5	5	0.5
	Medium	8	8	8	5	5	5	
	Large	8	8	8	5	5	5	

4.6 Calculate NWR, Separation from PI and NI, relative closeness from PI (OAR), rank the order of preference of alternatives

Given NPV figures from sections 4.4.1 and 4.4.2, The Classical TOPSIS procedure presented in section 3.4 was utilised in establishing the excel MCDM model as tabulated in tables 18,19,20,21,22, and 23. From the tables, it should also be noted that performance ratings for the Life Cycle Cost (NPV) criteria utilised in the model originates from the NPV analysis developed by the author of this work.

4.6.1 Container Ship

Table 18: Experts' and Author's preferences

Criteria	ship sizes	Pathway-A		Pathway-B		Criteria Weights (Author)	Cost (1) Benefit (0)
		PR (Expert)	PR (Author)	PR (Expert)	PR (Author)		
TRL	Small	5		6		0.2	0
	Medium	5		6			
	Large	4		6			
NPV	Small		99,531,948.93		147,007,862.87	0.3	1
	Medium		170,988,811.47		315,016,849.00		
	Large		279,704,201.78		579,908,514.70		
REG	Small	8		5		0.5	1
	Medium	8		5			
	Large	8		5			

Table 19:Topsis Ranking for Containership

		PATHWAY-A				PATHWAY-B			
SMALL		**PR**	**WNR**	**Vij-PI**	**Vij-NI**	**PR**	**WNR**	**Vij-PI**	**Vij-NI**
	TRL	5	0.1280	0.0007	0.0000	6	0.1536	0.0000	0.0007
	NPV	99,531,948.93	0.1682	0.0000	0.0064	147,007,862.87	0.2484	0.0064	0.0000
	REG	8	0.4240	0.0253	0.0000	5	0.2650	0.0000	0.0253
	S_i^+	0.1610				0.0802			
	S_i^-	0.0802				0.1610			
	OAR	0.3325				0.6675			
	RANK	**2**				**1**			
MEDIUM	**TRL**	5	0.1280	0.0007	0.0000	6	0.1536	0.0000	0.0007
	NPV	170,988,811.47	0.1431	0.0000	0.0145	315,016,849.00	0.2637	0.0145	0.0000
	REG	8	0.4240	0.0253	0.0000	5	0.2650	0.0000	0.0253
	S_i^+	0.1610				0.1205			
	S_i^-	0.1205				0.1610			
	OAR	1.1610				1.1205			
	RANK	**1**				**2**			
LARGE	**TRL**	4	0.1109	0.0031	0.0000	6	0.1664	0.0000	0.0031
	NPV	279,704,201.78	0.1303	0.0000	0.0196	579,908,514.70	0.2702	0.0196	0.0000
	REG	8	0.4240	0.0253	0.0000	5	0.2650	0.0000	0.0253
	S_i^+	0.1684				0.1399			
	S_i^-	0.1399				0.1684			
	OAR	1.1684				1.1399			
	RANK	**1**				**2**			

4.6.2 Bulk Carrier

Table 20: Experts' and Author's preferences

Criteria	**Ship sizes**	**Pathway-A**		**Pathway-B**		**Criteria Weights (Author)**	**Cost (1) Benefit (0)**
		PR (Expert)	**PR (Author)**	**PR (Expert)**	**PR (Author)**		
TRL	Small	4		6		0.2	0
	Medium	4		6			
	Large	3		5			
NPV	Small		110,591,054.37		148,702,917.37	0.3	1
	Medium		189,987,568.30		318,649,108.66		
	Large		310,782,446.43		637,298,217.32		
REG	Small	8		5		0.5	1
	Medium	8		5			
	Large	8		5			

Table 21: Topsis Ranking for Bulk carrier

		PATHWAY-A				**PATHWAY-B**			
SMALL		**PR**	**WNR**	**Vij-PI**	**Vij-NI**	**PR**	**WNR**	**Vij-PI**	**Vij-NI**
	TRL	4	0.1109	0.0031	0.0000	6	0.1664	0.0000	0.0031
	NPV	110,591,054.37	0.1790	0.0000	0.0038	148,702,917.37	0.2407	0.0038	0.0000
	REG	8	0.4240	0.0253	0.0000	5	0.2650	0.0000	0.0253
	S_i^+	0.1684				0.0617			
	S_i^-	0.0617				0.1684			
	OAR	0.2681				0.7319			
	RANK	**2**				**1**			
MEDIUM	**TRL**	4	0.1109	0.0031	0.0000	6	0.1664	0.0000	0.0031
	NPV	189,987,568.30	0.1536	0.0000	0.0108	318,649,108.66	0.2577	0.0108	0.0000
	REG	8	0.4240	0.0253	0.0000	5	0.2650	0.0000	0.0253
	S_i^+	0.1684				0.1040			
	S_i^-	0.1040				0.1684			
	OAR	1.1684				1.1040			
	RANK	**1**				**2**			
LARGE	**TRL**	3	0.1029	0.0047	0.0000	5	0.1715	0.0000	0.0047
	NPV	310,782,446.43	0.1315	0.0000	0.0191	637,298,217.32	0.2696	0.0191	0.0000
	REG	8	0.4240	0.0253	0.0000	5	0.2650	0.0000	0.0253
	S_i^+	0.1732				0.1382			
	S_i^-	0.1382				0.1732			
	OAR	1.1732				1.1382			
	RANK	**1**				**2**			

4.6.3 Tanker Ship

Table 22: Experts' and Author's preferences

Criteria	Ship sizes	Pathway-A PR (Expert)	Pathway-A PR (Author)	Pathway-B PR (Expert)	Pathway-B PR (Author)	Criteria Weights (Author)	Cost (1) Benefit (0)
TRL	Small	4		5		0.2	0
	Medium	4		5			
	Large	3		7			
NPV	Small		154,827,476.11		155,483,135.41	0.3	1
	Medium		265,982,595.62		333,178,147.30		
	Large		435,095,425.00		666,356,294.60		
REG	Small	8		5		0.5	1
	Medium	8		5			
	Large	8		5			

Table 23: Topsis Ranking for Tanker ship

		PATHWAY-A				PATHWAY-B			
SMALL		**PR**	**WNR**	**Vij-PI**	**Vij-NI**	**PR**	**WNR**	**Vij-PI**	**Vij-NI**
	TRL	4	0.1249	0.0010	0.0000	5	0.1562	0.0000	0.0010
	NPV	154,827,476.11	0.2117	0.0000	0.0000	155,483,135.41	0.2126	0.0000	0.0000
	REG	8	0.4240	0.0253	0.0000	5	0.2650	0.0000	0.0253
	S_i^+	0.1620				0.0009			
	S_i^-	0.0009				0.1620			
	OAR	0.0055				0.9945			
	RANK	**2**				**1**			
MEDIUM	**TRL**	4	0.1249	0.0010	0.0000	5	0.1562	0.0000	0.0010
	NPV	265,982,595.62	0.1872	0.0000	0.0022	333,178,147.30	0.2345	0.0022	0.0000
	REG	8	0.4240	0.0253	0.0000	5	0.2650	0.0000	0.0253
	S_i^+	0.1620				0.0473			
	S_i^-	0.0473				0.1620			
	OAR	1.1620				1.0473			
	RANK	**1**				**2**			
LARGE	**TRL**	3	0.0788	0.0110	0.0000	7	0.1838	0.0000	0.0110
	NPV	435,095,425.00	0.1640	0.0000	0.0076	666,356,294.60	0.2512	0.0076	0.0000
	REG	8	0.4240	0.0253	0.0000	5	0.2650	0.0000	0.0253
	S_i^+	0.1906				0.0872			
	S_i^-	0.0872				0.1906			
	OAR	1.1906				1.0872			
	RANK	**1**				**2**			

4.7 Discussions

This study was conducted in an effort to partly fill the research gaps pinpointed in the most recent literary sources on deployment of shipboard MSR type reactors particularly the work by (Emblemsvåg, 2021) as well as the one by (Furfari & Mund, 2022) respectively. Additionally, this study attempts to fill research gaps observed in the most recent study on indirect electrification fuel life cycle (Power-to-Ammonia-to-Power) conducted by(IRENA & AEA, 2022). For shipboard nuclear power systems, the study by (Emblemsvåg, 2021) approaches technology and life cycle costs from a generic perspective focusing only on a single ship type (Aframax Tanker) with disregard to varieties of propulsion requirements associated with different vessel types and sizes. In an effort to complement the aforementioned studies, the methodology adopted by this study covers ship type and size specific propulsion requirements in a holistic manner which encompasses technological readiness level, life cycle costs and regulatory complexity.

For the purpose of establishing life cycle costs as an input to the decision-making model at the centre of the methodology of this study, propulsion power demand and ships' operational profile are two main points of departure chosen by this study. In so far as ships' propulsion power is concerned, a key assumption on representative MCR values for representing ship sizes is adopted in this study starting from 7MW (Small Size), 15MW (Medium Size), and 30MW (Large Size) respectively. For Pathway A, a top-bottom approach to cost estimation was adopted because of cost uncertainties associated with low power capacity of marine MSR type plants under study that are not yet commercially available. In this approach, life cycle costs for small, medium and large ships' power plants have been analysed based on extrapolated values (by using the cost to capacity method) of reliable and updated cost elements from the 1000MW experimental MSR type power plant. In line with that, the number of operational days at sea is assumed to be the only factor representing ships' operational profile which is the differentiating factor between different types having the same MCR under this study. On the other hand, for Pathway B, a bottom-up approach to cost estimation was adopted because standardised cost elements per kW for Ammonia Fuelled PEMFC Ship Propulsion Arrangement are known except for the price of atomically generated ammonia which is sourced from the technoeconomic model by Core Power(UK) at approximately 2.35 times the recent price of IFO 380(CORE-POWER, 2021). In this approach, life cycle costs for small, medium and large ships have been analysed independently at 7MW, 15MW, and 30MW respectively. In a similar fashion to Pathway A, the number of operational days at sea is assumed to be the only factor representing ships' operational profile which is the differentiating factor between different types having the same MCR under this study.

4.8 Results

Overall results from the decision-making model reveal Pathway B to consistently be a dominant option for all vessel types of small size (7MW). Conversely, Pathway A is revealed to consistently be a dominant option for all vessel types of medium and large sizes (15MW and 30MW). This implies that Pathway A is a superior decarbonisation option for medium and large vessels while Pathway B is a superior decarbonisation pathway for small vessels regardless of ship type under study. This opens up a number of possibilities on the idea of the 4th propulsion revolution proposed in section 1.5 in which Pathway A could be the new S-Curve for medium and large vessels for all ship types, while Pathway B could be the new S-Curve for small vessels for all ship types. Another possibility could be Pathway B could be prioritised ahead of Pathway A for all ship types and sizes on the basis of ease of acceptability to both the public and the regulatory community assuming the life cycle cost is not a stumbling-block. In whatever way the circumstances are going to play out, the combination of nuclear energy as the source of abundant electricity, electro-fuels as the most efficient way of storage of electric energy as well as fuel cells which is the most efficient means for extracting energy from electro fuels makes a good candidate for the 4th propulsion ship revolution.

4.9 Chapter Summary

This chapter has presented the case study along with discussions and results of the study. However, along with the decarbonisation potentials of the two pathways analysed in this chapter, it is crucial to assess associated externalities in order to highlight the limitations of the proposed Pathways. In that regard, Chapter 5 presents externalities assessment of decarbonisation Pathways under Study as well as proposed mitigation means.

Chapter 5. Externalities Assessment of Decarbonisation Pathways under Study

5.1 Pathway-A

This pathway focuses on direct electrification through deployment of a shipboard MSR type nuclear reactor. It has been discussed in previous chapters that MSR type nuclear reactors under this study as part of the Generation IV initiative are rooted in their enhanced capabilities to generate manageable nuclear waste, competitive economics, secure nuclear energy systems and materials, high degree of safety performance(DoE, 2002; Hirdaris et al., 2014). However, their shipboard deployment which is the focus of Pathway A comes with a number of externalities that needs to be addressed particularly in the domains of environment, economics, human element, ship design and operation.

5.1.1 Environment

It is estimated that around half a million tonnes of spent nuclear fuel will be in dry or wet storage by 2050 (Taylor et al., 2022). In that regard, large scale uptake of nuclear fuel by marine transport is associated with the potential increased levels of nuclear waste that would need to be handled in the future.

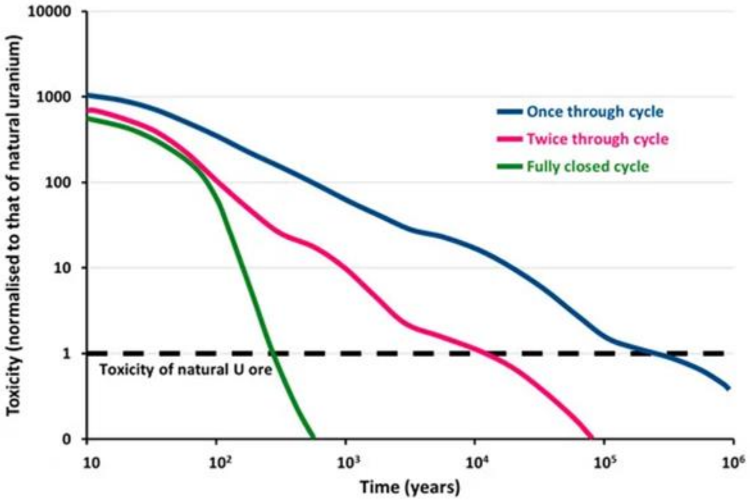


Figure 32: Nuclear Fuel Cycles(Taylor et al., 2022)

As stated in the study by (Kamei, 2011), it takes about one million years for spent nuclear fuel to reach the toxicity level of natural uranium ore (see the dotted line in figure 32) in a once-through fuel cycle as depicted by the blue line in figure 32.

However, as discussed in earlier sections, the use of generation IV nuclear reactors shows promise for not only reduced nuclear waste but also reusing spent nuclear fuel by closing the fuel cycle as shown in figure 33.

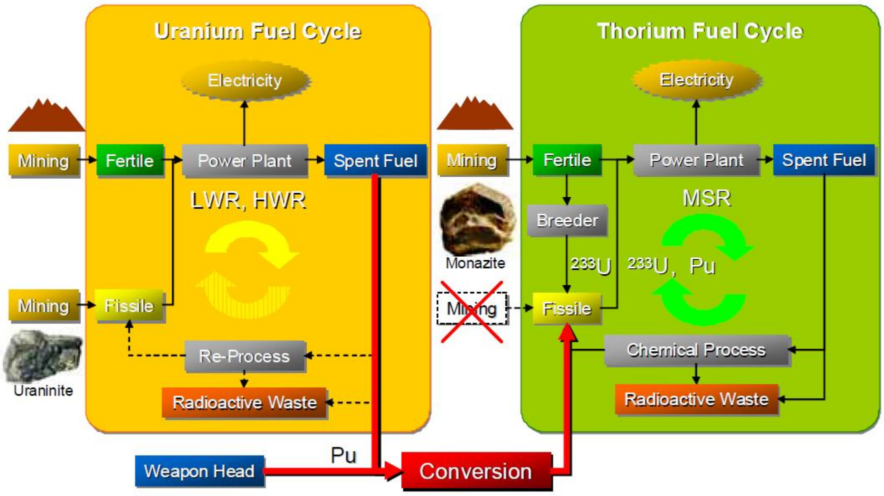


Figure 33: Closing the Nuclear Fuel Cycle (Kamei, 2010)

Closing the fuel cycle through reprocessing, recycling, and consuming Thorium-232, Uranium-238 and Plutonium-239 from conventional PWR/LWR power plants and retired nuclear warheads in generation IV nuclear reactors promises improved nuclear fuel utilisation thereby offering 10-20% savings in natural uranium extraction(Taylor et al., 2022) and under the right conditions eliminating the need for uranium mining altogether as shown in figure 33. Hence, the life span of the remaining nuclear waste to be stored would only be about 300 instead of millions of years(Kamei, 2011; Taylor et al., 2022), see the green line back in figure 32.

5.1.2 Emergence of unconventional ship design and operation requirements

Shipboard deployment of Generation IV nuclear reactors comes with externalities to ship design and operation that are worth discussing. According to Radiological Dose-Equivalent Limiting Recommendations shipboard deployment of generation IV nuclear reactors necessitates separation of accommodation deck and the engine by a thick radiological shield(Vergara & McKesson, 2002), otherwise the engine room is required to be located as far away from the superstructure as possible (Drosińska-Komor et al., 2022). On the other hand, the shipboard nuclear reactor is supposed to be positioned where it would experience less operational stresses as well as place with the least probability of collision impact so as to improve damage stability.

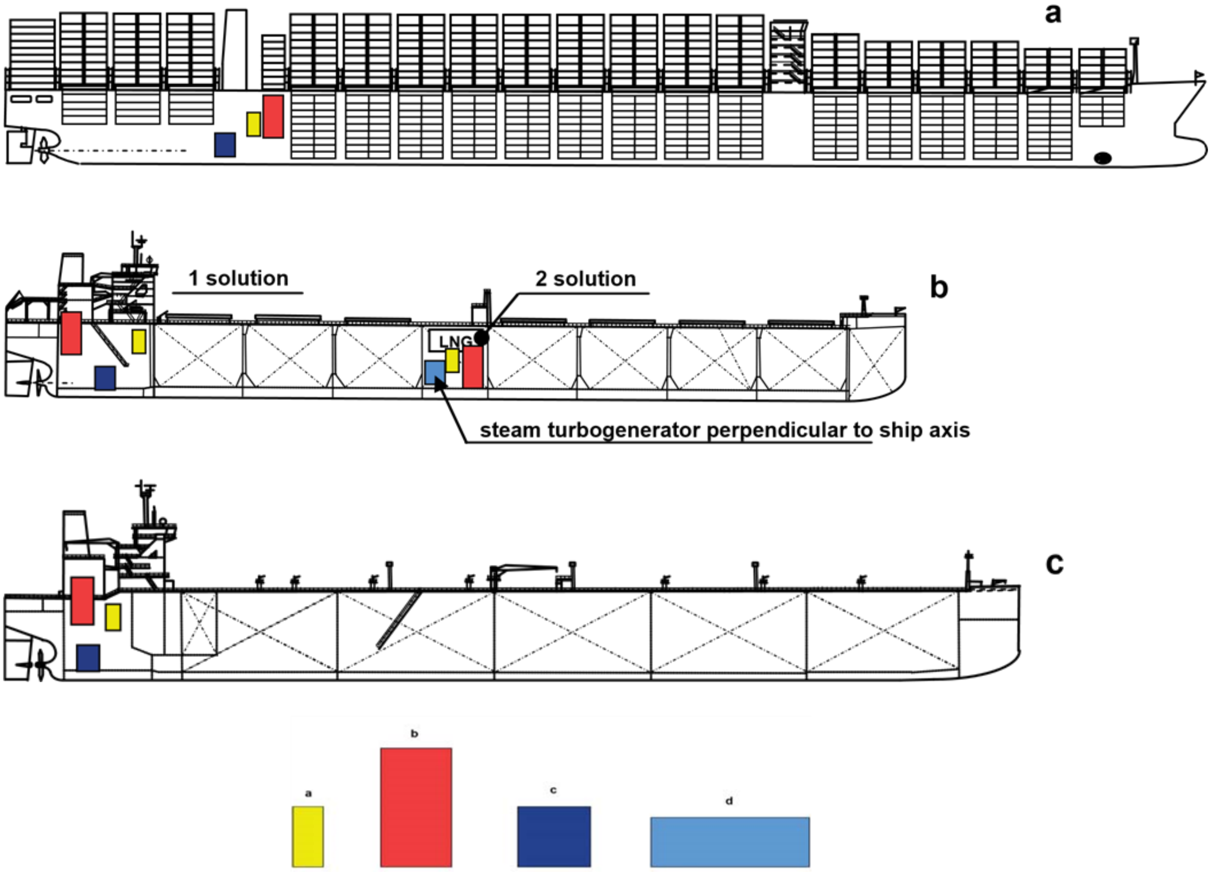


Figure 34: Implications of Incorporation of Generation IV Nuclear reactor in ship design (Drosińska-Komor et al., 2022)

From figure 34, colour coded cells represent actual sizes of power plant equipment with respect to actual ship sizes whereby; **Yellow**-steam generating plant, **Red**-Generation IV nuclear reactor, **Dark Blue-**35MW, turbo-mechanical plant and condenser, **Light Blue**-80MW turbo-electric plant and condenser.

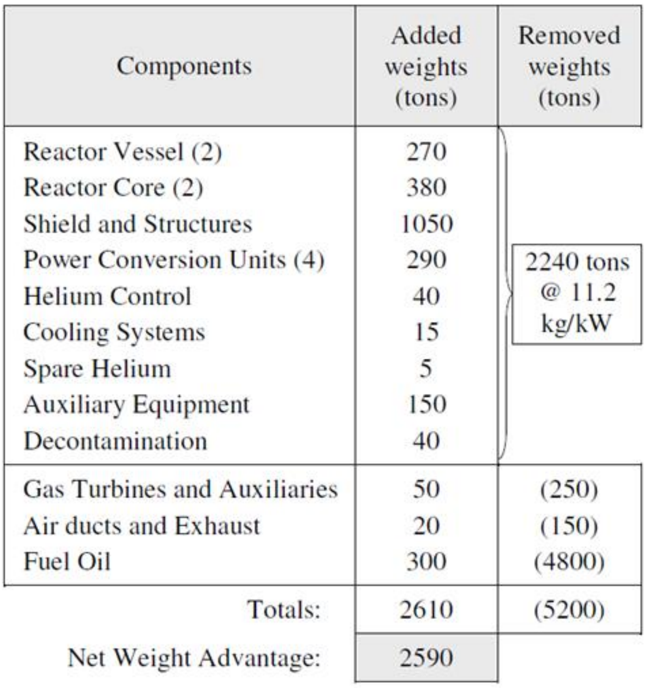
For a container ship in figure 34 a, the superstructure is located far away from the aft end hence the radiological separation requirement is automatically satisfied. However, for a bulk carrier and tanker in figure 34 b and 34 c respectively, there are two options to comply with the radiological separation requirement. The first option is to be implemented by using solution 1 which require installation of a thick radiological shield because both the superstructure and the engine room are located at the aft-end of the ship, on the other hand, the second option to be implemented by using solution 2 requires the engine room to be moved amid-ship in order to satisfy the requirement for radiological separation of the accommodation deck from the reactor compartment as well as the requirement for less operational stresses and improved damage stability.

Unconventional engine room location necessitates the need for new ship design and operation particularly cargo handling at ports. On the other hand, deployment of a turbo-mechanical propulsion system is highly unlikely for the propulsion system in which the engine room is located amid the ship as per the proposed solution 2 from figure 34 b. This is because of the presence of cargo storage hatches in between the middle of the ship and the aft end which prevents any possibility of installing a mechanical transmission system between the two points. Hence, the unconventional turbo-electric propulsion arrangement is the only feasible solution in this case (Drosińska-Komor et al., 2022).

5.1.3 Economics

Shipboard deployment of Generation IV nuclear reactors has shown to be economically competitive and in some circumstances it has been revealed to have better NPV than HFO fuelled 2-stroke marine engines (Emblemsvåg, 2021). Furthermore, even conventional (generation II-III) shipboard nuclear propulsion plants with their prohibitive feature particularly higher specific volume and weight(Vergara & McKesson, 2002) still attain better NPV than HFO fuelled 2-stroke marine engines(Namikawa et al., 2011) as discussed in earlier sections. Henceforth, it is safe to conclude that it is highly unlikely for the MSR type nuclear propulsion option to have negative externalities in the context of economics. Conversely, a number of studies reveals possible positive externalities as a result of deadweight gain due to less space and weight requirement of Generation IV nuclear propulsion option.

Table 24: Potential deadweight gain under nuclear propulsion



Components	Added weights (tons)	Removed weights (tons)
Reactor Vessel (2)	270	2240 tons @ 11.2 kg/kW
Reactor Core (2)	380	
Shield and Structures	1050	
Power Conversion Units (4)	290	
Helium Control	40	
Cooling Systems	15	
Spare Helium	5	
Auxiliary Equipment	150	
Decontamination	40	
Gas Turbines and Auxiliaries	50	(250)
Air ducts and Exhaust	20	(150)
Fuel Oil	300	(4800)
Totals:	2610	(5200)
Net Weight Advantage:	2590	

An assembly of two Helium-cooled Generation VI reactors model GT-MHR and four 50MW power conversion plants with the breakdown presented in table 24 powers a FastShip (Vergara & McKesson, 2002). The entire propulsion power assembly has a specific weight of 11.2kg/kW, factoring in the absence of the fuel storage tank onboard as all the fuel is fitted within the reactor results in a net weight advantage of 2590 tons over conventional propulsion plants. The attained deadweight saving in Generation VI nuclear propulsion opens up opportunities for potential revenue gains, hence increased profitability in ship operation(Emblemsvåg, 2021).

5.1.4 Human element

Deck officers are highly unlikely to be affected by the requirement for nuclear expertise unlike engineers due to the nature of their activities onboard. Moreover, competence in nuclear engineering for ships' engineering crew is not only expensive but also it takes a long time to develop(Freire & de Andrade, 2021). Furthermore, The existing short term contract employment regime in merchant marine is incompatible with the training needs as well as the extremely high safety culture that would be required for the uptake of nuclear merchant marine propulsion(Carlton et al., 2010). However, three compliance options are proposed with the first one being, training merchant marine engineering officers in a similar fashion to their naval counterparts. The second option is to have split engineering competencies onboard consisting of a few nuclear engineers including the chief engineer and the rest being general engineering officers. The third option is to outsource nuclear expertise to the technology provider(vendor) in the form of through-life operators in addition to supplying the plant. Having nuclear operators working for distinct companies other than shipping companies would help competence management through minimising the effects of a possible competition between land based and shipboard nuclear career paths as well as prevention of possible welfare activism of shipboard workers like the incident involving crew of the Nuclear powered merchant ship NS Savanna that happened in the past (Lange, 1990).

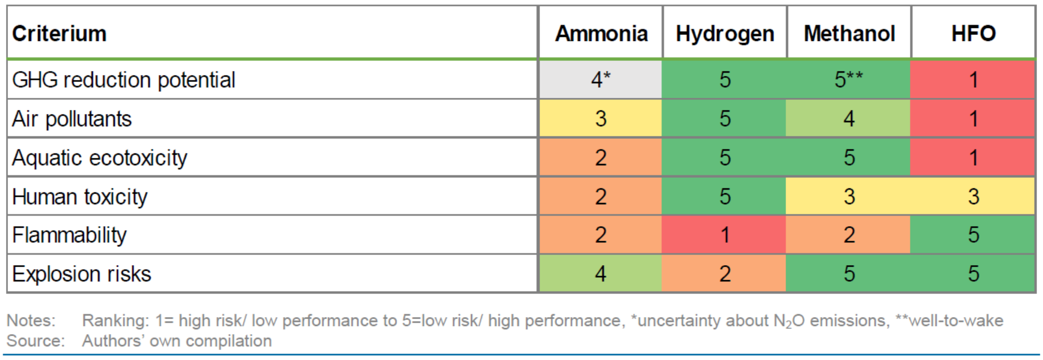
5.2 Pathway-B

This pathway focuses on the indirect electrification fuel life cycle (Power-to-Ammonia-to-Power) which starts with conversion of green electricity generated from floating nuclear power plants (MSR type) into ammonia (electro-fuel) at the production end by using electrolysers, ammonia is then converted back to electricity when needed at the consumption by using fuel cells (Mukelabai et al., 2021). The use of fuel cells is the most efficient means of energy extraction from electro-fuels such as hydrogen, ammonia and methanol (McKinlay et al., 2021). Therefore, the ship propulsion arrangement of choice under Pathway B employs fuel cells for power extraction from ammonia (Ammonia-to-Power) instead of internal combustion engines that are less efficient (McKinlay et al., 2021). Two key Fuel cell technologies that are considered for maritime applications are PEMFC and SOFC. Unlike PEMFC which only run on pure hydrogen with electrical efficiency of up to 65% when deployed with waste heat recovery, SOFC can be directly fed with ammonia making it the most effective way of extracting energy from ammonia with electrical efficiency of up to 90% when deployed with waste heat recovery (Mekhilef et al., 2012). However, there are a number of externalities associated with their deployment in the shipping industry. Toxicity of ammonia is the key environmental challenge that needs to be addressed. On the other hand, Fuel cells are currently more expensive than internal combustion engines(De Vries, 2019).It should be noted that only economic and environmental externalities are discussed in this session while those associated with human element as well as ship design and operation requirement are ignored because shipboard handling of ammonia is considered to be similar to volatile fuel handling in gas carriers of which the maritime industry is already accustomed to as seen in studies by(Kim et al., 2020; McKinlay et al., 2020)

5.2.1 Environment

Shipboard ammonia fuel is associated with a number of environmental impacts with the major concern being human toxicity. In cases of ammonia leakage, the level of exposure required for the loss of consciousness is relatively small(Klerke et al., 2008; Little et al., 2015).

Table 25:Environmental Footprint of Ammonia as Marine Fuel (Cames et al., 2021)



Criterium	**Ammonia**	**Hydrogen**	**Methanol**	**HFO**
GHG reduction potential	4*	5	5**	1
Air pollutants	3	5	4	1
Aquatic ecotoxicity	2	5	5	1
Human toxicity	2	5	3	3
Flammability	2	1	2	5
Explosion risks	4	2	5	5

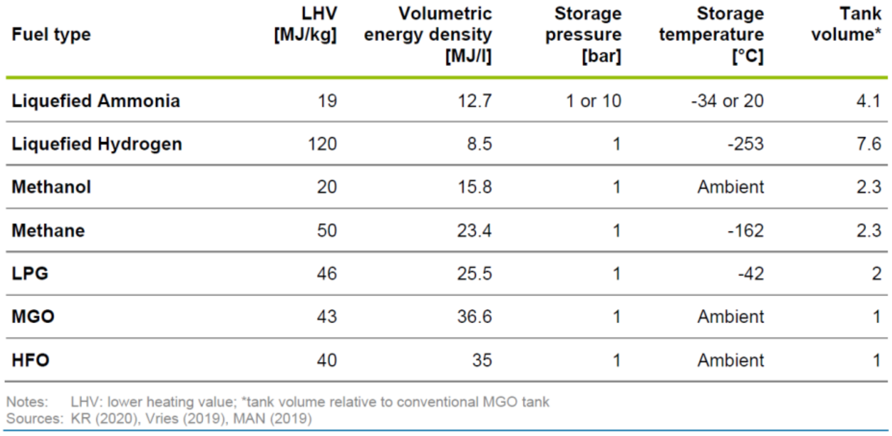
Notes: Ranking: 1= high risk/ low performance to 5=low risk/ high performance, *uncertainty about N_2O emissions, **well-to-wake
Source: Authors' own compilation

On the other hand, 70% of ammonia spilled into the marine environment dissolves in water which is likely to kill aquatic organisms in close proximity to lethal concentrations(Raj & Reid, 1978). Apart from shipboard Ammonia leakage risks, combustion of ammonia in internal combustion engines is known to produce harmful emissions such as direct ammonia slip, NOx, and N_2O with the latter having an extremely high global warming potential. Furthermore, due to poor combustion properties as a result of a combination of its high auto-ignition temperature and its narrow flammability limits (15-28% by volume in air), fossil based pilot fuels would likely be used to facilitate ammonia combustion in internal combustion engines(Kim et al., 2020), which further adds to green-house gas emission inventory(Cames et al., 2021). In order to mitigate the environmental footprint of ammonia, this study focuses on PEMFC as a means of energy extraction from ammonia instead of internal combustion engines.

5.2.2 Economics

As seen from table 26, shipboard ammonia storage requires 4.1 times larger fuel tanks as compared to HFO(Cames et al., 2021). Unconventionally large fuel tanks lead to either the loss of cargo space or the need for frequent refuelling under normal tank size. The loss of cargo space has economic implications as it leads to` revenue loss, similarly frequent refuelling leads to voyage time losses thus revenue losses.

Table 26: Space occupied by shipboard ammonia tank (Cames et al., 2021)



Fuel type	LHV [MJ/kg]	Volumetric energy density [MJ/l]	Storage pressure [bar]	Storage temperature [°C]	Tank volume*
Liquefied Ammonia	19	12.7	1 or 10	-34 or 20	4.1
Liquefied Hydrogen	120	8.5	1	-253	7.6
Methanol	20	15.8	1	Ambient	2.3
Methane	50	23.4	1	-162	2.3
LPG	46	25.5	1	-42	2
MGO	43	36.6	1	Ambient	1
HFO	40	35	1	Ambient	1

Notes: LHV: lower heating value; *tank volume relative to conventional MGO tank
Sources: KR (2020), Vries (2019), MAN (2019)

Moreover, in order to mitigate the risk of ammonia leakage to the environment as well as corrosiveness to materials, further improvement in existing handling protocols would be required particularly the need for an additional layer of casing and corrosion resistant materials which consequently leads to the increase in capital expenditure(McKinlay et al., 2021). However, PEMFC in combination with electric propulsion arrangement which is the focus of this study is more likely to help minimising loss of cargo space due to its less requirement for extra space as compared to both SOFC Fuel cells and conventional 2-stroke HFO fuelled marine engine(Kim et al., 2020). Another alternative solution for minimisation of extra space and weight requirements is the use of innovative solutions in ship design such as lightweight hull materials as well as optimised space layout(Kim et al., 2020).

5.3 Chapter Summary

This chapter has presented the externalities of the Decarbonisation Pathways under study in order to highlight limitations as well as areas that require further research. Chapter 6 presents concluding remarks and recommendations.

Chapter 6. Conclusion and Recommendations

6.1 Conclusion

This section provides concluding remarks by contextualising the findings presented in section 4.8 by considering exploring scenarios involving the total number of vessels in the fleet under study (Containerships, Bulk carriers, and Tanker ships). In this case the Crystal Ball Software running on Microsoft Excel was used in performing Monte Carlo Simulations for determining the decarbonisation potential of Pathways against the fleet under study.

6.1.1 Uncertainty Consideration of Potentials of Decarbonisation Pathways under Study

Considering that statistical data used in this study are based on estimates, it is then essential to perform uncertainty analysis in order to reflect reality and also to identify the main drivers of uncertainty. According to (Statista Research Department, 2021), the total number of vessel types covered by this study (containerships, bulk carriers and oil tankers) is approximately 24,915 vessels, of which the Fourth IMO GHG study(S. Faber et al., 2020) estimates the number of vessels with 15MW and 30MW of MCR as 3,490 vessels (S. Faber et al., 2020). After running 50,000 trials, results of a Monte Carlo Simulation shows that Pathway A has a decarbonisation potential of 23% (with respect to the number of vessels under study).As shown in figure 35.

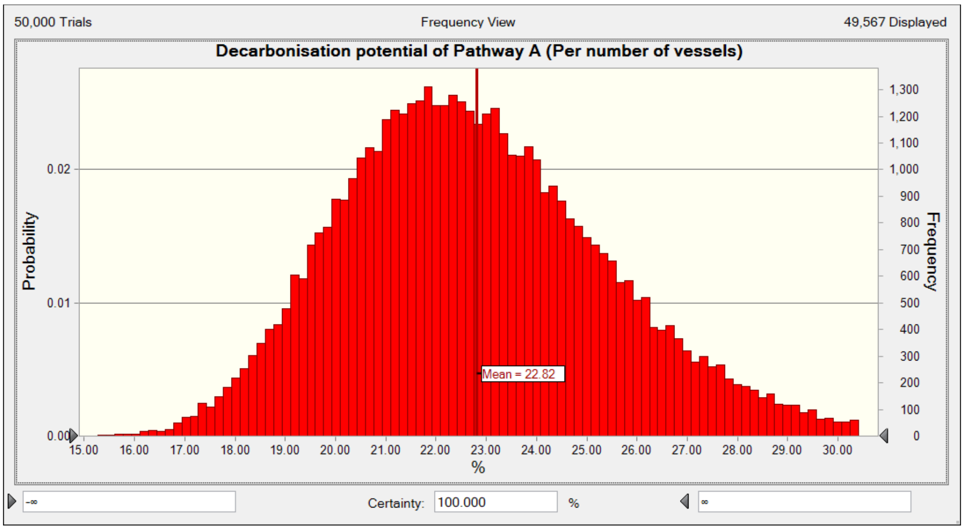


Figure 35: Monte Carlo Simulation of Decarbonisation Potential of Pathway A(Author)

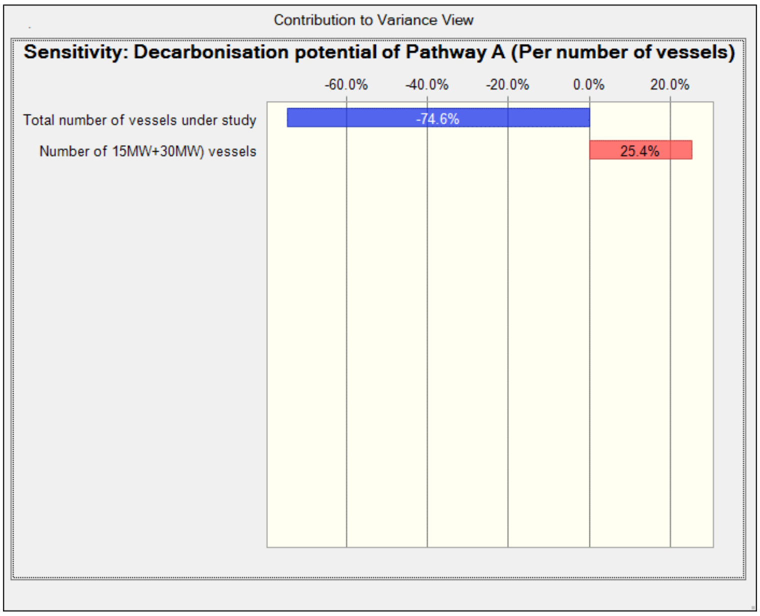


Figure 36: Sensitivity Analysis of Decarbonisation Potential of Pathway A (Author)

As observed in the sensitivity chart on figure 36, the main drivers of uncertainty are total number of vessels under study and number of representative vessels (15MW and 30MW), of which decarbonisation potential of Pathway A is observed to be more sensitive to changes in total number of vessels. In a similar method as the previous case, simulation results shows that Pathway B has a decarbonisation potential of 15% (with respect to the number of vessels under study) as shown in figure 37.

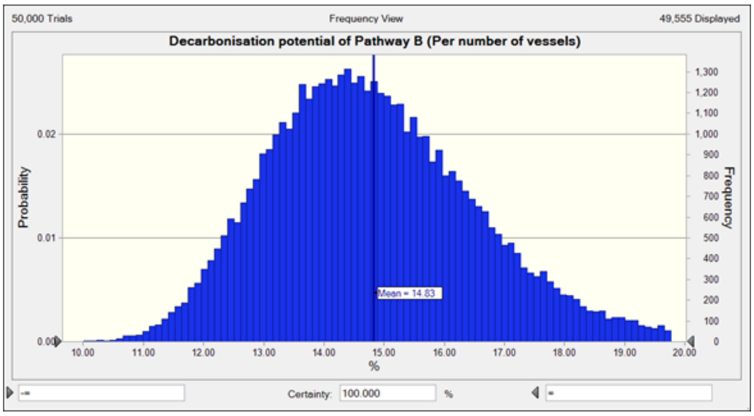


Figure 37: Monte Carlo Simulation of Decarbonisation Potential of Pathway B (Author)

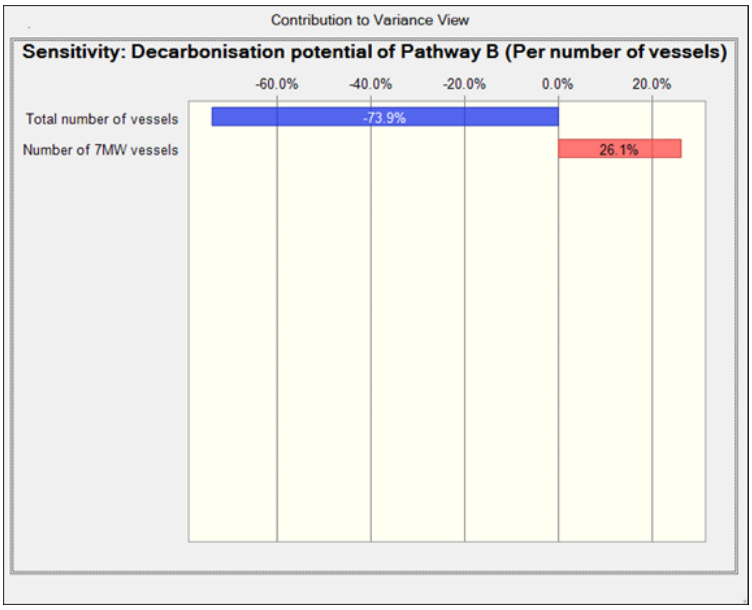


Figure 38: Sensitivity Analysis of Decarbonisation Potential of Pathway B (Author)

Similarly, as observed in figure 38, in this case the main drivers of uncertainty are total number of vessels under study and number of representative vessels (7MW), of which the Decarbonisation potential of Pathway B is observed to be more sensitive to changes in total number of vessels. The overall performance of the two decarbonisation Pathways is depicted by the overlay chart of Pathway A and B respectively as shown in figure 39.

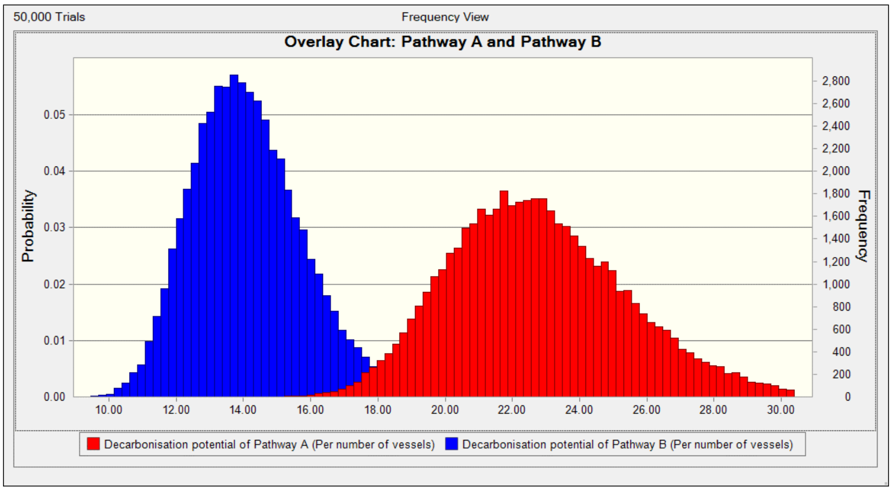


Figure 39: Overlay Chart Showing Pathways A and B (Author)

Occupying the extreme end to the right of the X-axis in figure 39, Pathway A is observed to have more decarbonisation potential (23%) than Pathway B in the overall assessment. It should also be noted that the decarbonisation potentials are based on existing vessels that are ready for retrofitting without considering new builds. However, with new design requirements that come along with alternative propulsion solutions, installation to new builds is a more realistic option. Hence, Decarbonisation Potentials for Pathways A and B would be different for new builds as for retrofits.

Furthermore, research questions set in section 1.5 are properly addressed as it has been clearly shown that Pathway A is suitable for medium to large vessels of all types, while Pathway B has been observed to be suitable for small vessels of all types. Additionally Regulatory Complexity has been observed to be the most influential factor that is why it carries more weight in criteria weightage. In addition to that, Regulatory Complexity is more likely to limit applicability of Pathway A as it involves Mobile Nuclear Asset across international jurisdictions unlike Pathway B whose Nuclear Asset is stationary within territorial waters under jurisdiction of a competent National Nuclear Regulatory Authority.

6.1.2 Areas that require further research

This study has approached the Technology Criteria from the Technological Readiness Level (TRL) perspective, however, it is essential for future studies to explore the actual equipment layout as well as shipboard system integration in order to reflect reality as much as possible. Furthermore, future works should also explore the possibility to deploy the bottom-up approach in establishing cost elements of the MSR type Power Plant instead of the top-bottom approach employed by this study due to lack of data on the actual system layout because MSRs are not yet commercially available. Lastly, further research should approach the regulatory framework in the up to date probabilistic nuclear safety regime as opposed to the existing prescriptive regime stipulated in Chapter VIII of the SOLAS convention, supplemented with IMO Resolution A.491 (XII) CODE OF SAFETY FOR NUCLEAR MERCHANT SHIPS.

6.2 Recommendations

This section provides recommendations based on how large-scale deployment of Nuclear Energy in the Marine Environment fits in the bigger picture particularly at the Policy Level. As it was discussed in earlier sections, the regulatory framework for merchant vessels at the international level though outdated but it already exists through earlier efforts (as accelerated by the oil crisis in the 1970's) by International Maritime Organisation (IMO), the International Atomic Energy Agency (IAEA), and Classification societies. However, National Nuclear Regulatory Authorities which is the focus of this section will play a crucial role in the large-scale uptake of Nuclear Energy in the future as discussed in sections 6.2.1 and 6.2.2.

6.2.1 Existing Functional Relations

This section provides recommendations by examining implementation of insights gained from this study at the Policy Level encompassing all stakeholders engaged in both nuclear and the maritime industries. Although detailed stakeholder analysis is beyond the scope of this study, the study refers to the results of the stakeholder analysis on incorporation of nuclear energy in the maritime domain in the existing scenario shown in figure 40 as an inspiration for development of the new structure presented in figure 41.

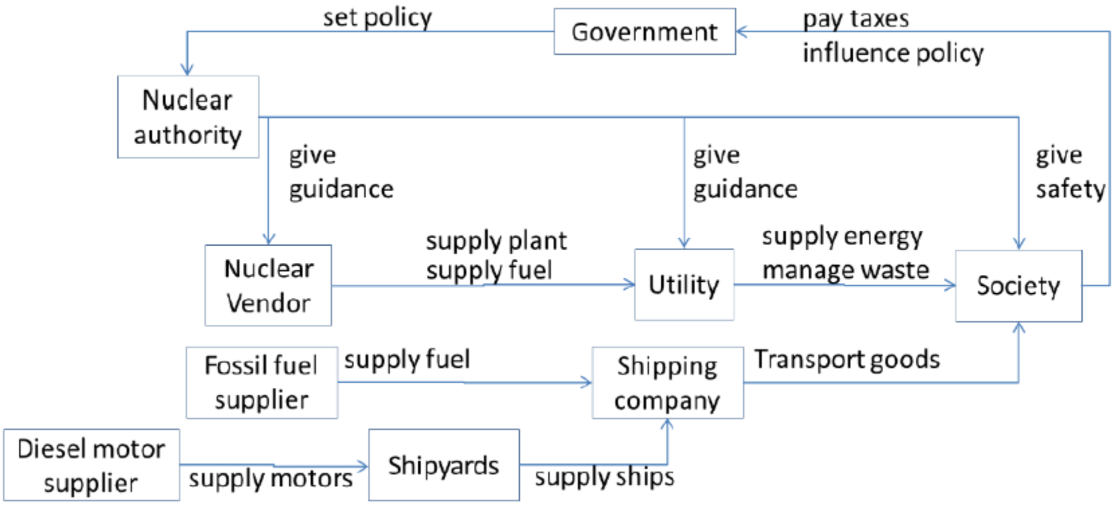


Figure 40: Functional relations amongst stakeholder under the current situation(Freire & de Andrade, 2021)

As seen from figure 40, the referred stakeholder analysis navigates two of the most important sectors in economic prosperity of any society namely energy and seaborne transportation in which a number of stakeholders with distinct interests are involved. Similarly, incorporation of nuclear energy into the maritime industry under the guidance of the insights obtained from this study should follow the same pattern. However, as seen in figure 40, there is a disjointed relationship between the two industries under the current situation as the nuclear industry is more dominant in electricity generation than in civilian ship propulsion. With consideration of the potential role that the nuclear industry could play to sustainability of the maritime industry as revealed by this study, the existing disjointed state of affairs does not satisfy all socio-environmental interests, this means while the use of fossil fuels over the years has contributed to economic prosperity through powering cheaper seaborne transportation and energy generation, fossil fuels have been detrimental to the environment at the same time. The limitations of the conventional nuclear reactors are arguably the reason for the failure of the nuclear energy to dominate the civilian marine propulsion market hence, emergence of the aforementioned disjoint between the two industries nuclear and maritime respectively.

The MSR reactors under the Generation IV initiative at the centre of this study aims at eliminating all the risks associated with conventional nuclear power through better utilisation of nuclear resources, manageable nuclear waste, competitive economics, secure nuclear energy systems and materials, and high degree of safety performance. Hence, this technology holds potential for merging the two industries under discussion. However, society has a key role to play in this area due to its capacity to influence policy-making through its perception of nuclear technology. In this regard, provided that the government through a competent body designated for operationalisation of the Nuclear Energy Policy (National Nuclear Regulatory Authorities) performs its duty of educating the society, the society should be able to influence formulation of favourable policies for the uptake of nuclear energy in shipping. Furthermore, the existence of the reliable regulatory framework, stakeholders in the business side particularly shipyards, nuclear vendors, utility companies, fossil fuels suppliers and shipping companies to accelerate their efforts to uptake the technology in the maritime industry. In order to effectively support the uptake of nuclear energy in shipping, the new structure representing functional relations between stakeholders has been proposed.

6.2.2 Proposed Functional Relations

In the proposed functional relations layout as seen in figure 41, the two industries, maritime and nuclear are merged in a potentially disruptive way to the existing practice in the maritime industry. In order to implement the proposed structure, the existing practice in ship classification, registry, construction and manning would require a drastic change in order to accommodate the advanced safety culture required for adopting shipboard nuclear energy. In the proposed functional structure only a handful of countries with competent nuclear regulatory authorities (Such as the U.S, U.K, France and Japan) would be required to build, class, own, operate and register nuclear powered vessels. In this arrangement, vessels would be classed by a competent national nuclear regulatory authority as well as the maritime class society with competence in shipboard integration of nuclear reactor modules, in order to achieve this, a nuclear energy vendor must work together with a shipyard under the guidelines provided by the national nuclear regulatory authority on producing nuclear/ammonia ready ships as well as floating nuclear-powered platforms for Power-to-Ammonia applications.

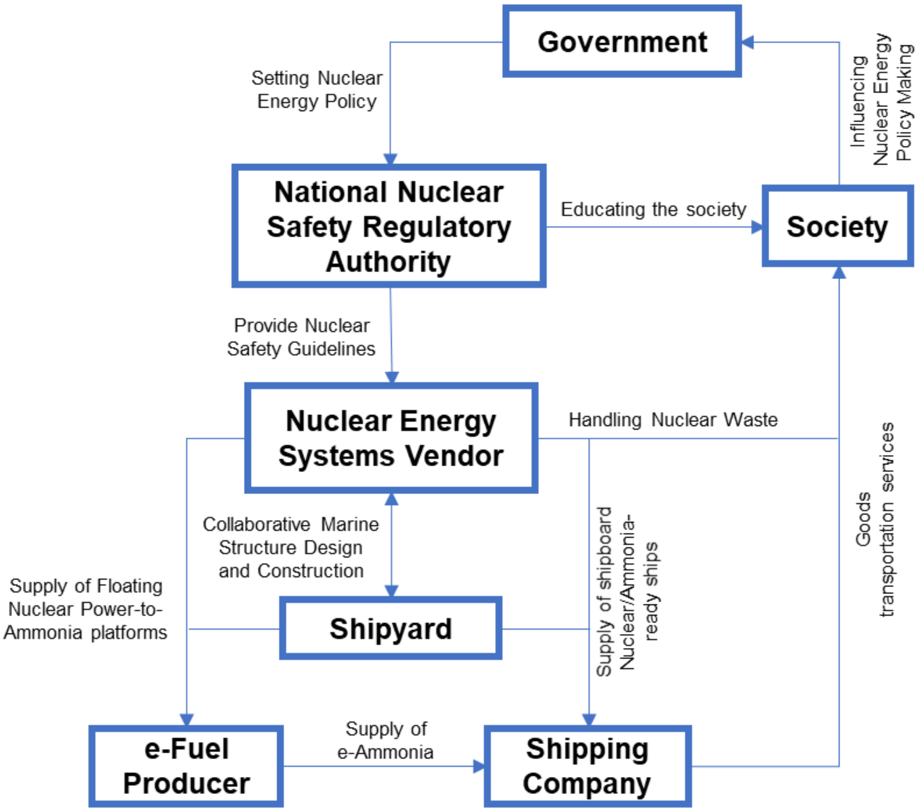


Figure 41: The Proposed Functional Relationships amongst Key Stakeholders (Author)

Furthermore, the Life Cycle Cost Analysis under this study reveals that higher CAPEX of investment in MSR based nuclear propulsion as analysed in Pathway A, favour ship owners having long term objectives as it takes a long time for this kind of investment to break-even as compared to both e-ammonia based propulsion system analysed in Pathway B and conventional HFO based propulsion system from literature. Ship owners/operators with short term vision can benefit from the leasing structure aimed at curbing the high CAPEX requirement in which a nuclear vendor gets to own the shipboard nuclear reactor and provide through-life operational support while selling propulsive energy to a shipowner/operator. Propulsive Energy Leasing arrangement would also help in solving waste disposal and manning challenges to the ship owner/operator because in this arrangement the vendor handles those arrangements.

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Appendices

Appendix 1: Total Annual Cost of Ownership for Pathway A for NPV Calculation

CONTAINER SHIP						
	Days at sea	**Cent/kWh**	**1000MWe**	**7MWe**	**15MWe**	**30MWe**
Capital	180	3.01	130,032,000.00	3,837,689.65	6,592,877.96	10,784,656.90
O&M		0.87	37,584,000.00	1,109,232.56	1,905,582.66	3,117,159.97
Fuel		1.66	71,712,000.00	2,116,466.72	3,635,939.34	5,947,684.54
Waste disposal		0.15	6,480,000.00	191,246.99	328,548.74	537,441.37
Decommissioning		0.06	2,592,000.00	76,498.80	131,419.49	214,976.55
Annual Total cost($)			248,400,000.00	**7,331,134.71**	**12,594,368.19**	**20,601,919.33**

BULK CARRIER						
	Days at sea	**Cent/kWh**	**1000MWe**	**7MWe**	**15MWe**	**30MWe**
Capital	200	3.01	144,480,000.00	4,264,099.61	7,325,419.95	11,982,952.11
O&M		0.87	41,760,000.00	1,232,480.62	2,117,314.07	3,463,511.08
Fuel		1.66	79,680,000.00	2,351,629.69	4,039,932.60	6,608,538.38
Waste disposal		0.15	7,200,000.00	212,496.66	365,054.15	597,157.08
Decommissioning		0.06	2,880,000.00	84,998.66	146,021.66	238,862.83
Annual Total cost($)			276,000,000.00	**8,145,705.24**	**13,993,742.43**	**22,891,021.48**

TANKER SHIP						
	Days at sea	**Cent/kWh**	**1000MWe**	**7MWe**	**15MWe**	**30MWe**
Capital	280	3.01	202,272,000.00	5,969,739.45	10,255,587.93	16,776,132.96
O&M		0.87	58,464,000.00	1,725,472.87	2,964,239.70	4,848,915.51
Fuel		1.66	111,552,000.00	3,292,281.56	5,655,905.64	9,251,953.73
Waste disposal		0.15	10,080,000.00	297,495.32	511,075.81	836,019.91
Decommissioning		0.06	4,032,000.00	118,998.13	204,430.32	334,407.97
Annual Total cost($)			386,400,000.00	**11,403,987.33**	**19,591,239.40**	**32,047,430.07**

Appendix 2: Total Annual Cost of Ownership for Pathway B for NPV Calculation

CONTAINER SHIP					
	Days at sea	**$/kW**	**7MWe**	**15MWe**	**30MWe**
PEM fuel cell Installation	180	371	2,597,000.00	5,565,000.00	11,130,000.00
Cracker and Purifier installation		111.3	779,100.00	1,669,500.00	3,339,000.00
Fuel tank installation		540	3,780,000.00	8,100,000.00	16,200,000.00
Fuel cost		1175	828,598.48	1,775,568.18	828,598.48
Annual Total cost($)			**7,984,698.48**	**17,110,068.18**	**31,497,598.48**
BULK CARRIER					
	Days at sea	**$/kW**	**7MWe**	**15MWe**	**30MWe**
PEM fuel cell Installation	200	371	2,597,000.00	5,565,000.00	11,130,000.00
Cracker and Purifier installation		111.3	779,100.00	1,669,500.00	3,339,000.00
Fuel tank installation		540	3,780,000.00	8,100,000.00	16,200,000.00
Fuel cost		1175	920,664.98	1,972,853.54	3,945,707.07
Annual Total cost($)			**8,076,764.98**	**17,307,353.54**	**34,614,707.07**
TANKER SHIP					
	Days at sea	**$/kW**	**7MWe**	**15MWe**	**30MWe**
PEM fuel cell Installation	280	371	2,597,000.00	5,565,000.00	11,130,000.00
Cracker and Purifier installation		111.3	779,100.00	1,669,500.00	3,339,000.00
Fuel tank installation		540	3,780,000.00	8,100,000.00	16,200,000.00
Fuel cost		1175	1,288,930.98	2,761,994.95	5,523,989.90
Annual Total cost($)			**8,445,030.98**	**18,096,494.95**	**36,192,989.90**

Appendix 3: Classical TOPSIS based MS Excel Model for Containership

		CONTAINER SHIP																	
		PATHWAY-A									PATHWAY-B								
		PR	**Weight**	**Cost(1)/ Benefit(0)**	**NR**	**WNR**	**PI**	**NI**	**Vij-PI**	**Vij-NI**	**PR**	**Weight**	**Cost(1)/ Benefit(0)**	**NR**	**WNR**	**PI**	**NI**	**Vij-PI**	**Vij-NI**
SMALL	**TRL**	5	0.2	0	0.6402	0.1280	0.1536	0.1280	0.0007	0.0000	6	0.2	0	0.7682	0.1536	0.1536	0.1280	0.0000	0.0007
	NPV	96,775,630.94	0.3	1	0.5674	0.1702	0.1702	0.2470	0.0000	0.0059	140,438,817.87	0.3	1	0.8234	0.2470	0.1702	0.2470	0.0059	0.0000
	REG	8	0.5	1	0.8480	0.4240	0.2650	0.4240	0.0253	0.0000	5	0.5	1	0.5300	0.2650	0.2650	0.4240	0.0000	0.0253
	S_i^+	0.1610									0.0768								
	S_i^-	0.0768									0.1610								
	OAR	0.3229									0.6771								
	RANK	**2**									**1**								
MEDIUM	**TRL**	5	0.2	0	0.6402	0.1280	0.1536	0.1280	0.0007	0.0000	6	0.2	0	0.7682	0.1536	0.1536	0.1280	0.0000	0.0007
	NPV	166,253,653.13	0.3	1	0.4836	0.1451	0.1451	0.2626	0.0000	0.0138	300,940,324.00	0.3	1	0.8753	0.2626	0.1451	0.2626	0.0138	0.0000
	REG	8	0.5	1	0.8480	0.4240	0.2650	0.4240	0.0253	0.0000	5	0.5	1	0.5300	0.2650	0.2650	0.4240	0.0000	0.0253
	S_i^+	0.1610									0.1175								
	S_i^-	0.1175									0.1610								
	OAR	1.1610									1.1175								
	RANK	**1**									**2**								
LARGE	**TRL**	4	0.2	0	0.5547	0.1109	0.1664	0.1109	0.0031	0.0000	6	0.2	0	0.8321	0.1664	0.1664	0.1109	0.0000	0.0031
	NPV	271,958,410.28	0.3	1	0.4407	0.1322	0.1322	0.2693	0.0000	0.0188	553,995,308.05	0.3	1	0.8977	0.2693	0.1322	0.2693	0.0188	0.0000
	REG	8	0.5	1	0.8480	0.4240	0.2650	0.4240	0.0253	0.0000	5	0.5	1	0.5300	0.2650	0.2650	0.4240	0.0000	0.0253
	S_i^+	0.1684									0.1371								
	S_i^-	0.1371									0.1684								
	OAR	1.1684									1.1371								
	RANK	**1**									**2**								

Appendix 4: Classical TOPSIS based MS Excel Model for Bulk Carrier

BULK CARRIER SHIP																			
		PATHWAY-A									PATHWAY-B								
		PR	**Weight**	**Cost(1) / Benefit(0)**	**NR**	**WNR**	**PI**	**NI**	**Vij-PI**	**Vij-NI**	**PR**	**Weight**	**Cost(1)/ Benefit(0)**	**NR**	**WNR**	**PI**	**NI**	**Vij-PI**	**Vij-NI**
SMALL	**TRL**	4	0.2	0	0.5547	0.1109	0.1664	0.1109	0.0031	0.0000	6	0.2	0	0.8321	0.1664	0.1664	0.1109	0.0000	0.0031
	NPV	107,528,478.82	0.3	1	0.6035	0.1811	0.1811	0.2392	0.0000	0.0034	142,058,128.88	0.3	1	0.7973	0.2392	0.1811	0.2392	0.0034	0.0000
	REG	8	0.5	1	0.8480	0.4240	0.2650	0.4240	0.0253	0.0000	5	0.5	1	0.5300	0.2650	0.2650	0.4240	0.0000	0.0253
	S_i^+	0.1684									0.0581								
	S_i^-	0.0581									0.1684								
	OAR	0.2567									0.7433								
	RANK	**2**									**1**								
MEDIUM	**TRL**	4	0.2	0	0.5547	0.1109	0.1664	0.1109	0.0031	0.0000	6	0.2	0	0.8321	0.1664	0.1664	0.1109	0.0000	0.0031
	NPV	184,726,281.26	0.3	1	0.5188	0.1556	0.1556	0.2565	0.0000	0.0102	304,410,276.17	0.3	1	0.8549	0.2565	0.1556	0.2565	0.0102	0.0000
	REG	8	0.5	1	0.8480	0.4240	0.2650	0.4240	0.0253	0.0000	5	0.5	1	0.5300	0.2650	0.2650	0.4240	0.0000	0.0253
	S_i^+	0.1684									0.1008								
	S_i^-	0.1008									0.1684								
	OAR	1.1684									1.1008								
	RANK	**1**									**2**								
LARGE	**TRL**	3	0.2	0	0.5145	0.1029	0.1715	0.1029	0.0047	0.0000	5	0.2	0	0.8575	0.1715	0.1715	0.1029	0.0000	0.0047
	NPV	302,176,011.42	0.3	1	0.4446	0.1334	0.1334	0.2687	0.0000	0.0183	608,820,552.34	0.3	1	0.8957	0.2687	0.1334	0.2687	0.0183	0.0000
	REG	8	0.5	1	0.8480	0.4240	0.2650	0.4240	0.0253	0.0000	5	0.5	1	0.5300	0.2650	0.2650	0.4240	0.0000	0.0253
	S_i^+	0.1732									0.1353								
	S_i^-	0.1353									0.1732								
	OAR	1.1732									1.1353								
	RANK	**1**									**2**								

Appendix 5: Classical TOPSIS based MS Excel Model for Tanker ship

TANKER SHIP																				
		PATHWAY-A									PATHWAY-B									
		PR	Weight	Cost(1) / Benefit(0)	NR	WNR	PI	NI	Vij-PI	Vij-NI	PR	Weight	Cost(1)/ Benefit(0)	NR	WNR	PI	NI	Vij-PI	Vij-NI
SMALL	**TRL**	4	0.2	0	0.6247	0.1249	0.1562	0.1249	0.0010	0.0000	5	0.2	0	0.7809	0.1562	0.1562	0.1249	0.0000	0.0010
	NPV	150,539,870.34	0.3	1	0.7118	0.2135	0.2107	0.2135	0.0000	0.0000	148,535,372.93	0.3	1	0.7024	0.2107	0.2107	0.2135	0.0000	0.0000
	REG	8	0.5	1	0.8480	0.4240	0.2650	0.4240	0.0253	0.0000	5	0.5	1	0.5300	0.2650	0.2650	0.4240	0.0000	0.0253
	S_i^+	0.1621									0.0000								
	S_i^-	0.0000									0.1621								
	OAR	0.0000									1.0000								
	RANK	**2**									**1**								
MEDIUM	**TRL**	4	0.2	0	0.6247	0.1249	0.1562	0.1249	0.0010	0.0000	5	0.2	0	0.7809	0.1562	0.1562	0.1249	0.0000	0.0010
	NPV	258,616,793.76	0.3	1	0.6306	0.1892	0.1892	0.2328	0.0000	0.0019	318,290,084.85	0.3	1	0.7761	0.2328	0.1892	0.2328	0.0019	0.0000
	REG	8	0.5	1	0.8480	0.4240	0.2650	0.4240	0.0253	0.0000	5	0.5	1	0.5300	0.2650	0.2650	0.4240	0.0000	0.0253
	S_i^+	0.1620									0.0437								
	S_i^-	0.0437									0.1620								
	OAR	1.1620									1.0437								
	RANK	**1**									**2**								
LARGE	**TRL**	3	0.2	0	0.3939	0.0788	0.1838	0.0788	0.0110	0.0000	7	0.2	0	0.9191	0.1838	0.1838	0.0788	0.0000	0.0110
	NPV	423,046,415.99	0.3	1	0.5535	0.1660	0.1660	0.2499	0.0000	0.0070	636,580,169.70	0.3	1	0.8329	0.2499	0.1660	0.2499	0.0070	0.0000
	REG	8	0.5	1	0.8480	0.4240	0.2650	0.4240	0.0253	0.0000	5	0.5	1	0.5300	0.2650	0.2650	0.4240	0.0000	0.0253
	S_i^+	0.1906									0.0838								
	S_i^-	0.0838									0.1906								
	OAR	1.1906									1.0838								
	RANK	**1**									**2**								