MASTER THESIS

Economic Feasibility of Battery-Powered Vessels

submitted as a requirement for the Degree of M.Sc. in Maritime Operations focused on Specialization in Sustainable Maritime Operations

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Abstract

The maritime sector is essential to the global economy, facilitating a significant portion of the global trade. However, as a primary sector, it is also responsible for greenhouse gas (GHG) emissions due to its reliance on conventional fuels for its operations. These emissions from the shipping sector are linked to climate change and have widespread ecological and environmental consequences. To curb emissions from the maritime sector, the International Maritime Organization (IMO) has implemented various policies and regulations. Various approaches are being adopted to curb emissions and meet IMO regulations; one such approach is using battery-powered vessels.

This research explored the economic feasibility and emissions reduction potential of battery-powered vessels compared to conventional vessels. It focused on two ferries: one battery-powered and the other diesel-powered. The economic feasibility was evaluated through an economic model that utilized net present value (NPV) and internal rate of return (IRR) as the leading economic indicators. The activity-based method was utilized for the emission assessment.

The research revealed that the battery-powered ferry not only showed considerable potential for being economically feasible but also outperformed the diesel ferry in most of the indicators. In terms of emissions reduction, the battery-powered ferry took a clear lead as its emissions were significantly lower than those of the conventional ferry.

Keywords: Battery powered vessels, GHG emissions, economic feasibility, emission calculations.

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List of Abbreviations

Abbreviation	Definition
AC	Alternative Current
BC	Black Carbon
BDN	Bunker Delivery Note
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DC	Direct Current
DME	Dimethyl Ether
DNA	Deoxyribonucleic Acid
DNV	Det Norske Veritas
ECA	Emission Control Area
EEDI	Energy Efficiency Design Index
EIA	Energy Information Administration
ETS	Emission Trading System
EU	European Union
GHG	Green House Gas
GT	Gross Tonnage
HVO	Hydrotreated Vegetable Oil
IEA	International Energy Agency
IMO	International Maritime Organization
IRR	Internal Rate of Return
KW	Kilo Watt
LCA	Life Cycle Assessment
LNG	Liquified Natural Gas
MEPC	Marine Environmental Protection Committee
MMT	Million Metric Ton
MWh	Mega Watt Hour
NO	Nitric Oxide
NO_X	Nitrogen Oxides
NO_2	Nitrogen Dioxide

NPV	Net Present Value
ODS	Ozone Depleting Substances
PM	Particulate Matter
SECA	Sulfur Emission Control Areas
SO	Sulfur Monoxide
SO_X	Sulfur Oxides
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
UVB	Ultraviolet B
VAT	Value Added Tax
VOC	Volatile Organic Compounds
WHO	World Health Organization

1 Introduction

Maritime trade is a vital part of the global economic system; with the rise in global trade, the significance of maritime trade is more than ever; the maritime industry is responsible for 90% of global trade (OECD, n.d.). The maritime industry is highly dependent on fossil fuels to transport goods, producing greenhouse gas emissions (GHG). The maritime sector accounts for almost 2% of global GHG emissions, and there has been a considerable growth in GHG emissions from the maritime sector every year; since 1990, this sector has seen 90% growth in GHG emissions (Ian Tiseo, 2023).The need for decarbonization in the shipping sector is more crucial than ever, as the conventional approaches cannot meet the ever-increasing environmental regulations.

The pace of decarbonization in the shipping sector remains low compared to the other industrial sectors. The International Maritime Organization (IMO), in its 2023 strategy, wants to achieve net zero GHG emissions by 2050. It further wants to reduce the emission to 20% by 2030 and 70% by 2040 (IMO, 2023).

Various approaches are being used to achieve IMO net zero targets, from using environment-friendly fuels such as hydrogen and ammonia to techniques such as the energy efficiency design index (EEDI). Among all the approaches, one of the viable options in the process of decarbonization in the marine sector is the adaptation of battery-powered vessels, which have been introduced on a small scale. However, one of the main challenges in the process of electrification of vessels remains the high cost because compared to conventional vessels, the initial investment remains high, along with varying electricity prices (Lin Suna, 2023).

Current estimates show that decarbonizing shipping lines by 2050 could cost between $8 billion and $16 billion annually. Moreover, the necessary carbon-neutral marine infrastructure could cost $28 billion to $90 billion annually (Decarbonizing Shipping | UNCTAD, n.d.).The staggeringly high cost of decarbonization in the marine sector is a considerable challenge, as the sector is dominated by profit-driven private entities, which makes carbon-neutral shipping not lucrative enough for private entities.

In this research, various economic models will be utilized to evaluate the economic feasibility of battery-powered vessels. As the full scale of electrification is yet to be explored, very limited data is available regarding the cost-effectiveness of battery-powered vessels. The economic assessment approach for battery-powered vessels involves the net present value (NPV) and internal rate of return (IRR), as these are considered one of the main approaches in assessing a project's economic viability.

The second major aspect of this research is assessing the impact of battery-powered vessels on decarbonization. The economic viability of battery-powered vessels is directly related to their GHG emissions. Therefore, this research will compare the GHG emissions of a better-powered vessel with those of a conventional vessel and analyze their environmental impact.

1.1 Objectives

In recent years, numerous technologies have emerged in the shipping sector to counter GHG emissions. One technology that has a promising future in the shipping sector is the battery-powered propulsion system.

All emerging technologies are faced with one question: their economic viability. Switching from one technology to another has a significant financial cost. In this research, the economic viability question will remain under focus by using various approaches.

The main objective of the research is to compare the financial viability of a battery-powered vessel with a conventional fuel-powered vessel. The secondary objective is to study the impact of battery-powered vessels on decarbonization. The main questions of the research are given below:

- Are battery-powered vessels economically feasible as compared to conventional vessels?
- How environmentally friendly are battery-powered vessels compared to conventional vessels?

1.2 Limitations

This research provides significant insights into battery-powered vessels' economic and environmental domains, but it has certain limitations. This study was focused only on the ferry sector and did not include other sectors, such as offshore support vessels, tugboats, cargo vessels, etc. It considered two ferries: one E-Ferry, which uses battery power for its operations, and its sister Diesel Ferry, which uses conventional fuel for its operations.

Furthermore, the Diesel Ferry only exists as a concept and does not exist in physical terms, as it is only designed for comparison purposes; thus, it limits the comparing potential of both ferries, as physical existence and operations might bring new considerations into the comparison of the ferries.

Moreover, economic models involving NPV and IRR depend heavily on assumptions and forecasting, which can result in potential inaccuracies. In the case of emission analysis, the activity-based approach also has certain limitations, as it relies on various assumptions and any error in assumptions can lead to inconsistent results.

Additionally, emissions were calculated using emissions factors, which are not constant and can change over time, leading to inconsistency in emissions as this research used the emissions factors of the Danish electric grid mix, which limited the generalizability of emission analysis. Another critical factor was this research only calculated and analyzed the operational emissions and did not consider the environmental impacts during the construction and recycling phases.

2 Literature Review

Despite a long history, the battery-powered propulsion system continues evolving, and various platforms are conducting extensive research and development. Numerous studies have been conducted on battery-powered propulsion systems in technological, environmental, and financial domains. This research has extensively reviewed and critically analyzed the existing literature.

2.1 Historical Overview of Electric Propulsion Systems

The electric propulsion system has a long history in the maritime shipping industry. Its first known usage dates to the 1830s, when Moritz Jacob used small electrically propelled boats in his experiment. After his experiment, the next milestone was achieved in the 1880s when SS Columbia used an electric direct current (DC) power system to illuminate bulbs (Paul, 2020).

After the initial achievements and developments, the electric propulsion system gained pace in the 1980s, which can be attributed to the new semiconductor-switching technologies; these switching technologies simplified the mechanical structure by providing complete control over the revolutions of propeller and thruster (Hansen & Wendt, 2015).

The new technologies started to give momentum to the electric propulsion system. In 1988, the Queen Elizabeth II steam-powered ship was retrofitted with a modern diesel-electric propulsion system and became a diesel-electric motor-powered ship. The retrofit of Queen Elizabeth *II* started a modern era for the electric propulsion system (Yang et al., 2016).

Further developments were made in the electrification domain to achieve a better fuel economy. As a result, hybrid drive vessels are being developed, and electric motors powered by diesel engines are configured to provide maximum efficiency (Skjong et al., 2016).

The electric propulsion system has evolved from experiments to electric drives. However, with the advancement of science and technology, a new domain has emerged: the battery-powered propulsion system. The battery-powered propulsion system utilizes battery energy storage systems or fuel cells (Skjong et al., 2016).

2.2 Technological Evolution of Electric Propulsion Systems

The propulsion system of the marine vessels has greatly expanded over the years. The driver in the evolution of propulsion systems is the system's efficiency. However, eco-friendly factors have also emerged in the development of propulsion systems along with efficiency.

Earlier propulsion systems used direct mechanical equipment coupled with the propulsion system, but modern propulsion systems use electric drive systems. Because of research into modern electronics and control systems, electric propulsion systems have developed into various types (Paul, 2020). Some of the propulsion systems are discussed below:

The diesel-electric propulsion system evolved in the early 1900s; however, its momentum came in the 1980s (Paul, 2020). It has several advantages over the conventional propulsion system; it is lighter and can have a better weight distribution. Moreover, progress has been made in alternative current (AC) drive technologies, which are now being utilized in different ship types (Diesel-Electric Propulsion, n.d.).

Furthermore, another propulsion system is the turbo-electric propulsion system, which uses gas turbines instead of diesel engines. It is mainly used in the cruise and ferry sectors. It has several advantages, such as reduced size and weight and fewer emissions (Yang et al., 2016).

Lastly, the hybrid propulsion system has also gained some pace. When gas turbines are used with diesel engines, this type of configuration is known as hybrid diesel turboelectric propulsion. This type of configuration provides enormous flexibility in efficiently utilizing the load. For example, when less power is required, only diesel engines can be used, and when the load requirement increases, the gas turbines can supplement the diesel engines (Yang et al., 2016).

2.3 Electric Propulsion Power Supply Systems

The electric propulsion systems use alternative and direct current power supply systems, which are known as

- AC systems
- DC Systems

In AC power supply systems, diesel engines run the electric generators; these generators run at a constant speed and produce 50 or 60 Hz, depending on their manufacturing origins (Paul, 2020) .

The DC power supply system’s configuration maximizes the system's efficiency by fairly distributing the load. DC power systems have an edge over AC systems. The advancement in DC electronics has enabled DC sources to power AC applications, thus eliminating the usage of much equipment (IEEE Practice, cited in Paul, 2020).

The power supply systems have two types of configurations: integrated and segregated designs. In the integrated design, the propellers are directly connected to the engines. Meanwhile, the segregated configuration does not directly connect the power systems and propellers. Because of higher fuel efficiency, the integrated power system configuration maintains an edge over the segregated configuration (Paul, 2020).

2.4 Battery Powered Propulsion System

In shipping, the propulsion system mainly relies on conventional energy sources such as fossil fuels; however, with recent technological developments in energy storage systems, the reliance on conventional sectors can be reduced.

One of the viable alternatives is battery-powered electric propulsion systems; these are now viewed as alternatives to conventional propulsion systems. Battery energy systems can supply power for a vessel's propulsion and electronic systems (Koumentakos, 2019).

2.4.1 Battery Systems

Battery systems consist of stacked cells that can convert chemical energy into electricity. Voltage and current depend on the combination of cells, which can be connected in series or parallel (Divya & Østergaard, 2009).

A battery system's power and energy depend on its initial configuration, and they are rated in terms of their power and energy capabilities. The important features of a battery system are energy density, efficiency, the temperature at which batteries can operate, life span, and depth of discharge (Divya & Østergaard, 2009). Figure 2-1 below provides a general working principle of a battery system.

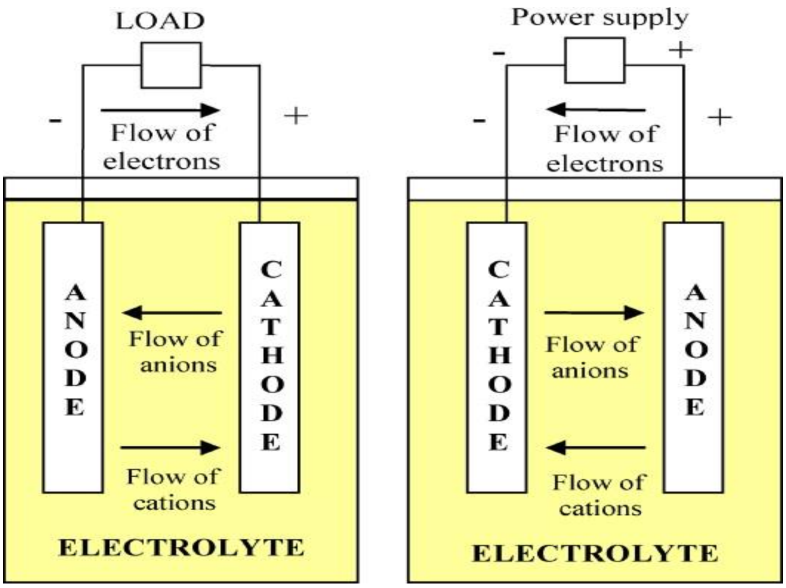

Figure 2-1 Working Principle of a Battery System (Hadjipaschalis et al., 2009)

2.4.2 Lead-Acid Batteries

These batteries have been used in the marine sector for over a century. They provide energy for the propulsion system and serve as a standby power source (Verma & Kumar, 2021). Lead-acid batteries are low-cost, easy to use, and require minimum maintenance. Because of their low self-discharge rate, they are ideal for long-term applications (Zhou et al., 2013). However, the limitations of this battery are the low life cycle and operational timeline, the depth of discharge, and the temperature, which can negatively affect the battery's life. Another issue is that electrodes may get damaged when the battery is fully discharged (Hadjipaschalis et al., 2009).

2.4.3 Nickel-Based Batteries

Nickel battery systems have also shown considerable progress compared to lead-acid batteries. There are three main variations in nickel-based batteries: nickel cadmium, nickel metal hydride, and nickel-zinc. All these types use nickel hydroxide for the positive electrode and electrolyte. In contrast, all three batteries use different materials for the negative electrode, including cadmium hydroxide, metal alloy, and zinc hydroxide.

Nickel-based batteries are considered to have a higher energy density and life cycles than lead-acid batteries. However, they also have higher costs and lower energy efficiency (Hadjipaschalis et al., 2009).Furthermore, Nickel-metal-hydride batteries have the potential to provide better characteristics than Lead-acid and Nickel-cadmium batteries (Andersson et al., n.d.).

2.4.4 Lithium-Based Batteries

Lithium-ion batteries are regarded as the most remarkable energy storage technologies, and they are now used for various shipping sector applications (Kerry Taylor-Smith, 2020).In Figure 2-2 we can see that a Lithium-ion battery consists of a positive and negative pole and a separator. The separator has small holes to allow the transportation of Li+ -ion. The separator is soaked with electrolytes to allow conductivity (Andersson et al., n.d.).

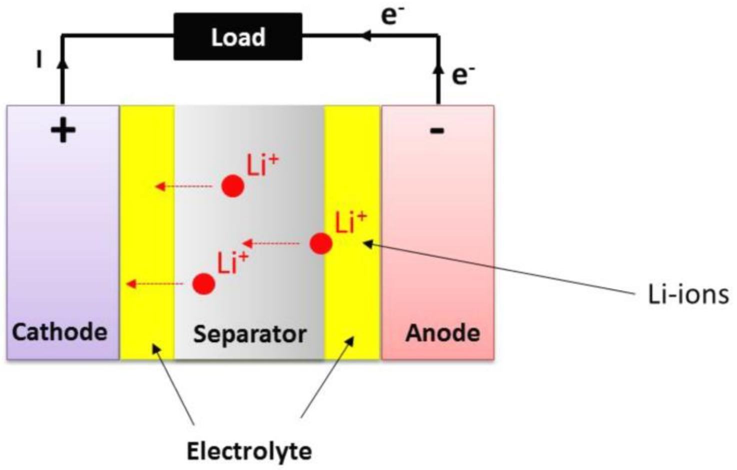

Figure 2-2 Schematic Representation of a Lithium-ion Cell (Andersson et al., n.d.)

Modern Lithium-ion batteries have shown significant progress in cost-effectiveness and efficiency in the marine environment (G.A. Elia et al. cited in Verma & Kumar, 2021). Advanced Lithium-ion batteries can be used in various configurations, such as utilization in a hybrid configuration to share the load as per requirement, and they can also be used to supply power to a fully electric propulsion system (Zhang et al., 2018).

The major characteristics of Lithium-ion batteries are given below :

- High energy density
- High energy efficiency
- Low self-discharge rate
- Minimum maintenance requirements

Despite all the advantages, the life of this battery system is highly dependent on temperature. High temperatures can significantly reduce the life span of lithium batteries. Another constraint is deep discharge, which can negatively impact the battery system's life (Hadjipaschalis et al., 2009).

Furthermore, although Li-ion batteries are becoming increasingly vital in maritime battery-powered systems, some estimates suggest that this technology has peaked in progress. Due to the chemical constraints of Lithium-ion batteries, the potential for significant improvements is limited (Verma & Kumar, 2021).

2.4.5 Sodium Sulfur Batteries

In sodium-sulfur batteries, a positive electrode is formed by the melted sulfur, while a negative electrode consists of molten sodium. A beta alum ceramic separates both electrodes, and the battery can operate at 300 °C (Divya & Østergaard, 2009).

These highly efficient battery systems are mainly composed of non-toxic, inexpensive materials. However, as these systems operate at high temperatures and sodium is corrosive, their applications are limited (Hadjipaschalis et al., 2009). Figure 2-3 explains the basic operating process of a sodium-sulfur battery.

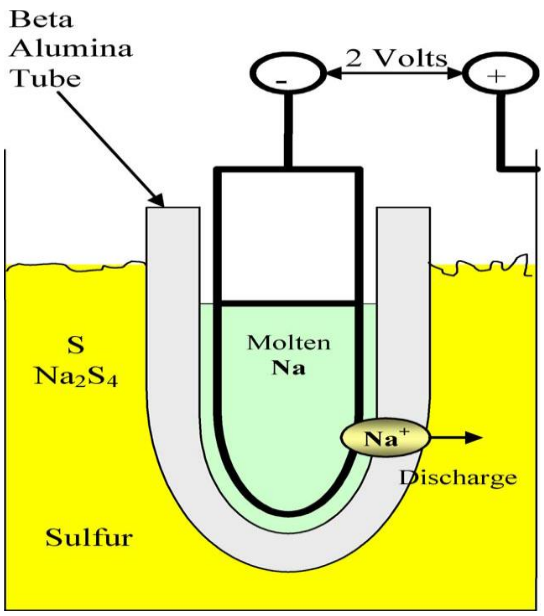

Figure 2-3 Basic Operation of a Sodium-Sulfur Battery (Hadjipaschalis et al., 2009)

2.5 Existing Literature on Battery-Powered Vessels

Because of increasing regulations, the maritime sector needs a paradigm shift to tackle the issue of GHG emissions. One of the most revolutionary approaches is using battery power as a main propulsion system, as it has the potential to greatly reduce GHG emissions. Various research studies have been carried out in this domain with different approaches, and the studies closely aligned with our research are critically analyzed in this section.

In the study conducted by (Yu et al., 2018), a micro-grid system was developed for a ship that utilized three sources for propulsion: the solar system, battery power, and diesel generator. A strategy was developed for optimal distribution and utilization of different power sources. In their case study, this system reduced carbon emissions and saved fuel costs. However, the system remains complex and dependent on various factors for its operations.

Most studies are confined to ferries because of the battery's energy density limitations and the power needed to operate a ship. Haibin Wang argues that the battery propulsion system can address the issue of zero-emission in the shipping sector; his research compared the battery propulsion system with a conventional propulsion system using a life cycle assessment (LCA) approach and found that the battery system can reduce 30% emissions during a life cycle depending on the type of electricity generation and a reduction of 15% in total life cycle cost compared to the conventional vessel (Wang et al., 2021). Figure 2-4 provides an overview of the configuration of a conventional vs battery-powered propulsion system.

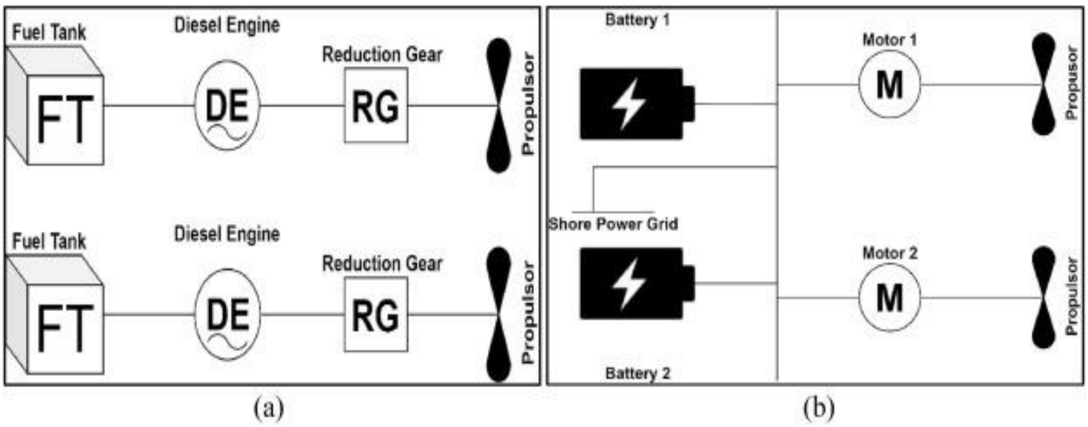

Figure 2-4 Conventional vs Battery Powered Power Plant Layout (Wang et al., 2021)

The multi-criteria decision analysis involving hybrid, diesel-electric, and diesel mechanical ships was conducted by (Jeong et al., 2018). It argues that a hybrid system has less annual operational cost than conventional vessels, and overall emissions are reduced as less fuel is consumed during operations. Furthermore, the hybrid electric system is safe and reliable compared to conventional systems.

The study on inland waterway transport highlights that conventional vessels cannot meet the strict emission guidelines. This research provided alternative solutions depending on tonnage, voyage distance, and navigational conditions. Thus, a battery and a hybrid engine system were considered.. By applying the new technologies, canal ships showed a reduction of 14.5% in emissions and a cost reduction of 17.78%, while for a bulk cargo ship, the reduction is 33.44%

in emissions and 39.15% in cost. Moreover, this research showed reduced emissions and cost of a ship over its life span when carbon credits are considered (Fan et al., 2021).

The offshore support vessels have multiple combustion engines and a dynamic positioning system. Because of the operational requirements, the engines operate at low power, which increases exhaust gas emissions (Lindstad et al., 2017). This study combined batteries and engines to form a hybrid propulsion system and concluded that utilizing the hybrid system can significantly reduce local pollution. Moreover, the hybrid system can reduce the global warming potential by 40-45% in Arctic areas and a reduction of 20% in the North Sea. However, the economic perspective relies heavily on the future prices of battery systems and fuels.

Furthermore, another research focused on the techno-economic evaluation of advanced fuels and the prospective application of renewable fuels in various vessel types such as general cargo, bulk carriers, container ships, and ferries. Among the various fuels used, it was found that the battery-electric option seems to be cost-competitive for ferries under given conditions. The remaining vessels include container ships, bulk carriers, and general cargo. For these vessels, methanol has the lowest total ownership cost for container ships, followed by dimethyl ether (DME) for bulk carriers and ammonia for general cargo. However, the research lacks conclusive life cycle environmental impacts (Korberg et al., 2021).

To counter emissions in inland shipping in Croatia, Perčić conducted a technical, economic, and environmental analysis of alternative fuels. The research selected five alternative fuels: electricity (battery), ammonia, methanol, Liquified Natural Gas (LNG), and hydrogen. Three vessels, including a cargo ship, a passenger ship, and a dredger, were considered for fuel utilization. The study concluded that battery-powered propulsion is the most environmentally friendly solution for all types of vessels.

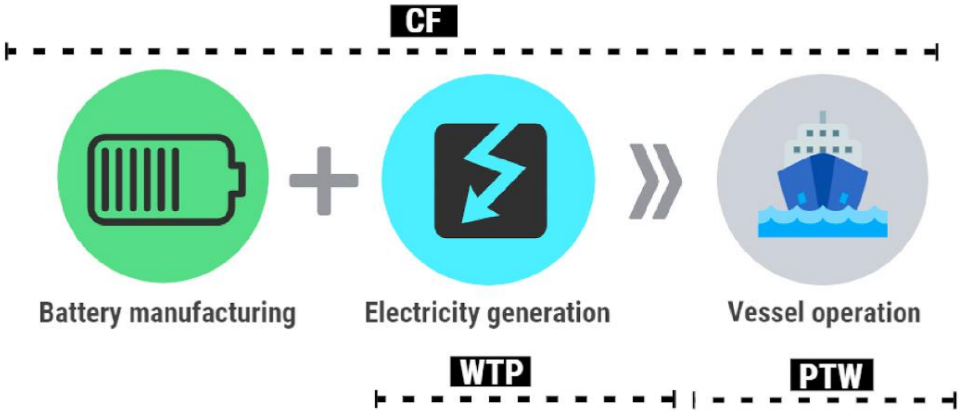

Figure 2-5 Life Cycle Assessment of Electric-Powered Vessel (Perčić, Vladimir, & Fan, 2021)

Figures 2-5 above provide a graphical illustration of the LCA of an electric power vessel, which includes the process from battery manufacturing to the vessel's operations.

However, the economic perspective presented a different picture, and each vessel type has its economic advantage with a specific fuel; for the passenger vessel, battery power is the most economical, and for the cargo ship, methanol maintains the economic edge. The dredger, on the other hand, shows the limitations of alternative fuels, as diesel propulsion remains the best economical solution.

2.6 Battery-Powered Vessels and Emissions

Most researchers concluded that utilizing battery-powered vessels has significantly reduced carbon emissions and costs. However, the study conducted by (Jeong, Jang, et al., 2022) argues that there is a misconception regarding battery-powered vessels and zero emissions; the researcher argues that the emissions are directly linked to the source of electricity being used for charging purposes.

The research concludes that the impact of battery-powered vessels can vary between regions. In Germany, the national grid is 30% dependent on fossil fuels, whereas in China, 60% of the electricity is generated through fossil fuels. Thus, depending on its operating location, the same vessel can impact emissions differently.

2.7 Conclusion

The comprehensive analysis of the literature review shows that there has been a significant technological advancement in the battery propulsion system; however, room for further development and challenges remain in the technological domain. Adaptation of new technologies has reinforced the importance of sustainability and innovation in the maritime sector.

The battery-powered propulsion system provides a promising path to decarbonizing the maritime industry. It has a clear edge in emission reduction compared to the existing alternative and viable options. However, its emission reduction depends highly on the source of electricity used during its operations.

Furthermore, the economic literature focuses more on analyzing the costs associated with fuel, and some studies analyze the life cycle cost, which depends on various assumed parameters. From the existing literature, it can be assessed that there is a notable gap regarding the viability of investment in battery-powered vessels, which can be attributed to the limitation of battery technology.

Summarizing all, the battery-powered propulsion system remains a promising alternative to the conventional system with its challenges. Because of the technological constraints in battery technology, it is mostly confined to the ferry sector; however, with improvements in the battery system, it has the potential to be applied in other types of vessels. The economic domain under the given assumptions has also shown positive trends. The most promising trait of battery-powered propulsion systems remains the reduction of emissions depending upon the electricity generation source.

3 Environmental Effects of Global Shipping

Despite being one of the most efficient modes of transportation, the shipping sector has negative environmental impacts. These impacts are multidimensional and lead to various ecological and environmental consequences.

The environmental impacts of shipping can be divided into three main types: discharge into water, physical effects, and air pollutants (Jägerbrand et al., 2019).

3.1 Water Discharges

The section of water discharges can be divided into two main types: oil spills and the operational discharge of cargo, antifouling paint, and oil (Jägerbrand et al., 2019). The number of large-scale oil spills, especially from oil tankers, has considerably reduced (HELCOM,2018; Hofer,1998a cited in Jägerbrand et al., 2019).

However, apart from oil spills, some other areas may contribute to 70% of oil discharge, such as improper cleaning of tanks and operational discharges that include the release of bilge water (Turvani et al., 2009).

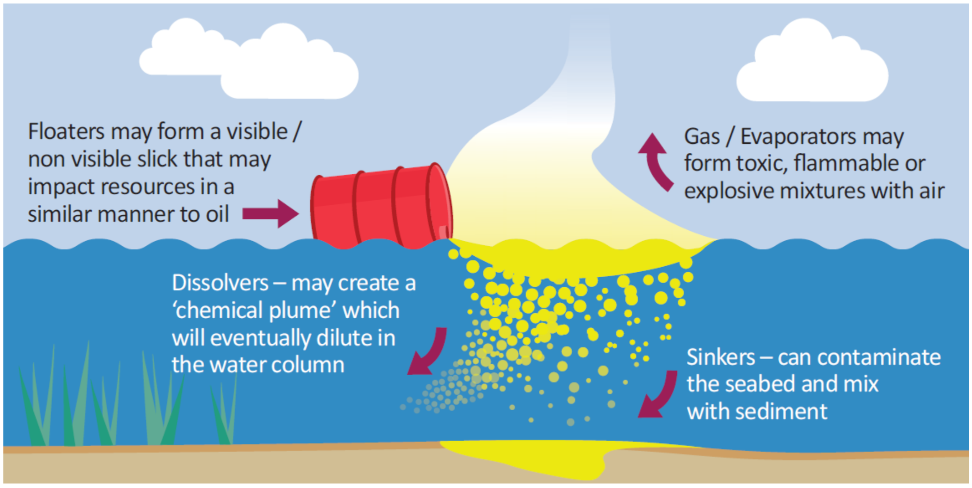

Figure 3-1 Behavior of Spilled Chemicals (ITOPF Handbook, 2021)

Figure 3-1 explains how the chemicals behave during an oil spill. Initially, a visible/non-visible slick is formed, which may form toxic flames. When it reacts with water, a chemical plume that dilutes the water column can contaminate the seabed and mix with the sediments.

Table 1 Impacts of Discharge into Water (Neuparth et al., 2012; Höfer, 1998b; Pennings et al., 2014; cited in Jägerbrand et al., 2019)

Discharge into water	Impacts
Oil and its Degraded Products	Damage to coastal wetlands
	Vulnerability for sea birds
	Ingestion may damage DNA
	Inhalation or ingestion may affect respiratory and circulatory systems
	Eco-system damage

Table 1 provides information about the negative impacts of oil and its degradable byproducts on the marine ecosystem. These effects are numerous, especially on sea birds, as the toxic chemicals can alter their deoxyribonucleic acid (DNA) structure and may damage their respiratory and circulatory systems.

3.2 Physical Impacts

There are numerous physical impacts of shipping on the ecosystem, ranging from erosion to biodiversity loss (Jägerbrand et al., 2019). If we look at the soil pollution from the shipping sector, it is primarily linked to terrestrial activities in the port area (Trozzi, 2003; cited in Turvani et al., 2009).

Several factors contribute to soil pollution, including:

- The deposition of oil in the soil during operations or accidental discharge
- Settlements of the surface because of heat and high load
- Chemical release during ship breaking, etc.

Another physical impact of shipping is soil erosion; when the ships navigate through areas such as navigation channels and beaches, it induces a flow that can cause erosion. Moreover, the demand for fast transportation also exacerbates soil erosion in that area (Trozzi, 2003; cited in Turvani et al., 2009).

3.3 Air Emissions

International organizations are exerting immense pressure on the maritime sector to counter its emissions. Because of their adverse environmental effects, GHG emissions from the shipping sector are attracting global attention.

The various pollutants emitted by the shipping sector are:

- Carbon dioxide (CO_2)
- Sulfur oxides (SO_x)
- Nitrogen oxides (NO_x)
- Carbon monoxide (CO)
- Volatile organic compounds (VOC)
- Particulate matter (PM)
- Black carbon (BC)

Table 2 provides an overview of air emissions' environmental and ecological consequences. As evident from Table 2, the emissions from shipping have both cooling and warming impacts on the environment.

Table 2 Impacts of Emissions from Shipping (Jägerbrand et al., 2019)

Air Emissions	Environmental and Ecological Consequences
GHG (mainly CO_2)	Acidification & Climate change (warming)
SOx	Climate change (cooling), pollution and acidification
NOx	Climate change (net cooling) and eutrophication
PM	Climate change (cooling) and air pollution
VOC	Climate change (warming) and air pollution
ODS	Structure changes in communities (by increased UVB)

These pollutants emitted by ships can negatively affect the environment in various ways, such as global warming, the formation of acid rain, and affecting human health (Serra & Fancello, 2020). The global share of emissions from the marine sector has grown from 2.76% in 2012 to 2.89% in 2018 (Fourth IMO GHG Study, 2020).

Figure 3-2 illustrates the trend in carbon dioxide emissions from 1970 to 2022. With a few exceptions, carbon emissions have remained steady and are increasing yearly. Over a period of 52 years, emissions increased from 353.80 million metric tons (MMT) in 1970 to 709.70 MMT in 2022. As carbon dioxide emissions from the shipping sector keep on rising, the sector can potentially become the top global GHG emitter if proper steps to curb emissions are not implemented.

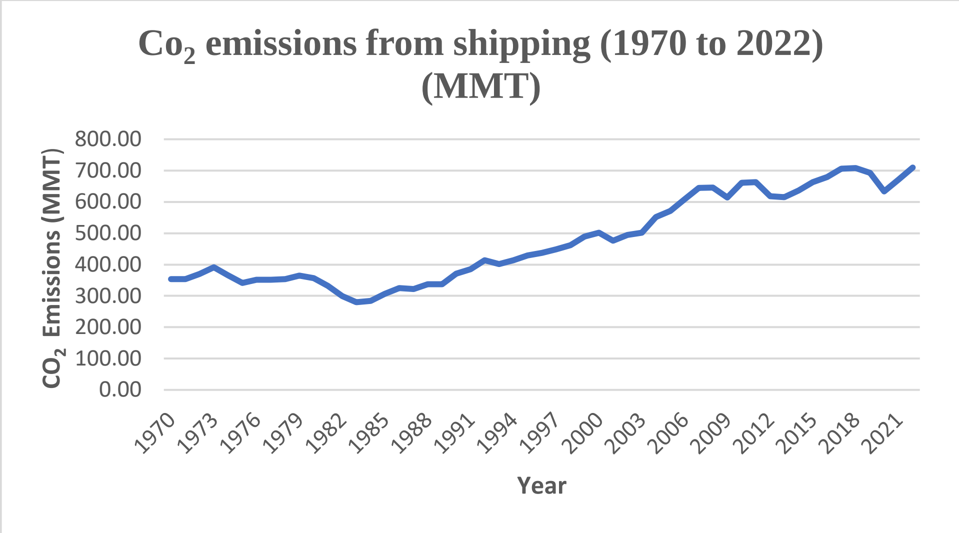

Figure 3-2 CO2 Emissions Shipping Worldwide (Global Shipping CO_2 Emissions 1970-2022 | Statista, n.d.)

The emissions from the shipping sector are mainly emitted at sea level. However, some portions of these emissions are also found in cities and harbors, which negatively affect the health of the inhabitants of these areas (Contini & Merico, 2021).

Air pollution is the most significant risk to human health; particulate matter (PM) emissions are strongly linked to adverse health impacts (WHO, 2022).The high mortality diseases such as lung cancer and cardiopulmonary are linked to high levels of PM emissions; the higher number of premature deaths in coastal regions of southern and eastern Asia and Europe can be attributable to the PM emissions as people are more exposed to emissions in these areas (Corbett et al., 2007).

Moreover, the NOx and SOx emissions from the shipping vessels are also linked to ocean acidification; the most significant impacts of acidification are mainly found in the northern ares of the hemisphere (Hassellöv et al., 2013).

GHG emissions from the shipping sector have long been responsible for global warming; the NOx and SOx emissions have a more direct impact on local areas while the acidic aerosols on the other hand have the potential to be deposited within a range of 10 to 100 km (Turner et al., 2018). Table 3 provides an overview of the estimated shipping emissions in various parts of the world.

Table 3 Estimated Shipping Contributions in Emissions (Dalsøren et al., 2009; Smith et al., 2015; Viana et al., 2014)

Pollutants	Estimate Contribution of Shipping	Area
CO_2	3%	Globally
SO_X	13%	Globally
SO_X	4.5% (wet deposition)	Globally
SO_X	15–25% (of wet deposition)	North America, Scandinavia
NO_X	15%	Globally
NO_X	7–24%	Coastal areas of Europe
NO_X	25–50% (of wet deposition)	Scandinavia
PM_{10}	1–7%	Coastal areas of Europe
$PM_{2.5}$	1–14%	Coastal areas of Europe
PM_1	11%	Coastal areas of Europe

GHG emissions from global shipping are considered to have a warming effect on the environment; however, climate change remains a complex system because some pollutants and particles are considered to have a net cooling effect, like SOx and NOx (Eyring et al., 2010;Fuglestvedt et al., 2009).

3.4 Decarbonization Efforts in the Shipping Sector

The economic cohesion of the globalized world relies heavily on maritime trade. The maritime sector is heavily reliant on traditional fossil fuels to power its engines. This traditional fossil fuel produces various harmful emissions that adversely impact the environment. The maritime sector is responsible for 1 billion tons of carbon dioxide emissions yearly (*Decarbonizing Shipping*, n.d.).The marine sector is one of the world's largest carbon emitters due to its high carbon emissions.

The shipping sector's emissions are rising, as evidenced by the 4.9 percent growth in emissions in 2021. This level of emissions accounts for almost 11 percent of the world's total carbon dioxide emissions. If we look at the maritime emissions from the year 1990, we can see that there has been a staggering increase of 90% in carbon emissions (Ian Tiseo, 2023). The current rate of carbon emissions is expected to surge by 50% to 250% by 2050 if no measures are applied to curb the emissions (Global CO2 Emissions, 2023).

Fuels such as Heavy Fuel Oil (HFO) used by vessels release carbon dioxide and other harmful substances, such as CH_4, NO_x, and SO_x. Container ships produce almost 16 grams of carbon dioxide per kilometer for every metric ton of cargo (Global CO2 Emissions, 2023).

However, efforts are being made to decarbonize the maritime sector; various alternative fuels are being considered for use in vessels that are environmentally friendly. Some of the alternative fuels and their properties are given in Table 4; among these options, we can see that electric power has the potential to eradicate carbon emissions completely through a battery propulsion system if electric generation is through renewable energy. The second most carbon-neutral substance is ammonia as a fuel; it can reduce carbon dioxide emissions by 43%. In the third place comes hydrogen, followed by LNG and advanced biofuels.

Table 4 Estimated CO2 Reduction, Alternative Fuels (ITF 2018;Bauman et al,2017;Brynolf et al,2014a;Bicer&Dincer,2018; Cited in Ampah et al., 2021)

Source of Propulsion	Reduction in CO_2 emissions
Advanced Biofuels (Bio-methanol, HVO etc)	25-100%
Liquified Natural Gas	5-30%
Ammonia as a fuel	1-43%
Hydrogen as a fuel	27-35%
Electricity	0-100%

If we look at Figure 3-3, we can see that replacing the existing system requires a paradigm shift. Adopting alternative fuels requires developing a new supply chain and infrastructure and formulating relevant policies. Considering these requirements, numerous organizations and states are adopting relevant policies to strengthen the adaptation process of alternative fuels in the marine sector.

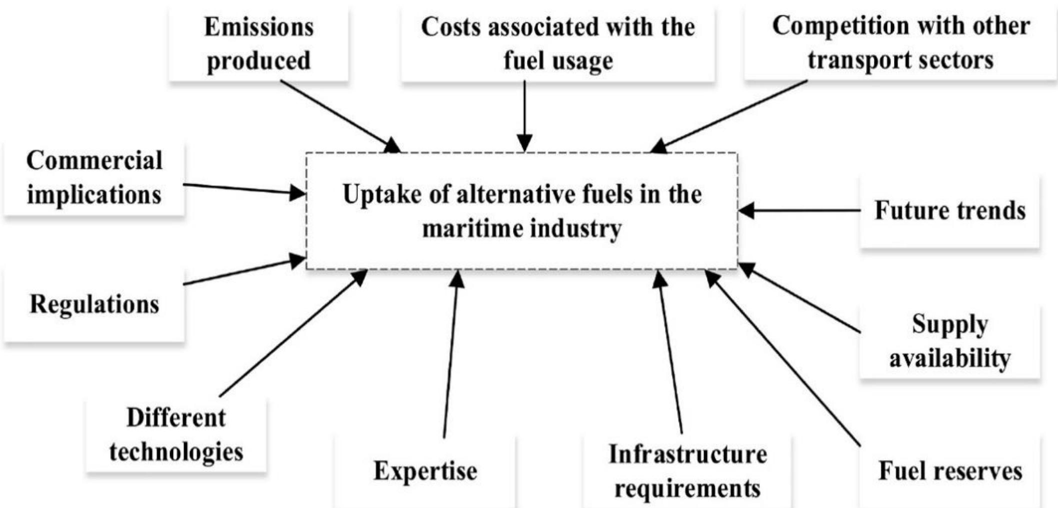

Figure 3-3 Structural Adaptation of Alternative Fuels (KLU Report for JRC; cited in Prussi et al., 2021)

3.5 IMO’s Role in Decarbonization

IMO is a United Nations agency that monitors various aspects of the shipping sector, such as shipping security and safety, as well as preventing ship-related marine and air pollution (*IMO,* n.d.). It plays a key role in decarbonizing the marine sector and implementing environmentally friendly policies. Below is the timeline of IMO's main steps and initiatives to counter the emissions.

The concept of decarbonization in the shipping sector was introduced in the 1970s. In 1973, the IMO adopted the International Convention for Preventing Pollution from Ships, also known as MARPOL. The scope of MARPOL has widened over the years, encompassing areas such as sewage and garbage. Moreover, the IMO introduced the "Prevention of Air Pollution from Ships" regulation to MARPOL in 1997, which deals with emissions (Sustainability and De-Carbonisation, 2021).

In the year 2011, the IMO added the mandatory energy efficiency standards to MARPOL Annex VI. As per this new requirement, all new vessels must have the Energy Efficiency Design Index (EEDI), and all current vessels must use the Ship Energy Efficiency Management Plan (IMO GHG Emissions from Shipping, n.d.).

In 2016, IMO initiated a new mandatory regulation requiring ships over 5000 gross tonnage (GT) to provide data regarding fuel oil consumption; this initiative aims to enhance the monitoring of GHG emissions from the shipping sector. The initial full year of data collection was made possible in 2019 (IMO GHG Emissions from Shipping, n.d.).

Moreover, in 2018, IMO adopted a comprehensive strategy to regulate GHG emissions; as per this regulation, GHG emissions should be halved from their 2008 levels, and carbon dioxide emissions should be reduced by 40% by 2023 and 70% by 2050 as compared to their 2008 levels (IMO GHG Emissions from Shipping, n.d.). In this formulation, a clear agenda regarding reducing GHG emissions was defined, which is an essential part of the decarbonization process, as in the previous regulations, clear goals were not defined.

IMO, in 2023, adopted a new strategy known as MEPC 80; as per this regulation, a new strategy was adopted in which zero or near zero GHG emissions technology should form a minimum of 5% of the energy utilization by the shipping sector. However, the goal should be to reach 10% of near zero or zero GHG emissions technologies energy utilization by international shipping (2023 IMO Strategy , n.d.).

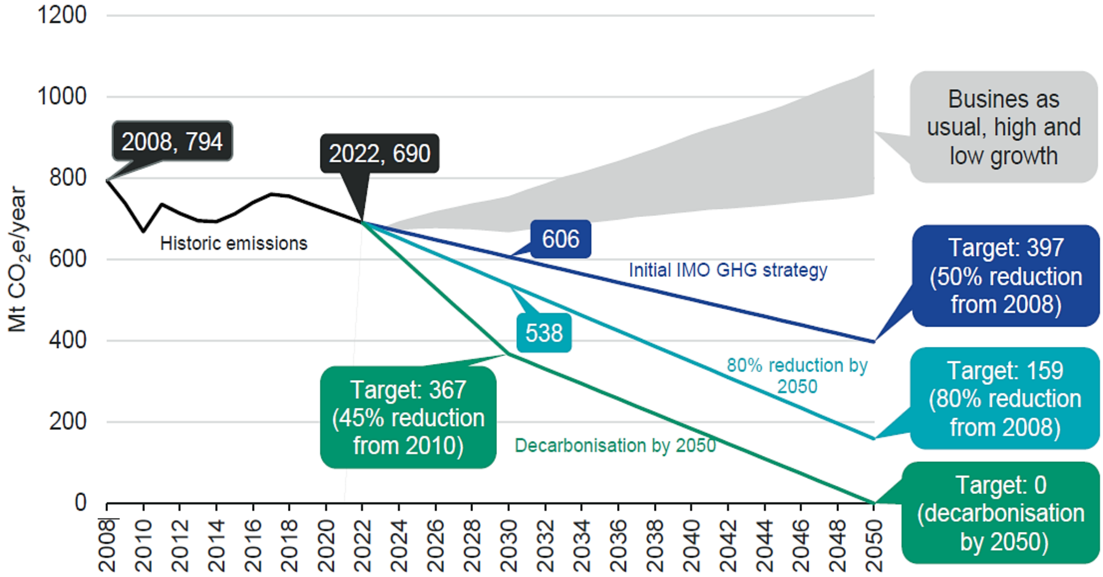

Figure 3-4 Three Decarbonization Scenarios with Targets Compared to Business-As-Usual GHG Emissions ("MEPC80, 2023)

Figures 3-4 above provide an overview of IMOs' different scenarios and strategies for reaching net zero emissions levels. The strategies are divided into different target zones; target 397 aims to reduce emissions by 50% from the 2008 level, target 159 aims for a reduction of 80% in 2050 from the 2008 level, and the aim is to reach target 0, which is to decarbonize the marine sector by the year 2050 completely.

3.5.1 Emission Control Areas (ECAs)

IMO introduced various strategies to counter decarbonization in the shipping sector. One unique approach is emissions control areas (ECA) or sulfur emission control areas (SECA); the initial ECA was adopted in 1997 and came into force in 2005 (Sun et al., 2020a). Table 5 provides the timeline of ECAs.

Table 5 Emission Control Areas Timeline (Sun et al., 2020a)

	Emission Control Areas (ECAs)			
	The Baltic Sea	North Sea and English Channel	North American	US Caribbean coasts
Adopted Year	1997	2005	2010	2011
Entered into Force	2005	2006	2012	2014

IMO has divided the emission control areas into three different zones. The zones, including the North American and US Caribbean coasts, are emission control areas; PM, SOx, and NOx emissions are regulated in these locations. The North Sea and Baltic Sea regions are included in the second zone, known as SECA. The worldwide waters outside the first two zones make up the third zone. IMO has defined the limit of sulfur content in the SECA and the areas outside of this jurisdiction (Bilgili, 2021).

Table 6 SOx Limits SECA and non-SECA (IMO,2020; cited in Bilgili, 2021)

Outside of SECA	Inside of SECA
4.50% before 1st January 2012	1.50% before 1 July 2010
3.50% on and after 1st January 2012	1.00% on and after 1 July 2010
0.50% on and after 1st January 2020	0.10% on and after 1st January 2015

Table 6 provides the timeline of sulfur limits in and outside of the SECA; the timeline shows that the limits have become more stringent over time. This reflects the strictness of IMO regulation aimed at reducing GHG emissions.

3.6 EU's Role in Decarbonization Efforts

The European Union (EU) has been a prime advocate for decarbonization in the transport sector. It has passed various legislation and initiatives to decarbonize the transport sector. In 2011, the European Commission proposed a 60% decrease in carbon emissions from 2008 levels by 2050 and a 40-50% reduction in carbon emissions in the maritime transportation sector by 2050 compared to 2008 levels (Dong et al., 2022).

The European Commission, through the European Climate Initiative, has initiated various proposals to counter carbonization. Some of the proposals are mentioned below.

- EU Emission Trading System
- Fuel-EU Maritime
- Energy Taxation Directive
- Alternative Fuel Infrastructure

EU Emission Trading System: This system works like a Cap-and-Trade system and limits ship emissions; a ship must buy extra emission rights or adhere to the defined limits. Ships with over 5000 GT and above are included in this system regardless of their flag. If the limits are exceeded, a fine of at least 100 euros per ton of GHG emissions will be imposed (Jeong, Kim, et al., 2022). Figures 3-5, given below, illustrate the EU plan for the progressive implementation of EU-ETS.

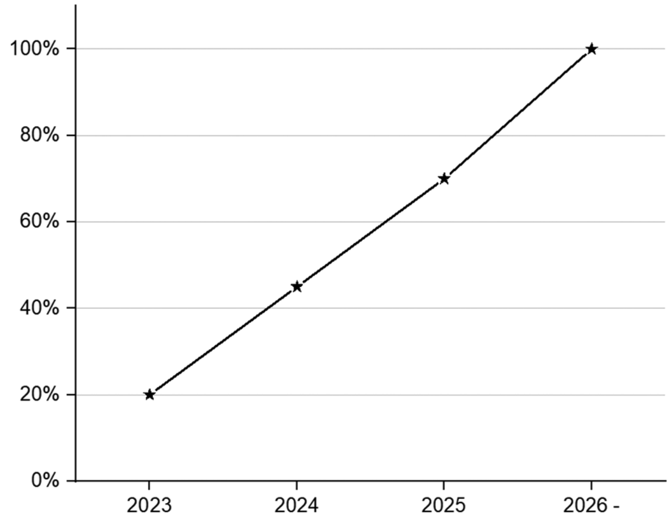

Figure 3-5 Progressive Plan for EU-ETS (European Council 2022; cited in Jeong et al., 2022)

Fuel-EU Maritime: This proposal is a part of the "Fit for 55" project; it focuses on the fuel used in the maritime sector and advocates for a cleaner and more sustainable fuel by resolving market issues and developing new cleaner technologies. This proposal includes all vessels 5000 GT or above, regardless of their flag; it aims to reduce GHG emissions by 2% by 2025 and 75% by 2050 (European Commission,2021; Cited in Jeong et al., 2022).

One of the most unique aspects of this proposal is that it does not only count onboard GHG emissions but also life cycle emissions. It aims to include the environmental impact of fuel in its Bunker Delivery Note (BDN), which will include its life cycle emissions (Jeong, Kim, et al., 2022). Figures 3-6 show the plan for this proposal and the timeline for curtailing greenhouse gas emissions through this initiative.

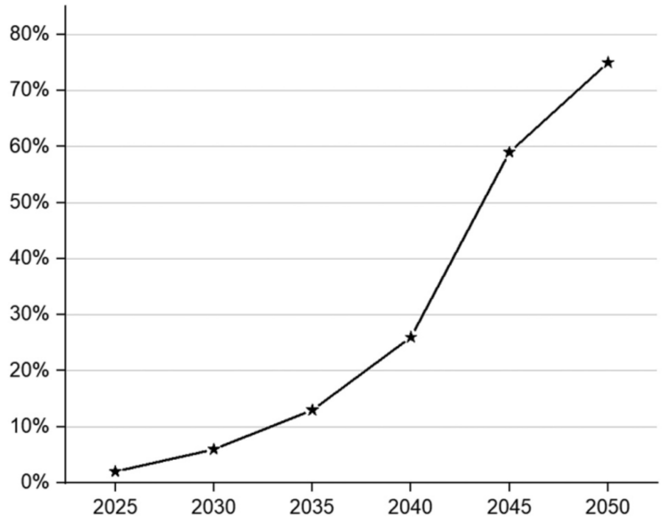

Figure 3-6 GHG Emission Reduction Plan FuelEU (European Commission,2021; Cited in Jeong et al., 2022)

Energy Taxation Directive: This initiative targets the EU taxation system. It aims to create a taxation system that encourages using alternative fuels in the maritime system by providing tax cuts and incentives. It aims to lure ship owners and companies to switch from traditional fuel to alternative fuel through financial incentives in terms of taxation (Jeong, Kim, et al., 2022).

Alternative Fuel Infrastructure: This initiative supplements the Fuel-EU proposal by building infrastructure that promotes the usage of sustainable fuel. One consideration in this regard is to build the bunkering infrastructure, particularly for LNG, by 2025 and supply power to the port that can meet the requirements of passenger and container ships (European Parliament,2022; cited in Jeong et al., 2022). It is vital to have the necessary infrastructure to support the transition from conventional fuels to more sustainable fuels, which will decarbonize the shipping sector.

3.7 National Efforts in Decarbonization

The maritime sector has an international outlook; however, the decarbonization drive must start at the national level. Around the globe, numerous states have started initiatives for its sustainability. Some states that have taken the lead in decarbonizing the maritime sector and have formed supporting policies and rules are mentioned below.

Norway is leading the maritime transition. It aims to reduce the carbon emissions of its domestic and fishing vessels by 50% by 2030. It has carried out the necessary legislation that provides financial support for developing the sustainable maritime sector. By 2026, all the vessels visiting the Norwegian fjords that are declared world heritage sites must achieve zero emissions (Dong et al., 2022).

The United Kingdom is the only state in the world to include shipping in its national carbon budget. By 2035, it wants to cut its carbon emissions from 1990 levels to 78%. It has also committed to providing funds to its shipping companies to increase research intensity in decarbonizing its shipping sector (Dong et al., 2022).

As one of the leading players in the shipping sector, China has also initiated and supported the decarbonization drives globally and in its domestic shipping sector. Following the guidelines of IMO, China has also set Emission control areas in its territorial waters (Dong et al., 2022).

3.8 Economic Challenges in Decarbonizing Maritime Sector

Maritime transportation has a significant role in global trade (Psaraftis, 2021); this critical role in global trade brings maritime transportation to the forefront of the global economy. The maritime transportation industry influences larger parts of the global economy both in direct and indirect terms; the transportation of essential resources to manufacturing hubs is highly dependent on marine transportation (Bai,x, et al., cited in Fratila et al., 2021).The maritime sector has a direct relationship with economic progress; a study that was conducted on the economy of the Caspian Sea states found that economic growth is linked to better management of maritime transportation (Akbulaev & Bayramli, 2020).

However, the decarbonization drive has to overcome the economic challenges. The various approaches of the IMO to curb shipping emissions directly impact shipping costs. ECAs or SECAs are designated areas where the IMO wants to curb sulfur emissions (Sun et al., 2020). In these specific areas, vessels must comply with strict emissions regulations, leading to the adoption of new technologies or fuel that produces few emissions, which can directly impact shipping costs. Two methods that are generally applied to comply with SECA's requirements involve using a scrubber or switching to LNG-powered engines; both options involve high capital costs (Doudnikoff & Lacoste, 2014).

Moreover, in liner shipping, if differentiating speeds are used, the overall cycle cost and SOx are reduced; however, the local reduction of SOx can harm overall emissions, as SOx emission reduction in SECAs results in higher CO2 emissions throughout the process (Doudnikoff & Lacoste, 2014). Furthermore, shipping companies can incur substantial abatement costs by installing new technologies or using a different fuel source. Depending on the compliance requirements, these costs can be immediate or continuous (Lähteenmäki-Uutela et al., 2017).

The increase in the cost because of compliance with regulations can be either moved forward or backward in the value chain; the cost can be passed on to the customers or sustained by the company by cost-cutting methods such as lowering the salaries of employees, etc. (Määttä & Tala, 2015; cited in Lähteenmäki-Uutela et al., 2017). This increase in cost can negatively impact the process of sustainability in the marine sector. High costs can result in an economic slowdown for least-developed and small-island developing countries that depend highly on trade for essential commodities (Rojon et al., 2021). The maritime sector is a global sector, and the exclusion of any stakeholders can negatively impact the whole process of carbon neutralization.

Additionally, opportunity costs can arise when the costs meant for a certain preferred productive use are diverted to regularity compliance. In the case of the marine sector, compliance in one sector can deprive investment in another potential sector that might have been more beneficial for overall decarbonization. However, determining the exact opportunity cost remains a complex process. The opportunity cost is the difference between the returns generated by adhering to regulatory compliance and the return offered by the best alternative. Thus, opportunity cost depends on the return on capital for business ("OECD," 2014). Thus, decarbonization in shipping remains a complex system; changing one variable can negatively affect the others. The decarbonization process should be sustainable and guarantee the inclusion of all stakeholders.

3.9 Summary

The global shipping sector's environmental effects are manifold and have extreme consequences for the environment and its inhabitants. The maritime sector is not only responsible for air emissions but also negatively impacts land and water. Air emissions, in particular, are believed to directly affect the inhabitants of areas where there are high emissions from the shipping sector. As per the World Health Organization (WHO), air pollution is the most significant risk to human health because PM emissions are strongly linked to adverse health impacts (WHO, 2022).

International organizations are using different approaches to mitigate the shipping sector's environmental impacts. IMO, the leading organization, has taken numerous initiatives and legislative measures to counter the emissions from the shipping sector. Some of its initiatives include mandatory energy efficiency standards and the Ship Energy Efficiency Management Plan (IMO GHG Emissions from Shipping, n.d.).

Furthermore, to counter the most harmful emissions, IMO, in cooperation with the local authorities, has formed the ECAs or SECAs, where all the ships are instructed to limit or control the amount of emissions (Sun et al., 2020a). Moreover, the EU, along with some states such as the UK and Norway, has also initiated various counter-emission strategies. One of the major challenges in decarbonizing the shipping sector is the economic domain. All the major counter-emissions initiatives require considerable costs in the form of infrastructure development or compliance costs. Thus, a united front involving all parties, such as IMO, national authorities, and shipping companies, is required to counter the emissions from the maritime sector.

4 Methodology for Economic Feasibility Analysis

Decarbonization in the shipping sector demands a paradigm shift in all dimensions of the global shipping sector. All the technologies essential for decarbonization are in the development phase and require financial input for mass utilization. This section of research will analyze the economics of carbon-neutral shipping compared to conventional shipping; the E-Ferry represents carbon-neutral shipping, while the Diesel Ferry represents traditional shipping.

4.1 Methodology

A comprehensive economic model with various parameters will be designed to evaluate the economic feasibility of a battery-powered vessel compared to a conventional-powered vessel. The selected vessels will be based on a similarity index for a comprehensive economic analysis. In the first step, we will select two vessels: an E-Ferry, which is powered by a battery system, and a Diesel Ferry, which uses conventional fuel for its propulsion system.

After selecting the vessels, all their technical details and related costs will be defined, and a comprehensive investment model will be created using MS Excel. Figure 4-1 provides a graphical overview of the methodology for economic assessment of the E-Ferry and the conventional ferry.

Figure 4-1 Methodology of Economic Assessment

The economic analysis will use two vital financial methods: Net Present Value (NPV) and Internal Rate of Return (IRR). These two methods are widely used to evaluate project economic viability and are explained below.

4.1.1 Net Present Value (NPV)

NPV is a method used to assess the financial viability of an investment. It is extensively used in various economic and financial assessment models. NPV can be defined as the value of all future cash flows over the entire investment time discounted to the present (CFI Team, n.d.).

The formulas for NPV are given in the equation (1) and (2)

$$C_o = -I_o + \frac{R_1}{q} + \frac{R_2}{q^2} \ldots . + \frac{R_n}{q^n} \pm \frac{L_n}{q^n} \quad (1)$$

or

$$C_o = -I_o + \sum_{t=1}^{n} \frac{R_t}{q^t} \pm \frac{L_n}{q^n} \quad (2)$$

C_o = Net present value (€)

R_n = Returns (difference between incoming and outgoing payments for year n) (€/year)

L_n = Liquidation proceeds or expenses in the nth year (€)

q = 1+i, where i=imputed interest rate (%)

q^n = Compounding factor = $(1+i)^n$

q^{-n} = Discounting = $\frac{1}{q^n} = \frac{1}{(1+i)^n}$

t = Individual periods from o to n

n = Duration of use of the investment object (years)

I_o = Investment amount (acquisition and ancillary costs) (€) (Jörg Wöltje, 2009)

Once the value of NPV is known, a conclusion can be made on the preliminary effectiveness of the investment.

If NPV=0, only the investment has been recovered, and the project can neither be called profitable nor unprofitable.

If NPV>0, it means that the project can be accepted as it will generate profit after being compared with other projects and finding the best alternative.

If NPV<0, This shows that the investment project cannot be accepted as it is inherently unprofitable (Zakharchenko et al., 2020).

4.1.2 Internal Rate of Return (IRR)

The second approach in economic assessment is IRR. It is defined as the discount rate at which the difference between the investment costs and the added value of all the income and cash interest is zero (Zakharchenko et al., 2020).In other words, IRR is the discount rate that makes the NPV of a project zero (Tim Vipond, n.d.-a).

The formula of IRR is given in the equation (3).

$$C_o = 0 = -I_o + \frac{R_1}{q} + \frac{R_2}{q^2} \dots + \frac{R_n}{q^n} \pm \frac{L_n}{q^n} \tag{3}$$

R = Returns (incoming payments - outgoing payments)

I_o = Acquisition value, investment amount

L_o = Liquidation proceeds

The approximation formula of IRR is given in equation (4)

$$r = i_1^+ + \frac{C_{01}^+ \times (i_2^- - i_1^+)}{C_{01}^+ - C_{02}^-} \tag{4}$$

r = Internal rate of return

i_1^+ = Trail interest rate 1

i_2^+ = Trail interest rate 2

C_{01}^+ = Net present value (positive) at i_1

C_{02}^- = Net present value (negative) at i_2 (Jörg Wöltje, 2009)

The greater the excess of IRR over the interest rate, the higher the investment efficiency (Mazur, Shapiro; Olderogge 2001a; cited in Zakharchenko et al., 2020).

4.2 Vessels Selection for Economic Analysis

We have selected two vessels for our economic feasibility analysis. The first vessel is a battery-powered ferry, and the second vessel is a diesel-powered ferry, as mentioned below:

- E-Ferry Ellen
- Diesel Ferry LMG 50.1

Firstly, the economic feasibility of the E-Ferry will be analyzed. After that, the investment model for the Diesel Ferry will be evaluated.

4.3 E-Ferry Ellen and its Technical Details

The vessel that has been selected for economic feasibility is known as “E-Ferry-Ellen.” It is an electric battery-powered ferry. The ferry is part of EU Horizon 2020, which wants to decarbonize waterborne transportation. AEROE-ferries currently operates the E-Ferry between Søby-Fynshav and Søby-Faaborg. It has a battery capacity of 4.3 MWh, which can power it to travel 22 nautical miles (Annie Kortsari et al., 2020). Figure 4-2 provides a picture of the E-Ferry Ellen.

Figure 4-2 E-Ferry-Ellen (Peter Therkildsen, 2022)

The technical details of the E-Ferry are vital in analyzing its economic competence. The technical details of the electric ferry are divided into four categories, which are given below.

- Dimensions of the Vessel
- Overall Capacity and Crew Members
- Power and Propulsion System of the Vessel
- Flag and Classification of the vessel

Table 7 below provides all the technical details of the E-Ferry, including the categories such as power and propulsion system and dimensions of the vessels, etc.

Table 7 Technical Details of E-Ferry (Annie Kortsari et al., 2020).

Dimensions of the E-Ferry	
Overall Length	59.4 Meters
Length Between Perpendiculars	57 Meters
Moulded Breadth	12.8 Meters
Moulded Depth	3.70 Meter
Gross tonnage	996
Displacement	933 Ton
Designed Draught	2.5 Meter
Designed Deadweight	187 Ton
Lightweight	746 Ton
Service speed	13.5 knots
Maximum speed	14.2 knots
Overall Capacity and Crew Members	
Vehicle Deck Lane Length	145 Meters.
Capacity of Cars	31
Capacity of Trucks and Trailers	5
Passengers Count	147-196
Total crew Members	3-4
Power and Propulsion System of Vessel	
Primary Engines	2x700 kW
Thruster Engines	2x250 kW
Nominal Capacity of Battery	4.3 MWh
Charging efficiency	4 MW
Flag and Classification of Vessel	
Flag of the Vessel	Denmark
Classification society	DNV

4.4 Investment and Financing Forecast of Electric Ferry

E-Ferry cost of construction: This cost is divided into five categories. The initial phase is planning, where the designs and drawings of the vessels are finalized and documented. The second phase includes the manufacturing part, where the Hull for the vessel is produced; in the third phase, the fitting of the components is carried out, along with the installation of the electric and propulsion system. The final phase of the construction includes procurement and installation of the battery system. Table 8 provides a complete, detailed description of the construction cost of E-Ferry.

Table 8 Construction Cost of E-Ferry (Annie Kortsari et al., 2020).

Construction Cost of E-Ferry	
Cost Description	Cost (€)
Designing, Drafting, and Documentation	475,000
Hull Fabrication	2,642,000
Outfitting and Equipment installation	7,161,511
Electrical and Propulsion system setup	2,100,000
Integration of Battery System	4,283,276
Total	**16,661,787**

Necessary infrastructure cost of E-Ferry: For smooth operations of the battery-powered vessel, additional investment is required, including the infrastructure cost necessary for operations. This cost has been divided into three main categories. The first cost category consists of the charging system, which includes cables, a cooling system, VAT, and fees for the electric supplier. The second cost category includes a one-time connection fee for electricity connection, and the final cost is for the modern auto mooring system. Table 9 provides a complete description of the E-Ferry construction cost.

Table 9 Infrastructure Cost of E-Ferry (Annie Kortsari et al., 2020).

Cost of Infrastructure	
Cost Description	Cost (€)
Charging system Cost (On-Shore)	1,068,502
Connection Fee	1,383,157
Automooring Cost	1,146,739
Total	**3,598,398**

The operational cost of E-Ferry: The main operational cost is divided into two types: the salaries for the vessel's crew and its subsidiary costs, and the energy cost, which includes the cost of electricity for charging the batteries and hotel load when the ferry is idle. Table 10 provides the yearly operational cost based on five ferry trips per day.

Table 10 Operational Cost of E-Ferry (Annie Kortsari et al., 2020).

Operational Cost of E-Ferry	
Cost Description	Cost/Year (€)
Crew Costs	975,514
Energy Cost	241,615
Total	**1,217,129**

General cost of E-Ferry: The general cost of the E-Ferry is divided into three subtypes. The first is the maintenance cost, which includes costs such as repair and service of the vessel, battery system maintenance, docking and surveys, etc. The second type, known as other expenses, comprises costs that include maintenance of the onshore system, e.g., auto mooring system, etc. The third type of general cost is insurance expenses, which include the insurance cost for the vessel and the onshore systems. Table 11 provides a detailed description of the general costs of E-Ferry.

Table 11 General Costs of E-Ferry (Annie Kortsari et al., 2020).

General Costs of E-Ferry	
Cost Description	Cost/Year (€)
Maintenance Costs	228,456
Other Expenses	157,550
Insurance Expenses	79,463
Total	**465,469**

4.5 Design of the Economic Evaluation Model

The economic evaluation model uses various approaches based on investment and financing forecasts. All the calculations are carried out using MS Excel and can be found in the file "Calculations E-Ferry". In the first step, an investment forecast includes a complete investment plan. After the investment forecast, the financing forecast is created, including all the financing aspects and the debt capital forecast. Once these forecasts are crafted, a Base Case is formed, and key variation points are determined; the base case serves as the central reference point for further variation.

After the base case is formed, two more cases are also formed, named best and worst case; as the name suggests, in the best case, all the favorable variations are considered, and an ideal case is formed that gives the best results for the investment. On the other hand, in the worst case, all the negative scenarios are considered, and the limitations of the investment are analyzed. Once all the cases are formed, a sensitivity analysis is performed using the variables of the base case; Table 12 gives an overview of the process for sensitivity analysis.

Table 12 Sensitivity Analysis Model E-Ferry

Variable	Negative Variation	Negative Variation	Negative Variation	Base Case	Positive Variation	Positive Variation	Positive Variation
Time Charter Rate (%)	-15	-10	-5	0	5	10	15
Ship Operation Cost (%)	15	10	5	0	-5	-10	-15
Tax Reduction (%)	15	10	5	0	-5	-10	-15
Bank Interest Rate (%)	3	2	1	0	-1	-2	-3
Proceeds of Ship Sale (%)	8	12	16	20	24	28	32

4.6 Description of Investment Forecast

The section describes the main parameters of the investment forecast in detail.

Price of the E-Ferry: The total price of the vessel, including the construction from design to manufacturing and the cost of the necessary infrastructure essential for its operations, is 20,260,185 € (Annie Kortsari et al., 2020).

Time charter rate of the E-Ferry: For our vessel, a charter rate of 9,500 € per day is considered, based on the data assessed through the operator of the E-Ferry Ellen; the calculations of the time charter rate are given in Table 13.

Table 13 Earnings of E-Ferry

Earnings of E-Ferry			
	Persons	Cars	Trucks
Quantity	147/196	31	5
Ticket Price (€)	6.9	21.24	30
Earnings per section (€)	1,104	658.44	150
Total Earnings (€)			1912.44

The calculations are dependent on data from the E-Ferry Operator's website. The ticket prices for cars and trucks also included the drivers; thus, the total number of 160 passengers is considered. The ferry operates 5 times a day and will make a total of 10 trips. So, the total earnings for one day will become 1,912.44*10=19,124.4 € per day. However, this is the maximum amount of earnings per day, and to make our investment more realistic and conservative, we have selected half the amount, which is 9,500 € per day. Moreover, some internet sources were also used to check the time charter rate (Gary Andrews, 2021).

Operational cost of the E-Ferry: In investment calculations, operating costs are divided into three categories. The main category consists of operating costs, including crew and energy costs, which total 1,217,129 € per year (Annie Kortsari et al., 2020).

Estimated onshore infrastructure maintenance docking, classification, onshore, and vessel maintenance cost: This section is the second operating cost category. Its main costs include docking, classification, onshore, and vessel maintenance. In total, this cost is 386,006 € per year (Annie Kortsari et al., 2020).

Insurance cost of E-Ferry and onshore systems: The third operational cost includes the insurance cost for the E-Ferry and the onshore charging system. The total annual amount is 79,463 € per year (Annie Kortsari et al., 2020).

Battery replacement cost of E-Ferry: The E-Ferry's main source of propulsion is the battery system. As it has an operational life of 12 years, a new battery system is required, and the replacement system will cost 406,500 € (Annie Kortsari et al., 2020).

Interest rate for E-Ferry finance: To finance our investment, we will be taking a loan from a bank; thus, we have considered an interest rate of 5%; the European Central Bank's interest rate on 22 December 2023 was 4.50% (Deutsche Bundesbank, n.d.).

Re-sale price of E-Ferry: As our vessel is of a new type and there is no exactly defined resale price for it, and the price keeps changing depending upon market fluctuation, we assumed that the resale price would be 20% of the total price of our vessel. In our case, the price is 4,052,037 €. This value also includes the infrastructure that will be sold along with the vessel.

4.7 Assumptions in Investment

The E-Ferry is modern and New-built; we assume it will have a life of 30 years. We will consider its use for 18 years. After that time period, we assume it will sell for 20% of its total price, as it will be in good working condition.

Vessel finance: The total price of the vessel, including the necessary infrastructure cost, is 20,260,185 €. For vessel finance assumption, a down payment of 30%, which is 6,078,056 €, the buyer pays the manufacturer, and the remaining 70%, 14,182,130 €, is financed through a banking channel.

Time charter rate: We have selected a time charter rate of 9500 € per day. We will keep it constant without any change for the first six years. After that, an increment of 1% is applied for the next six years, and an increment of 2% is applied for the remaining six years.

Operating cost: The operating cost of the ferry consists of the cost associated with the crew and the energy cost, which is 1,217,129 € per year. It will remain constant without any change for the first six years. After that, an increment of 1% is applied for the next six years; for the remaining years, an increment of 1,5% will be applied.

Dry dock, onshore maintenance, and survey costs: According to E-Ferry's evaluation reports, a yearly amount of 386,006 € is considered for dry dock, onshore maintenance, and survey costs. This cost remains constant for the initial five years; in the sixth year, it will increase by 2%, followed by an increase of 2% every three years thereafter.

Interest rate: We have selected an interest rate of 5% for vessel finance. It is based on the European Central Bank's interest rate, which on 22 December 2023 was 4.50%. We selected a 5% interest rate because we have opted for a conservative approach to mitigate potential market fluctuations. This rate remains fixed for the first six years of the investment. After that, an increment of 0.5% is added for the next four years, and the interest rate will rise to 5.5%. For the following four years, it will be set at 6%. The last four years of investment will have an interest rate of 7%.

Insurance cost: The total insurance cost for the ship and shore charging system is 79,463 € per year. There is no change in the insurance cost for the initial four years. However, from the fifth year, there has been an annual increase of 1.5% in insurance costs, which remains same for the following four years of investment. In the tenth year of investment, there is a 1.5% increase from the previous year's amount, and this increased rate is maintained for the next four years. For the remaining years of the investment, the same approach is utilized.

Re-sale price: The ferry can sustain 30 years of sea time; it will be 18 years old when we sell the ferry. It still has some sea time; besides, there's no immediate need for battery replacement.

We expect six more years of uninterrupted operations. Based on these assumptions, it will provide a return of 20%, which will be 4,052,037 €.

Bank Loan: In the investment, 70% of the total cost of the vessel is paid through a Bank loan. The total cost of the vessel is 20,260,185 €; thus, 70% of this amount is calculated to be 14,182,130 €.

Tax Exemptions: As the E-Ferry is a battery-powered vessel with no direct emissions, we have considered tax exemptions. In Excel calculations, we have designed this in a way that, depending upon the assumption, tax exemption will reduce or increase the operational cost, which consists of electricity and crew salaries. For example, a 5% tax reduction will mean the operational cost will be reduced from 1,217,129 € to 1,156,273 €. Technically, this 5% is the amount that we receive from the authorities in the form of tax incentives for investment.

Working Days: As the ferry plays a vital role in connecting islands, we consider it to be working for 360 days a year.

4.8 Forecasting

- Our charter rate is 9500 € per day, the inflow value. As per our assumptions, we will continue to vary our charter rate over the years.
- The operating cost of the ferry includes operational expenses, including crew salaries and energy costs, in our case, electricity. Other costs include dry dock, onshore maintenance, survey, and insurance. These costs will vary as per the description in the assumptions section.
- The bank loan is 70% of the total amount, 20,260,185 €, calculated to be 14,182,130 €. This loan amount will be returned in installments every year; in our case, it will be returned in 15 years.
- The loan amount of 14,182,130 € will be paid over 15 years, and the bank will receive an installment repayment of 14,182,130/15=945,475 € every year.
- The loan amount we have to pay interest on is 14,182,130 €. We will pay an interest rate of 5% for the first six years. After that, the rate will increase to 5.5% for the next four years, followed by another increment to keep it at 6% for the following four years. Finally, we will pay an interest rate of 7% for the remaining period. However, as the loan amount will be returned in the first fifteen years, no loan will be repaid for the remaining 3 years.

- Our vessel will be sold after 18 years, as the battery has to be replaced after 12 years. When we sell it, its battery can continue to operate for 6 years without a significant overhaul. It will be sold for 4,052,037 euros, 20% of the total price.
- The total amount of the current account overdraft is 250,000 €; we will pay an interest rate of 5% for the first six years. After that, the rate will increase to 5.5% for the next four years, followed by another increment to keep it at 6% for the following four years. We will pay an interest rate of 7% for the remaining period
- Net cash flow is the overall amount after subtracting all operational expenses. In the Base case, it is 12,649,412 €.
- Liquidity is derived from net cash flow. In our base case, liquidity is 16,701,449 €, which is more than the net cash flow because it includes the vessel's resale value.
- In the base case, we have an IRR of 7.5%, and the NPV is also positive, at 1,223,607 €.
- We have selected a discount rate of 6% for all the cases we will analyze.

4.9 Diesel-Powered Vessel and its Technical Details

The second vessel for economic feasibility analysis is a diesel-powered ferry, also known as LMG 50.1; this vessel was designed by the maker of E-Ferry to resemble the E-Ferry Ellen. Thus, most of LMG 50.1's dimensions and capabilities are equivalent to or similar to its battery-powered counterpart.

The technical details of a conventional ferry are similar to those of the E-Ferry Ellen in many ways, except for the power source of the propulsion system. The particulars are divided into four categories, which are given below.

- Dimensions of the Vessel
- Overall Capacity and Crew Members
- Power and Propulsion System of the Vessel
- Flag and Classification of the vessel

Table 14 provides a complete description of the technical details of LMG 50.1.

Table 14 Technical details of Diesel Ferry LMG 50.1 (Annie Kortsari et al., 2020).

Dimensions of the Diesel Ferry	
Overall Length	59.4 Meters
Length Between Perpendiculars	57 Meters
Moulded Breadth	12.8 Meters
Moulded Depth	3.70 Meter
Gross tonnage	996
Displacement	933 Ton
Designed Draught	2.5 Meter
Designed Deadweight	187 Ton
Lightweight	746 Ton
Service speed	13.5 knots
Maximum speed	14.2 knots
Overall Capacity and Crew Members	
Vehicle Deck Lane Length	145 Meters.
Capacity of Cars	31
Capacity of Trucks and Trailers	5
Passengers Count	147-196
Total crew Members	4-5
Power and Propulsion System of Vessel	
Primary Engines	2x700 kW
Thruster Engines	2x250 kW
Diesel Generator	2x1215 KW
Flag and Classification of Vessel	
Flag of the Vessel	Denmark
Classification society	DNV

4.10 Investment and Financing Forecast of Diesel-Powered Ferry

Construction cost of Diesel Ferry LMG 50.1: The construction costs of this ferry are divided into various phases. The first phase is finalizing the designs and drawings for the ferry; the second phase involves hull production; after that, various components are fitted, the propulsion system is installed, and approvals are obtained from the authorities (Annie Kortsari et al., 2020). The construction cost of the ferry LMG 50.1 is given in Table 15.

Table 15 Construction Cost of Diesel-Ferry (Annie Kortsari et al., 2020).

Construction Cost of Diesel-Ferry	
Cost Description	Cost (€)
Design and Drawings	
Hull production	
Outfitting	13,000,000
Propulsion systems	
Approvals	
Total Cost	**13,000,000**

Necessary infrastructure cost of Diesel Ferry: In order to reduce the required manpower in the mooring process, the Diesel Ferry is equipped with 2 auto-mooring systems in its ports of operations. This cost includes purchasing and installing the mooring system, ship-side system installations, and commissioning. Compared to E-Ferry, the infrastructure cost remains low because there is no requirement for a charging system and special electricity connection cost (Annie Kortsari et al., 2020). The infrastructure cost of the Diesel Ferry is provided in Table 16.

Table 16 Infrastructure Cost of Diesel Ferry (Annie Kortsari et al., 2020).

Cost of Infrastructure: Diesel Ferry	
Cost Description	Cost (€)
Automooring	1,146,740
Total	**1,146,740**

Operational cost of Diesel Ferry: The Diesel Ferry's operational cost is divided into three types: the salaries for the ferry's crew and its subsidiary costs, fuel cost, and electricity cost. When the ferry is idle, the power for the hotel load is supplied through on-shore power systems. Compared to an E-ferry, the operational cost of the Diesel Ferry is higher due to the utilization of two power sources. The yearly operational cost given in Table 17 is based on 5 daily ferry trips (Annie Kortsari et al., 2020).

Table 17 Operational Cost of Diesel Ferry (Annie Kortsari et al., 2020).

Operational Cost	
Cost Description	Cost/Year (€)
Salaries of Crew	1,093,830
Fuel Consumption	492,259
Electricity Cost (Hotel load and Idle Period)	30,519
Total	**1,616,608**

General cost of Diesel Ferry: The general cost of the Diesel Ferry is divided into three subtypes. The initial is the maintenance cost, which includes various costs such as vessel service and repair, docking, surveys, etc. The second cost, other expenses, comprises costs that include maintenance of the onshore system, e.g., auto mooring system. The third cost is insurance expenses, including the ferry's insurance cost. As the Diesel Ferry requires more maintenance than the E-Ferry, the overall general costs of diesel ferries remain high even with the low insurance cost (Annie Kortsari et al., 2020). A detailed description of the general cost is given in Table 18.

Table 18 General Costs of Diesel Ferry (Annie Kortsari et al., 2020).

General Costs	
Cost Description	Cost/Year (€)
Maintenance Costs	365,127
Other expenses	174,578
Insurance Expenses	64,429
Total	**604,134**

4.11 Design of the Economic Evaluation Model

The economic assessment framework of the Diesel Ferry is based on the economic model of E-ferry. All the calculations are performed using MS Excel and can be found in the file "Calculations Diesel Ferry".Initially, an investment forecast is formed that includes a complete investment plan. After the investment forecast, the financing forecast is created, including all the financing aspects and the debt capital forecast. Once these forecasts are crafted, a Base Case is formed, and key variation points are determined; the Base Case serves as the main reference point for further variation.

Apart from the base case, two more cases are formed: the best and worst cases. In the best case, all possible investment scenarios are considered, while all negative scenarios are considered in the latter. Moreover, the investment is also analyzed through sensitivity analysis; the base case is considered the main reference point. Table 19 provides all the variables and variations for the sensitivity analysis.

Table 19 Sensitivity Analysis Model Diesel Ferry

Variable	Negative Variation	Negative Variation	Negative Variation	Base Case	Positive Variation	Positive Variation	Positive Variation
Time Charter Rate (%)	-15	-10	-5	0	5	10	15
Ship Operation Cost (%)	15	10	5	0	-5	-10	-15
Bank Interest Rate (%)	3	2	1	0	-1	-2	-3
Proceeds of Ship Sale (%)	8	12	16	20	24	28	32

4.12 Description of Investment Forecast

This section describes all the main parameters of the investment forecast.

Price of Diesel Ferry: The total cost of the ferry includes the construction from design to manufacturing and the cost of the infrastructure essential for its operations. For Diesel Ferry, the infrastructure cost includes the cost of the auto mooring system, and the total cost is 14,146,740 € (Annie Kortsari et al., 2020).

Time charter rate of Diesel Ferry: Since both ferries have identical capabilities and passenger capacities, the charter rate has been maintained at the same level for Diesel Ferry and E-Ferry; a charter rate of 9,500 € per day is considered.

Operation cost of Diesel Ferry: The operating costs are divided into three categories. The first category comprises operating costs, including crew, fuel, and electricity, totaling 1,616,608 € per annum (Annie Kortsari et al., 2020).

Estimated onshore maintenance, docking, and classification costs: This section is the second category of operating costs. It encompasses various expenditures such as docking fees, classification expenses, and vessel upkeep. It also includes maintaining onshore facilities such as ramps and auto-mooring systems. This cost is 539,705 € per annum (Annie Kortsari et al., 2020).

Insurance cost of Diesel Ferry: The third operational cost includes the insurance cost of the Diesel Ferry. In total, the annual amount is 64,429 € (Annie Kortsari et al., 2020).The insurance cost is low compared to the electric ferry, as it only includes the insurance of the vessel and not the insurance of onshore systems.

Interest rate for Diesel Ferry: In this case, we have considered the same interest rate as E-Ferry's.To finance our investment, we will be taking a loan from a bank; thus, we have considered a 5% interest rate. We have selected a higher interest rate than the bank's rate because selecting a higher rate than the bank's provided rate makes the investment resilient to fluctuations in the rate.

Resale price of Diesel Ferry: The diesel-powered ferry is only designed for economic and technical comparison with the E-Ferry and is not constructed; thus, the same assumption of the E-Ferry re-sale price will be applied for a better comparison. The diesel power ferry will be sold for 20% of its total value, which is 2,829,348 €, and includes the auto-mooring system.

4.13 Assumptions in Investment

Ferry operation: In the case of Diesel Ferry operations, we apply the same assumptions as those of E-Ferry as they are conceptually based and theoretically designed only for comparison purposes. We will consider its use for 18 years. After that time period, we assume it will sell for 20% of its total price, as it will be in good working condition. An important consideration in this assumption is that the life of an E-Ferry is directly linked with the battery system, and it needs an overhaul after 12 years in service; however, in the case of the Fiesel Ferry, no such overhaul is required after 12 years.

Vessel finance: The Diesel Ferry will adhere to the same financial principles in vessel finance as the E-Ferey. The overall cost of the vessel, encompassing essential infrastructure, is 14,146,740 €. For the vessel finance assumption, the buyer pays the manufacturer a down payment of 30%, 4,244,022 euros, and the remaining 70%, 9,902,718 €, is financed through a banking channel.

Time charter rate: The Diesel Ferry and the E-ferry operate under identical assumptions regarding the time charter rate. For the first six years, a daily charter rate of 9500 euros will remain constant without any change. After that, an increment of 1% is applied for the next six years, and an increment of 2% is applied for the remaining six years.

Ferries operational cost: The diesel ferry's operating cost includes fuel, crew, and electricity, which is 1,616,608 € per annum. The main variance between the Diesel Ferry and the E-ferry lies in the inclusion of fuel costs, as the E-Ferry is entirely reliant on electricity. The operational cost will be kept constant without any change for the first six years. After that, an increment of 1% is applied for the next six years, and after that, an increment of 1,5% will be applied for the remaining years.

Dry dock, onshore maintenance, and surveys cost: A yearly amount of 539,705 € has been allocated for dry dock services, onshore maintenance, and survey expenses. We have assumed that this cost will remain constant without any change for the first five years; in the sixth year, it will increase by 2%, followed by a subsequent increase of 2% every three years thereafter.

Interest rate: The Diesel Ferry and the E-Ferry share the same assumptions regarding the interest rate. An interest rate of 5% is considered for the investment. This rate remains constant throughout the initial six years of the investment period. Following this period, an increment of 0.5% is added for the next four years, and the interest rate will rise to 5.5%. For the following four years, it will be set at 6%. The remaining four years of investment will have an interest rate of 7%.

Insurance costs: The insurance coverage for the Diesel Ferry has an annual expenditure of 64,429 €. The insurance cost remains the same for the initial four years. However, from the fifth year, there will be an annual increase of 1.5% in insurance costs, which remains same for the following four years of investment. In the tenth year of investment, there is a 1.5% increase from the previous year's amount, which will remain intact for four years. For the remaining years of the investment, the same approach is utilized.

Resale price of the ferry: The ferry can endure 30 years of maritime service, and by the time we sell it, it will be 18 years old, thus having significant sea time; besides, as it is diesel-powered, there is no need for battery replacement. Based on these assumptions, it will provide a return of 20%, which will be 2,829,348 €.

Bank Loan: In the investment, 70% of the total cost of the vessel is paid through a Bank loan. The total cost of the vessel is 14,146,740 €; thus, 70% of this amount is calculated to be 9,902,718 €.

Working Days: As the ferry plays an important role in connecting islands, we consider it to be working for 360 days a year. This ensures a consistent and reliable service, which is essential for facilitating seamless connectivity between island communities.

4.14 Forecasting

- The in-flow value is selected at a 9500 € per day charter rate. As per our initial assumptions of the base case, we will continue to vary our charter rate over the years.
- The ferry's operating costs include operational expenses, including crew salaries, fuel, and electricity costs. Other costs include dry dock, maintenance, survey, and insurance. These costs will vary as per our description in the assumptions section.
- The bank loan is 70% of the total amount, 14,146,740 €, calculated to be 9,902,718 €. This loan amount will be returned in installments every year; in our case, it will be returned in 15 years.
- The loan amount of 9,902,718 euros will be paid over 15 years, and the bank will receive an installment repayment of 9,902,718/15=660,181 € every year.
- The loan amount we have to pay interest on is 9,902,718 €. We will pay an interest rate of 5% for the first six years. After that, the rate will increase to 5.5% for the next four years, followed by another increment to keep it at 6% for the following four years. Finally, we will pay an interest rate of 7% for the remaining period. However, as the loan amount will be returned in the first fifteen years, no loan will be repaid for the remaining three years.
- The Diesel Ferry will be sold after 18 years as it still has some years of service. We assume it will be sold for 2,829,348 €, 20% of the total price.
- The total amount of the current account overdraft is 200,000 €; we will pay an interest rate of 5% for the first six years. After that, the rate will increase to 5.5% for the next four years, followed by another increment to keep it at 6% for the following four years. We will pay an interest rate of 7% for the remaining period.
- Net cash flow is the overall amount after subtracting all operational expenses. In the Base case, it is 9,049,924 €.
- Liquidity is derived from net cash flow. In our base case, liquidity is 11,879,272 €, which is more than the net cash flow because it includes the ferry's resale amount.
- In the base case, we have an IRR of 7.5 %, and the net present value is also positive, at 902,275 €.

- We have selected a discount rate of 6% for all the cases we will analyze.

4.15 Summary

This chapter explained the economic model and methodology for determining ferries' financial viability. Firstly, the economic assessment model of E-Ferry is formed, which includes the investment and financing forecast, design of the economic model, description of the economic forecast, and assumption. Diesel Ferry utilizes the same economic assessment approach and methodology as E-Ferry so that a better economic comparison is formulated.

The financial assessment mainly relies on parameters such as the NPV and the IRR. One notable difference in the assessment of ferries is the inclusion of a tax exemption for the E-Ferry, as it has no direct emissions. No such exemption is possible for the Diesel Ferry, as it has direct operational emissions. All the calculations mentioned in this section have been carried out in MS Excel, where a detailed investment plan is formulated for both ferries.

5 Result and Discussion

In this chapter, we will discuss the economic evaluation outcomes of the E-Ferry and Diesel Ferry, conducting a comparative analysis to distinguish their respective strengths and weaknesses.

5.1 Electric Ferry Ellen

The economic evaluation is structured into four categories. The first category is the base case, where the initial forecast and assumptions about the economic model are made in the investment strategy. Different scenarios are crafted, and results are assessed using NPV and IRR.

The second economic scenario is the best case, an optimistic portrayal wherein all favorable economic indicators are utilized. The third case is called the worst case; in this case, all the possible worst economic conditions enable a thorough exploration of potential challenges.

The final case is a sensitivity analysis of the complete investment, which comprehensively examines the investment's potential under various economic indicators. The sensitivity analysis considers the base case as a main reference point, and all the variations are with respect to that case.

5.1.1 Base Case

The first case in the economic analysis of E-Ferry is the base case, which serves as the main reference case; all the variations are directly linked with this case; in our analysis, the base case is assumed as a reference point. The NPV and IRR of the base case are given as follow

- NPV = 1,223,607 €
- IRR = 7.5 %

In the base case, we can see that we have a positive value of NPV, which shows that our investment will have positive returns. On the other hand, the discount rate used for this selection is 6%, and we have received an IRR of 7.5%, which is more than the discount rate, which also shows a positive sign. However, as our investment period is stretched over 18 years and consists of various variables and assumptions, an IRR of 7.5% doesn't provide us with a clear choice, and the selection of investment depends on the priorities and goals of the company.

5.1.2 Best Case

In this case, all positive scenarios are used for the economic strategy. Thus, it provides the highest NPV value and maximum IRR rate, which are given below.

- NPV = 15,313,019 €
- IRR = 25.6 %

If the conditions of the best case are considered, it provides an outlook for a good investment with a positive NPV and a high IRR. The best case remains ideal for selecting the ferry in terms of investment.

5.1.3 Worst Case

As evident from the name, in this case, all the worst possible scenarios for the investment are considered. Negative variations while evaluating investments are essential as these can highlight the investment's limitations. The NPV and IRR, in this case, are given as follows.

- NPV = -12,297,963 €
- IRR = -8.0 %

In the worst case, both investment indicators show a negative trend; negative NPV means the investment is not profitable and thus cannot generate positive returns, and the negative IRR means the investment is not viable.

5.1.4 Graphical Representation of the Cases

A graphical overview of the three cases provides a much clearer picture of our investment strategies in our research. Figure 5-1 graphically represents all three cases regarding their NPV and IRR values.

If we look at the base case, we can see that it has positive indicators: the value of NPV is positive, and the IRR is above the discount rate of 6%.

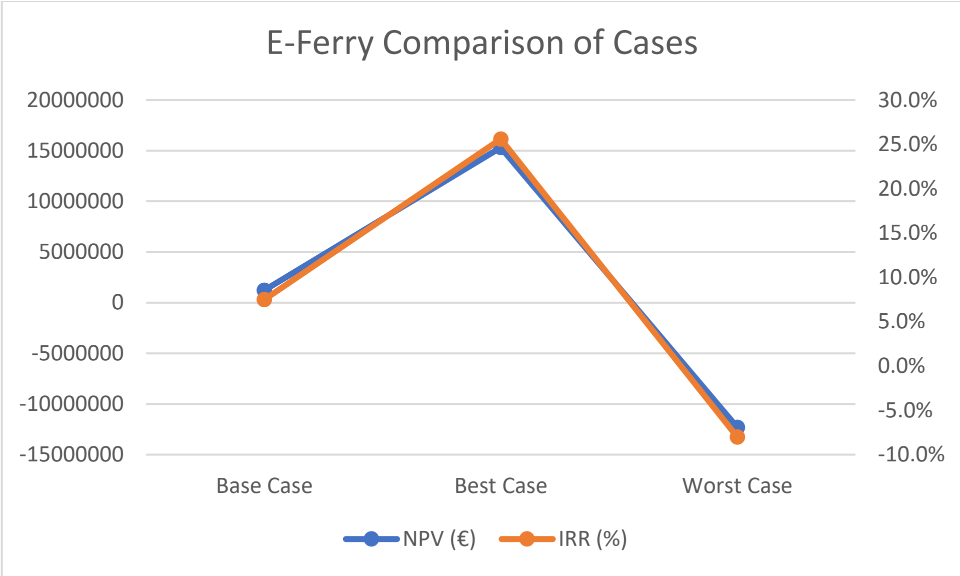

Figure 5-1 Comparison of Cases E-Ferry

The best case clearly stands as a lucrative investment that will bring positive returns, as its NPV and IRR are significantly higher than the base case. The worst case remains negative in all the indicators, as it has a negative NPV and its IRR is below the discount rate, so investment cannot be considered based on this case.

5.2 Sensitivity Analysis

The fourth category in the economic evaluation model is sensitivity analysis. This approach, used in numerous financial models, assists in analyzing how independent variables under certain conditions affect the dependent variables (Tim Vipond, n.d.-b).

We have used sensitivity analysis in the economic evaluation of E-Ferry. Table 20 provides a comprehensive model for the sensitivity analysis by utilizing the variables and variations. All five variables are analyzed under different variations; three positive and three negative variations are considered for each variable. The base case remains the primary reference for all the variables and variations.

Table 20 E-Ferry Sensitivity Analysis based on NPV

Variable	Negative Variation (€)	Negative Variation (€)	Negative Variation (€)	Base Case (€)	Positive Variation (€)	Positive Variation (€)	Positive Variation (€)
Time Charter Rate.	-4,559,794	-2,631,994	-704,194	1,223,607	3,151,407	5,079,208	7,007,008
Ship Operation Cost.	-1,599,825	-658,681	282,463	1,223,607	2,164,751	3,105,895	4,047,039
Tax Reduction.	-826,283	-142,986	540,310	1,223,607	1,906,903	2,590,200	3,273,497
Bank Interest Rate.	-1,357,319	-497,010	363,298	1,223,607	2,083,916	2,944,224	3,804,533
Proceeds of Ship Sale.	371,843	655,764	939,686	1,223,607	1,507,528	1,791,449	2,075,370

It also provides information about all the variations in the form of NPV; each variable and variation's NPV is declared while keeping the base case value the same. Figure 5-2 provides the graphical illustration of the data in Table 20, which further assists in analyzing the economic model.

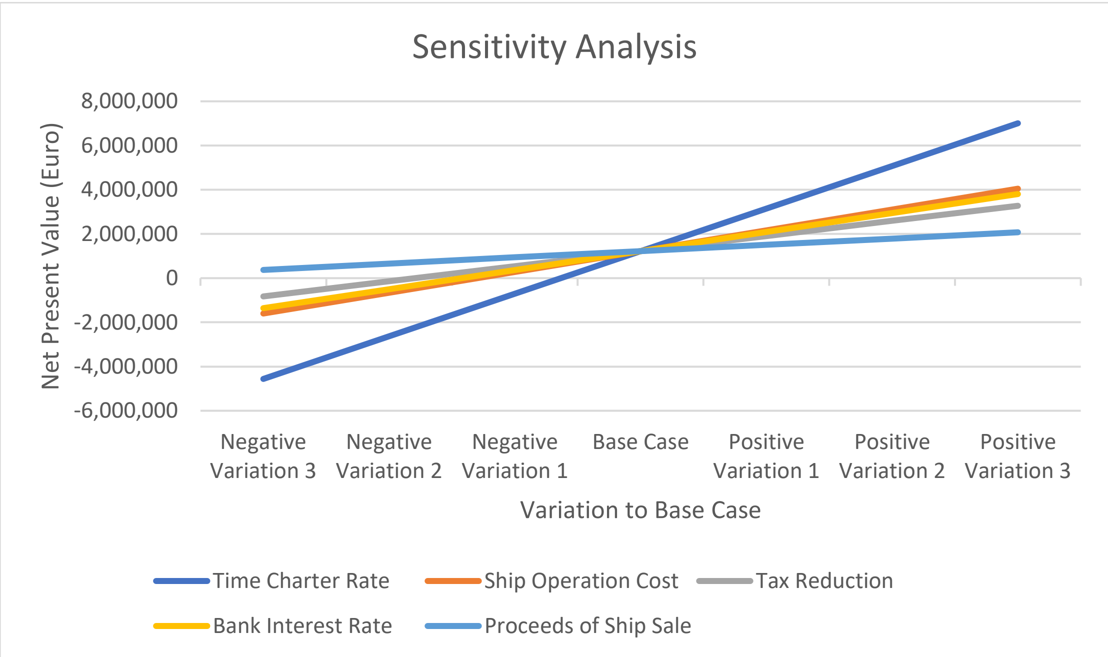

Figure 5-2 Graphical Representation of E-Ferrys Sensitivity Analysis

In the sensitivity analysis, we have in total used five different variables, which are given below

- Time Charter Rate
- Ferry operation Cost
- Tax Exemptions
- Banks Interest Rate
- Proceeds of Ship Sale

Time charter rate: It is the first variable of the economic model; in the base case, all the other variables are kept constant, and the time charter rate varies. We have considered three positive and three negative variations while keeping the base case as a reference point.

In the case of negative variations, the NPV becomes negative at all the given negative points; however, in the case of positive variations, the NPV increases significantly. The graphical representation, Figure 5-2 of sensitivity analysis shows that time charter has the highest sensitivity compared to the other variables.

Ferries operation cost: The second variable with the highest impact on the investment's NPV is the ship's operating cost; like the first variable, three positive and three negative variations are considered for the ship's operating cost.

In the two negative variations, the NPV goes negative when the ship's operating cost increases by 10% and 15%. In contrast, for the other variations, including an increase of 5% in the operating cost and all the positive variations where the operating cost is reduced, the NPV remains positive.

Tax Exemptions: As E-Ferry is powered by a battery and generates no emissions during operations, we have considered tax exemptions and incorporated them into the section of the ship's operational cost that includes the cost of crew and electricity. It will receive these exemptions in the form of tax benefits, three positive and three negative scenarios are considered.

For the positive scenarios where the ferry receives tax benefits, the NPV increases considerably; in the case of negative scenarios, when the tax is increased at the initial 5% of increase, the NPV remains positive; however, for an increase of 10% and 15%, the NPV becomes negative. Thus, tax exemptions greatly impact the investment potential of E-Ferry.

Banks' Interest rate: The fourth variable in the sensitivity analysis is the interest rate; as 70% of the ferry's total investment is bank loans, any change will significantly impact the investment. In this case, the interest rate varies from negative 3 points to positive 3 points about the interest rate of the base case.

When the interest rate increases by 1 point with respect to the base case, the NPV remains positive. On the other hand, when the increment is 2 and 3 points, the NPV becomes negative. In the case of reducing the interest rate, the NPV remains positive irrespective of the reduction in the points of interest rate.

Proceeds of ship sale: The fifth and final variable in sensitivity analysis is the ship's resale value. In the case of proceeds of ferry sale, all the variations, including the negative ones, show a positive NPV, which means that it is the least sensitive variable in the sensitivity analysis.

5.3 Diesel Powered Ferry

In the case of the diesel-powered ferry, we have also divided economic evaluation into four categories; the first is the base case. It serves as a foundation for the economic model, in which the initial economic variables are selected to provide a fundamental framework for the economic model.

The second case is the best case. This case considers all the positive scenarios and crafts an investment strategy based on optimistic projections. The third case is named the worst case; in this case, all the negative possible scenarios are considered, and the limitations of the economic model are examined.

The final economic assessment model is known as the sensitivity analysis; in this method, the base case is used as a reference point, and different variations are utilized. This approach enhances the effectiveness of our economic model and provides valuable insights for investment decision-making.

5.3.1 Base Case

The base case functions as the main reference case in the economic evaluation of the diesel-powered ferry. In this analysis, all the variations are made in relation to the base case. The NPV and IRR of the base case are as follows.

NPV = 902,275 €

IRR = 7.5 %

In this case, we have a positive NPV value, which indicates that this investment has the potential to yield favorable returns. Furthermore, an IRR of 7.5% exceeds the discount rate of

6%, which is a positive sign of this investment. However, as the investment period is stretched over 18 years and the multitude of variables and assumptions involved, an IRR of 7.5% doesn't appear to be an optimal economic investment, and its acceptance remains subjective.

5.3.2 Best Case

In the best-case scenario, all positive circumstances are utilized to formulate the economic strategy. As a result, this strategy has the highest NPV value and maximum IRR rate, which are as follows.

- NPV = 12,817,893 €
- IRR = 29.4 %

If the best-case conditions are considered, the investment looks very lucrative. This case provides favorable returns and exceeds the discount rate by a considerable margin.

5.3.3 Worst Case

In this case, the investment strategy considers all adverse scenarios for the investment. This approach is essential for acknowledging and mitigating potential negative investment variations. The NPV and IRR, in this case, are as follows

- NPV = -11,013,344 €
- IRR = -14.5 %

In the worst case, both investment indicators show a negative trend; negative NPV means unprofitability and the inability of the investment to generate positive returns, and a negative IRR means the investment cannot retrieve expected returns.

5.3.4 Graphical Representation of the Cases

As employed in the E-Ferry case, we have also used graphical representation to evaluate the economic model of the Diesel Ferry. A graphical overview of the three cases is provided in Figure 5-3,

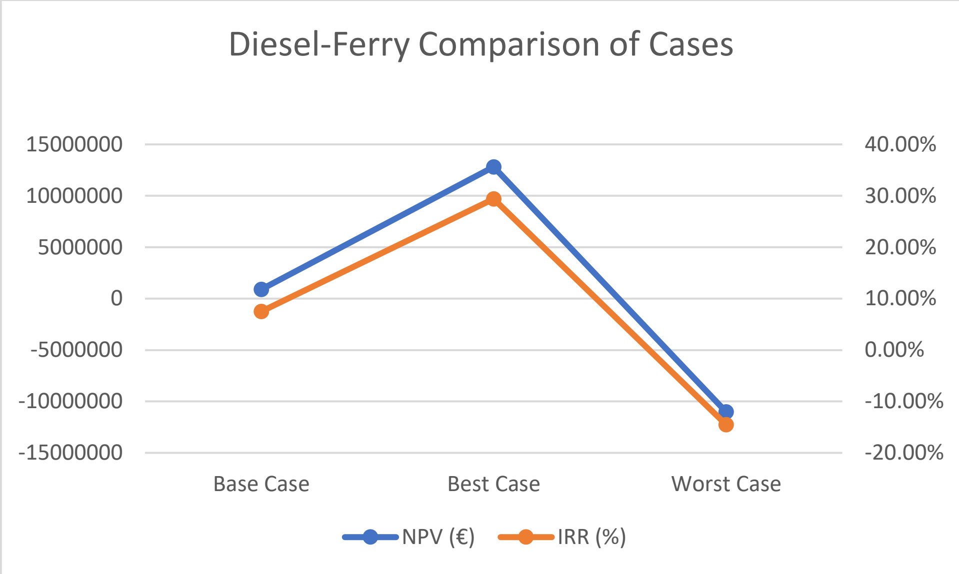

Figure 5-3 Comparison of Cases Diesel Ferry

A graphic overview provides a much clearer picture of the investment strategies that we employed in our research. Even though the base case demonstrates positive indicators, its viability as an investment option presents challenges. The best case is a compelling investment opportunity, promising substantial positive returns. However, the worst-case scenario presents a negative outlook, with all indicators signaling negative outcomes.

5.4 Sensitivity Analysis

The fourth tool for economic analysis is sensitivity analysis, which can also be considered the most comprehensive approach among the previous approaches. Sensitivity analysis relies mainly on the NPV obtained under various approaches.

The sensitivity analysis model in Table 21 provides a unique approach to evaluating the impact of variations on the various investment variables. The three positive and three negative variations for each variable provide information about the potential outcomes of the investment in different scenarios.

Table 21 Diesel Ferry Sensitivity Analysis based on NPV

Variable	Negative Variation (€)	Negative Variation (€)	Negative Variation (€)	Base Case (€)	Positive Variation (€)	Positive Variation (€)	Positive Variation (€)
Time Charter Rate	-4,881,127	-2,953,326	-1,025,526	902,275	2,830,075	4,757,875	6,685,676
Ship Operation Cost	-2,824,794	-1,582,438	-340,081	902,275	2,144,631	3,386,987	4,629,343
Bank Interest Rate	-908,128	-304,660	298,807	902,275	1,505,742	2,109,210	2,712,677
Proceeds of Ship Sale	307,528	505,777	704,026	902,275	1,100,524	1,298,772	1,497,021

Moreover, it also provides a clear view of the impacts of variations on the variables in terms of NPV. Each variable and variation's NPV is declared while keeping the base case value the same.

Figure 5-4 provides a graphical illustration of the sensitivity analysis, which is helpful in the investment analysis.

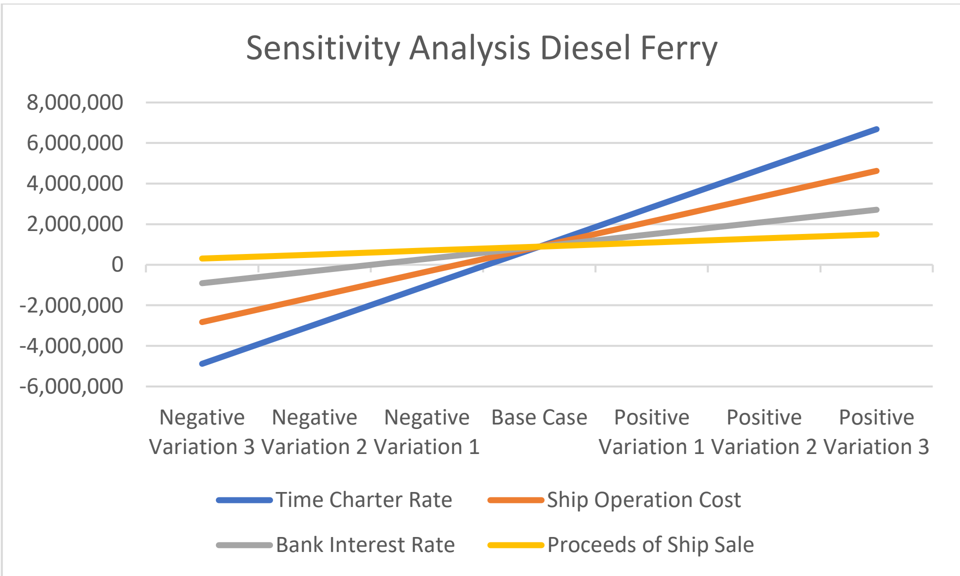

Figure 5-4 Graphical Representation of Diesel Ferry Sensitivity Analysis

In the sensitivity analysis of Diesel Ferry, we have in total used four different variables given below

- Time Charter Rate
- Ferry's Operation Cost
- Banks Interest Rate
- Proceeds of Ship Sale

Time charter rate: It is the first variable of the sensitivity analysis. All other factors remain constant in the base case scenario, and the time charter rate fluctuates. In this scenario, we consider three positive and three negative deviations from the base case, which is the main reference point. Through Figure 5-4, our sensitivity analysis shows that the time charter rate significantly influences the NPV compared to other variables. As we reduce the time charter rate, all the variations show a negative NPV, and when we increase the time charter rate, the NPV increase is significant compared to other variables. Thus, the time charter rate is the most sensitive variable in this analysis.

Operational Cost of Diesel Ferry: The sensitivity analysis shows that among the variables influencing NPV, the operating cost of the ferry is the second most influential factor. Three positive and three negative variations are considered for the operating cost. When the operating cost is reduced, all variations show positive NPV; however, as the operational cost increases, all three variations result in a negative NPV.

Banks Interest rate: The third variable in the sensitivity analysis is the interest rate; as bank loans constitute a substantial 70% of the investment's financing, any change in this rate can significantly influence the investment's viability. In this case, we have varied the interest rate by ±3 points relative to the base case. When we increase the interest rate by +1 point with respect to the base case, the NPV remains positive. On the other hand, when the increment is +2 and +3 points, the NPV goes negative. The net present value is positive in the case of a reduction in the interest rate in all three points -1,-2, and -3.

Proceeds of ship sale: The last variable in the sensitivity analysis of Diesel Ferry is its resale value; three positive variations and three negative variations are considered. The NPV remains positive in all the positive and negative variations.

5.5 Comparison of E-Ferry and Diesel Ferry

In the above section, we thoroughly discussed ferries and their economic models. Depending on various factors, which ferry will provide better economic investment opportunities? In this section, we will compare and discuss both ferries.

The comparison is designed to cover three scenarios: base case, best case, and worst case for both ferries. Each case will be compared based on its NPV and IRR. Secondly, a sensitivity analysis comparison for both ferries encompassing the different variables will be performed.

5.6 Comparison of E-Ferry and Diesel Ferry: NPV and IRR Analysis

This section will analyze and compare the base, best, and worst cases of E-Ferry and Diesel Ferry. Based on the ferries' NPV and IRR, a comparative analysis will be performed.

5.6.1 E-Ferry vs Diesel Ferry: NPV

The net present value of the base, best, and worst case encompassing both ferries is compared and illustrated in Figure 5-5.

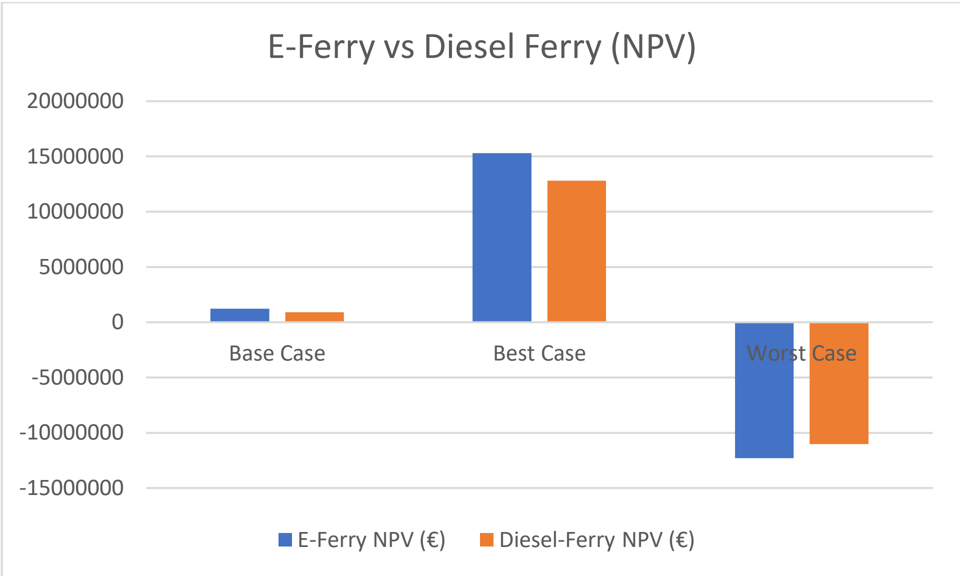

Figure 5-5 E-Ferry vs Diesel Ferry (NPV)

Looking at the NPV value in all the cases, we can observe that the E-Ferry outperforms the Diesel Ferry in the base and best-case scenarios. In the worst-case scenario, both ferries have negative NPV; however, only in this case do we get a slightly less negative value of NPV for the Diesel Ferry than the E-Ferry. Thus, from Figure 5-5, we can conclude that the E-Ferry performs better in the base case and the best case; however, in the worst-case scenario, although the NPV is negative for both the ferries, the Diesel Ferry has an edge over the E-Ferry, as its NPV is less negative. In the base case and under favorable economic conditions, the E-Ferry remains a choice for investment in terms of NPV.

5.6.2 E-Ferry vs Diesel Ferry: IRR

The second economic indicator, the IRR for the base, best, and worst case, is compared and analyzed for both ferries. Figures 5-6 illustrate the comparison of both ferries regarding IRR.

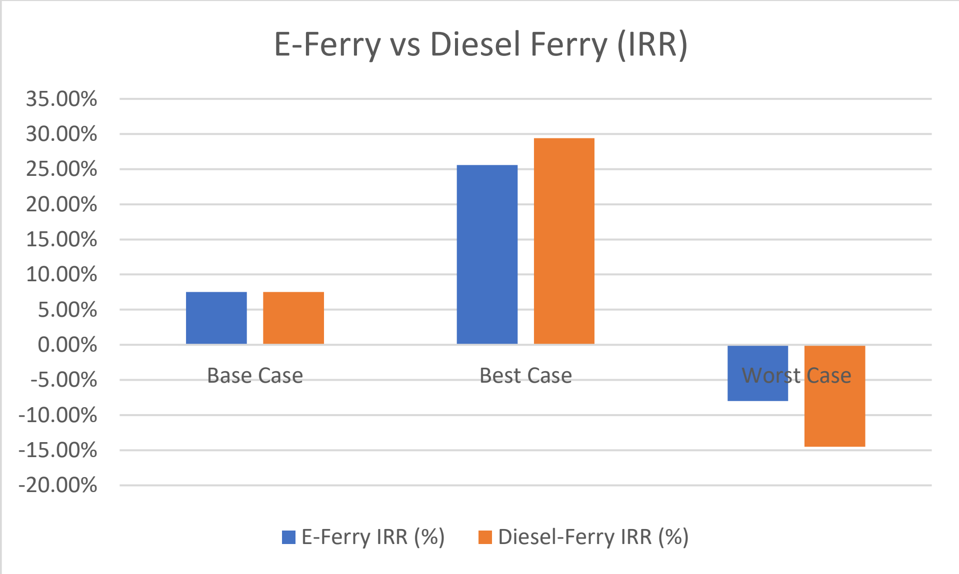

Figure 5-6 E-Ferry vs Diesel Ferry (IRR)

If we observe the base case regarding IRR, its rate is more than the selected discount rate; both the E-Ferry and the Diesel Ferry have the same IRR, which is 7.5%. In the best case, where all the positive scenarios for the investment are considered, the IRR of both the ferries exceeds the discount rate by a considerable margin; however, the Diesel Ferry has a clear lead over the E-Ferry in terms of IRR in the best case.

In the worst-case scenario, the IRR remains below the discount rate of the ferries, making the investment unattractive. In this case, the E-Ferry performs better than the Diesel Ferry. Thus, for the base case, IRR remains the same for both the ferries; in the best case, the Diesel Ferry leads its way, and in the worst case, although both ferries have a negative IRR, the E-Ferry has less negative IRR than the Diesel Ferry.

5.7 E-Ferry vs Diesel Ferry: Sensitivity Analysis

In this section, we will compare the E-Ferry and Diesel Ferry based on their sensitivity analysis; for a comprehensive analysis, all the variables of both ferries' sensitivity analyses are compared and analyzed.

5.7.1 Time Charter Rate

As we compare the time charter rate and its variables in both ferries, we observe that in all the variations, including the positive and negative variations, the E-Ferry outperforms the Diesel Ferry in terms of its NPV.

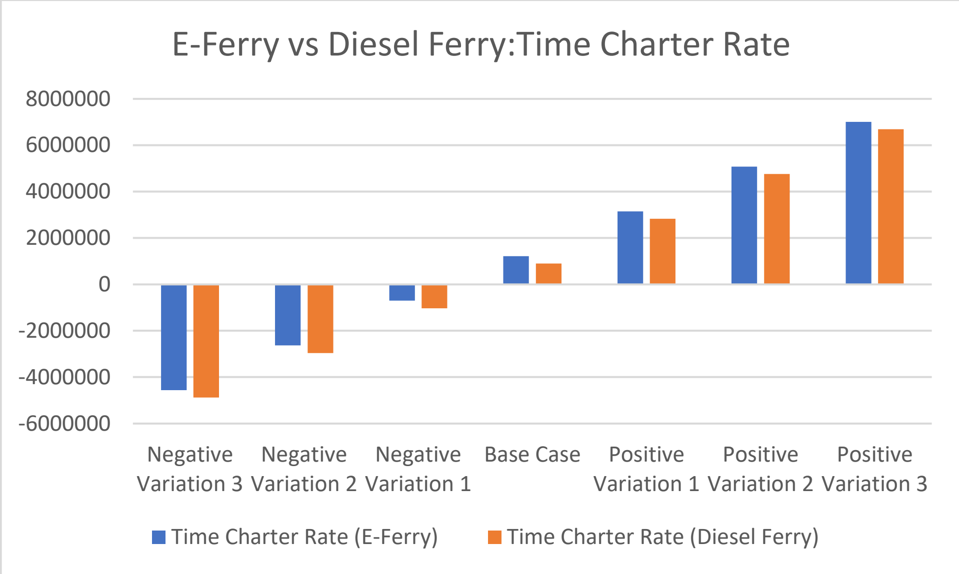

Figure 5-7 E-Ferry Vs. Diesel Ferry: Time Charter Rate

Figure 5-7 shows the visual representation of the comparison; in the case of negative variations, the NPV is negative for both ferries, but the E-Ferry has a less negative NPV than the Diesel Ferry. Thus, the E-Ferry clearly leads to a better investment choice in the time charter variable.

5.7.2 Operating Cost of Ferry

In the sensitivity analysis of the operating cost of ferries, we observe a unique pattern of NPV with different variations. In Figure 5-8 we can see that in the base case, the E-Ferry has a higher NPV; furthermore, when we decrease the operating cost by 5%, the E-Ferry maintains a slightly higher NPV than the Diesel Ferry. However, when the operating cost is reduced by 10% and 15%, the Diesel Ferry performs better in NPV.

When we observe the negative variations, we can see that when the operation cost increases by 5%, the E-Ferry performs better and maintains a positive NPV. At the same time, the Diesel Ferry has a negative NPV. Furthermore, when the operation cost increases by 10% and 15%, both ferries have negative NPV; however, the E-Ferry has a less negative NPV than the Diesel Ferry.

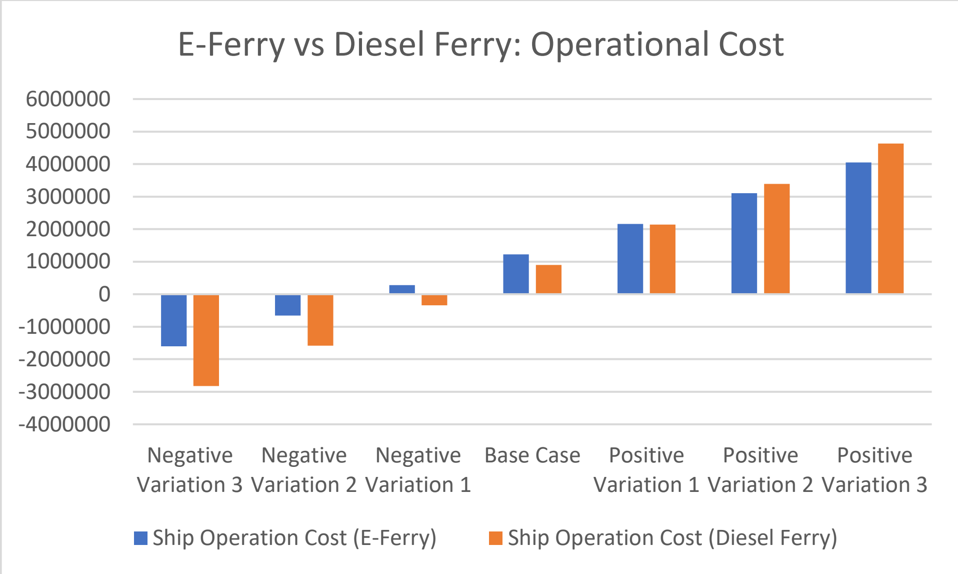

Figure 5-8 E-Ferry vs Diesel Ferry: Operational Cost of the Ferries

5.7.3 Banks Interest Rate

The initial 70% of the total investment is sourced through a bank loan, making the interest rate a significant factor in the investment. Therefore, the sensitivity analysis involving interest rates for the E-ferry and Diesel Ferry becomes a key aspect of our investment strategy.

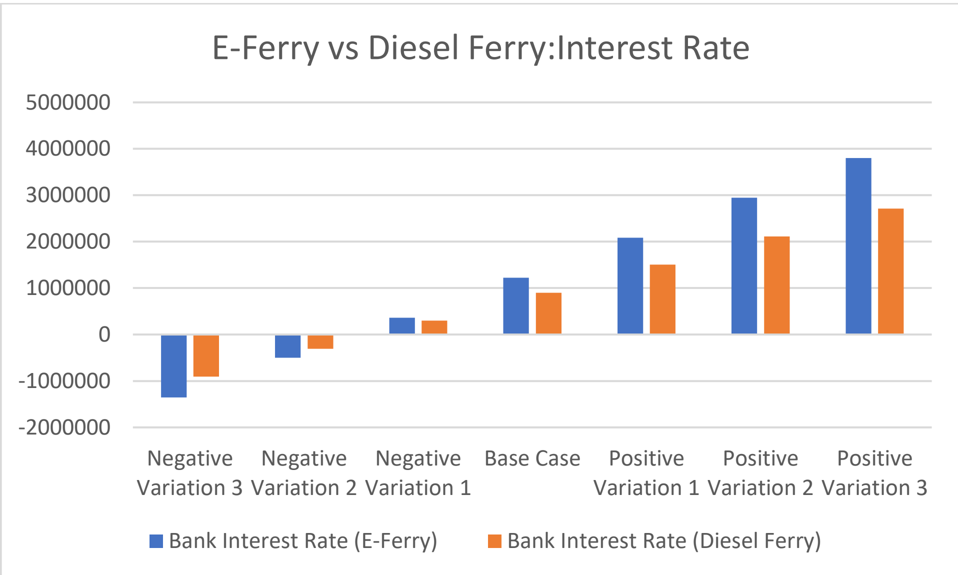

Figure 5-9 E-Ferry vs Diesel Ferry: Bank's Interest Rates

As per Figure 5-9, we can observe that the NPV remains positive for both the ferries in the base case and all the variations where the interest rate has been reduced. However, in the case of negative variations, we observe a unique pattern of NPV for both ferries. When the interest rate increases by +1 point, the NPV remains positive, and E-ferry performs better in terms of NPV, but when the rate is increased by +2 and +3 points, the NPV remains negative for both ferries in these two cases; although both the ferries have a negative NPV the Diesel Ferry has less negative NPV than the E-Ferry. The E-Ferry leads its way in all the variations where the interest rate has been reduced along with negative variation where the interest rate was slightly increased.

5.7.4 Proceeds of Ship Sale

In the sensitivity analysis of proceeds from ship sales, the base case remains constant while being the center point at 20% of the initial cost of the ferry. This rate decreases from 20% to 8% for the negative variation; it increases from 20% to 32% for the positive variation.

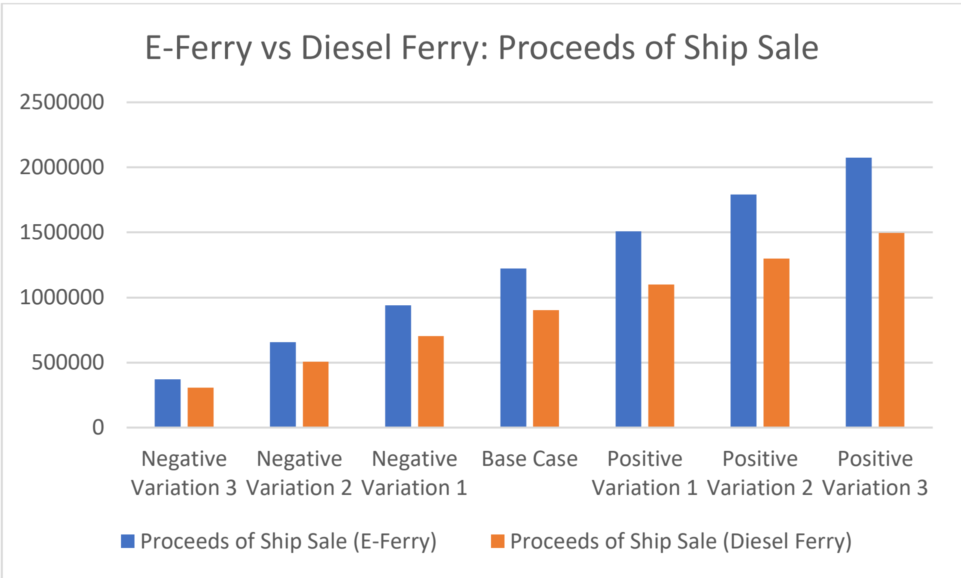

Figure 5-10 E-Ferry vs Diesel Ferry: Proceeds of Ship Sale

Figure 5-10 shows that the NPV for both ferries remains positive in all variations. The E-Ferry maintains a higher NPV in all variations, including the base case. Even in the most adverse cases, the E-Ferry maintains a significant edge over the Diesel Ferry. Thus, in the proceeds of ship sale, E-Ferry ensures a clear edge over the Diesel Ferry in terms of NPV.

5.7.5 Tax Returns

This economic model provides exclusive tax incentives to the battery-powered vessel because of its contribution to emissions reduction. As there are no tax incentives for Diesel Ferry, this section will only deal with E-Ferry. Incorporating these tax benefits significantly impacts the investment's NPV.

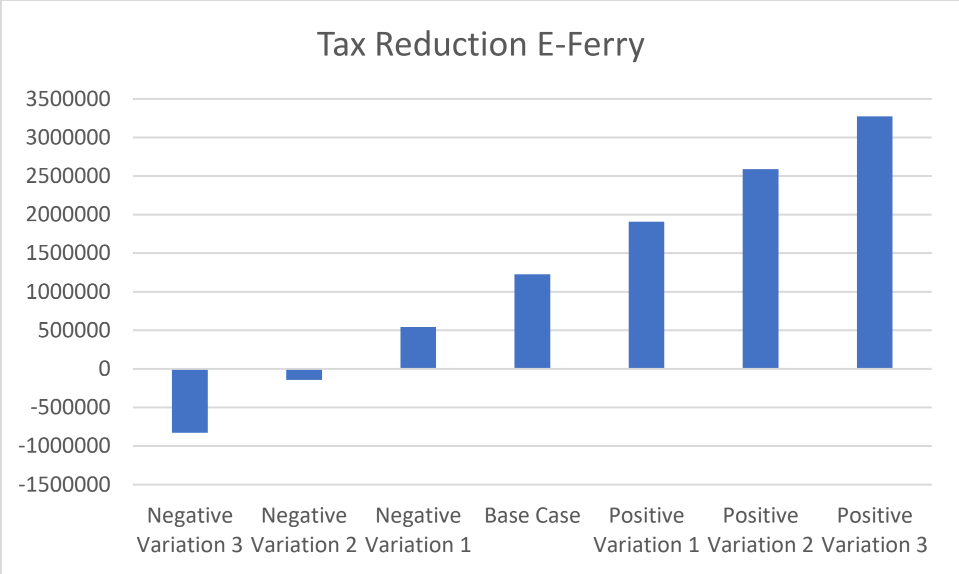

Figure 5-11 E-Ferry: Tax Reduction

Figure 5-11 shows that the NPV remains positive in the base case and all the positive variations, indicating the benefits of tax incentives for the investment. When we initially increase the same tax amount in the form of a negative variation for an increase of 5%, the NPV remains positive. However, the NPV becomes negative for the 10% and 15% variations. These results highlight how important tax incentives are in preserving the economic appeal of E-Ferry investments.

6 Emission Analysis of E-Ferry and Diesel Ferry

Environmental regulations are the main drivers of the maritime industry's shift from fossil fuel propulsion systems to carbon-neutral alternatives. These regulations aim to reduce GHG emissions and protect the marine ecosystem.

This research section will analyze the environmental impacts of the battery-powered vessel, focusing specifically on emissions. As our economic analysis is based on an electric-powered ferry known as an E-Ferry and its counterpart, a Diesel Ferry, the emission analysis will be framed around these two ferries.

6.1 Overview of Emission Analysis

Emission analysis is a process through which various impacts of pollutants are observed and analyzed. The emissions generated from a vessel depend on various parameters, depending upon the scope of the engine analysis; the emissions are mainly dependent on the following parameters of the engine (Chin et al., 2022).

- Engine size
- Type of load
- Current speed.

Furthermore, an important consideration in emissions analysis is the fuel used for propulsion; certain emissions depend entirely on the fuel type, irrespective of the engine's combustion conditions (Cooper & Gustafsson, 2004).

Emission Analysis Methodology:

Two methods are mainly employed in emission analysis. These two methods are known as

1. Top-down method
2. Activity-based or bottom-up method

Top-down method: The initial method, known as the top-down method, relies on the sales of marine fuel bunkers and emission factors linked to fuel. This method would have been the most reliable if reported marine bunker sales presented the actual scenario. The data is collected by three agencies.

- Energy Information Administration (EIA)
- The International Energy Agency (IEA)
- United Nations Framework Convention on Climate Change (UNFCCC)

The EIA and IEA have different definitions of bunker fuels, which makes it hard to unify all the bunker sales data. The data regarding bunker fuel sales in certain states is unreliable, which impacts the whole process. Moreover, the carbon dioxide emissions derived from the energy estimates differ significantly from the activity-based emissions. Hence, these issues jeopardize the accuracy of the data used in this method (Psaraftis & Kontovas, 2009).

Activity-based or bottom-up method: The second main method used in emission calculation is the activity-based or bottom-up method. It adopts a unique approach, as world fleet emissions are estimated by utilizing shipping movements and their characteristics, such as size, engine type, etc. It also utilizes emission factors and fuel consumption figures. This method has various variants, depending on the assumptions and the use of inputs (Psaraftis & Kontovas, 2009).

6.2 Understanding Factors Influencing Emissions

Many factors influence the emissions from marine vessels. The major influencing factors and emissions are explained below.

Carbon dioxide emissions: CO_2 emissions are linked to the amount of carbon in the fuel and the amount of fuel consumed. Therefore, with a change in fuel type and consumption, CO_2 emissions can change. In the case of marine diesel engines, specific fuel consumption, the CO_2 emissions at low loads are high, and when the load increases by 75%, the emissions tend to go down. However, as the load again peaks to the highest level, so do the emissions. The marine industry is introducing new fuel types like LNG and methanol, which contain less carbon content, so CO_2 emissions remain low (DNV,2020; cited in Grigoriadis et al., 2021). Thus, the CO_2 emissions depend on the fuel, consumption, and operational requirements (Wood-yard,2004; cited in Grigoriadis et al., 2021).

Sulfur oxide emissions: These emissions are highly dependent on the type of fuel used in the engines for the combustion process, as sulfur content in the fuel is responsible for the emissions during the oxidation process.

Considering engine load with specific fuel consumption, SOx emissions are high at lower loads and decrease at optimal loads. SO_2, which is 95% of the total emissions, is the major component of SOx emissions, along with SO_3 and sulfates (Miller et al., 2012).

Nitrogen oxide emissions: The NO_x emissions are produced because of the combustion of nitrogen from the fuel and the nitrogen and oxygen from the air at a high temperature (Agarwal,2008; cited in Grigoriadis et al., 2021). In nitrogen emissions, the primary emitter remains NO rather than NO_2 because it is formed in the later stage of the combustion process and during the process of flowing through the exhaust (Kristensen, 2012).

Carbon monoxide emissions: CO emissions result from incomplete combustion of carbon during combustion. In the combustion chamber near the wall of cylinders, combustion takes place at low temperatures, and when the fuel is injected near the cylinder walls because of low temperature, the reaction rate is lower, and carbon monoxide is created instead of carbon dioxide (Woodyard, 2004; cited in Grigoriadis et al., 2021).

CO emissions are lower at higher loads because, during higher loads, oxygen is in surplus amount, and the temperature of the combustion chamber is also higher. Thus, as the combustion is complete, CO is not generated at higher loads (Lehtoranta et al.,2017,agraval et al.,2010,zetterdhal et al., 2016; cited in Grigoriadis et al., 2021).

Particulate matter emissions: PM emissions consist of various components: carbon, metals, inorganic ions, sulfates, and organic matter (Huang et al., 2018). PM emissions depend on the engine's operations and the fuel's characteristics for combustion because when the air and fuel are not premixed, poor oxidation results, and thus, soot particles are formed.

The elementary part of PM emissions is linked to the incomplete combustion process, which includes soot and black carbon. The organic part, which consists of traces of lube oil and heavy fuel components, depends on the type of fuel; the organic part can become a significant part of the PM emissions (Moldanová et al., 2009).

6.3 Emissions from E-Ferry Ellen

E-Ferry utilizes battery power for its propulsion and hotel system during its operations, so its operational emissions are non-existent. However, to charge its battery, it needs power from an external source, so the emissions from that power source are considered emissions of the battery-powered ferry. As Denmark operates the ferry, the emissions are calculated based on the Grid mix of Danish electricity.

Energy consumption and emissions:

Table 22 provides detailed information about the E-Ferry's emissions and the emission factors of the Danish electricity grid mix. The propulsion system and the hotel load together account for 9443 KWh of the E-Ferry's daily energy usage (Annie Kortsari et al., 2020). The emissions factors of the Danish electricity grid mix are used in Table 22 for calculating the total emissions (Emission Factors, 2019).

Table 22 E-Ferry Emissions

Energy Consumption Per Day (KWh)	Emissions	Emission Factors (g/KWh)	Emissions per day (kg)	Emissions Per Year (kg)
9443	CO_2	145	1369.235	492,925
	NOx	0.21	1.98303	714
	CO	0.14	1.32202	476
	CH_4	0.12	1.13316	408
	SO_2	0.03	0.28329	102
	PM	0.01	0.09443	34

Figure 6-1 is a graphical illustration of E-Ferry emissions; it shows that the carbon dioxide emissions are the highest among all the pollutants, followed by NOx at second place, and the third highest emissions are of CO; a unique pattern in the emissions of the E-Ferry is that the CH_4 is higher than the SO_2 emissions, which can be because of the source from where the electricity is being generated that charges the E-Ferry. Lastly, we have PM emissions, which are considerably less than the emissions from other pollutants.

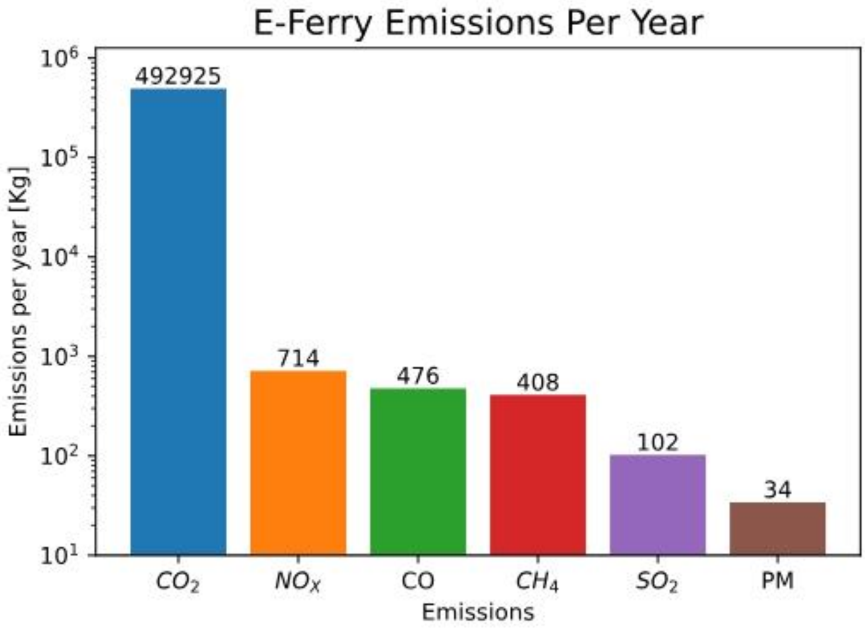

Figure 6-1 Battery Powered Ferry Emissions

6.4 Emissions of Diesel Ferry

As the Diesel Ferry utilizes two power sources, its emissions are linked with two sources. In the operational phase, the diesel ferry uses conventional fuel for its propulsion and hotel load. However, when the ferry is idle, it utilizes power from a land source for its hotel load. The emissions of the Diesel Ferry are divided into two types: the direct emissions from the engine during operations and the indirect emissions that result from the use of on-shore electricity (Annie Kortsari et al., 2020).

Table 23 provides information about the Diesel Ferry's propulsion system emissions. The total fuel consumption for its operations per day is 2,152 kg (Annie Kortsari et al., 2020). Diesel emission factors are considered when calculating the ferry's overall operational emissions.(Perčić, Vladimir, & Koričan, 2021; Moreno-Gutiérrez & Durán-Grados, 2021).

Table 23 Emissions of Diesel Ferry: Fuel-Based

Energy Consumption Per day (Kg)	Emissions	Emission Factors (g/Kg)	Emissions per day (Kg)	Emissions per year (Kg)
2,152	CO_2	3206	6899.312	2,483,752
	NOx	61.21	131.72392	47,421
	CO	2.77	5.96104	2,146
	Sox	2.64	5.68128	2,045
	PM	1.02	2.19504	790
	CH_4	0.06	0.12912	46

The emissions from the second source of the Diesel Ferry are given in Table 24. The total energy consumption from onshore electricity is 1195 kWh per day (Annie Kortsari et al., 2020).The Danish electric grid provides onshore electricity, so the emissions factors of Danish electricity have been considered for the emission calculation. (Emission Factors, 2019)

Table 24 Emissions of Diesel Ferry: Electric Power Source

Energy Consumption per day (KWh)	Emissions	Emission Factors (g/KWh)	Emissions per day (Kg)	Emissions per year (Kg)
1195	CO_2	145	173.275	62,379
	NOx	0.21	0.25095	90
	CO	0.14	0.1673	60
	CH_4	0.12	0.1434	52
	SO_2	0.03	0.03585	13
	PM	0.01	0.01195	4

Table 25 gives the total emissions of the Diesel Ferry, including the diesel emissions and the emissions from the electricity.

Table 25 Diesel Ferry Emissions, Including Fuel and Electricity

Emissions	Total Emissions per year (kg)
CO2	2,546,131
NOx	47,511
CO	2,206
Sox, SO_2	2,058
PM	795
CH4	98

Figure 6-2 illustrates the combined emissions of Diesel Ferry, including emissions from fuel and electricity, with CO2 being the highest and CH_4 being the lowest.

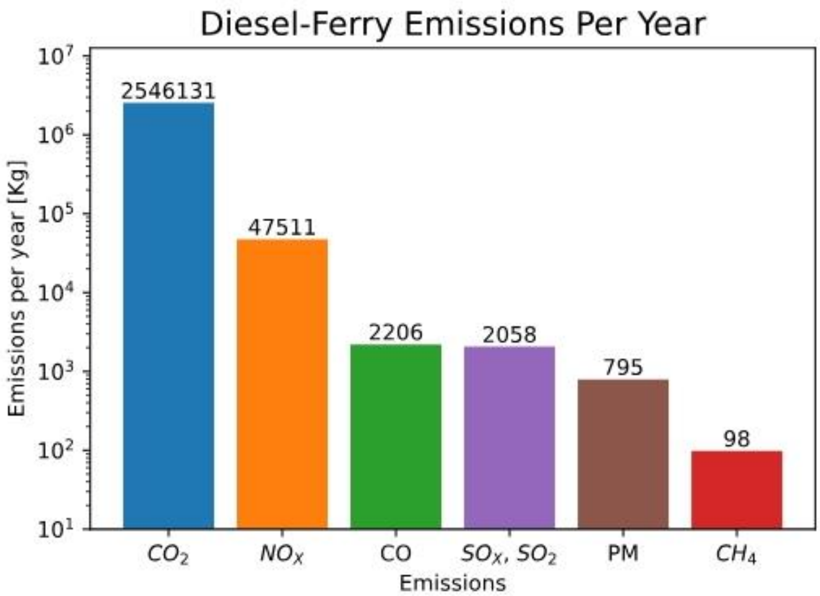

Figure 6-2 Combined Emissions of Diesel Ferry

6.5 E-Ferry vs Diesel Ferry: Emissions Comparison

In the maritime shipping sector, various new technologies are being pursued to overcome the challenge of emissions; the decarbonization drive faces two major hurdles: one on the economic front and another on emission reduction.

Our emissions comparison of a battery-powered ferry with a conventional ferry shows that the E-Ferry uses electricity for all its operations, including charging its battery and hotel load when idle. Its emissions are directly linked to the electricity being provided; if it is generated from a renewable source, its emissions can be significantly reduced. The Diesel Ferry, on the other hand, uses two sources of power: fuel for its operations and electric energy for the hotel load when the ferry is idle.

Table 26 E-Ferry vs Diesel Ferry Emissions

Emissions	E-Ferry Emissions per year (kg)	Diesel-Ferry Emissions per year (kg)
CO2	492,925	2,546,131
NOx	714	47,511
CO	476	2,206
Sox, SO_2	102	2,058
PM	34	795
CH4	408	98

The comparison in Table 26 shows that the E-Ferry outperforms the Diesel Ferry by significant margins in emission reduction. The emissions from E-Ferry are much less than those of Diesel Ferry. If we only look at the CO_2 emissions, we can observe that the E-Ferry produces 493 tons annually while the Diesel Ferry emits 2546 tons of CO_2, which is almost five times more than the E-Ferry.

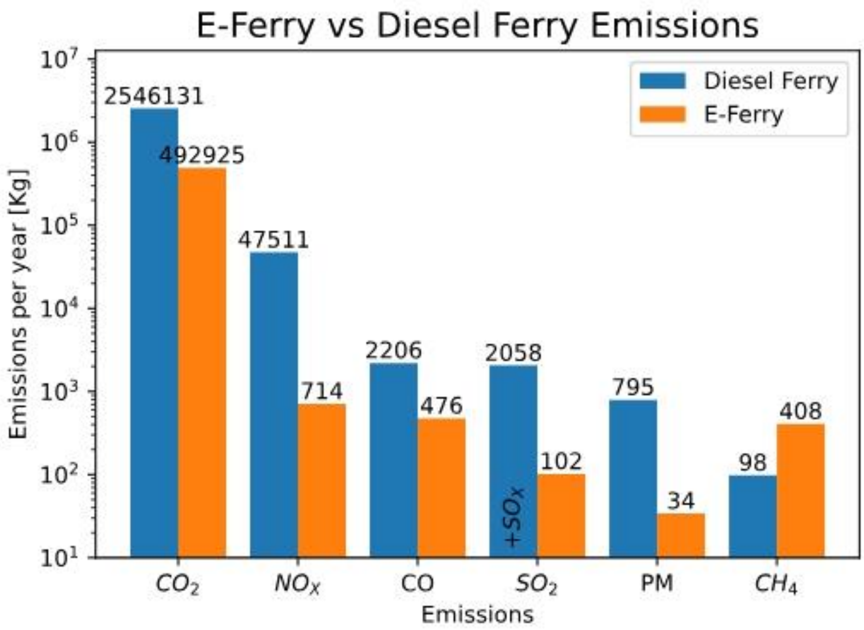

Figure 6-3 Battery-Powered Ferry vs Diesel Ferry Emissions

The above-given Figure 6-3 provides a graphical view of the emissions of the E-Ferry and the Diesel Ferry. In this graphical view, it is clearly evident that the emissions of the Diesel Ferry are higher than those of the E-ferry, with the exception of CH4 emissions, which are lower than those of the E-ferry.

7 Conclusion and Future Scope

7.1 Conclusion

In this chapter, we have summarized the main findings of the research in relation to the research aims and objectives. The main aim of this research was to assess the economic feasibility of the battery-powered vessels compared to the conventional vessels and evaluate the emissions of both vessels.

This research considered two ferries, one powered by a battery and the other by a diesel engine. For the economic feasibility analysis, various techniques were utilized to evaluate the ferries' economic potential. The NPV and IRR methods served as the primary economic indicators. Initially, three cases were crafted in the economic assessment.

- **Base case**: The initial and the main case, where the initial forecast and assumptions about the economic model were made in the investment strategy. In the base case scenario, the E-Ferry was found to have a higher NPV than the Diesel Ferry, and both ferries were found to have the same IRR.
- **Best case**: The second case optimistically portrayed all favorable economic indicators. In the best-case scenario, the E-Ferry had a higher NPV; however, the Diesel Ferry led in terms of IRR.
- **Worst-case**: The third scenario in which all the worst economic conditions were considered. In the worst-case scenario, both ferries had negative NPV and IRR; the Diesel Ferry had less negative NPV than the E-Ferry, and in terms of IRR, the E-Ferry had less negative IRR than the Diesel Ferry.

Along with the three cases, a sensitivity analysis of the complete investment was carried out, which examined the investment's potential under various economic variations. In this analysis, the base case served as a central reference point, and all the variations that are positive and negative for the investment were made with reference to the base case.

In the sensitivity analysis, both ferries were compared in regard to their variables,

- **Time Charter Rate**: The E-Ferry clearly led in all the positive and negative variations along with the base case when compared with the Diesel Ferry. However, In the negative variations, both ferries had negative NPV, while the E-Ferry had less negative NPV than the Diesel Ferry.

- **Operating Cost**: The E-Ferry maintained a higher NPV in the base case. In the positive variation when the costs were slightly reduced, the E-Ferry had a higher NPV, but when the cost reduction was higher, the Diesel Ferry had a higher NPV. In the negative variations, when the costs were slightly increased, E-Ferry had a positive NPV while Diesel Ferry had a negative NPV, but when the costs were increased further, both ferries had negative NPV while E-Ferry had a less negative NPV.
- **Banks Interest Rate**: In the base case and positive variations, E-Ferry maintained an edge over the Diesel Ferry in terms of NPV. In the negative variations, when the interest rate increase was minimal, E-Ferry maintained a higher NPV; however, when the increase in the interest rate was high, the NPV of both ferries was negative, but the Diesel Ferry had a less negative NPV.
- **Proceeds of Ship Sale**: The E-Ferry had a higher NPV than the Diesel Ferry in all the positive and negative variations, including the base case, thus getting a clear edge over the Diesel Ferry.
- **Tax Returns**: As E-Ferry is emissions-free, it received tax incentives. When E-Ferry received tax incentives, its NPV increased compared to the base case. When it received no tax incentives and had to pay further taxes, the NPV was highly impacted, and in the case of large tax proportions, it went into negative.

Another important dimension of this research was analyzing the emissions of E-Ferry and Diesel Ferry. The E-Ferry relied on batteries during its operational phase and on-shore electricity when it was idle; thus, it had no direct emissions rather the emissions from the source that was being used for electricity production. On the other hand, the Diesel Ferry utilized two sources of power: diesel as a fuel during its operational phase and on-shore electricity for its idle phase. Thus, during its operational phase, it was directly responsible for the emissions, and during the idle phase, the emissions from the electricity were dependent on the source that was being used for electric production.

When we compare the emissions of both the ferries, we can see that the E-Ferry had a clear edge over the Diesel Ferry; in the comparisons, we observed an 80.6 % reduction in CO_2 emissions, a 98.5% reduction in NO_x emissions, a 78.4% reduction in CO emissions, a reduction of 95% in SO_x and SO_2 emissions, and a decrease of 95.7% in the case of PM emissions. The only case where E-Ferry lagged behind the Diesel Ferry was CH_4 emissions. Here, the E-Ferry emissions were found to be higher.

The E-Ferry showed a better economic outlook in most scenarios and took a clear lead in the economic domain compared to the Diesel Ferry. In environmental terms, the E-Ferry's emission reduction potential was quite significant. Almost all the main emissions were reduced considerably, with few exceptions. Overall, battery-powered vessels in the domain of ferries under the provided conditions proved to be economically feasible and environmentally friendlier than conventional vessels.

7.2 Future Scope

Battery-powered vessels are an emerging segment in the maritime sector; thus, further research can be carried out in various dimensions. As this research was only limited to the ferry sector in Denmark, further research can be carried out in a different part of the world and different segments of marine vessels, such as RoRo or inland cargo vessels, etc., so that the scope and generality of the research could be increased.

Furthermore, in the environmental domain, as production, transportation, and recycling emissions were not considered, this new domain can also be included in future research to further enhance the environmental assessment of the research.

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9 APPENDICES

9.1 Appendix 1

This section of the appendix deals with E-Ferry. All the Calculations can be found in the Excel file titled " Calculations E-Ferry"

The description of all the taps in the Excel sheet is given below.

Vessel Details: This tab contains the details of the vessel, such as its propulsion system and capacity.

Cost Details: This tab includes the initial "Investment and Financing Forecast"

Base Case: This tab includes the main framework of the economic assessment model.

Best Case: In this tab the optimal economic conditions are utilized for economic assessment.

Worst Case: In this case, the worst possible economic conditions are utilized for economic assessment.

Sensitivity Analysis: This tab contains all the information about the sensitivity analysis, including the variables and the positive and negative variations. Table 1 provides details about the variable and their variations. Table 2 provides information about the NPV for the variables under different variations.

SA-Ship Sale 24%: This tab is part of the sensitivity analysis where the ship sale variable is considered with with positive ship sale variation of 24%.

SA-Ship Sale 28%: This tab is part of the sensitivity analysis where the ship sale variable is considered with with positive ship sale variation of 28%.

SA-Ship Sale 32%: This tab is part of the sensitivity analysis where the ship sale variable is considered with with positive ship sale variation of 32%.

SA-Ship Sale 16%: This tab is part of the sensitivity analysis, where the ship sale variable is considered with a negative 16% ship sale variation.

SA-Ship Sale 12%: This tab is part of the sensitivity analysis where the ship sale variable is considered with with negative ship sale variation of 12%.

SA-Ship Sale 08%: This tab is part of the sensitivity analysis where the ship sale variable is considered with with negative ship sale variation of 8%.

SA-Time Charter Rate 5%: This tab considers the variable, Time Charter Rate with a positive variation of 5%.

SA-Time Charter Rate 10%: This tab considers the variable, Time Charter Rate with a positive variation of 10%.

SA-Time Charter Rate 15%: This tab considers the variable Time Charter Rate, which has a positive variation of 15%.

SA-Time Charter Rate -5%: This tab considers the variable Time Charter Rate, which has a negative variation of -5%.

SA-Time Charter Rate -10%: This tab considers the variable, Time Charter Rate with a negative variation of -10%.

SA-Time Charter Rate -15%: This tab considers the variable, Time Charter Rate with a negative variation of -15%.

SA-Operational Cost 5%: This tab is part of the sensitivity analysis in which the variable, operational cost is considered with a negative variation of 5%.

SA-Operational Cost 10%: This tab is part of the sensitivity analysis in which the variable operational cost is considered with a negative variation of 10%

SA-Operational Cost 15%: This tab is part of the sensitivity analysis in which the variable, operational cost is considered with a negative variation of 15%

SA-Operational Cost -5%: This tab is part of the sensitivity analysis in which the variable, operational cost is considered with a positive variation of -5%

SA-Operational Cost -10%: This tab is part of the sensitivity analysis in which the variable, operational cost is considered with a positive variation of -10%

SA-Operational Cost -15%: This tab is part of the sensitivity analysis in which the variable, operational cost is considered with a positive variation of -15%

SA-Interest Rate 1%: This tab considers the interest rate variable, which is part of the sensitivity analysis; in this, a negative variation of 1% increase in interest rate is considered.

SA-Interest Rate 2%: This tab considers the interest rate variable, which is part of the sensitivity analysis; in this, a negative variation of a 2% increase in interest rate is considered.

SA-Interest Rate 3%: This tab considers the interest rate variable, which is part of the sensitivity analysis; in this, a negative variation of a 3% increase in interest rate is considered.

SA-Interest Rate -1%: This tab considers the interest rate variable, which is part of the sensitivity analysis; in this, a positive variation of -1% decrease in interest rate is considered.

SA-Interest Rate -2%: This tab considers the interest rate variable, which is part of the sensitivity analysis; in this, a positive variation of -2% decrease in interest rate is considered

SA-Interest Rate -3%: This tab considers the interest rate variable, which is part of the sensitivity analysis; in this, a positive variation of -3% decrease in interest rate is considered

SA-Tax Reduction 5%: This tab is part of the sensitivity analysis of the variable tax reduction. In this tab, a negative variation of a 5% increase in the tax rate is considered.

SA-Tax Reduction 10%: This tab is part of the sensitivity analysis of the variable tax reduction. It considers a negative variation of a 10% increase in the tax rate.

SA-Tax Reduction 15%: This tab is part of the sensitivity analysis of the variable tax reduction. It considers a negative variation of a 15% increase in the tax rate.

SA-Tax Reduction -5%: This tab is part of the sensitivity analysis of the variable tax reduction. In this tab, a positive variation of a -5% decrease in the tax rate is considered.

SA-Tax Reduction -10%: This tab is part of the sensitivity analysis of the variable tax reduction. It considers a positive variation of a -10% decrease in the tax rate.

SA-Tax Reduction -15%: This tab is part of the sensitivity analysis of the variable tax reduction. In this tab, a positive variation of a -15% decrease in the tax rate is considered.

9.2 Appendix 2

This section of the appendix deals with the Diesel Ferry. All the Calculations can be found in the Excel file titled “ Calculations Diesel Ferry”

The description of all the taps in the Excel sheet is given below.

Vessel Details: This tab contains the details of the vessel, such as its propulsion system and capacity.

Cost Details: This tab includes the initial "Investment and Financing Forecast"

Base Case: This tab includes the main framework of the economic assessment model.

Best Case: In this tab the optimal economic conditions are utilized for economic assessment.

Worst Case: In this case, the worst possible economic conditions are utilized for economic assessment.

Sensitivity Analysis: This tab contains all the information about the sensitivity analysis, including the variables and the positive and negative variations. Table 1 provides details about the variable and their variations. Table 2 provides information about the NPV for the variables under different variations.

SA-Ship Sale 24%: This tab is part of the sensitivity analysis where the ship sale variable is considered with with positive ship sale variation of 24%.

SA-Ship Sale 28%: This tab is part of the sensitivity analysis where the ship sale variable is considered with with positive ship sale variation of 28%.

SA-Ship Sale 32%: This tab is part of the sensitivity analysis where the ship sale variable is considered with with positive ship sale variation of 32%.

SA-Ship Sale 16%: This tab is part of the sensitivity analysis, where the ship sale variable is considered with a negative 16% ship sale variation.

SA-Ship Sale 12%: This tab is part of the sensitivity analysis where the ship sale variable is considered with with negative ship sale variation of 12%.

SA-Ship Sale 08%: This tab is part of the sensitivity analysis where the ship sale variable is considered with with negative ship sale variation of 8%.

SA-Time Charter Rate 5%: This tab considers the variable, Time Charter Rate with a positive variation of 5%.

SA-Time Charter Rate 10%: This tab considers the variable, Time Charter Rate with a positive variation of 10%.

SA-Time Charter Rate 15%: This tab considers the variable Time Charter Rate, which has a positive variation of 15%.

SA-Time Charter Rate -5%: This tab considers the variable Time Charter Rate, which has a negative variation of -5%.

SA-Time Charter Rate -10%: This tab considers the variable, Time Charter Rate with a negative variation of -10%.

SA-Time Charter Rate -15%: This tab considers the variable, Time Charter Rate with a negative variation of -15%.

SA-Interest Rate 1%: This tab considers the interest rate variable, which is part of the sensitivity analysis; in this, a negative variation of 1% increase in interest rate is considered.

SA-Interest Rate 2%: This tab considers the interest rate variable, which is part of the sensitivity analysis; in this, a negative variation of a 2% increase in interest rate is considered.

SA-Interest Rate 3%: This tab considers the interest rate variable, which is part of the sensitivity analysis; in this, a negative variation of a 3% increase in interest rate is considered.

SA-Interest Rate -1%: This tab considers the interest rate variable, which is part of the sensitivity analysis; in this, a positive variation of -1% decrease in interest rate is considered.

SA-Interest Rate -2%: This tab considers the interest rate variable, which is part of the sensitivity analysis; in this, a positive variation of -2% decrease in interest rate is considered

SA-Interest Rate -3%: This tab considers the interest rate variable, which is part of the sensitivity analysis; in this, a positive variation of -3% decrease in interest rate is considered

SA-Operational Cost 5%: This tab is part of the sensitivity analysis in which the variable, operational cost is considered with a negative variation of 5%.

SA-Operational Cost 10%: This tab is part of the sensitivity analysis in which the variable, operational cost is considered with a negative variation of 10%

SA-Operational Cost 15%: This tab is part of the sensitivity analysis in which the variable, operational cost is considered with a negative variation of 15%

SA-Operational Cost -5%: This tab is part of the sensitivity analysis in which the variable, operational cost is considered with a positive variation of -5%

SA-Operational Cost -10%: This tab is part of the sensitivity analysis in which the variable, operational cost is considered with a positive variation of -10%

SA-Operational Cost -15%: This tab is part of the sensitivity analysis in which the variable, operational cost is considered with a positive variation of -15%