Henrik Schrøder Norderhaug

Nuclear Energy in the Marine Industry

How may a nuclear propulsion system affect the operations of a vessel financially, and can a land based nuclear powerplant contribute to produce cost effective and green synthetic fuels?

Bacheloroppgave i Shipping Management
Veileder: Jan Emblemsvåg
Desember 2022

Bacheloroppgave

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Fakultet for ingeniørvitenskap
Institutt for havromsoperasjoner og byggteknikk

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Innhold

Tables

Figures

Summary

In this bachelor it will be accounted for how a nuclear propulsion system may affect a vessel financially, and whether nuclear energy could contribute with cost-effective production of synthetic fuel. For vessel operations the focus is to see whether a Thorium Molten Salt Reactor (TMSR) could be a cost-efficient alternative compared to current vessels, by comparing voyage performance and lifecycle cost. For the synthetic fuel production, it is to investigate if the TMSR could provide production of competitive green synthetic fuels. The theory that has been used is based on literature analyses, reports and research articles regarding shipping industry's current situation, nuclear and the fuel industry. The study presents specific projects that are under development for nuclear energy and renewable fuel production, and the potential for these are discussed.

It has been conducted one quantitative survey and two qualitative interviews. The quantitative method was used for gathering a general opinion towards the nuclear solutions, and the qualitative method was used to find out how a nuclear reactor may affect a vessel financially. The participants in the survey work in different departments within two shipping companies, like ship service, ship management and energy sourcing. By including different departments and companies the study gets a better understanding of how the industry may look upon nuclear solutions, and which solutions they would prefer.

For the two persons interviewed, one of them was a previous nuclear submarine officer and the other one is working with creating a civil market for modern nuclear reactors. By combining their answers and experience it have been created a potential cost for a nuclear vessel, both short and long termly. This is presented as OPEX, CAPEX and lifecycle costs, to be compared with traditional vessel.

Furthermore, there are discussed whether the TMSR could be an alternative for the maritime future. This study indicates that there is a significant potential and belief in the TMSR technology both for vessel operations and for green fuel production. The total lifecycle and CAPEX for a nuclear vessel is higher than a traditional vessel. However, the OPEX and voyage performance for nuclear vessel indicates a potential for cost efficiency that could generate more income. This study presents only a few aspects of the technology. Therefore, the technology needs to be further studied, enhanced and industrialised to get more accurate understanding on the actual costs.

Forewords

This bachelor was written during an internship in Wilhelmsen Ship Service. The internship has been exiting and instructive, and I want to thank my mentor and everybody at the team for welcoming me with open arms. I have had a large interest for the shipping industry, and I do not regret choosing this internship and my bachelor program “Shipping Management” at NTNU Aalesund. During this semester it has been some challenges, both academical and personal, which made it more difficult than first expected.

I want to thank everybody that has participated with answering the survey and attended in the interviews, to help me conduct my study.

Enjoy reading!

Oslo: 15.12.2022

Dictionary

OPEX	Operational Expenses
CAPEX	Capital Expenses
HFO	Heavy Fuel Oil
SOx	Sulphur Oxide
MSR	Molten Salt Reactor
TMSR	Thorium Molten Salt Reactor
PWR	Pressurized Water Reactor
RoRo vessel	Roll on, Roll off vessel
GHG	Green House Gases
IMO	International Maritime Organisation

1.0 – Introduction

1.1 Background information

The global fleet accounts for 1 billion tons, or 3,1 %, of the global CO_2 emissions per year – which is more than Germany, the sixth largest emitter by country, (Schlanger, 2018). The largest 17 000 vessels or approximately 20% of the global fleet accounts for about 80 % of the annual CO_2 emissions. This means that there is a large potential for reducing annual emissions in the shipping industry. By developing zero-emission technology for their largest vessels the industry can potentially reduce their emission by 800 million tons of CO_2 annually, (Martime Nuclear Application Group, 2022). As an effect of the large amounts of pollution from the industry, the International Maritime Organisation (IMO) has initiated a Green House Gas (GHG) strategy towards 2050 to prevent further damage to the environments. This strategy says that shipping must reduce their GHG emissions by at least 50% compared with the 2008 levels within 2050, (IMO, 2019).

For decades large combustion engines have provided vessels with reliable and effective propulsion, making the shipping industry the heart of international trade and the source of globalization. Roughly 90% of all international traded goods are transported by sea, and the global fleet had in 2021 a total capacity of over 2,1 billion dead weight tonnages (DTW's), (UNCTAD, 2021). Even though shipping has a large environmental impact they also have a massive capacity, which is why vessels are considered the most cost and environmentally friendly method for transporting goods, (Trans Global Auto Logistics, 2020). With IMO's new regulations, they are forcing the industry to a green shift and to search for new technologies that can contribute to bring zero-emission voyages. Some important aspects to consider are that the new technology should be able to maintain the vessels competitiveness and capacity, but at the same time comply with IMO's regulations, (Martime Nuclear Application Group, 2022).

Therefore, it has been chosen to investigate the potential of a new generation of advanced nuclear reactors; the Molten Salt Reactors (MSR). Nuclear technology has a proven record of being highly efficient, emission free and can create extreme amounts of clean energy, making it a potential deep-sea technology. There is currently a handful of different MSR's that are under discussion. For this study it has been chosen to investigate the Thorium Molten Salt Reactor (TMSR). This is an unknown technology for most people and a less discussed topic in a marine context, which isn't strange since the TMSR has been excluded by all nuclear engineering textbooks since the 1970's. The reason for choosing the TMSR technology, and not the other reactor, is because the MSR's are the only reactors that has been proposed as a possible technology in a civil marine context. In addition, the U.S. Nuclear Regulatory Commission has stated that, in terms of the regulations, "…thorium potentially could be licenced under the current regulations without additional rule making.", (Emblemsvåg, 2021). By combining these two elements the industry could have a zero-emission technology suited for the deep-sea sector.

1.2 Thesis statement:

Through this study we will investigate whether the TMSR technology can be attractive alternative for the shipping industry. This will be done by looking into two different segments; vessel operations and fuel production, which are segments with large potential for reducing emissions and costs. Thereby it has been chosen this thesis statement:

- ***How may a nuclear propulsion system affect the operations of a vessel financially, and can a land based nuclear powerplant contribute to produce cost effective and green synthetic fuels?***

The intention of having this thesis statement is to enlighten the potential behind nuclear energy, show what kind of benefits the industry can exploit, and find out whether this technology is cost efficient and suited for marine implementation. For the first part of the thesis, the focus is on operational expenses, capital expenses and lifecycle costs for a nuclear vessel. These expenses will be compared with the expenses from a traditional RoRo-vessel and see what differences they may have. For the second part, the focus is finding out the potential of producing green synthetic fuels with a TMSR, and if it could be produced cost competitive compared with today's methods. To answer the thesis there have been collected relevant articles, projects, reports and conducted two analyses: one qualitative and one quantitative. They will be used together with logic to try finding out if this technology could be a viable option for the future.

There will be other aspects concerning this technology that must be studied and developed before it can be implemented in a civil context. Regarding the technology there is for instance need for developing a legal framework, a training and education program, and create a supply chain for the nuclear fuel. In addition, there will also be other accepts on how a TMSR could affect a vessel financially. For instance, the vessels capacity could change which could generate more income. Keep in in mind that these are important aspects that can be further discussed in another study, but it will not be included in this thesis.

2.0 – Theory

Before reviewing the TMSR, there will first be a need for some basic information on nuclear energy, historical happenings, and the nuclear navy. This is to understand why current nuclear technology would most likely not be used in a civil marine context. It will also give the reader a better understanding of nuclear before presenting the TMSR technology.

2.1 Nuclear Energy

Nuclear energy is energy that comes from the core of an atom. By splitting the atom, in a process called nuclear fission, it creates a chain reaction that releases energy through heat. The heat warms up a cooling agent – usually water, liquid metal, or molten salt – which then produces steam that drives a turbine. That turbine is linked to a generator that creates electricity without almost no harmful by-products like fossil fuels have. The exception is the nuclear waste material, which is radioactive, and can be harmful if not stored properly, (National Geographic, 2022). Today, nuclear energy provides about 10 percent of the annually produced electricity from about 440 reactors, (World Nuclear Association, 2022)

2.1.1 History

Ever since the 1950's the U.S and U.K Navy has developed over nine generations of Pressurized Water Reactors (PWR), which is the most common reactor design today. Nuclear energy has the many benefits of being clean, safe, and having a small footprint compared to other energy sources. To answer why this technology haven't been fully implemented in societies and industries, there is a need to presents some historical happenings, (Martime Nuclear Application Group, 2022).

World War II

What many often relate with nuclear technology are nuclear bombs, radiation, and catastrophic accidents. One example was nuclear bombs that was released during the World War II. These bombings caused a sever number of civilian casualties, (History.com, 2022).

Chernobyl 1986

In 1986 one of the largest and oldest nuclear powerplants at that time; Chernobyl, caused a severe accident due to a design false in the reactor. This resulted in a widespread of radioactive contamination in surrounding areas. Directly linked to the accident there has been reported 28 deaths, and another 19 between 1987-2004, (United Nations, 2008).

Fukushima 2011

In 2011 there was the Fukushima accident which was a result of the tsunami that hit Japan. There was an overheating in the reactor which could have caused even further damage than it did. It was reported high radioactive release, but no reports of casualties regarding radioactive sickness – only a large public evacuation as a safety measure, (World Nuclear Association, 2022).

The Ukraine-Russia Conflict 2022

In the resent years, in the second half of 2022 the Ukraine-Russia Conflict occurred, which has increased a concern related to the use of nuclear bombs. Vladmir Putin has expressed his dissatisfaction of the Western countries contribution of weapon supplies to help Ukraine defeat Russia, making him to remind the contributors about his nuclear weapon supplies, (Kruse & Strømme, 2022).

As history shows, there are some devastating accidents that illustrates what the consequences could be if the reactors are not used correctly or properly operated. Even though some of these examples are not concerning nuclear reactors, the nuclear bombs have still participated with creating fear and putting nuclear technology in a bad image, (Spencer, 1991).

2.1.2 The Nuclear Fleet

Today there are about 160 naval and civil nuclear vessels, powered by 200 reactors. Naval reactors are mostly based on the PWR technology and are used for several reasons. “Unlimited” range, large energy outcome and higher travel speed over longer distances are some of them. There is also the efficiency and compactness that delivers large amounts of energy from a relatively small volume. The technology has a proven record of being "…one of the safest, most efficient ways to power large ships with the benefit of zero emissions", (Martime Nuclear Application Group, 2022). This is due to the high level of standardisations in their operations and maintenances, great knowledge and expertise, and high-quality training programs for the crews. (World Nuclear Association, 2021).

Figure 1, "USS Nautilus" sailing into New York city, (History.com Editors, 2022).

However, there are reasons why the PWR technology are not suited for civil vessels. It is expensive and uses enriched nuclear material like uranium 235 as fuels. There is a concern regarding the reactor design, and the crew is expensive and complex to train. Maintenance takes long time and is expensive. The PWR technology is also unique, nation specific and rarely shared between countries, which increases the development price. The enriched uranium is likely to not be allowed for commercial use is because of the international security and proliferation concerns associated with the fuel, (Martime Nuclear Application Group, 2022). If we consider operational purchase costs, the U.S Congress estimates that in 2011 the running cost of their nuclear navy fleet was 120 billion USD (Congressional Budget Office, 2011). In addition, an Indian Nuclear submarine was in 2009 purchased for 2,9 billion USD (World Nuclear Association, 2021), that's twice the cost of the most expensive cruise vessels per 2022, the Oasis Luxury Class at about 1,4 billion USD, (Mambra, 2022)

Civil Nuclear Vessels:

There have been attempts to develop nuclear merchant vessels. The first was the "NS Savannah," that was in service between 1959-1967 with great technical success. The vessel was taken out of service for not being economically viable. Russia has developed civil nuclear ships; the “NS Sevmorput” and three icebreakers that all are in service as of 2022. The icebreakers serve an important task to maintain a passage though the Northern Sea Route. Even though they are expensive to operate, they are chosen over diesel alternatives because of the reactor’s capabilities and the artic conditions (World Nuclear Association, 2021).

Although civil nuclear vessels never reached the intended potential due to costs and technological concerns, the safety records from the U.S. Navy are considered as excellent. Combining the experience, safety procedures, training, and operational regime from the navy with an affordable reactor. It could be possible to develop civil nuclear merchant vessels. To see if this is true or not remains to se. Therefore, it will be presented the Thorium Molten Salt Reactor, which have been proposed as an alternative.

2.3.4 Thorium Molten Salt Reactor

The thorium MSR dates to the 1960s, when a team of scientist created a 7-MW thorium MSR. Even though they managed to solve all the nuclear engineering issues, the project was shut down after 17 655 successful operating hours and it was never proceeded any further. In later studies it was said that "The Molten Salt Reactor has the highest probability of achieving technical feasibility", and that "…thorium potentially could be licenced under the current regulations without additional rule making.", (Emblemsvåg, 2021).

The Thorium Molten Salt Reactor (TMSR) is breeder reactor which means it produces more fissile material than it consumes. In difference from the PWR technology, the MSR's operates with liquid and not solid fuels. The liquid mixture works as the primary fuel and reactor coolant. The thorium and the molten salt create a chemical reaction which produces heat and steam into a turbine and a generator that creates energy, see Figure 2. The MSR is an "advanced nuclear reactor", described as a "nuclear fission reactor with significant improvements over the most recent generation of nuclear fission reactor, which may include (Martime Nuclear Application Group, 2022);

I. Inherent safety features
II. Lower waste yields
III. Greater fuel utilization
IV. Superior reliability
V. Increased resistance to proliferation
VI. Increased thermal efficiency, and
VII. The ability to integrate into electric and nonelectric applications."

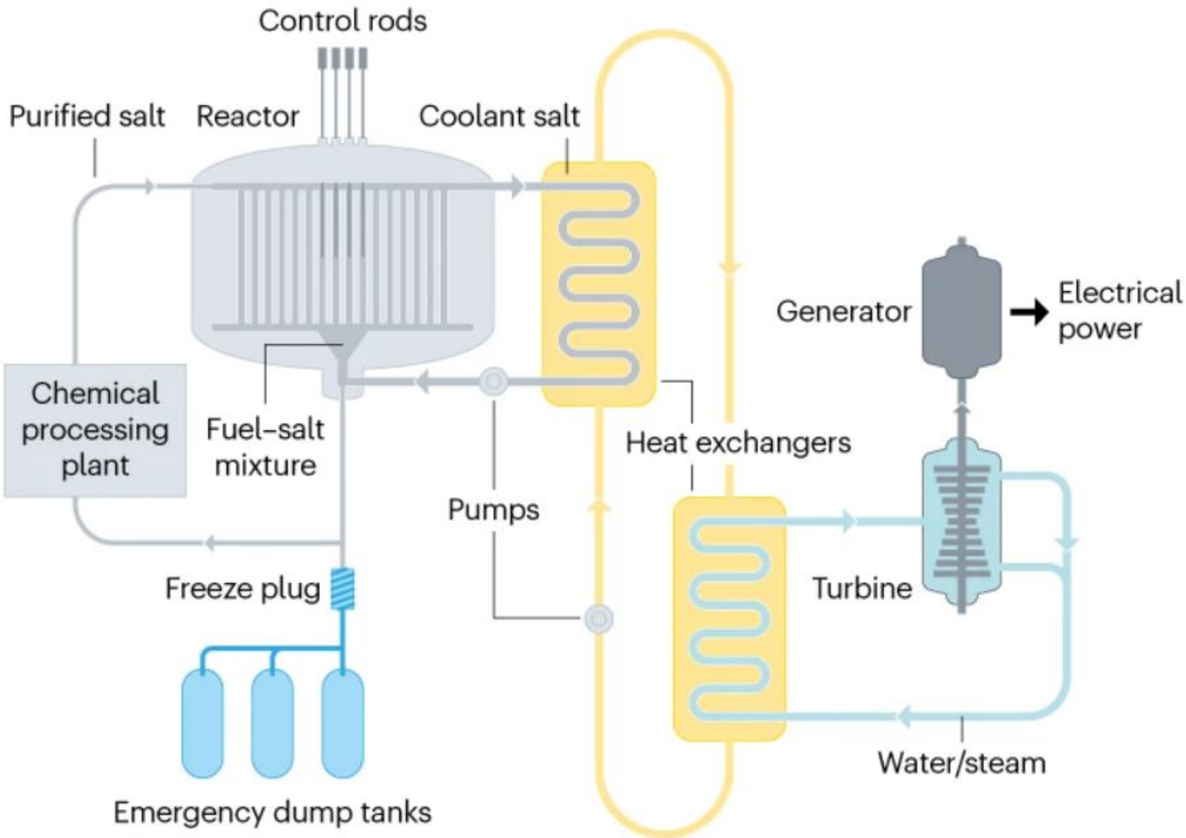

Figure 2, Illustration of the reactor design of the MSR (Mallapaty, 2021)

Key Criteria for Nuclear Success in the Marine Industry

From a marine perspective the new era of advanced nuclear reactors can extinguish many of the concerns regarding radiational safety, proliferation, fuel and waste handling. There are three main evaluation criteria that should be fulfilled to make nuclear reactors appropriate for the marine environments, (Martime Nuclear Application Group, 2022):

1. High-efficiency fuels that mitigate nuclear proliferation and reduce nuclear waste
2. Reactors that are passively safe with minimal licensing complexity
3. Economic viability

The most optimal would be a reactor that fulfils all three criteria. Based on the results in this study, it could be possible to see whether the TMSR fulfils these criteria or not.

TMRS Benefits

There are significant differences between a traditional pressurized water reactor and a thorium molten salt reactor. Here are some key benefits and arguments for making TMSRs appropriate for marine environments, (Emblemsvåg, 2021) (Martime Nuclear Application Group, 2022):

1. The liquid molten salt works as both fuel and coolant in a closed loop, with no need for adding coolant water like traditional reactors.
2. It operates at an ambient pressure meaning that can reduce the Emergency Planning Zone (EPZ).
3. The reactor operates at high temperatures; 500°C – 700°C which permits higher conversion efficiency that can enable efficient hydrogen production.
4. In the TMSR there is no scenario called "fuel meltdown".
5. It has full passive walk-away safety. Even under worst case scenarios the fuel will automatically get drained into a safe storage tank, see Figure 2.
6. It can use a variety of spent fuels. For instance, the thorium fuel or other fuels can be reprocessed and used again, creating better utilization of the fuel resources
7. Suited for productional scalability and standardization, meaning it could be cost effective in the long term.
8. Several non-proliferation advantages.
9. Potentially few or no refueling of nuclear material during the life cycle.

The Economy Behind Molten Salt Reactors

The general principle of nuclear reactors is that the economics behind the reactor are mostly influenced by the capital cost, which can be as much as 60-70% of the total lifecycle costs. Once a reactor is up and running, the operational costs are proven to be low and predictable, (World Nuclear Association, 2022).

There is no straightforward approach of finding the exact economy behind the thorium MSR. Some information lack updated information and other sources are based on a different technology. However, a company called CorePower, is building a market for advanced nuclear energy in the marine industry. They have made some estimations on a Molten Chloride Fast Reactor (MCFR), a which is different MSR technology.

They believe it is possible to manufacture the MCFR at the cost of 400 million USD per reactor, which will include;

- 150 million USD for the machinery and systems
- 250 million USD for fuel and decommissioning funds for the nuclear fuel
- 3 mill USD annually for operational and maintenance related costs

This study will use the MCFR cost as guidance to estimate what the costs could be for the TMSR, when comparing nuclear vessels with traditional vessels. This is mostly because there is not enough literature guidance to give exact reactor cost on the TMSR. It will be discussed how a nuclear propulsion system may affect the operations and related expenses, and how the total lifecycle cost; OPEX and CAPEX, could look like. This is based on the estimations for the MCFR. In addition, discuss different measures that could reduce the financial risk for shipowners who invest in nuclear vessels. This will be presented in the "Discussion" section later.

2.4 Ro-Ro vessel

Figure 3, Picture of traditional RoRo vessel; (Marine Traffic, 2022)

The RoRo vessel that's going to be used in this study is owned by Wallenius Wilhelmsen. A fixed route from Rotterdam to New York will be used to compare voyages cost between a traditional and nuclear vessel. The vessel data was provided by the shipping companies; Wilhelmsen and Wallenius Wilhelmsen. In following subchapters, calculation will be made based on vessel data to show the operational, capital expenses (OPEX and CAPEX) and lifecycle cost for the vessel.

2.4.1 The Voyage Rotterdam to New York

The reason for choosing this route is because the automobile market in U.S and Europe are the two largest automobile markets, after China, (Carlier, 2022), and could therefore also be a realistic voyage. The sea route is considered a relatively easy voyage with approximately 3300 nautical miles, and more or less continuously sailing from point A to B, (Smart Freight Centre, 2022)

2.4.2 Vessel Data

Table 1 represent the relevant vessel data for calculations of the operational expenses (OPEX) of the fixed route, which will be presented in the next subchapter. There will be shown both short- and long-term expenses. For this study “short term” means the voyage cost with the focus on bunker fuel, maintenance & repair, crew wages, lubricants, speed and travel time. Keep in mind that there are other operational expenses that realistically also would affect the operations, but for this study they are excluded.

Table 1: Vessel Data, (Nordhagen, 2022)

Length Overall (L.O.A.)	199,99 m
Total Capacity	6504 units / 21 965 DWT
Bunker/Fuel Capacity	3079 m3
Main Engine Output	13 240 kW
Speed	20 knots – Service speed
	14 knots – Average speed
Fuel Consumption	50 MT/day of HFO
	CO_2 emissions: 14,86 gram/kWh
Crewmembers	23

By “long term” means the total life cycle expenses of the vessel which includes the OPEX’s over the amount of service years, the amount of dry dockings required, carbon taxes and purchase cost of the vessel, CAPEX. Carbon taxes are included in the long termly calculation because it is not settled how it should be paid; per trip, monthly or annually, and how large the tax would be; 1 USD, 50 USD or 150 USD per ton. As a “worst case scenario” there will be used a carbon tax of 150 USD per ton CO_2, because it was currently the highest proposal, (Gerretsen, 2022). It’s assumed the vessel will operates for 30 years, and that during that time will have a total of seven dry dockings.

2.4.3 RoRo Vessel's Expenses

Regardless of the vessel type there will always be a handful of expenses affecting the revenue, which will verify from ship to ship and voyage to voyage. The cost of running a ship is dependent on the combinations three factors, (Stopford, 2009):

1. The ship itself – fuel efficiency, amount of crew members required to operate it and the frequency of maintenances and repairs.
2. The bought-in items – mainly bunkers, consumables, crew wages, repair cost and interest rates. Often driven by economic trends outside the shipowner's control.
3. The company management which effects the administrative overheads and operational efficiency.

For this study, the focus will include the first and second factors. Company management are excluded because it's likely to be the same regardless of the propulsion system, and it was not possible to find specific costs for this factor.

Collected Expenses

In Figure 4, there is presented the annual OPEX, additional costs and CAPEX for the RoRo-vessel. This will used for the voyage calculations in Figure 5, and to calculate the lifecycle cost in Figure 6.

Expenses collected		
Average bunkerprice for HFO 2021	**535**	p/MT
OPEX		
Annual Fuel Consumption for 2021	9 330	MT
Annual Lubricants	180 000	USD
Annual Crew Cost (23 pax)	1 380 000	USD
Annual Maintainance&Repair	590 000	USD
Cost per drydock	2 000 000	USD
Additional costs		
Carbon Tax	150	USD
Tons of CO2 per MT HFO consumed	3,15	
CAPEX		
Purchasing Cost (100% loan)	75 000 000	USD
Interest rate over 30 years	6%	

Figure 4, Expenses collected for the RoRo vessel, OPEX and CAPEX, (Nordhagen, 2022)

The bunker price of 535 USD shown in Figure 4, is an average price based on what a vessel paid for bunkers in 2021, (Nordhagen, 2022). The carbon tax is at 150 USD per ton CO2. One ton of HFO contains approximately 3,15 tons of CO2. With knowing the annual consumption, and the cost per ton CO2 it's possible to calculate the annual carbon tax cost, (Mandra, 2021).

Voyage Expenses: Rotterdam – New York

The voyage expenses for the Rotterdam – New York route are shown in Figure 5. With an average speed of 14 knots gives a travel time of 9,85 days, and a fuel consumption of 492,26 metric ton (MT). With a bunker price of 535 USD gives a total fuel cost of approximately 263 000 USD. Combined with the other expenses gives a total voyage cost of about 329 000 USD. This means that about 77 percent of the voyage expenses are related to the total fuel consumption.

Traditional propulsion		
Distance	3308	nm
Speed	14	knots
Average HFO Price	535	p/mt
Daily costs		
Fuel/Bunkers	50	mt/day
Crew	3 781	p/day
Lubricants	493	p/day
M&R	1 616	P/day
Other running cost	1 781	p/day
Travel time:	**9,85**	Days
Total bunker consumption	**492,26**	MT
Voyage costs		
Cost of bunker	263 360	USD
Crew	37 223	USD
Lubricants	4 855	USD
M&R	15 914	USD
Other running cost	17 533	USD
Total voyage cost	**338 885**	**USD**

Figure 5, Total voyage cost for the roro vessel with traditional propulsion

Lifecycle Expenses

Figure 6 shows the name of expenses in the first column, annual OPEX in the second, lifecycle expenses in the third, the item's value in percentage of the total OPEX in the fourth and the item's value in percentage of the total lifecycle expenses in the fifth.

Expenses	Annual OPEX	Lifecycle Expenses	OPEX in %	Lifecycle in %
Fuel/Bunkers	4 991 550	149 746 500	39%	28%
Crew	1 380 000	41 400 000	11%	8%
Lubricants	180 000	5 400 000	1%	1%
M&R	590 000	17 700 000	5%	3%
Other running cost	650 000	19 500 000	5%	4%
Drydocking (7)		14 000 000	4%	3%
Carbon taxes ($150)	4 408 425	132 252 750	35%	24%
Total OPEX		**379 999 250**	**100%**	**70%**
Vessel cost	5 400 000,00	162 000 000		30%
Total CAPEX		**162 000 000**		30%
Total Lifecycle		**541 999 250**	USD	**100%**

Figure 6, Annual and Lifecycle Expenses for a RoRo vessel

OPEX

The largest OPEX for the vessel would be bunker costs and carbon taxes, valued at approximately 150 million USD and 132 million USD per lifecycle, see Figure 6. The bunker costs are based on the annual fuel consumption and the average bunker price. The carbon taxes are based on the amount of carbon emissions from the annual consumption. The total OPEX accounts for 70 percent of the total lifecycle expenses, and about half of those are from bunker costs and carbon taxes alone. For this example, it shows a large potential for reducing the OPEX, if future voyages contain zero-emission technology.

CAPEX

The vessel cost is estimated at 75 million USD, which is the market price for similar vessels, (Nordhagen, 2022). For this study, the vessel will be financed through a 100 percent loan, with a 6 percent interest rate over 30 years. This will give a yearly payment on 5,4 million USD with total CAPEX of 162 million USD, see Figure 6. Over 30 years the actual vessel cost increased by 87 million USD due the rates. The CAPEX account for 30% of the total lifecycle cost.

Total Lifecycle Cost

The total lifecycle cost is the sum of the total OPEX and CAPEX, (Stopford, 2009). During 30 years' service the expenses for the vessel would be about 542 million USD. In reality there would likely be different because would have a volatile and not average bunker price. There would also be additional costs included, for instance: canal fees, port charges, insurance and other variable costs (Stopford, 2009). However, this example gives an impression how some of the important expenses affects the operation a RoRo-vessel today.

2.5 Fuel Types and Fuel Production

For this part of the study, it will be presented the fuels that is most common today; HFO, and some that potentially can replace HFO in the future; hydrogen, ammonia and methanol, (DNV AS, 2022). In addition, it will be pointed out some challenges that can arise during combustion and production, and how a nuclear powerplant can contribute with production of these fuels.

2.5.1 HFO – Heavy Fuel Oil

Over several decades HFO has been a reliable and common fuel, mostly because of its low price and global availability, (Stopford, 2009). From January 2020 to December 2020 the average bunker price for HFO in Rotterdam was 324 USD per metric ton, between 150-550 USD cheaper than the other fuel alternatives at the port, (Ship and Bunker, 2022). One of the downsides for this fuel is its large environmental impact. It has a content of 3,5 percent sulphur oxide (SOx), along with other harmful materials that are released to the environment during combustion, (Stopford, 2009). With new regulation after 2020 its required that HFO vessels needs to install scrubbers; an exhaust cleaning system that removes most of the SOx. By fitting a scrubber system, a vessel will reduce the sulphur content to 0,5 percent, which will be within the IMO's 2020 regulations, (Yildirim, 2021)

2.5.2 Alternative low-carbon and zero-carbon fuels

In a futuristic perspective the shipping industry would be dependent on many different fuel alternatives. Some would be more appropriate for short sea and others for deep sea vessels. Therefore, it's not likely to be a "one fuel fits all" approach in the fuel supply, (Pribyl, 2022). For deep sea shipping, the main challenges would be creating fuels with large enough energy density to not impact vessels range of operations, in addition for not creating any fuel storage and capacity problems onboard vessels as well, (Stopford, 2009).

The fuels presented underneath are sometimes referred to as green, blue or grey fuels, which refers to the carbon footprint of the fuel, (Choksey, 2021);

- Green fuels have no carbon footprint and are produced with clean renewable energy sources where no harmful gases are released.
- Blue fuels have some carbon footprint and uses fossil fuels in the production, with a CO2 capturing for reducing the amount of pollution entering the environment.
- Grey fuels have a larger carbon footprint by using fossil fuels, with no carbon capturing present during production

Ammonia

A potential zero-carbon fuel that is being considered is ammonia. It is mostly made from using natural gas and hydrogen and has a high energy density. Ammonia has the potential of being net-zero in a Well-to-Wake perspective, which is the entire supply chain of the fuel. This will be further explained in the next subchapter. There are still some obstacles concerning the supply chain of ammonia, like productional scalability and availability, but also in engine designs, onboard safety regulation and barriers of handling the toxicity of the fuel, (Pribyl, 2022). Regardless of these obstacles DNV considers ammonia as one of the best potentials for succeeding as an alternative fuel for deep-sea voyages, (DNV AS, 2022).

Methanol

Methanol is a liquid chemical fuel, and green methanol has the potential of reducing the CO2 emissions by up to 95%, and eliminate all the SOx emissions, (Methanol Institute, 2022). It may not be a "net zero emission fuel" due to some emissions of methane (Pribyl, 2022). However, methanol is certainly a better option than HFO – in terms of the amount of emissions they create (DNV, 2020). The current technology readiness for methanol is also higher than for hydrogen and ammonia, and according to DNV there are becoming availability of green methanol container ships during the mid-2020's (DNV AS, 2022).

Hydrogen

Hydrogen as an alternative fuel is currently under development, and the technology may play an essential role in decarbonization of the short-sea shipping segments, (Pribyl, 2022). This is also backed up in a report by the Centre for International Climate Research (CICERO) that stated, "the most promising potential for hydrogen is for short to medium shipping distances", (CICERO, 2021). According to these two sources hydrogen will require large storage volumes onboard, that could lead to capacity problems for larger vessels. In addition, the necessary power required for larger vessel will be too high and the volume too great, for hydrogen to succeed as a fuel for deep-sea vessels.

The reason for including hydrogen in this study is because nuclear energy and the TMSR can produce sufficient green hydrogen through nuclear fission on a large scale (Emblemsvåg, 2021). In 2021 only about 1% of the produced hydrogen was green hydrogen, so there is a large potential for increasing the annual production, (IRENA, 2022). One of the reasons why there such small quantity of green hydrogen is lack of renewable energy. In an article released by Recharge, claims there are massive needs for "terawatts of renewable energy", to produce green hydrogen on a large competitive scale, (Collins, 2020).

When it comes to the future of hydrogen supply, Rotterdam Port are committed to become the hydrogen hub of Europe, with production of blue and green hydrogen mostly reliant on windfarms, (Port of Rotterdam, 2022). However, windfarms are fully dependent on the wind to generate electricity which isn't always available, (Energysage, 2022). This can create unpredictability in the production of hydrogen.

2.5.3 What is renewable and sustainable fuels, and why do we need it?

A fuel is renewable when it's produced from natural raw materials, like for instance methanol can be extracted through biomass, or when hydrogen is produced using renewable energy like wind or solar. A fuel is considered sustainable if it can be maintained over an extended period and continuously satisfy our needs (Wagner, 2020).

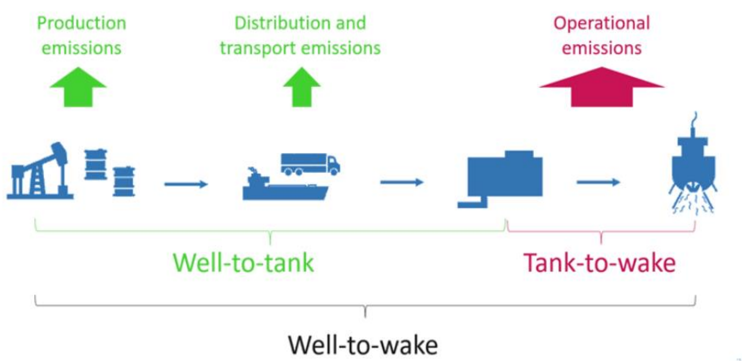

Figure 7, Illustration of Well-to-Tank and Tank-to-Wake emissions, (IMO, 2022).

As mentioned, the fuel's supply chain is called well-to-wake; which consist of well-to-tank and tank-to-wake, see Figure 7. Tank-to-wake emissions are easier to measure and there are many different ways to cut those emissions; efficient engines, scrubbers, higher density fuels, new alternative fuels to mention some. Well-to-tank on the other hand includes the emissions like oil extraction, refining, transport emissions by land or sea, handling and storage emissions. (World Nuclear Association, 2021).

With hydrogen and ammonia, the industry may enable carbon-free voyages, or with methanol reduce it significantly. They are all approximate emissions free when combusted, but if they are to be consider as fully sustainable and renewable the Well-to-Tank must also be considered environmentally friendly, (Pribyl, 2022). For instance, according to the U.S Department of Energy, they wouldn't consider hydrogen as a renewable fuel if the production was reliant on coal energy, (U.S Department of Energy, 2012). In the current fuel production industry there is a large need for renewable and sustainable resources, that can help scale up the production of green synthetic fuels – and reduce the well-to-tank emissions in the industry, (IRENA, 2022)

2.5.4 Using Nuclear Power for Synthetic Fuel Production

In this section it will be presented some examples on how a TMSR reactor can provide clean energy in the synthetic fuel production industry. In a series on reports by the World Bank it has been highlighted that the future fuel markets could be worth more than one trillion USD (World bank, 2021). In the search for technologies that can provide zero-carbon fuels, the TMSR has a unique opportunity for facilitate with "reliable, clean electricity with high temperature heat for efficient hydrogen production", (Martime Nuclear Application Group, 2022). In Figure 8 there is an illustration on how syntetic fuels can be generated in an MSR; "chemical production".

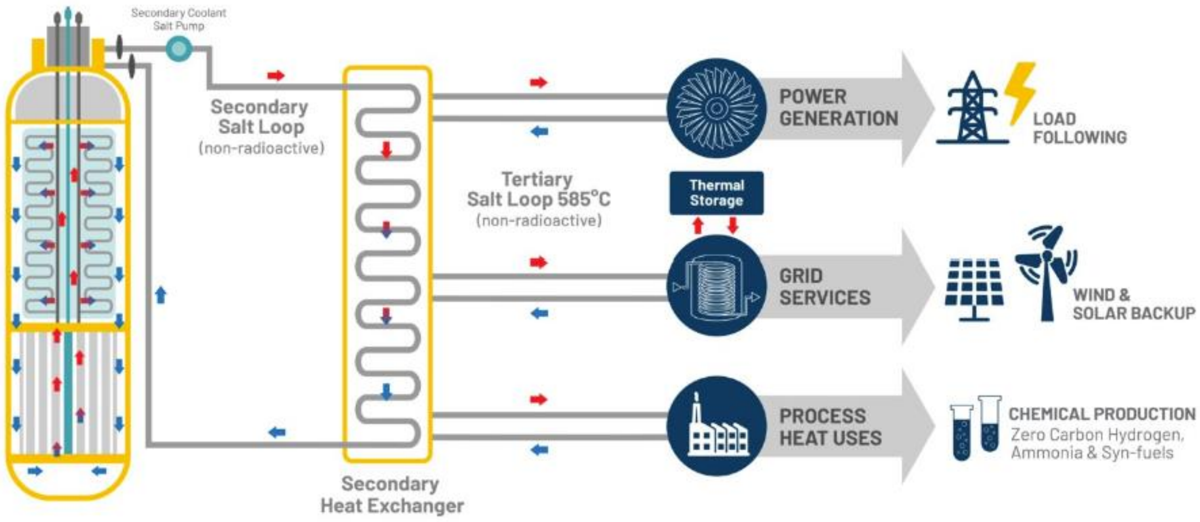

Figure 8, Illustration of the TMSR's multiple industrial use, including zero carbon hydrogen, ammonia & synthetic fuel production, (Terrestrial Energy, 2022)

One project that has been presented, is a floating nuclear powerplant for green ammonia that has a potential production capacity of one million metric tons annually. This floating powerplant could be attractive for areas where land-based infrastructure or available space are limited. The idea is to utilize the hydrogen generated from nuclear power to be use in the production of green ammonia, by "converting water and air into a carbon-free fuel or feedstock for chemical manufacturing and industrial processes including fertilizer production", (Martime Nuclear Application Group, 2022).

The same principal can also work as a land-based powerplant, where space for infrastructure is available. The U.S Department of Energy (DOE) are currently teaming up with the Office of Nuclear Energy to support four hydrogen projects at four nuclear PWR powerplants, (Nuclear Energy, 2022). They estimate that a 1,000-megawatt powerplant can produce 150 000 tons of hydrogen annually at a cost of 3 USD p/kg – and a potential for reducing this even more. As a comparison green hydrogen are today produced at a cost between 2,5-6,8 USD p/kg, with wind, solar and hydro energy, (Collins, 2020).

3.0 – Method

To be able to answer the thesis statement one is dependent on collecting relevant data – data that somehow is observed or registered. There are two ways of collecting data, either through a quantitative or qualitative approach. It’s important to specify that data can’t reflect the true reality as this is complex, constantly changing and it is impossible to observe or register all of it (Larsen, 2017).

3.1 Choice of Theme

The reason for choosing this theme was because I was inspired by a nuclear seminar that I attended. By continue following the technology I was able to find an approach relevant for the decarbonization of the industry, and for the company a was working for. The reason for having a divided thesis statements was because I wanted to enlighten two different solutions, from the same technology. Both solutions have the potential for contribute with the decarbonization and help the shipping industry to reach IMO’s requirements for 2050. My thought was that the industry needs a technology that can both contribute with zero-emission voyages emissions and create environmentally friendly fuels. The information that was collected in advance of this study, indicated that the TMSR could be a solution for both problems, and I wanted to investigate this further. This theme has also some relevance and similarities with my bachelor program, to the extent that decarbonization, zero-emission technology and sustainability within the industry has been a large focus in the curriculum.

3.2 Choice of methods:

When it come to the decision of how to collect the data there are two options: quantitative and qualitative methods. Quantitative methods are when you collect data in the form of numbers and statistics, often through surveys. This can be used as measurements to draw general conclusions towards a subject. One can reach out to a larger crowd, which can be an advantage when the researcher wants to collect several opinions upon a subject. Qualitative methods on the other hand are when you want information that describes a phenomenon or a subject, often conducted through interviews. The advantage with this method is that the researcher can get a deeper understanding of the subject or the thought of the participant, (Larsen, 2017).

It will be both strengths and weaknesses by studying this with quantitative or with qualitative methods. For that reason, it was chosen to use both methods in a "Mixed Methods Research". By combining both methods one could utilize each methods true potential. Where one of the methods has a weakness, it can be offset by the strengths of the other, (Larsen, 2017).

The procedure for this study was to use the quantitative survey gather a public opinion on nuclear solutions for vessel operations and within fuel production. This was to see whether there is an appetite for nuclear solutions or not. For the qualitative method, the purpose was to gather information on how nuclear technology may affect the OPEX, CAPEX and lifecycle expenses, and what the industry may need from the technology to make it a more feasible and attractive solution. Based on the qualitative method and theory it will be accounted for a potential cost of a nuclear vessel. By combining both methods it will be discussed whether TMSR technology could be a viable option for vessels and fuel production in the future.

3.3 Choice of Selection and Distribution:

It was chosen use employees from the two shipping companies: Wallenius Wilhelmsen and Wilhelmsen. Both are multinational and respected companies that can play an important role in decarbonizing the industry towards 2050. However, it was a large chance that the TMSR technology was unknown for many since nuclear isn't their primary field. This meant finding a way where they still could be valuable for this research. The most reasonable approach was to use their knowledge and company data to find out how the OPEX's are affected today. Then conduct research with the companies' employees to collect opinions and thoughts on the subject. Last step was to find out how nuclear propulsion systems may affect a vessel financially, and how to make it a more attractive and feasible alternative for the future. This was done through the qualitative methods.

For the two interviews that was conducted, one of them was internal and one was external. The internal was selected by a coincidence. During the research I received information about his experience with nuclear submarines from the Royal Navy of United Kingdom, and that he was interested to participate in the study. The external was selected due to his current work in creating a market for the MSR technology. Both was seen as relevant attendances that could give valuable insight and experience towards nuclear solutions, which could be used to find out how a TMSR may affect a vessel financially. I did not find any particular weaknesses with selecting these specific participants, because there are not many people that could have given the information they gave.

For the people that attended in the quantitative survey they were mostly selected randomly through the companies' internal network. It was sent electronically to managers at different departments of the two companies, and then sent to their employees. At no point was I in control of who received the survey, part from the managers that was contacted. A total of 63 attendances received the survey, where 60 of these conducted it.

The strengths with the selection in the quantitative method was that they represent two large, well established shipping companies and different departments. Some of the participants worked in the departments of energy sourcing, others in ship management and ship service – giving the selection a large width of experience, knowledge and different opinions.

The weakness with the selection in the survey was that they only represent one part of the industry – the shipping companies. With a different selection or a greater width of participants, the outcome of this research may have been differently. Thereby, it's important to state that the data from the survey only represents this selection's opinions and not necessary the whole industry. However, it may show a particular trend that could be representative for the rest of the industry.

3.4 The Design of the Quantitative Survey – Strength and Weaknesses

The survey was standardized and anonymous, and included 17 questions regarding the thesis statement, see “Attachment 2”. The same questions were given to a larger crowd and was sent internally through different managers and departments. The purpose was to map general opinions towards nuclear solutions, to see if there are any patterns or similarities that stood out. The survey involved questions towards:

- Knowledge of the industries decarbonization goal, and their belief of reaching them,
- Opinions on nuclear solutions
- TMSR and opinion towards the technology
- Fuel and fuel production
- Two hypotheses about the focus on well-to-tank and tank-to-wake in fuel production

Some of the strengths of having a quantitative approach was that it was easy to conduct, and it was time efficient. Having it anonymous was considered a strength because nuclear solutions have a tendency of being a sensitive subject, and anonymity could increase the chance of collecting honest answers. The data was also easier to convert into statistics that simplified the process of analysing and discuss the content.

The weaknesses by choosing quantitative methods were that it wasn’t possible to get information on all the aspects of the research, and it needed to be narrowed down. In addition, it would have been an advantage to be able to give follow-up questions to immerse further into each reply, and to understand the participants answers and point of views towards the subject. Another weakness was that many of the participants was likely to be unfamiliar with the TMSR, and how it worked. This led to some difficulties regarding the design of the survey. The survey needed to be created in a way that included both basic information of the TMSR and not too complicated questions, to make them understands the content good enough to finish the survey. The result was a very simple survey that barely scratched the surface on the subject. However, there was still valuable data to extract, and it gave perspective to the analysis and the discussion.

3.5 Qualitative method – Strength and weaknesses

In the qualitative method there was conducted two interviews, one internal and one external. It was chosen to conduct a semi-structured interview format with a premade interview guide. This was to give both attendance the same questions where I could customize the interview based on their knowledge, and at the same time create a calm and open conversation, (Larsen, 2017). Both interviews were conducted through Teams and was recorded with their approval. It was estimated to take 45-60 minutes per interview, but they ended up at about 1,5 hour each. The participants were informed about their anonymity and that they won't be mentioned by name. The interviews contained questions within the areas: knowledge of nuclear and molten salt reactors, vessel operation and fuel, see Attachment 1. All questions were not seen relevant, but the totality of the interviews gave the necessary information required for answer the thesis statement.

The reason to include a qualitative method was due to the method's strength and the possibility to get information on areas that couldn't be extracted through the quantitative survey. The physical presence gave an advantage when collecting data. This enabled the possibility to make follow-up questions, understand how a nuclear reactor works and how it would affect the operational expenses. It also made it possible to ask for clarifications and get rid of any misunderstandings along the way. Another advantage was to be able ask elaborating questions with additional questions, which contributed with the decoding of the data, (Larsen, 2017).

With the quantitative method it was more difficult to make generalized and categorized statistics, and it was a more time-consuming process. They spoke freely around the questions, which gave a need for decoding and comparing their statements. However, the data was still transferable and valuable. One of the more common weaknesses with this method is the control effect; the possibility that the participants aren't honest or gives untrue statements. It's common that some answers what they think is the general opinion or what they think the interviewer wants to hear. This can weaken the validity of the research, (Larsen, 2017). This was kept in mind during the analysing and there is a chance that they may have done it. However, I didn't get the impression that they did.

4.0 – Case Analyse

The quantitative survey contained 17 questions, see Attachment 2. Not all questions were seen relevant, and it will therefore be presented what's seen as relevant for the thesis statement. Of the total 63 people that received the survey, 60 of these completed every question. The questions were voluntarily, which has led to small deviations in the number of answers regarding some questions.

4.1 Quantitative survey

4.1.1 Findings nr. 1: The majority are familiar with IMO

The majority: 61 people or 97%, of the selection was familiar with the IMO. This was expected, since they are employees at two shipping companies – and many may know what their companies must comply with. What we can say before continuing, is that the majority might have a good understanding of how their companies and the industry are working to satisfy the IMO's regulations.

4.1.2 Findings nr. 2: Disagreement whether IMO's 2050 emission goals are reachable

There is a large disagreement in the selection, when it comes to their thoughts of reaching the IMO's 2050 goals, as shown in Figure 9. Out of the 63 answers,

- 28 people, or 44%, find it possible to reach it.
- 25 people, or 40%, don't think it's possible it with today's technology.
- 6 people, or 10%, don't have an opinion,
- And 4 people, or 6%, don't think it's possible

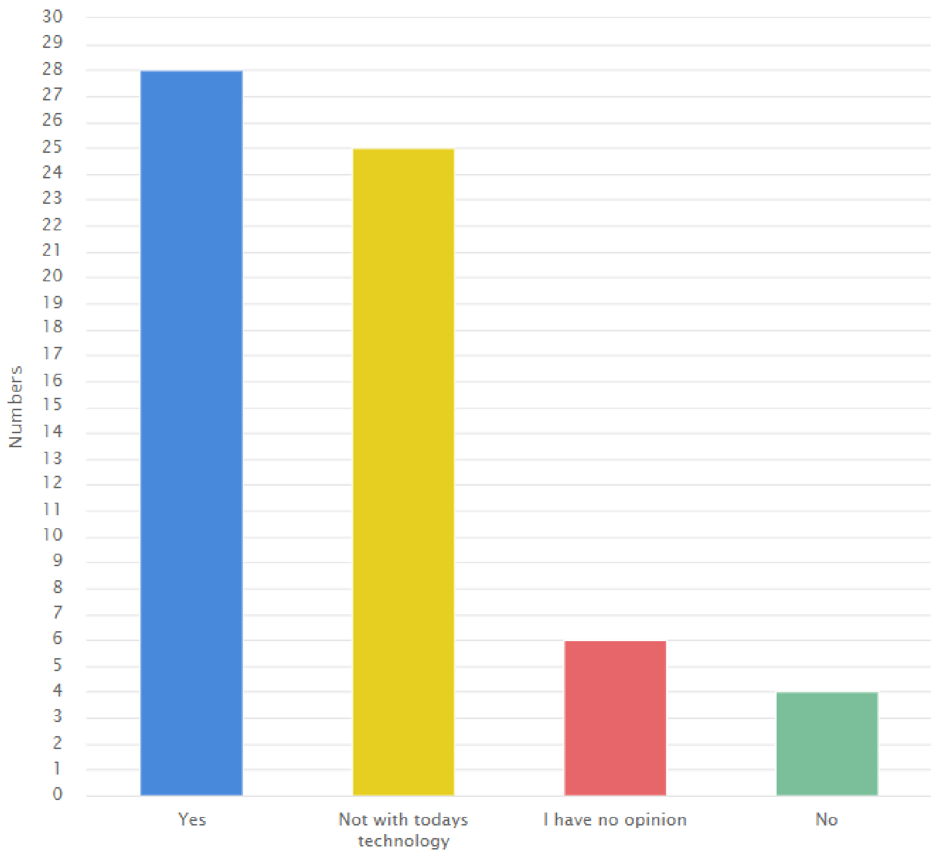

Figure 9, Question: "In the light of IMO's Green House Gas (GHG) strategy towards 2050, the shipping industry has to cut their GHG emissions with 50% by 2050. In your opinion is this possible?

One of the disadvantages with this question is that we don’t know what technology they are referring to, or the reasons why they don’t think it’s possible. Some might be referring to a specific fuel, engine type or a combination of them both, that would make it possible to satisfy the emission goals. Others could believe that the IMO’s regulations are too optimistic, and impossible to reach as of today. For those who didn’t have an opinion might be because they don’t have enough knowledge in this area or that they prefer to be neutral. What we can say is that they have a divided opinion for this specific question, and many believes the industry needs a new technology to reach IMO’s requirements.

4.1.3 Findings nr. 3: The majority have the biggest belief in synthetic fuels

To further enlighten how the industry may reach IMO's 2050 emission goal, the attendance was presented 11 different fuels. They were to choose one fuel which they considered as the best option for deep sea vessels, see Figure 10.

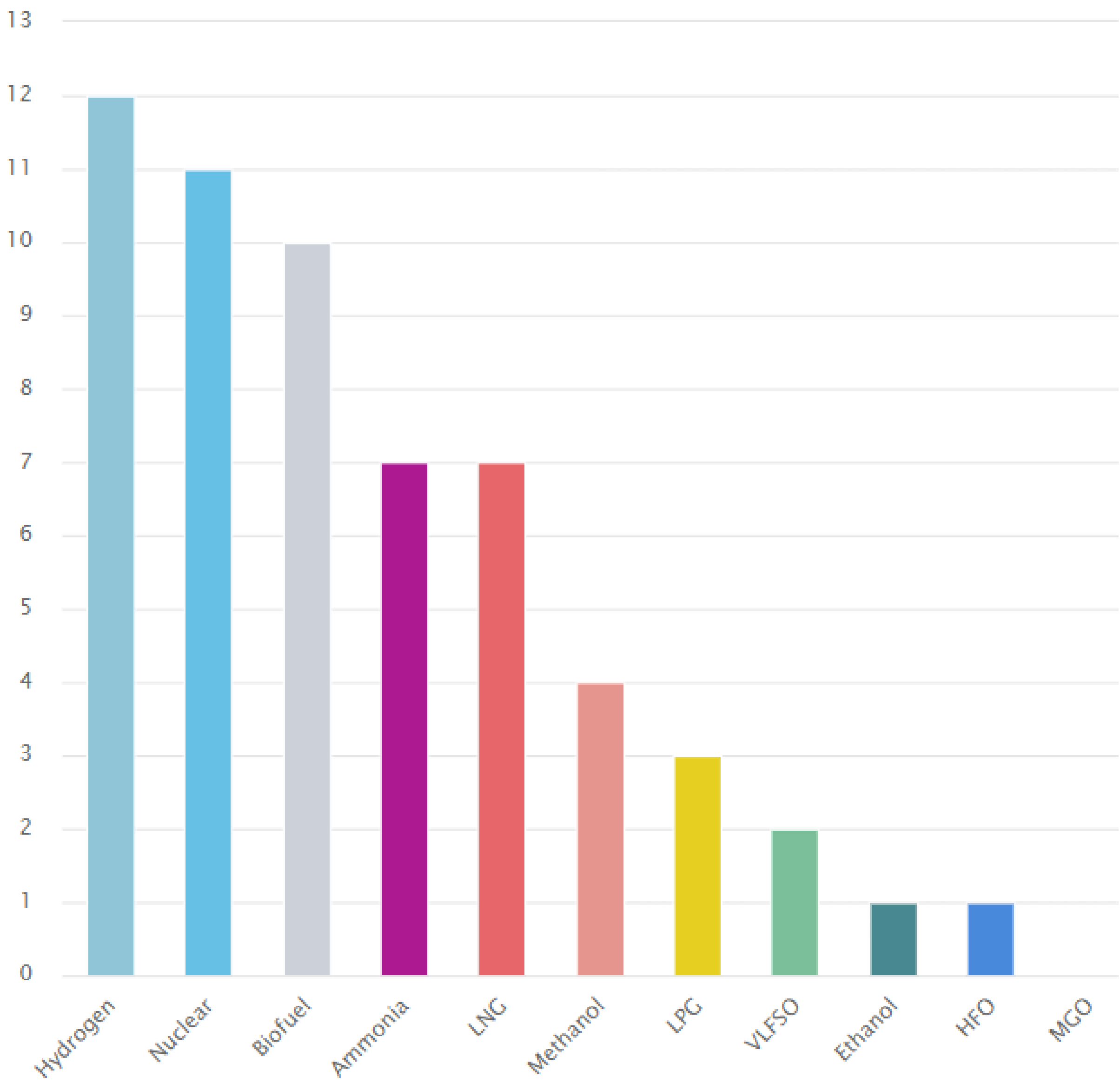

Figure 10, Question: «What fuel do you consider to be the best option for the deep-sea sector, if they are to reach IMO's 2050 emission target?"

Out of the 58 answers it was hydrogen, nuclear and biofuel that represents the top three, see figure 10. An interesting finding is their belief in hydrogen in the deep-sea sector. This was an unexpected outcome, mostly because hydrogen often is considered as a potential short-sea fuel, and not a deep-sea fuel. Hydrogen could have been chosen because they knew it's used in production of other synthetic and is therefore a necessary fuel. It could also be because they misunderstood the question and they thought the question was referring to both short- and deep-sea vessels, and they choose it as the best option for short-sea vessels.

If we divide the fuels in three categories; synthetic fuel, nuclear and oil&gas, it's easier to analyse what kind of fuels the selection has belief in. By categorising and adding the votes together we can see that:

- 34 people, or 59%, voted for synthetic fuels (Hydrogen, biofuel, ammonia, methanol, ethanol)
- 13 people, or 22% voted for oil&gas fuels (HFO, MGO, VLSFO)
- 11 people, or 19%, voted for nuclear

What we can read from this data is that the majority has belief in the synthetic fuels, then oil&gas and then nuclear. When not categorising, nuclear received the second most votes and was considered as a promising "fuel". Regarding the "oil&gas" category they are mostly based on LNG and LPG, and not the "traditional fuels" VLSFO, HFO and MGO. This could indicate that the majority believes conventional oil fuel would be phased out and be replaced with cleaner alternatives. By the look at the spread of the answers, can indicate that they believe the future may include several types of fuels and not just one specific fuel.

4.1.4 Findings nr. 4: The general opinion is positive for nuclear solutions and that the TMSR could be an alternative as a propulsion system.

One of the main focuses for this survey was to find the selection's opinion on nuclear solutions in the shipping industry, as a nuclear propulsion system and an energy source for synthetic fuel production.

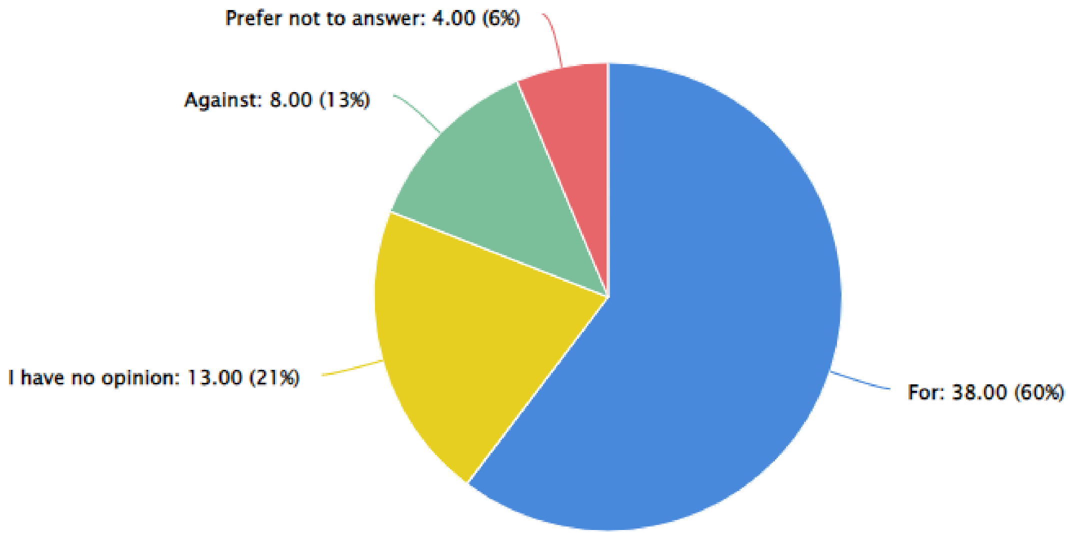

Figure 11, Question: "Are you for or against nuclear solutions"

As shown in Figure 11, out of the 63 attendances:

- 60% are positive for nuclear solutions,
- 13% are against nuclear solutions.
- 27 % either had no opinion or didn't want to answer.

They were also asked if they were familiar with the TMSR. Out of the 63 answers, 25% answer they was familiar with it and 75% were not. This was expected in advance, and precautions was therefore made. They were listed the TMSR key benefits and what this technology may bring to vessel operations. Based on that they were to rate too which degree they believe the TMSR could be an alternative as a propulsion system.

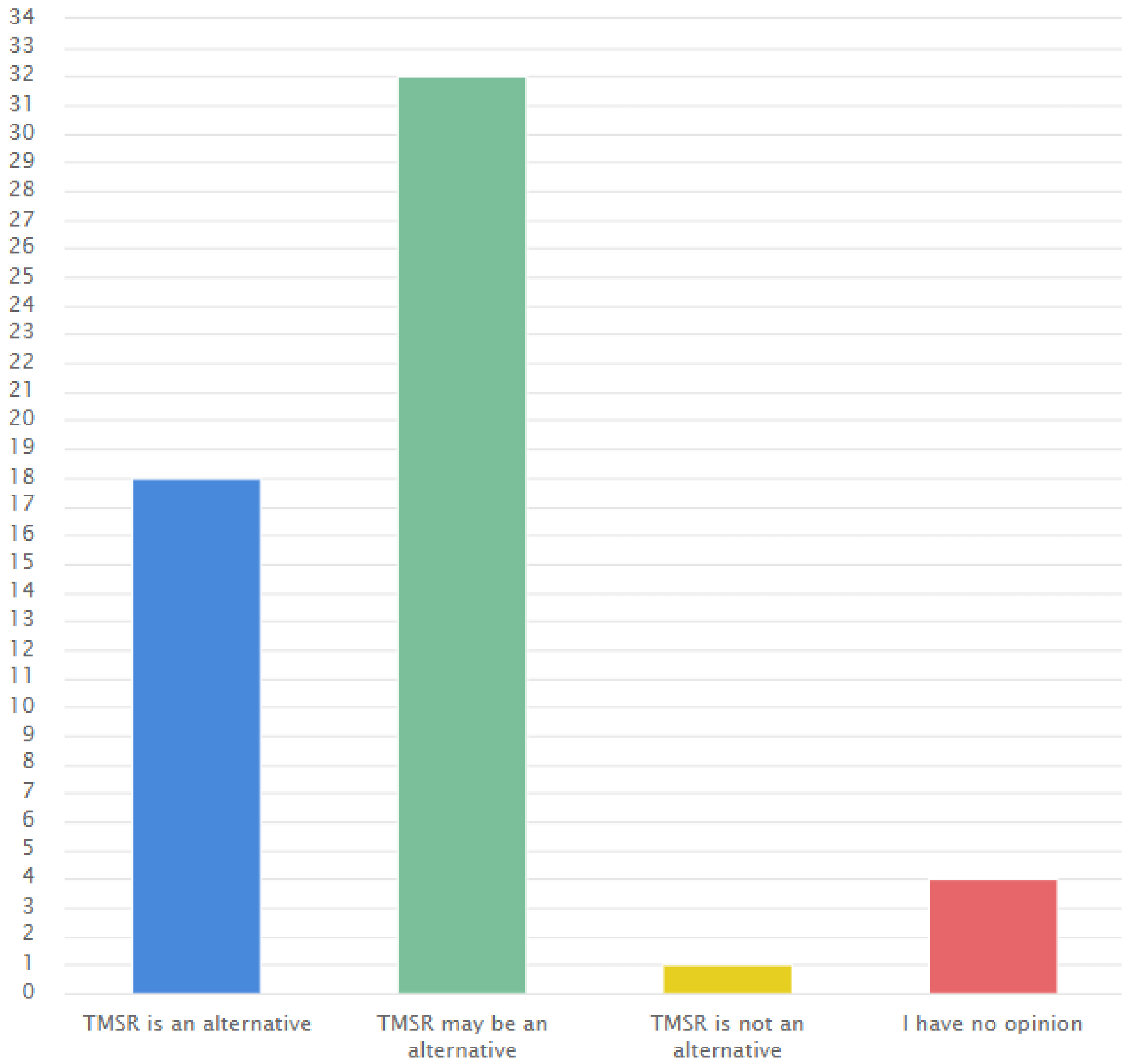

Figure 12, Question: Please rate to what degree do you agree with the statement "This technology is a viable alternative for ship's propulsion".

As Figure 12 shows, 18 people believe it is an alternative. The majority thinks it may be an alternative, and the rest either didn't have an opinion or didn't think of it as an alternative. Based on the data there is a positivity regarding the TMSR. A reason for this could be that the additional information about its benefits, gave impressions that vessel operations can be done safely, efficient and cost effectively – making it a viable option. Based on the data, it could be argued that about 91% of the attendance partly have a large belief in the TMSR as a propulsion system – if we consider "may be an alternative" as having belief.

4.1.5 Findings nr. 5: Agreement for improvement of and larger focus on the well-to-wake emissions

Regarding the use of TMSR in production of synthetic fuel, the attendance was first presented two hypotheses about the well-to-wake and tank-to-wake emissions in the shipping industry. They were to rate to what grade they agreed or disagreed in the hypothesis using a scare from 1-5. The intention of this hypothesis was to find if there is a need for more focus on renewable energy in the supply chain of fuels.

The first hypothesis was "*The fuel production industry improves their well-to-wake emissions, and not use energy from coal to supply production*", and the result is shown in Figure 13.

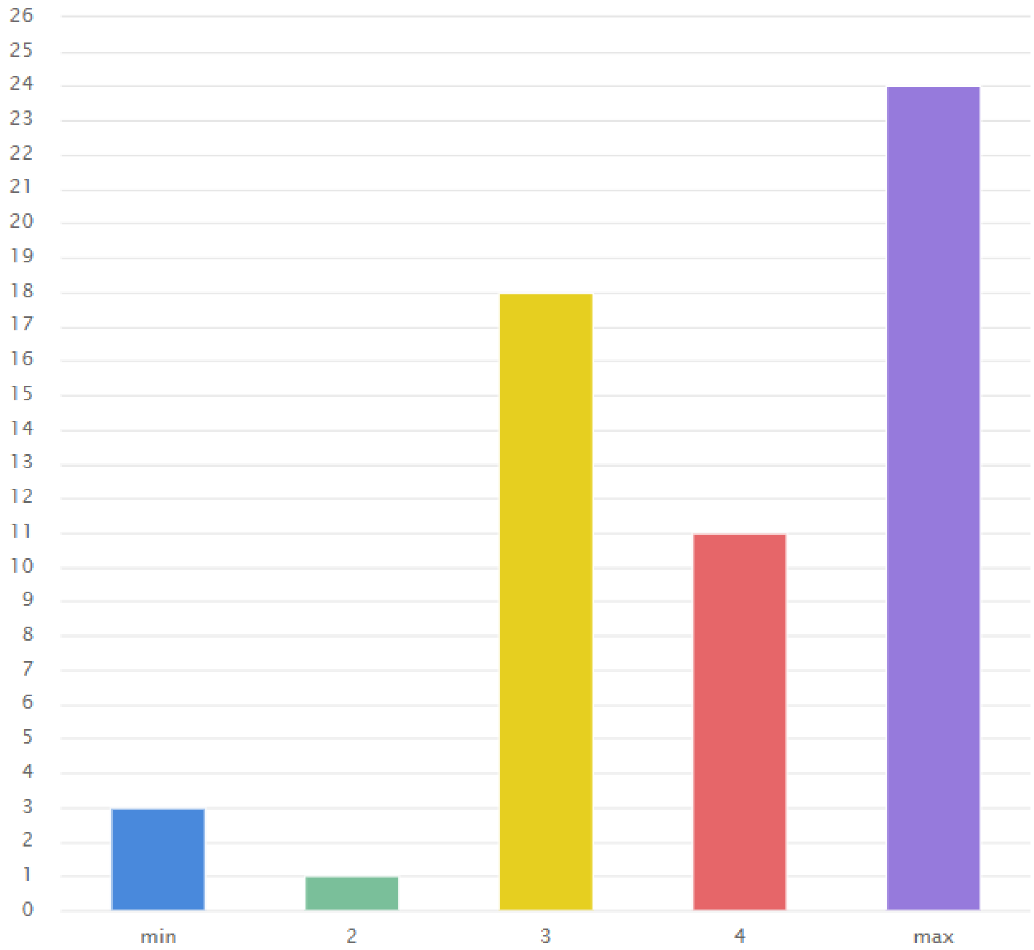

Figure 13, Hypothesis nr 1: "The fuel production industry must improve their well-to-wake emissions, and not use energy from coal to supply production"

From the 57 attendances:

- 24 was fully agree
- 11 was agree
- 18 was neither agree nor disagree
- 2 was disagree
- 3 was fully disagree

The average answer was 3,91 on a scale of 1-5 with a standard deviation of 1.13. The standard deviation indicated the spread in answers and can show whether the attendance agrees or disagrees with each other. A standard deviation around or less than 1 indicates that there is great agreement, (Larsen, 2017). The data shows that the selection believes the fuel production need to improve their Well-to-Wake emissions and exclude coal energy in the production. It could be reasonable to believe that they think renewable energy must substitute the coal energy.

The second hypothesis was: "*Emission cuts within shipping has more focus on Tank-to-Wake emissions rather than "Well-to-Wake emissions*", and the results are shown in Figure 14

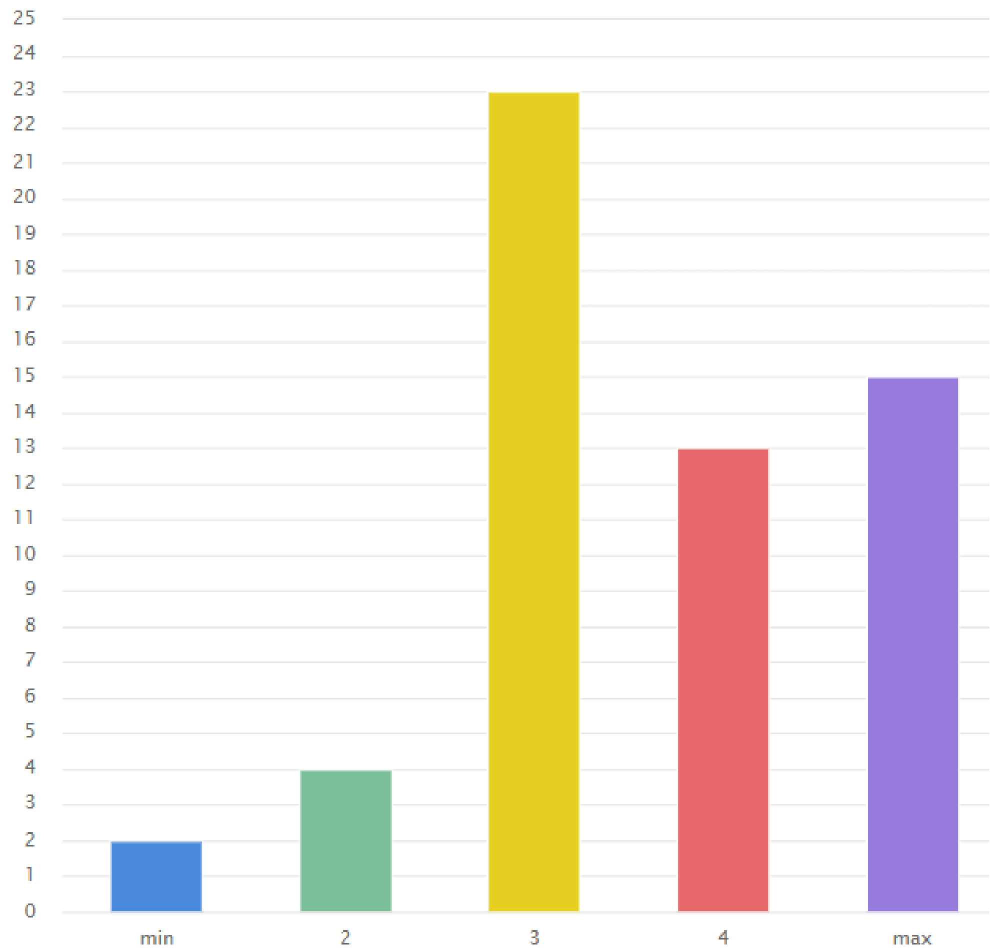

Figure 14, Hypothesis 2: "Emission cuts within shipping has more focus on Tank-to-Wake emissions rather than "Well-to-Wake emissions"

From the 57 answers:

- 15 or 26% was fully agree
- 11 or 23% was agree
- 23 or 40% was neither agree or disagree
- 4 or 7% was disagree
- 2 or 4% was fully disagree

The average answer was 3,61, with a standard deviation of 1,06. This indicated that there was less spread in the answers, and a common agreement between the answers. Based on the average answer there is a slightly greater agreement that the industry has more focus on the Tank-to-Wake emissions, rather than Well-to-Wake emissions. This is marginal and most of the selection was neither agreed nor disagreed in the hypothesis. However, the totality of the data shows a tendency that they believe there should be a larger focus on the well-to-wake emissions, rather than the tank-to-wake.

By combing the answers from both hypotheses, the selection indicates that the fuel production industry should have a larger well-to-wake focus – and phase out the use of fossil fuel energy like coal. It's to believe that the substitutes would be renewable resources.

4.1.6 Findings nr. 6: Large agreement for using TMSR in fuel production

The attendance was then asked whether we should use a TMSR to decarbonize the supply chain for fuels, given that is can safely provide energy. Here we can see a clear agreement, as shown in Figure 15.

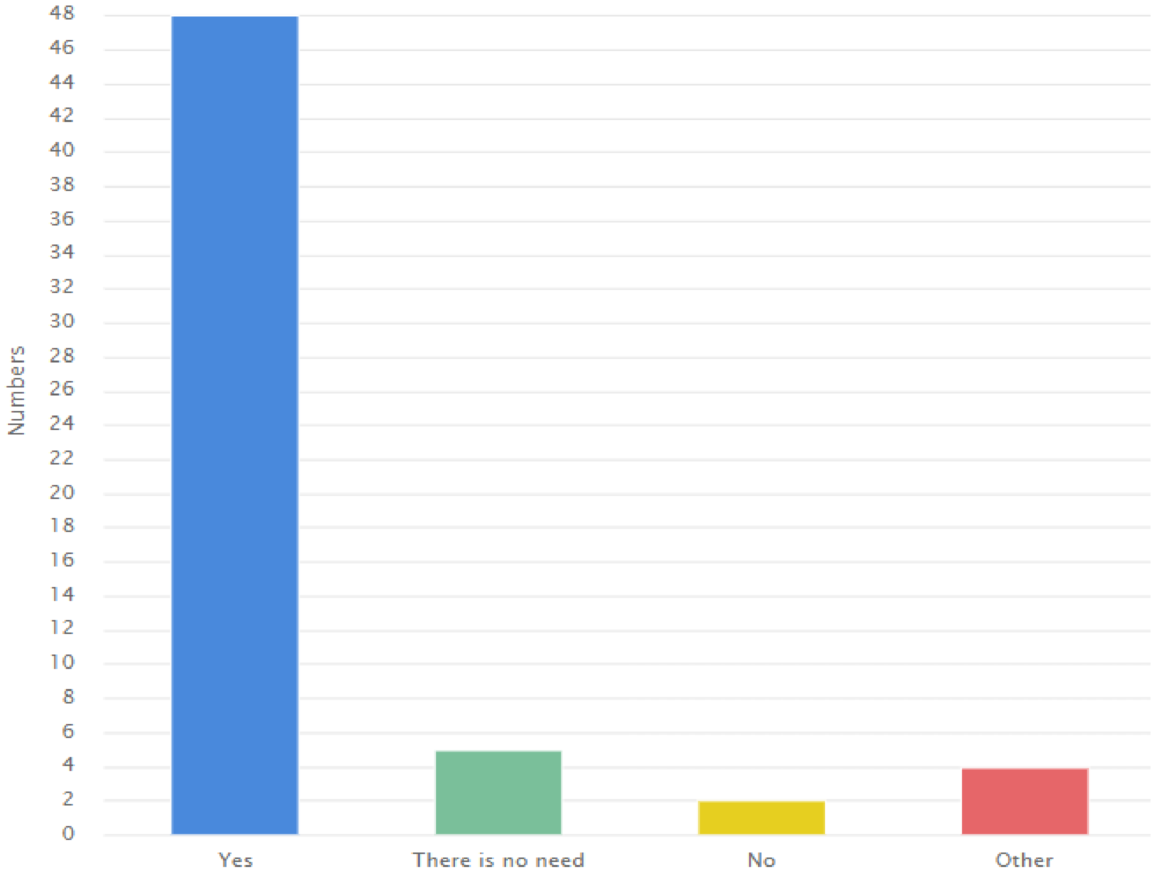

Figure 15, Question: Given that a land based TMSR can safely provide fuel production facilities with energy, should we use it to decarbonize the supply chain?

Out of the 59 answers,

- 48 or 81% answered yes
- 5 or 8% answered it was no need
- and 2 or 3% answered no
- 4 or 7 % answered other

With a crowed this large there would often be some spread in the answers, as shown in Figure 15. However, the data indicates that 81 percent of the selection is positive for considering TMSR within the fuel production industry, given that it can be done under safe circumstances.

4.1.7 Findings nr. 7: The majority think the TMSR can be used both as a propulsion system and a land based powerplant for fuel production

After the selection was presented towards both solutions, they were asked which of the solution they thought was most suited for the industry, see Figure 16.

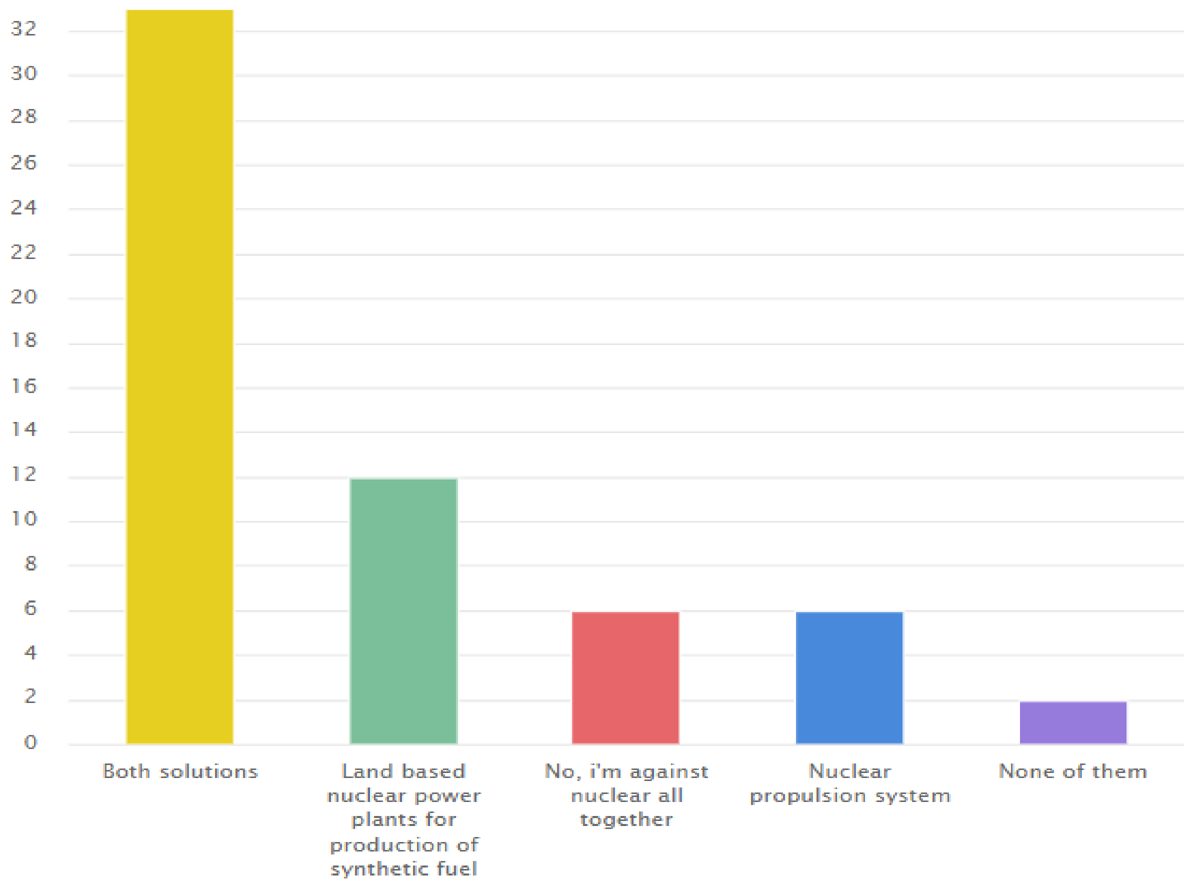

Figure 16, Question: «If nuclear solution were to be developed, wither as propulsion system or a fuel production facility, what solutions would you think are most suited for the shipping industry?"

As shown in Figure 16, there is a great agreement that both solutions could be suited for the industry. Only 8 people or 13% was either against nuclear or don't think they was suited for the industry. The rest answered either;

- Both solutions; 33 people or 56% for land based nuclear
- Land based nuclear power for fuel production; 12 people or 20%
- Nuclear propulsion; 6 people or 10%

This gives a total of 51 people or 85%, that was positive and believed one or both nuclear solutions could be suited for the shipping industry.

4.1.8 Findings nr. 8: The survey had an impact on some of the participants point of view on nuclear technology

As a last question the survey asked whether this survey may have changed their view on nuclear solutions. This was to see if the selection had changed their views on nuclear after being introduced to the TMSR technology.

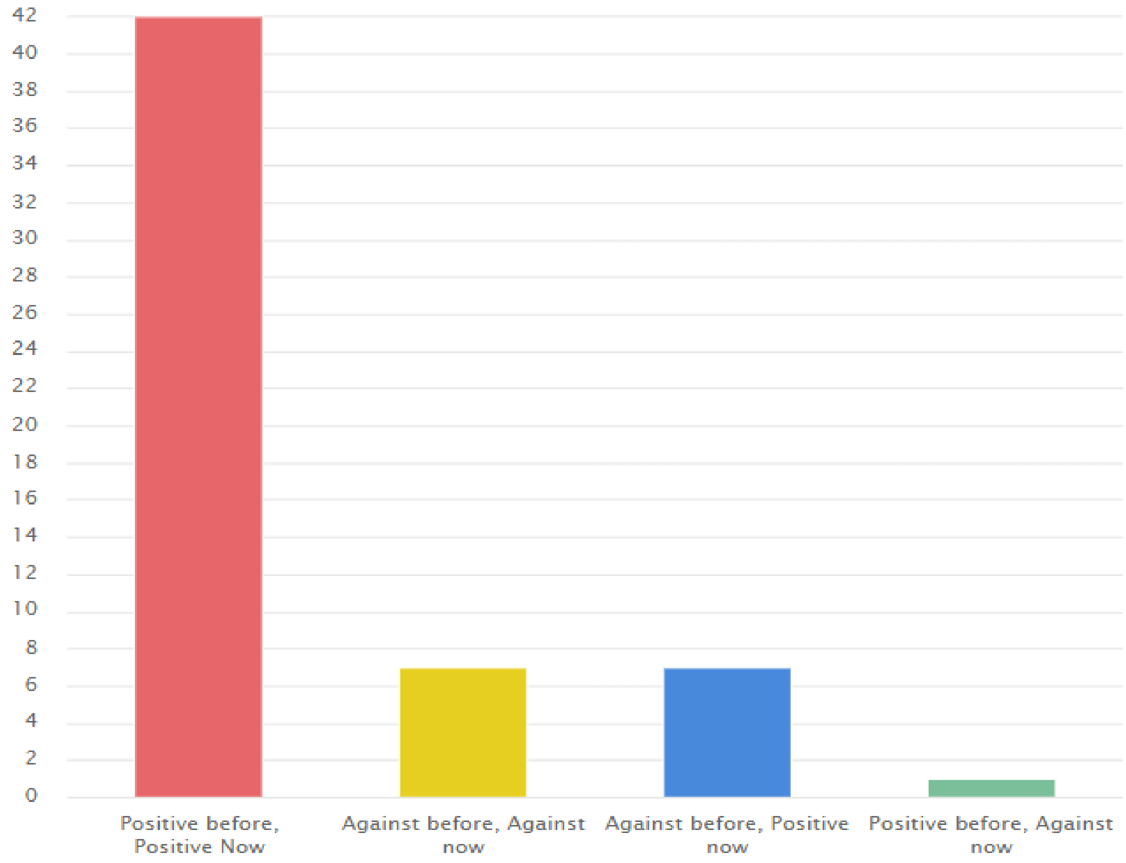

Figure 17, Question: "What is your opinion on nuclear now compared to before the survey?"

As shown in Figure 17, the majority did not change their view. Out of the 57 answers

- 7 people changed from "against before" to "positive now"
- 1 individual changed from "positive before" to "against now"
- 42 people did not change their mind

This shows that there is possible to change people's view towards, both for the positive and negative of the technology. The majority of those who changed their opinion, went from being opponents to supporters of nuclear solutions. This indicates that by intruding this technology to a bigger crowd, the nuclear solutions in general and the TMSR technology could gain more support.

4.2 Qualitative Interviews

For the qualitative method purpose was to collect information on how a nuclear reactor may affect the vessels expenses. In addition, find out what the industry may need from the nuclear technology to make it a more feasible and attractive solution. The participants would be referred to as "internal" and "external", and the findings are based on what they said during the interviews.

4.2.1 What the industry may need from the technology

They believed the industry would need a reactor that would at least cover the current need for transportation. Something that would give similar or even better operations than today's vessel, in terms of safety, performance and efficiency.

Safety

From a safety perspective it was mentioned that the reactor must be totally safe, even in a worst-case scenario. This meant that if the reactor brakes down or something similar happens, no radioactive contamination or proliferation can be present. The vessel should also have a small Emergency Planning Zone (EPZ) and a walkaway safety. Best scenario would be to have the EPZ to not exceed beyond the vessels hull. According to the external this would make for instance the emergency protocols, no more difficult than for a traditional vessel. This is something they believed the MSR technology should be able to provide. If we consider that the industry needs these specifications would exclude the PWR technology as an option. The internal gave the impression that the PWR technology would not be allowed for civil matters because of risk and expenses following it.

The Ideal Reactor

Regarding crew, the internal mentioned the industry would need a reactor that is easy to operate and to train the crew. From an operator's perspective the ideal reactor design should allow less or no interference during operations. It should be able to operate on its own. The crew should only be there as supervision to watch the parameter, which was something the external believed the MSR technology would allow.

Strategies

There was stated proposals of changing some of the current business strategies and look towards other industries, like the aviation industry. These strategies could be ideal and reduce some of the risks, like investing in and operate the reactors.

One of the proposals was an investment strategy involving a leasing structure between the shipowner and the owner of the reactor. The idea was that the shipowner would not own the reactor like they do with current machineries, but rather rent it to reduce some of the financial risks. The leasing agreement would include the cost of machinery and systems, fuel and decommissioning funds, and maintenance and operations (M&O). Meaning every cost related to the reactor would be within the leasing structure. For the owner of the reactor, they would be the responsible for maintenance and making sure the reactor operates as intended.

Another strategy was to develop an onshore control centre consisting with nuclear scientist. The control centre would have full access and live data from the vessel and reactors. The idea for this strategy was to involve it in the investment strategy, mentioned above. By paying for M&O through the leasing structure, the shipowner would be included in the control centre. In addition, the owner would be able to tell when maintenance would be necessary. The external claimed this could reduce some of the operational risks, because the nuclear scientist would be able to operate and interfere with the reactor from the control centre, as a second safety after the crew.

A third strategy involved crew training. It was proposed to train a crew for a specific reactor through a specialised training program similar to what is conducted in the aviation industry – where pilots are trained for a specific jet engine and aviation type. Through the training program it could be possible to develop a crew capable of handling every possible scenario that could happen during a voyage. According to the external, a more educated crew could give safer and more efficient vessel operations compared to today's operations.

These strategies could make nuclear solutions more attractive to the industry. However, they both agreed the most important aspect to consider are the costs. A reactor must be able to generate efficient voyage for the shipowners to an acceptable cost.

4.2.2 How would nuclear propulsion affect the OPEX, CAPEX and lifecycle cost?

In terms of cost, the industry would need a technology that is economically viable and not too expensive. Both agreed that with nuclear technology shipowners would see a change in the relations between OPEX and CAPEX. The CAPEX would increase significantly, but the OPEX would be much lower. If compared to traditional vessels the OPEX and CAPEX would be the opposite. The external said that the more frequently a nuclear vessel is used the "cheaper" it would get. This was because of two things. The first was because a nuclear vessel wouldn't need to consider bunker costs, which is both volatile and significant for traditional vessels. The second was that most of the expenses would be fixed or less significant, like the cost included in the leasing structure. What he meant by "cheaper" was that the vessel would generate more income per trip due to fixed and predictable costs, and no bunker fuels. For a traditional vessel it will be the opposite: the more it's used the larger is the consumption and the more it would pay for bunkers. The significance of vessels OPEX would therefore be dependent of how frequent the vessel is used.

There was also mentioned other costs affecting the vessel, for instance unexpected repairs or similar, insurance and licensing. However, these was not included any further in the interview because it was outside the focus area.

OPEX and Performance

The external claimed a molten salt reactor will have a positive effect on the OPEX – it would get cheaper and more predictable. A volatile bunker cost would instead be a fixed fuel payment included in the leasing structure. This could "lead to more predictability for the shipowners", as he stated. This will also exclude the carbon taxes since nuclear don't emit CO_2.

They believed the number of crewmembers would remain the same. Instead of having machine engineers, you would need about four nuclear engineers: two per shift. By changing the machinery of the vessel and the staff, they thought it's likely to get an increased cost for all crew members. The external thought nuclear engineers may get double the salary than what current machine engineers has, because their training and education would be more expensive. The rest might have an 20% increase from what is considered normal, due to some extra nuclear safety training that would be needed.

In terms of performance, they were confident that a nuclear vessel would achieve more efficient voyages. They believed because of energy potential would likely to be considerably higher gives advantages. Both believed that a vessel could travel according to the design speed and not an economical speed. This gives a potential for cutting down the travel time and increase annually port arrivals. However, it would also be dependent on the vessel type. The external believed that container and RoRo vessels could achieve significant higher speeds than a bunker and tanker vessel. This was due the vessels aqua dynamics and hull design. For this study it would mean that the vessel could increase from the economical speed;14 knots, to the design speed; 22 knots.

CAPEX

Unlike the OPEX, the CAPEX of a nuclear vessel would increase because of the reactor cost are significantly compared to traditional vessels. Neither the internal nor the external knows the exact cost for the TMSR. Therefore, the cost presented are based on estimation of the Molten Chloride Fast Reactor (MCFR). The cost for a thorium reactor could therefore look differently because the cost of thorium could be different than chloride. However, the MCFR are still a molten salt reactor. Meaning some costs may still be the same for both reactors, like the cost of machine, system and M&O.

The external believed it could be possible to manufacture the MCFR at the cost of 400 million USD per reactor.

- 150 million USD for the machinery and systems,
- 250 million USD for fuel and decommissioning funds,
- 3 mill USD annually for operational and maintenance related costs.

This could be paid through a leasing structure over 30 years, through for instance an annually payment. This business model is similar to what is conducted in the aviation industry to reduce risk. The external proposed that the reactor could have a residual value of around 75%, because there is still a large value in the remaining fuel even after it's been used. Let's say the reactor has consumed 10-20% of the original fuel, there could still be about 80-90% of valuable fuel left that can be repressed and used again, (CorePower, 2022). By including inflation, he said it's possible to get a roughly indication of how the capex may look like, which will be presented in the next section along with the voyage cost

4.2.3 Results – Nuclear Vessel Voyage Cost: Rotterdam – New York

The costs that will be discussed are crew wages, maintenance & operation, other running costs, and for the performance of the vessel it will be discussed the new service speed for the vessel. Based on the cost from the traditional vessel and the qualitative interviews, it will be presented a potential voyage cost for a nuclear RoRo vessel.

Nuclear propulsion		
Distance (nm)	3308	
Speed (knots)	**22**	
Daily Costs		
Crew	5 063	USD/day
M&O	8 219	USD/day
Other running cost	1 781	USD/day
Travel time	**6,27**	**days**
Bunker consumption	**0,00**	**MT**
Voyage costs		
Crew	31 721	USD
M&R	51 494	USD
other running cost	11 157	USD
Total cost	**94 372**	**USD**

Figure 18, Estimations of the nuclear vessel's OPEX per voyage

Performance

As shown in Figure 18, the new voyage speed are 22 knots. This is based on the maximum speed for this RoRo vessel, and it's therefore not designed for higher speeds. With a different hull design, it could potentially sail even faster. However, the new speed makes the travel time just above 6 days.

Crew

The nuclear crew would consist of 4 new nuclear officers with a double salary, and the rest would see a 20 percent increase. This gives a daily crew cost of 5 063 USD. By multiplying this with the travel time gives a total crew cost of 31 721 USD per voyage.

Maintenance and Operations

Maintenance and operations (M&O) cost per day represent the annual 3 million USD from the leasing structure, presented as a daily cost. Even though the M&O are within the leasing structure it's included to illustrate what you pay for supervision and maintenance of the reactor. For this specific voyage, the M&O are the largest expense at 8 200 USD per day which gives a total of about 52 000 USD per voyage, see Figure 18,

Running Cost

For the running cost there has been assumed that this cost will not change from the original example, because nothing in this study indicates nuclear propulsion to affect this cost. The running cost are therefore about 1 800 USD per day and 11 000 USD per voyage, see Figure 18.

Total Voyage Cost

By combining all these costs gives a total voyage cost of 94 272 USD, see Figure 18.

4.2.4 Results – Nuclear Vessel's Total Lifecycle Cost

In this section there will be discussed the total lifecycle cost per 30 years, see Figure 19.

Expenses	Annual OPEX	Lifecycle Expenses	OPEX in %	Total % of lifec
Crew	1 848 000	55 440 000	62%	9%
Other running cost	650 000	19 500 000	22%	3%
Drydocking		14 000 000	16%	2%
Total OPEX		**88 940 000**	**100%**	**14%**
Cost of leasing	18 500 000	555 000 000		86%
Total CAPEX		**555 000 000**		**86%**
Total Lifecyle Cost		**643 940 000**		**100%**

Figure 19, Estimations of the nuclear vessel's total lifecycle cost after 30 years

OPEX

The total OPEX are almost 89 million USD over 30 years, see Figure 19. About 60 percent of this represents the crew cost; 1,9 million per year and 55,5 million per lifecycle. Regardless of the propulsion, the ship's hull would still need maintenance and to be dry docked during the lifecycle. It's estimated that it would have same number of dry dockings; 7, at the same price; 2 million per drydock and 14 million USD per lifecycle. The same regarding the running cost; 19,5 million USD per lifecycle. In difference from this OPEX and the one presented in voyage calculation; Figure 18, is that M&O are no longer included. Instead, it is included in the "Cost of leasing" as part of the leasing agreement.

CAPEX

For the CAPEX of the nuclear reactor, there's these estimations that was suggested by the external, and will represents the cost of leasing:

- 150 million for machine and system, and 250 million for fuel including decommissioning funds. Total cost of 400 mill
- 3 million per year for maintenance and operations
- Leasing agreement/structure over 30 years

- 6% interest rate
- 2% inflation
- A residual value of 75% of the initial fuel value

Leasing structure

To find the cost of the leasing structure you take the present value of building the reactor and the fuel cost, minus the residual value of the fuel, and add the present value of maintenance and operations. The external suggested to use a formula to estimate total cost of leasing, see Attachment 3. By creating this formula, the final cost of the leasing agreement can be calculated:

PV(i,Y,-PMT(PMT(X,Y,-400))-75% x 250 + 3 x Y

- Y = Years
- X = Interest rate
- i= Inflation
- PMT = Yearly payments
- PV = Net present value

This calculation was implemented in Excel and gave the total cost of the leasing at approx. 555 million USD, see Figure 19. This would mean that the shipowner would have a yearly pay of approximately 18,5 million USD per year for leasing the reactor, see Figure 19. This includes the cost of building of machinery and systems, cost of fuel, decommissioning funds, maintenance and operations. In addition, there included a residual value of the fuel at 75%, because the external assumes the already spent fuel could have about 80-90% of remaining and valuable fuel that could be reprocessed and used again.

The Total Lifecycle Cost

The total lifecycle cost is estimated at 644 million USD. The CAPEX stands for 86% of the total expenses, and are considerably higher than the OPEX, see Figure 19. According to the section “Economics Behind the Molten Salt Reactor” mentioned earlier, there is common that nuclear technology has significantly higher CAPEX than OPEX. These estimations only based on a few expenses and assumptions. In reality there is likely to be more cost and externalities affecting the reactor, vessel operations and CAPEX. An example is for instance the cost of the vessel without any machinery. This cost was unfortunately not possible to collect for the companies, so keep in mind this would be an additional cost. However, there is still valuable information to collect from these estimations, and it gives an indication on how the nuclear reactors could affect a merchant vessel in the future.

5.0 – Discussion

For this part of the study there will be discussed the findings and results presented in the preview chapter and see how they comply with the thesis statement and the theory presented in Chapter 2. The discussion will be divided in three parts. The first part will include the general opinion towards nuclear solutions and try to find out why their opinions are the way they are based on the analysis and theory. For the second part it will be compared voyage cost and the total lifecycle expenses between a traditional vessel and a nuclear vessel. For the third part it will be discussed whether there is potential of nuclear energy supply in fuel production. Based on this discuss the whether the TMSR could achieve success as an alternative technology in the future for marine industries.

5.1 Opinion towards nuclear solutions

When it comes to developing nuclear solutions there are allot of factors that needs to be considered, developed and discussed. In this study one of the focuses has been towards finding out people's opinion. The reason is because for a new solution to be considered there must be a market for it, and a certain degree of appetite to make people invest in the technology. As the data from the quantitative survey presented, the majority was positive for nuclear solution and a large part of them thinks that the TMSR could be a viable solution both at land and sea.

If we are to consider "Findings nr 2" in the quantitative survey, there was a disagreement in the belief of reaching the IMO's 2050 goals. Almost half of the participants meant the industry would need a different technology to reach it. They could be referring to the need of technology that has enough potential to decarbonise every sector of the industry; from the largest to the smallest vessels and to every other sector that would need energy – but it can also be that they think current technology is not good enough. However, the data indicates that the TMSR could be a technology the participants believe can contribute with decarbonisations of the industry – and reaching the IMO's 2050 goals. If we consider the facts presented earlier, the TMSR has the possibility to provide large amounts of energy under safer circumstances than other nuclear technologies, with the benefits of being a zero-emission technology.

Seven people even changed their view from “against” to “for” nuclear solutions by participate in the survey. A reason could be that some people don’t fully understand the technology or isn’t aware of the progress nuclear technology have made. By educating the industry about this technology, it could be possible to gain more nuclear support, as shown in Figure 17. What is possible to say is that people believe in nuclear solutions and want it to be part of the future – at least according to this study. However, there was still some who was against nuclear solutions, which is something that can be argued as “normal”. Nothing comes without risks and with the TMSR follows for instance a financial risk and a proliferation risk of radioactive material – which could have been too great of a risk for some. Unfortunately, the reasons for why they were against was not possible to collect thought the quantitative method, and we can only speculate. The TMSR technology is expensive, and the reactor is still operated by radioactive material. Therefore, it possible to argue that it comes down to the individual’s willingness to accept a certain risk. With the TMSR it is possible to reduce the proliferations risk significantly compared to other nuclear alternatives, and the reactor may be cost efficient longtermly. For some people, this may not be enough to accept the risks, and they chose therefore to be against. In addition, this study only represents data from a small part of the industry, and the opinion for other parts could be different or deviate from these results.

5.2 Financial Impact of a Nuclear Propulsion System

For this section it will be discussed the differences of the financial impact between the nuclear and the traditional vessel. It will first be compared the voyage costs of the Rotterdam-New York route, shown in Figure 20, and then the total lifecycle, shown in Figure 21.

5.2.1 Differences of Voyage Cost

In Figure 20 there is presented the daily and total voyage cost for each of the vessels, which are showing some interesting differences. For this example, the change in speed, travel time, crew cost and the total voyage cost are considered interesting to discuss.

VOYAGE CALCULATIONS							
	Traditional Vessel		**Nuclear vessel**		**Differences**		
Distance	3308	nm	3308	nm			
Speed	**14**	knots	**22**	knots		**8**	
Average HFO Price	535	p/mt	-	p/mt			
	Daily Costs		**Daily Cost**				
Fuel/Bunkers	50	mt/day	-	mt/day			
Crew	3 781	p/day	5063	p/day		1 282	
Lubricants	493	p/day	-	p/day	-	493	
M&R	1 616	P/day	8219	P/day		6 603	
Other running cost	1 781	p/day	1781	p/day		-	
Travel time:	**9,85**	Days	**6,27**	Days	**-**	**3,58**	**-36%**
Total bunker consur	**492**	MT	-	MT			
	Voyage Cost		**Voyage Cost**				
Cost of bunker	263 360	USD	-	USD	-	263 360	
Crew	37 223	USD	31 721	USD	-	5 503	-15%
Lubricants	4 855	USD	-	USD	-	4 855	
M&R	15 914	USD	51 494	USD		35 580	224%
Other running cost	17 533	USD	11 157	USD	-	6 375	-36%
Total voyage cost	**338 885**	**USD**	**94 372**	**USD**	**-**	**244 513**	**-72%**

Figure 20, Differences between the voyage cost for a nuclear vessel and traditional vessel

Travel time

The nuclear vessel has an 8 knots higher service speed, which makes the travel time of the voyage about 3,5 days faster, see Figure 20. Potentially, this means is that for every voyage the nuclear vessel conduct is about 36 percent more efficient than the traditional vessel. Let say the traditional vessel has 20 successful voyages annually. If we exclude the potential time spent in laytime, port hick-ups and say that their time in ports are the same. It would mean that a nuclear vessel could potentially have 36 percent more voyages per year. That would make about 6 extra voyages per years, which is about 180 voyages over a lifetime of 30 years.

This tells there is a potential for generating more income with a nuclear ship than a traditional ship. If this RoRo vessel was designed for higher speeds, it would have been even more efficient.

Crew Cost

A nuclear crew would be about 5 000 USD per day, which is about 1 300 USD more expensive than the current crew, see Figure 20. An interesting finding is that even if the nuclear crew wages are more expensive, the crew cost per voyage are less compared to the traditional vessel. This is due the increase efficiency of nuclear voyages and by saving more than 3 days would make the crew cost about 5 500 USD cheaper per voyage.

Total Voyage Cost

The total voyage cost for a nuclear vessel is considerably lower than the traditional vessel. Almost 250 000 USD or 72% less per voyage. This is mostly because the nuclear vessel doesn't have any bunker costs, which is the largest expense for a normal vessel, see Figure 21. Let say both vessels conducts 20 voyages annually. After 30 years this would potentially make the cost of nuclear voyage approximately 150 mill USD cheaper. This means that a nuclear ship is considerably cheaper to operate than a traditional vessel.

The theory claimed that nuclear reactors are considered quite cheap to operate, so there is a similarity with theory and what found here.

5.2.2 Total Lifecycle Cost

In Figure 21, it is presented the expenses related to the vessel's total lifecycles, which consist of OPEX and CAPEX.

	Traditional Vessel		Nuclear Vessel	
Epenses	Annual	Lifecycle	Annual	Lifecycle
Fuel/Bunkers	4 991 550	149 746 500	-	
Crew	1 380 000	41 400 000	1 848 000	55 440 000
Lubricants	180 000	5 400 000	-	
M&R/M&O	590 000	17 700 000		
Other running cost	650 000	19 500 000	650 000	19 500 000
Drydocking (7)		14 000 000		14 000 000
Carbon taxes ($150)	4 408 425	132 252 750	-	
Total OPEX		**379 999 250**		**88 940 000**
Vessel cost	5 400 000	162 000 000		
Cost of leasing			18 500 000	555 000 000
Total CAPEX		**162 000 000**		**555 000 000**
Total Lifecycle		**541 999 250**		**643 940 000**
			Increased TLC:	19%

Figure 21, Differences between the total lifecycle of a traditional and nuclear vessel

OPEX

As Figure 21 shows, the total OPEX for a nuclear vessel are considerably lower, about 290 million USD cheaper per life cycle. The main reason is the exclusion of bunker fuel and carbon taxes, which accounts for about 280 million USD of the traditional vessel's OPEX. Another difference is the crew cost, which is about 14 million USD more expensive for a nuclear vessel. This was something to expect due the nuclear crew that would require a higher salary – at least according to the qualitative analysis.

CAPEX

When we consider the CAPEX there is a large difference between the vessels. The cost of leasing a reactor makes the nuclear vessels CAPEX almost 400 million USD more expensive, see Figure 21. This is because the reactor cost and the fuel cost in the leasing structure are considerably high. The leasing structure therefore about 555 million USD per lifecycle compared to the traditional vessels 162 million USD per lifecycle. The total CAPEX for the nuclear vessels is likely to be even higher since there is not included any cost for the vessel without the machinery- only the cost of the reactor. This cost was unfortunately not possible to collect, so keep in mind that it could be an even larger difference between a nuclear and traditional vessels CAPEX.

Total Lifecycle Cost

When combining the OPEX and CAPEX for each vessel, it shows that the traditional vessel has a total lifecycle of about 541 million USD and the nuclear vessel about 643 million USD. The differential is about 100 million USD, which is an increase of about 19% for the nuclear vessel. This is a quite large difference over 30 years, but whether a nuclear vessel is too expensive for a shipowner, is difficult to say only based on the costs. An important aspect to consider is the vessels potential for generating income. As discussed under the voyage costs, the nuclear vessels have the potential for better voyage efficiency, that could generate more income. Whether it would generate more or less than the differential of 100 million USD is difficult to say based on this. This is an aspect that could be further studied in the future.

5.3. Nuclear Potential in Synthetic Fuel Production

Towards 2050 it is to believe there will be some changes in which fuels that will be allowed. There are indications that HFO is likely to be phased out due its large environmental impact. For that matter, the industry is looking for alternative fuels. Fuels that are reliable, emission free and cost competitive. Today, the synthetic fuels are more expensive than HFO, and it’s likely that alternative fuels will continue to remain so if measures are not made. In the production of hydrogen, only about 1% of it is considered green. There is currently a lack of renewable resources to produce green hydrogen a large and competitive scale, see section 2.5.2. *Hydrogen*. A consequence is that the fuel industry often substitutes renewable with fossil energy to remain the production scale and competitiveness. Therefore, it possible to say the industries need more resources. Resources that are renewable, more reliable and efficient than current alternatives. To make it possible to produce more green hydrogen on a large scale with a competitive cost, which could substitute the grey and blue hydrogen.

Nuclear reactors have proven to operate with an enormous energy density and to be highly efficient, which could be an ideal solution for fuel production. According to the hydrogen projects in the U.S, it is estimated that the nuclear powerplants could produce 150 000-ton hydrogen annual at the cost of 3 USD p /kg. Against current market price of 2,5-6,8 USD p/kg, this is a competitive and more predicable price. Regarding the TMSR this could be the similar, but it is not certain. Hydrogen could be produced more efficient with a TMSR than it would with a PWR, due to the higher heat and thermal efficiency. Theoretical speaking this could increase the efficiency of hydrogen production, which could give the TMSR a chance of competing with the 3 USD p/kg costs. The efficiency on the TMSR may be one of the reasons why so many turned out to be positive for using nuclear energy in fuel production, see Figure 15.

The shipping industry is likely to not have "one fuel fits all" approach, but rather a larger range of different fuels that can be used for different ships and segments. By looking at the spread in quantitative data there are some similarities for this approach, see Figure 10. The combined majority has most belief in synthetic fuels, but nuclear also gained large support as a viable fuel for the deep-sea sector. Hydrogen which gained most votes would most likely not be viable in the deep-sea segment, as stated in section 2.5.2 *Hydrogen*. However, hydrogen has still a great potential for contribution in the decarbonisation of the short sea segment, and the fuel production of other potential deep-sea fuels like ammonia and methanol. With nuclear energy, a hydrogen facility could maintain their production scale at a predictable and competitive cost – at least if we consider the US hydrogen project. In addition, instead of producing the common grey and blue hydrogen it could be produced more green hydrogen. This can be used as a short sea fuel, or in the production of other synthetic fuels like ammonia or methanol. This would give the fuel market more green synthetic fuels suited for both sea segments and reduce well-to-wake emission for the fuels.

It is likely that the fuel supply approach; having a variation of different fuel, could be ideal for the energy sector as well. By leveraging different kind of renewable resources when they are effective, the industry can fully utilize the potential for all the resources available. Let consider an example and discussed the potential for implementing nuclear energy in the Rotterdam hydrogen hub. The current plan is to produce both green and blue hydrogen. When produced green it will be reliant on windfarms, and fossil fuel with carbon capturing when producing blue. A proposal could be to produce green hydrogen as much as possible when wind energy is effective, and to equalize with nuclear energy when it's necessary to keep up the scale. By combining wind energy and nuclear the hydrogen hub could be able to produce green hydrogen at all times, and not only when it's effective to utilize the wind resources. With this proposal it could be possible to provide the fuel market with a production scale that could be cost competitive, predictable, and environmentally friendly.

5.4 Degree of Success for the TMSR within the Marine Industry

According to the Maritime Nuclear Association Group there are three criteria's for achieving success in the maritime industry, and the optimal solution would be to fulfil all three.

1. High-efficiency fuels that mitigate nuclear proliferation and reduce nuclear waste
2. Reactors that are passively safe with minimal licensing complexity
3. Economic viability

Criteria Number 1

The TMSR needs to have a high security and risk profile. This means creating an outstanding fuel efficiency and long-lasting fuel cycles with the potential of few or no refuelling of nuclear materials. According to the section "TMSR Benefits", it operates at a high temperature that creates fuel efficient that utilises more of the nuclear material compared to conventional PWR. In addition, the TMSR should be able to operates at an ambient pressure that mitigates the concerns of explosions and proliferation to almost non-existent. The activities around handling spent fuel and refilling of nuclear material are one of the most critical factors of operating reactors. If the industry manages to develop the necessary experience together with the required handling and security protocols, much of the risks could extinguish. Most of the expertise and protocols of naval reactors comes through the Navy that has a proven record for conducting safe operations, maintenance and decommissioning of fuel. By having fewer or no fuel replacement together with the right protocols, the security, handling and proliferation risk could be reduced quite significantly, compared to the PWR. Based on this there is possible to argue that the TMSR may fulfil criteria number one.

Criteria Number 2

A merchant vessel arrives at several ports annually; port that often are heavily trafficked and close to other society. There is therefore vital that the reactor even under worst case scenarios don't cause any explosions or proliferation of nuclear radiation that can affect nearby environments or society. With the TMSR design it allows a walk-away safety meaning an operator can safely evacuate the vessel, if necessary, with no need for shutting down the reactor in advance. The ambient pressure in the reactor could potentially make the Emergency Planning Zone (EPZ) to not exceed beyond the vessels hull. This could be beneficial both when a vessel is in trafficked areas and for eventual licensing measures in the future. There is also stated by the external that the reactor design should be quite simple, with no direct interference by the operators. If we are to consider the impression given by data and theory, the operations from a safety perspective shouldn't be very different than for a normal vessel. However, it may include some different approaches. Based on this it could be reasonable to say the TMSR fulfils criteria number two.

Criteria Number 3

Whether the TMSR is economical viable we can look at what the theory means. To make an affordable reactor, the theory stated that small modular reactors with standardized designs are preferred. Through standardization it creates a potential for scalability in production, and limited size reduces the weight and volume, which could ease the installations onboard the vessels. Based on the theory the TMSR align with other MSR designs could potentially be suited for standardized designs, and therefore also mass production.

However, there is uncertainties around the exact cost of the TMSR. If we consider the MCFR design and the cost of that reactor; approximately 400 million USD. This may be feasible, but nuclear technology in general would make the investments cost more expensive than traditional technology. From a long-term perspective nuclear may be affordable and provide more predictability, cost efficiency and better voyage performance for shipowners. Only based on this study there is unclear whether the TMSR would fulfil criteria number three of being economic viable, but there is some promising indicating that it may do it to a certain degree. Therefore, further studies on other aspect of the reactor would be required to see whether the TMSR would fulfil criteria number three.

6.0 – Conclusion

This study has analysed and discussed the thesis statement:

- **How may a nuclear propulsion system affect the vessel operations financially, and can a land based nuclear powerplant contribute to produce cost effective and green synthetic fuels?**

Like all new technologies, there should be a market for it, or at least an advantage, if the technology is to succeed. According to the findings from the quantitative survey there seems to be an appetite for nuclear technology for both vessel operations and fuel production. This study indicates that a TMSR propulsion system could be able to provide zero-emission voyages for deep-sea vessels. It also indicates that the TMSR have a potential for gaining more support if further people are introduced for it.

If considering the financial impact from a nuclear vessel versus a traditional vessel, there would be differences regarding the OPEX and CAPEX – according to this study. For instance, a nuclear vessel would be considerably cheaper to operate than a traditional vessel, mostly because it will not require any bunker fuel or carbon taxes. However, the capital expenses will be the opposite. For this study, the total lifecycle cost for a nuclear vessel would be about 20 percent higher than a traditional vessel, mostly because of the significance regarding the nuclear reactor and fuel cost.

In terms of vessel performance there is indications that nuclear voyages would be more efficient and could reduce the travel time significantly. According to the analyses, the crew and maintenance would be more expensive, but not considerably more. A nuclear vessel would require the same number of crewmembers. However, instead of having machine engineers they would be replaced with nuclear engineers. For the remaining crew they could be provided with additional nuclear safety training. According to this study, a nuclear crew could increase the annual crew cost by about 30 percent. That being said, because of increase voyage efficiency there is indications that the actual crew cost per voyage would be less for a nuclear vessel.

Since the capital cost for nuclear technology shows to have a larger financial impact than current technology, could increase the risk of investing in nuclear reactors. This is one of the weaknesses with this technology, and there would be an advantage if this was to be reduced. There was proposed implementing a new investment strategy, like for instance a leasing structure on the reactor. According to the analyses, this could potentially reduce some of the risk and make the technology more feasible.

The TMSR’s potential for fuel production depends on whether it would produce cost effective and green synthetic fuels. There are indications it could provide green synthetic fuel production that could produce hydrogen through nuclear fission. By using the hydrogen to produce additional synthetic fuels like ammonia and methanol, could potentially reduce the well-to-wake emissions for these fuels. Whether this can be produced cost effective or not depends on the actual cost of the reactor. According to a hydrogen project in the US, there was claimed nuclear powerplants could produce the hydrogen at the cost of 3 USD p/kg. If the TMSR could provide similar production costs it should be able to competitive against the alternatives; wind and solar, which produces it between 2,5-6,8 USD p/kg as of today – this is though uncertain at this stage. However, nuclear energy and the TMSR should be able to provide the fuel industry with green synthetic fuels. These fuels could potential contribute with the decarbonisation in both the short- and deep-sea segment.

This study indicates that the TMSR could be suited for marine implementation in terms the safety, performance, and efficiency aspect – and that it could be a potential for technology within the fuel production industry. The actual cost for the reactor seems high is at this stage. However, in this early stage the cost is uncertain and too early to predict. The technology needs to be further enhanced and industrialised before the TMSR would be fully feasible for both vessel operations and green fuel production. Further studies would therefore be needed to provide more reliable data on whether this technology will be economical affordable.

7.0 – Criticism and Further Studies

7.1 Challenges

In the process of writing this study one of the main challenges have been to write alone and to not have someone to discuss with along the way. To be able to discuss the processes, the content and to criticise own work with another has proven in previous task to be very helpful. When that possibility was not present to the same degree made it sometimes difficult. Of course, good planning and research was helpful, but it would have been easier if you had someone to share the amount of work with. In addition, I had an 50% internship besides writing this study. This was something was excited about, and in periods I may have focused more on working in the company than writing my bachelor. This consumed valuable time, time that I could have spent on develop better research and analyses.

7.2 Limitations

When writing a bachelor study like this, there is a large amount of work to conduct. Even though I have learned a whole lot, there is some things I would have done differently if I started with the knowledge I now possess.

7.2.1 Thesis Statement

I would say the thesis statement was too broad, and there were two different areas of focus. This is something I would have changed and maybe only focused on financial aspects, to go even further into the statistics and costs. I did make some changes along the way, but I should have narrowed it even more.

7.2.2 Choice of selection

I wouldn’t change the methods I choose, because the technology is too unknown for many in the industry – which was why I choose to focus on their opinions towards the technology in the quantitative survey However, I do have some regrets in the choice of who attended the quantitative survey. They only represent two shipping companies. It would have been more relevant to have a wider range of participants from different companies and segments in the industry, to get a bigger understanding of the “actual” point of view within industry, and not only from a small part of it. However, one reason for not doing this was due to the limit time and resources

7.2.3 Implementation and follow-up of interviews

Since the interviews was more of an open conversation around the questions, there was some questions that was answered without asking them. This made it sometimes difficult to remember what has been answered and not. If I was to do this again, I would have had more structure during the interviews. In addition, I did not make any follow-up interviews, which was what I intended to do. There was limited time, and it took a while before the approval of my research could go further, so when I first started interviewing there was not enough time to conduct follow-up interviews. There was much time spent on analysing the data from both methods, and I couldn’t find the time for it.

7.2.4 Further studies

If I were to continue this study, I would have continued the work on the financial aspect and go even further into the depth. This study has a broad focus on the expenses, and it could be interesting to find even more precise estimations. In addition, it would be interesting to look what the potential income could be, because this study showed that a nuclear vessel would have more efficient voyages. This could open the possibilities for increase annually port arrivals and capacity, which can have a great effect on the vessel’s income.

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Attachments

Attachment 1 – Qualitative Interview Guide

1. What is your current work?
2. Have you any experience with nuclear reactors? If yes how so?
3. Are you familiar with the TMSR, and what are your thoughts on it?
4. How do you think the TMSR will affect the OPEX of a vessel?
5. How many crew members would be required to operate a nuclear TMSR reactor, and what will actually be required by rest of the onboard personnel
6. How much do you see the crew cost increase, and how do you a shipping company will react to this?
7. Do you think it's possible to develop competitive reactors suited for marine use as a propulsion system? If yes, for what reasons should a shipping company invest in nuclear vessels?
8. Have you any experience in your current work regarding operations of the vessel, or are you familiar with what affects the vessel financially during operations/a voyage?
9. What are your thoughts about nuclear solutions in the shipping industry?
10. If developed, what type of solutions do you think will get developed – and why?

Operations:

11. How do you think a nuclear reactor will affect the performance of the vessel?
12. What kind of competence will it be required to have from the crew members
13. How do you train the crew onboard the vessel
14. Do you think a nuclear propulsion system will affect or change the current way of sailing a vessel? If yes, how so?
15. In the thought of crew onboard the vessel, what kind of crew must a nuclear vessel have to be able to operate safely?
16. Will a nuclear vessel lead to the ship having less or more crewmembers?
17. Do you know how much the salary of a nuclear engineer is? How did you come up with that number?
18. In the U.S the average paid nuclear engineers ranges from $80 000-$150 000. Do you believe shipping companies can afford or accept such salaries?

19. Are there any other factors that are important to consider during with nuclear propulsion, which must be at place to make it feasible for merchant vessels?
20. Do you think it will be wise for a shipping company to invest in nuclear vessels if they become available? If yes, for what reasons?

Fuel:

21. What is your thought on the fuel prices towards the future – more expensive or cheaper, and how will this influence the consideration of nuclear solutions in the shipping industry?
22. How do you think shipping companies will deal it, and how will it affect them?
23. Will increased fuel prices be an important reason for considering nuclear propulsion
24. In the search for more sustainable voyages, what do you think are more important for a shipping company when choosing fuel and propulsion systems – the price of the fuel or the environmental impact?
25. If a shipping company are to discuss future investment of nuclear propulsion. What do you think will be factors or reasons for them to choose it, and not choose it?
26. If nuclear propulsion gets well developed and approved to marine usage. Is this something you think your company could consider investing in? if yes or no, for what reasons?

Attachment 2 – Quantitative Survey

1. How old are you?
   - 20-30
   - 30-40
   - 40-50
   - 50-60
   - 60-70

2. What genre are you?
   - Male
   - Woman
   - Other

3. Are you familiar with IMO (International Maritime Organization) and what they do?
   - Yes
   - No

4. In the light of IMO's GHG (Green House Gas) strategy towards 2050 the shipping industry needs to be decarbonized to reach IMO's 2050 emission targets. Do you think that it's possible for the Deep-Sea fleet to cut their transport emissions with 70% by 2050, compared with 2008.
   - Yes
   - No
   - Not with today's technology

5. When you hear Nuclear Power, what do you think off or what is your first thought?
   - The future of energy supply

- Disasters like Chernobyl (1986), Fukushima (2011) and Three-mile Island (1979)
- Clean & Sufficient Energy
- Nuclear Bombs like the ones used in Nagasaki and Hiroshima – World War 2
- Navy Ships – Aircraft carriers, submarines etc.
- Waste handling issues
- Ulstein's "Thor" concept vessel
- Radiation
- Russia & Ukraine War/Conflict
- Others/None of the above

6. Are you for or against nuclear solutions?
    - For
    - Against
    - Neutral

7. Do you think that the shipping industry needs nuclear solutions to be able to reach IMO's 2050 targets.
    - Yes
    - No
    - I Don't know

Today there are different concepts of advanced nuclear reactors that are considered to be better, safer and more durable than the traditional Pressurized Water Reactor (like the ones used in Aircraft carriers, submarines and Chernobyl). Thorium Molten Salt Reactor (TMSR) is one of them.

8. Are you familiar with this type of reactor?
    - Yes
    - No

A TMSR uses none-weaponized nuclear material meaning it's not possible to convert the fuel to produces nuclear bombs. Here is a summary of some benefits of a TMSR and why this technology is suited for deep-sea vessels:

- The core is under atmospheric pressure, meaning no potential blow-ups or explosion
- it has walk away safety and you can turn it off, like a normal engine.
- It can't have a reactor meltdown that leads to radioactivity leakage due to safety system, infrastructural improvements and new technology
- it has greater fuel utilization than the PWR, meaning less nuclear waste
- The thorium fuel has far less radiation concerns than Uranium and plutonium (fuel used in PWR's/traditional nuclear reactors)
- A TMSR has the potential for being standardized and to be mass produced meaning it can be produced at a lower price than previous solutions. This also means it could be implemented on commercial deep-sea vessels for them to still be competitive.
- Potentially, no need for refuel after being installed in the vessel – lifecycle would be the same as the vessel
- The demand for maintenance and supervision is far less than for traditional PWR's and normal diesel engines
- The size of a TMRS is much smaller than a normal diesel engine onboard today's vessel, and there is no need for bunker fuel capacity. Meaning there would be an increase in vessel dead weight tonnage.
- When in port the vessel can provide electricity to the port or be turned off

9. After reading this. Do you think with this technology could be used onboard vessel?
    - Yes
    - If no, please explain (comment)
    - Maybe

If shipping where to start using nuclear reactors like the TMSR it would mean a great change in how to run a shipping company and finance ships (if you look at the total lifecycle costs of a vessel). Today's vessel - depending on the vessel - about 60-80% of the total lifecycle cost comes from operations mostly related to bunkers and crew cost. Meaning the operational expenses (OPEX) is far bigger than capital expenses (CAPEX).

For a nuclear ship it would be opposite. The CAPEX would be larger due to the cost of the reactor, and the OPEX would decrease due to no bunker fueling (nuclear fuel would be a part of CAPEX). Instead of paying for volatile bunker fuel prices, the shipping company would pay down payment of the investment through the vessel's lifetime. Meaning it's likely that most of the expenses would be fixed, creating more predictability in a volatile industry.

10. Given the thoughts that the total lifecycle revenue for a nuclear ship, compared with a vessel of today, would mostly likely be higher. Do you think this is a better/acceptable way of running a shipping company?
    - This is better way than today's methods because it would give more predictability in an already volatile industry and market
    - This would not lead to more predictability
    - This is too risky
    - Why change something that works
    - I don't know

A nuclear reactor has a far greater energy density than any other technology available. With a new ships design a nuclear vessel can potentially have a service speed of 30 knots for 30 years, compared to 13-20 knots that conventional vessels normally has. This would mean that a shipping company can have a smaller fleet but still be able to handle more cargo. Meaning that it also could create better relations for the international commercial traffic and fewer bottlenecks in ports and canals, since it would be fewer vessels arriving.

Fuel and fuel production

11. What fuel do you think would be the best option for the deep-sea sector, from a long term perspective?
    - VLFSO
    - LPG
    - HFO
    - MGO
    - Hydrogen
    - LNG
    - Methanol
    - Ammonia
    - Ethanol
    - Biofuel
    - Nuclear

A TMSR can also be used on land based facilities as a nuclear powerplant to supply the society and production facilities with clean emission free energy. This can be used to produce clean alternative fuel like hydrogen, methanol and ammonia - and to charge short-sea vessels and ferries who runs on battery with clean energy.

12. Using a scale from 1-5 where 5 is agree fully and 1 is disagree fully, how much do you agree with the following hypothesis; “The fuel production industry must improve their Well-to-Wake emissions, and not use energy from coal to supply production”. *FYI: Well-to-wake is the emissions along the entire process from fuel production to burning the fuels onboard the vessel*
    - 1-5

13. From a scale from 1-5 where 5 is agree fully and 1 is disagree fully how much do you agree with this hypothesis: “Emission cuts within shipping has more

focus on Tank-to-Wake emissions than Well-to-Wake emission”. FYI: Tank-to-Wake is the emission directly related burning fuel onboard vessels

- 1-5

14. Given that a land based TMSR can safely provide fuel production facilities with sufficient energy to decarbonize the Well-to-Wake supply chain?
    - We should use it
    - There is no need for it, current method works
    - We should not use it
    - Other/comment option

15. What do you believe most in when it comes to the nuclear solutions:
    - Nuclear propulsion systems in large ships
    - Land based nuclear powerplants for productional of synthetic fuel
    - None of them, do not believe in nuclear solutions in this context
    - No I’m against nuclear all together

16. Has this survey changed your view on nuclear technology?
    - Yes, I was against it but now I’m positive for it
    - Yes, I was positive for it but now against it
    - No, still against it
    - No, I was positive for it before and are still positive for it

Attachment 3

---------- Message ---------
From: **"External"**
Date: 29. Nov. 2022 kl. 12:52
Subject: Re: *Bachelor discussion*
To: Bachelor Candidate

Hello,

There are many different ways of doing it, depending on what you are looking for.
I think that the best way is to compare the Net Present Value at the time of delivery.

Suppose you have an overnight cost of 400 M USD at the time of building (150 CAPEX + 250 Fuel)
Suppose that the residual value of the fuel at decommissioning is 75%.
Suppose you have a yearly O&M cost of 3 MUSD per Year.

You will pay that over "Y" years at a "X" interest rate.
In addition, there will be yearly inflation equal to "i".

The yearly payment will be:
PMT (X,Y,-400) this is an excel function

The Net Present Value of all these payments is:
PV(i,Y,-PMT) this is also an excel function

Now, let's consider the value of the fuel, we can suppose that in the future it will increase with the inflation (for lack of better knowledge) but at the same time we need to discount the future value to the present value as per the inflation, so the two things cancel out

So, the residual value of the fuel at the time of building is 75% x 250

Also, for the O&M we can consider it escalating in the future and discounted to the present as per inflation
So, it the present value of year 1 is 3 MSD, and the present value of year X is still 3 MSD

The final cost is therefore:
present value of the financing of the building and fueling cost, minus residual value of the fuel, plus present value of O&M

PV(i,Y,-PMT(PMT (X,Y,-400)) - 75% x 250 + 3 x Y

I hope the above is clear.

Kind regards
"External"

NTNU

Kunnskap for en bedre verden