National Technical University of Athens

School of Naval Architecture and Marine Engineering

Division of Marine Engineering

Diploma Thesis:

Feasibility study on the retrofit of conventional ferry covering the distance Argostoli-Lixouri into battery-powered one

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I also want to thank my family for all the support and encouragement throughout my studies.

Abstract

The purpose of this thesis is to investigate the technical and financial viability of retrofitting a conventional ferry into a battery powered one, utilizing modern commercialized battery chemistries and technologies.

The challenge is to ensure, with batteries, the necessary power for heavy duty onboard power requirement such as propulsion and energy to auxiliary systems throughout the ship operational profile.

We first examine the history of electricity in ships from Jacobi's boat to the first diesel-electric propulsion systems and the T2 tankers used with success in the Second World War. Modern electric propulsion applications and current technology are reviewed meticulously. We then review the most promising energy storage systems for ships with emphasis naturally in batteries. Lithium battery technology, battery systems costs and future technologies are examined among others.

With the expected fast development of electric and hybrid-electric solutions for ships it is also highly relevant to focus on the regulatory context, both strictly regarding regulations but also standardization. The present study lists the existing relevant regulatory and standards.

The input parameters and equations of the program Marine Electrical used to calculate the necessary data for the retrofit, is presented in chapter eight.

The retrofit is applied into a small ferry and the results are shown in chapter nine.

The ferry will be "VASOS K" which will be operating in the trip Argostoli-Lixouri. Its range will be of four nautical miles. The operational profile of the ferry is based on an eight-hour daily operation, 350 days per year.

As part of the financial and technical analysis, two scenarios will be examined concerning the frequency of charging the batteries. Each scenario's outcomes are the total number of batteries needed, their price, their weight and volume, and life expectancy.

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1. Introduction

1.1 Background of the study

Shipping in general is highly fuel-efficient, but its sheer volume and rapid growth makes it a major consumer of energy and source of carbon air-polluting emissions. Global shipping is the next largest energy consumer and carbon emitter after road passenger and commercial vehicles.

Switching from conventional oil products to alternative fuels is more important than ever in the marine industry, since environmental concerns are growing larger and the International Maritime Organizations as well as local governments are enforcing stricter regulations. Electric propulsion with battery systems has been recognized as one of the most promising options to address this issue and achieve decarbonization in the marine industry.

For shipping applications, the use of batteries can be separated in two main categories. The batteries can be used to create either a fully electric vessel - where batteries are used much the same way as diesel; or a hybrid vessel – where the role of the batteries is to supplement the other fuel and enable the system to operate as optimally as possible. The potential to use batteries for fully electric vessels is growing year by year.

In Europe ferries are very popular, where more than one third of the world fleet operates. However, the European Union ferry fleet is old and in need of newer, more energy efficient and less CO_2 emitting and polluting types. By far the majority of European ferries are older than twenty years. Moreover ferry services in the European Union and around the globe are facing (among others) the challenges of increasing energy prices, and of the demand for renewable energy-efficient sources. Thus most ships are at the mercy of fluctuations in oil prices, making it difficult to plan ahead for long term economic and environmental sustainability.

Ferries are in general predictable, following a relatively short, fixed route every day. This makes them suitable for fully electric operation. The environmental considerations coupled with battery innovations were proven to be catalysts of a new trend towards ferry electrification in Europe. This led to building several new electric vessels and retrofitting many existing ones.

Norway is currently at the forefront of electrification of ferries and other vessels for short-distance transportation. It is expected that the country will have seventy battery-electric ferries by 2022. Moreover, almost all of generated electricity comes from renewable energy sources, mostly hydropower, and charging from shore is therefore providing green electric energy to the onboard batteries and results in zero-emission ships.

Greece is a country with a long and distinguished maritime tradition. It has been prominent in the world maritime industry for decades. The country undoubtedly, plays an important role in international shipping. Therefore, the response from its shipping industry can be a catalyst factor for the efforts of the international community in reducing emissions from ships.

In our country there are over one hundred vessels serving routes of short sea shipping connecting neighboring coastal communities. All of them though are powered by fossil fuels. Greek shipping sector shall set a fine example for other countries. Hopefully in the following years electric ships fleet will augment and electricity consumed for propulsion and hoteling loads on board may be generated solely from renewable energy sources.

1.2 Problem Statement & Objectives

The high fuel oil prices, strict regulations and lower battery prices combined with the Energy Efficiency Design Index (EEDI) requirements and expected additional CO_2 and NOx regulations will lead to the development and use of novel technologies and fuels such as fully electric propulsion systems and cost effective and safe battery systems on the shipping industry.

The aim of the present study is to investigate the environmental and financial viability of retrofitting a conventional ferry to a battery powered one, utilizing modern commercialized battery chemistries and technologies. Therefore we describe the options that can make such a venture viable and evaluate these options regarding the issues of operation and financial efficiency of the installation. Two different scenarios for this reason will be examined in order to find the optimal solution.

It is essential that the installed capacity on board will ensure safety for passengers and the vessel and redundancy according to the ferry's operational profile. Compliance with national and international rules is prerequisite for having certified a battery ship.

The program called Marine Electrical is used for all the calculations in order to acquire the investment appraisal of the project.

1.3 Structure of the Study

The analysis and findings will be structured according to the following layout:

- **Chapter 2 – Marine Transport and Environment**
  An overview of the impact of shipping industry in the environment is presented.
- **Chapter 3 –Historical Review of the Use of Electricity in Ships**
  A historical review of the use of electricity in ships is presented.
- **Chapter 4 –Overview of Today's Electric Propulsion Systems**

Electric propulsion in ships is presented together with applications.

- **Chapter 5 – Energy Storage Systems for Ships**

  The most promising energy storage systems are presented.

- **Chapter 6 – Fully Electric, Battery-Powered Ships**

  Overview of today's battery market, technology, costs etc.

- **Chapter 7 – Standards and Regulations**

  An overview of regulations, standards, rules, requirements and guidelines that apply to battery technologies in the maritime space is provided.

- **Chapter 8 – Retrofit Methodology & Case Study: Argostoli-Lixouri**

  Presentation of Marine Electrical and Results from the implementation of the methodology in the case study of: Argostoli –Lixouri are presented.

- **Chapter 9 – Conclusion**

  Final conclusions on vessel's retrofit

2. Marine Transport and Environment

Maritime shipping is the world's most carbon-efficient form of transporting goods - far more efficient than road or air transport, as it is shown in figure 2.1 .The arrival of containers and intermodalism revolutionized the shipping industry and played a crucial role for ships to achieve high efficiency. Containers could be efficiently stacked, allowing more and more goods transported across the seas. Labor costs dropped dramatically and containers were sealed, theft declined. Over time, the marine transportation industry and the size of ships, trucks, trains, docks, and ports increased and expanded to handle the growing use of containers. The impact on global commerce was enormous, leading to a boom in international trade due to lower transportation and handling costs.

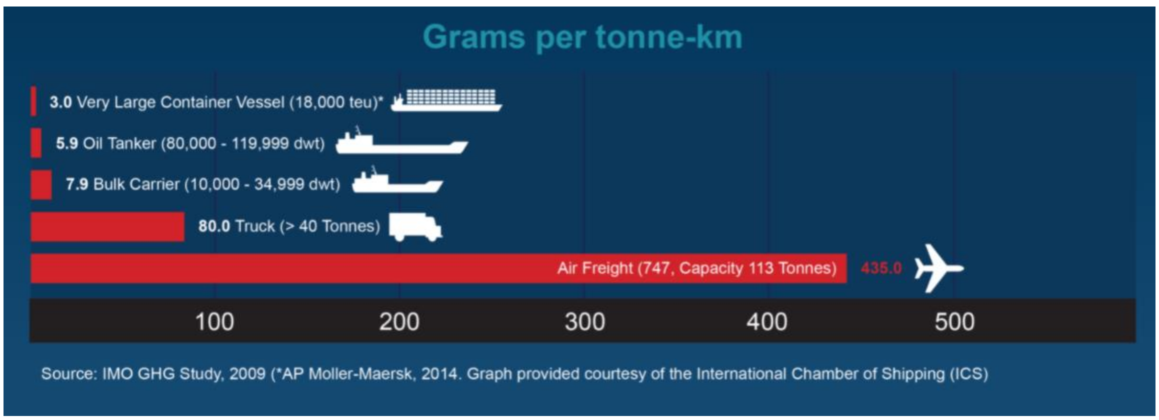

Figure 2.1: Grams per tonne-km for different modes of transport

Although in the movement of a given mass of cargo a given distance, ships are the most energy-efficient method, the sheer size of the maritime transport industry means that it has a significant effect on the environment. The annual increasing amount of shipping overwhelms gains in efficiency, such as from slow-steaming. The growth in tonne-kilometers of sea shipment has averaged 4 percent yearly since the 1990s, and it has grown by a factor of 5 since the 1970s. There are now over 100,000 transport ships at sea, of which about 6,000 are large container ships. The fact that shipping enjoys substantial tax privileges has contributed to the growing emissions.

In 2015, global shipping was responsible for 932 million tonnes of CO_2 emissions. This amount represented 2.6% of the global CO_2 emissions from fossil fuel use and industrial processes. As seen below in Figure 2.3, this was equivalent to 2-3 times the UK’s annual CO_2 emissions, 1.02 times Germany’s annual emissions, and the CO_2 emissions from 231 coal-fired power plants (Darby 2017). In the same year, if there was a country known as ‘’international shipping’’ (with regards to CO_2 emissions) it would rank sixth in the world (representing 2.6% of the global CO_2 emissions), just above Germany.

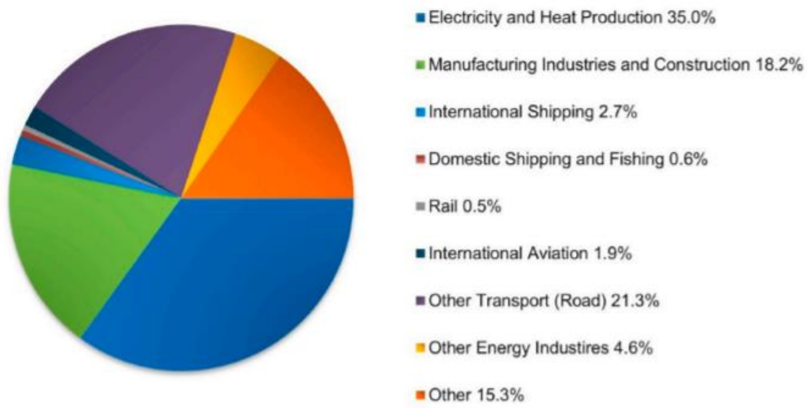

Figure 2.2:CO2 emissions from shipping industry compared with global total emissions (2nd IMO GHG Study)

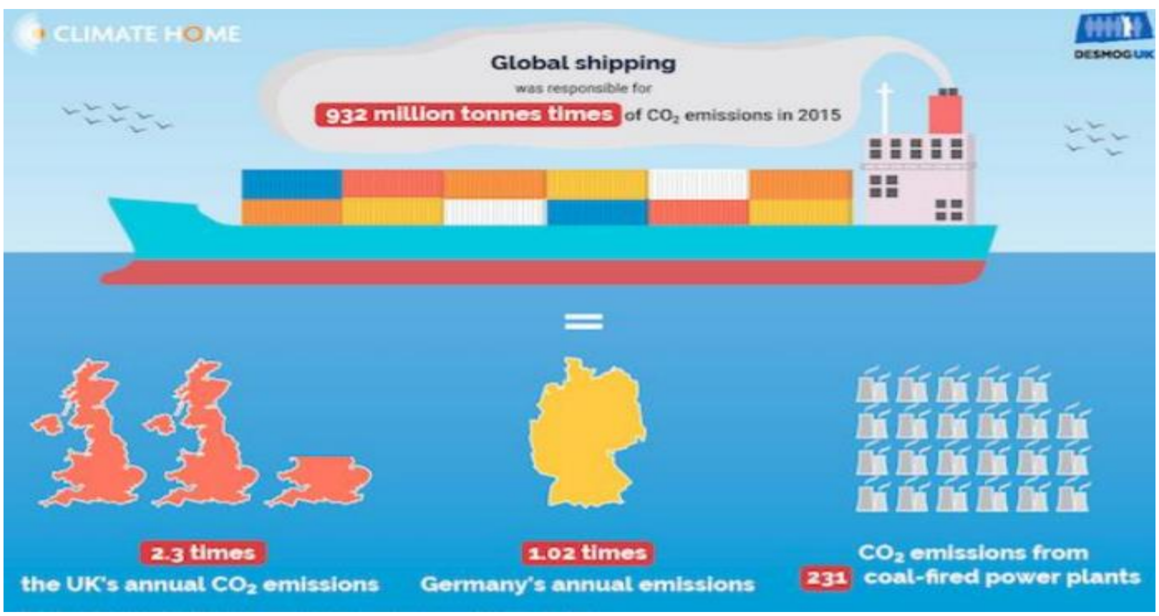

Figure 2.3: Shipping emission in comparison with countries and coal-fired power plants

In October 2018 Dr. Tedros Ghebreyesus, the head of the World Health Organization (WHO), warned that air pollution is the world's 'new tobacco' and is responsible for killing 7 million people annually and causing harm to billions. He mentioned that this is a global crisis which requires urgent attention from all relevant stakeholders (Carrington and Taylor 2018). Researchers from the International Council on Clean Transportation (ICCT), The George Washington University Milken Institute School of Public Health, and the University of Colorado Boulder conducted a study assessing the premature mortality attributed to air pollution from transportation. This data was released in March 2019 and revealed that in 2015, particulate matter and ozone non-road engines, on-road vehicles and oceangoing vessels were responsible for an estimated 385,000 premature deaths globally. Approximately 15% or 60,000 deaths resulted from air pollution from 70,000 international ships (Rutherford and Miller, 2019). It is evident from the above-mentioned information that many health and environmental risks are associated with emissions from ships as a result of fossil fuel burning.

2.1 Global Warming

Climate scientists agree that the main cause of the current global warming trend is the human expansion of the 'greenhouse effect'. Warming results when the atmosphere traps the heat radiating from Earth towards space. Certain gases in the atmosphere block heat from escaping otherwise referred to as GHGs. Climate change results in extreme and unusual weather pattern shifts within the Earth's atmosphere.

Considering the ecological damage induced by global warming, the disappearance of some endangered species is a concern because this destabilizes the natural resources that feed some populations. There are also concerns about the migration of some species from warm seas to previously colder northern seas, where they can potentially destroy indigenous species and the economies that live off those species.

Global temperature rises, increase of ultraviolet radiation, extreme weather phenomena, melting of glaciers and rising levels of the sea are just some of the various effects of such changes on the ecosystems. These changes imply a direct impact on humans and the other elements of the ecosystem: desertification of zones previously featuring a temperate climate will damage agriculture: the difficulties in the supply of drinking water and food can lead to malnutrition and disease. Considering the ecological damage induced by global warming, the disappearance of some endangered species is a concern because this destabilizes the natural resources that feed some populations. There are also concerns about the migration of some species from warm seas to previously colder northern seas, where they can potentially destroy indigenous species and the economies that live off those species. The World Health Organization (WHO) estimates that between 2030 and 2050 the deaths due to these effects will increase significantly (with an order of 250,000 deaths per year more). Latest statistics indicate that the number of natural disasters and catastrophic events has tripled in the world compared to 1960s, with an increased impact on the human society (as well as on other the life forms). The increase in the production of CO_2 will lead to an acidification of the oceans with damage to the marine ecosystems.

Because of all the examples cited above and many other types of negative implications, the increase of GHG content in the Earth's atmosphere does have a social cost, which the Human Kind is called to pay , unless major changes happen in the present and near future.

2.2 Air Pollutants

Oxides of Nitrogen

Oxides of Nitrogen (NOx) is the generic term for a group of highly reactive gases; all of which contain nitrogen and oxygen in varying amounts. Most NOx are colourless and odourless.

Sources of NOx: NOx forms when fuel is burned at high temperatures, as in a combustion process. The primary port-related NOx sources are from the exhaust from engines that power landside equipment and vehicles, marine vessels, non-renewable energy generation, other industrial and commercial sources that burn fuel.

Health and environmental effects of NOx: NOx can react with other compounds in the air to form tiny particles adding to PM concentrations. NOx can also bind with VOCs and sunlight to form ground level ozone or smog. NOx and VOCs are ozone precursors. Ozone is linked to shortness of breath, coughing, sore throat, inflamed and damaged airways, and can aggravate lung diseases such as asthma, emphysema and chronic bronchitis.

Particulate Matter

Particulate matter (PM) refers to discrete solid or aerosol particles in the air. Dust, dirt, soot, smoke and exhaust particles are all considered PM. PM is typically categorised as Total PM (or just PM) or divided into two smaller size categories: PM10, which consists of particles measuring up to 10 micrometres in diameter; and PM2.5, which consists of particles measuring 2.5 micrometres in diameter or smaller. Diesel particulate matter (DPM) is a species of particulate matter important in some jurisdictions.

Sources of Particulate Matter: airborne PM is a mixture of solid particles and liquid droplets generated in numerous ways. The primary port-related PM sources are from the exhaust of engines that power landside equipment and vehicles, marine vessels, non-renewable energy generation, other industrial and commercial sources that burn fuel. PM can also be generated from large open areas of exposed earth or dirt roads, where vehicles and equipment can disperse PM into the air.

Health and environmental effects of Particulate Matter: fine particles are a concern because their very tiny size allows them to travel more deeply into lungs and enter the blood stream, increasing the potential for health risks. Exposure to PM2.5 is linked with respiratory disease, decreased lung function, asthma attacks, heart attacks and premature death.

Oxides of Sulphur

Oxides of sulphur (SOx) is a group of colourless, corrosive gases produced by burning fuels containing sulphur.

Sources of Sox: SOx (a group of gases) is released when fuels containing sulphur are burned in the combustion process. The primary port-related SOx sources is exhaust from engines that power landside equipment and vehicles, marine vessels, non-renewable energy generation, other industrial and commercial sources that burn fossil fuel.

Health and environmental effects of Sox: SOx is associated with a variety of respiratory diseases. Inhalation of SOx can cause increased airway resistance by constricting lung passages. Some of the SOx become sulphate particles in the atmosphere adding to measured PM levels. High concentrations of gaseous SOx can lead to the formation of acid rain, which can harm trees and plants by damaging foliage and decreasing growth.

Volatile Organic Compounds

Volatile organic compounds (VOCs) are any compound of carbon (other than CO, CO2, carbonic acid, metallic carbides or carbonates and ammonium carbonate) which participates in atmospheric photochemical reactions.

Sources of VOCs: VOCs are generated when fuel is burned in the combustion process. The primary port-related VOCs sources are from the exhaust from engines that power landside equipment and vehicles, marine vessels, non-renewable energy generation, other industrial and commercial sources that burn fuel. In addition, liquids containing VOCs are used by numerous industrial and commercial applications, where they can volatilize into the air.

Health and environmental effects of VOCs: In addition to contributing to the formation of ozone, some VOCs are considered air toxics which can contribute to a wide range of adverse health effects. Some VOCs are also considered PM.

Carbon Monoxide

Carbon monoxide (CO) is a colourless, odourless, toxic gas commonly formed when carbon-containing fuel is not burned completely.

Sources of CO: CO forms during incomplete combustion of fuels. The primary port-related CO sources are from the exhaust from engines that power landside equipment and vehicles, marine vessels, non-renewable energy generation, other industrial and commercial sources that burn fuel.

Health and environmental effects of CO: CO combines with haemoglobin in red blood cells and decreases the oxygen-carrying capacity of the blood. CO weakens heart contractions, reducing the amount of blood pumped through the body. It can affect brain and lung function.

Climate Change Pollutants

Greenhouse gases (GHGs) that are typically emitted from port-related sources include carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Additional gases that are not significantly emitted by maritime related also contribute to climate change.

Sources of GHGs: GHGs come from both natural processes and human activities. The primary port-related GHG sources are from the exhaust from engines that power landside equipment and vehicles, marine vessels, non-renewable energy generation, other industrial and commercial sources that burn fuel.

2.3 INTERNATIONAL MARITIME ORGANIZATION

The International Maritime Organization (IMO) is a specialized agency of the United Nations (UN) which has been tasked with the responsibility of adopting and implementing numerous regulations to govern maritime safety, maritime security, oil pollution and environmental protection (IMO, 2019). Indeed, the IMO is the main international institution charged with the responsibility of ensuring that the shipping industry and its operations prevent further harm and damage to our global environment. In 1948 in Geneva, an international conference was held resulting in the adoption of the Convention on the Intergovernmental Maritime Consultative Organization - its name at the time was the Inter-Governmental Maritime Consultative Organization (IMCO) - which formally established the IMO. In 1958, this convention entered into force and the first organization meeting of the IMCO took place the following year. In 1982 the name IMCO was officially changed to the International Maritime Organization.

The IMO currently has 174 member states and 3 associate members (Faroe Islands, Hong Kong and Macao). Most United Nations Member States are also members of the IMO, except some landlocked countries such as Afghanistan, Botswana, Liechtenstein, Rwanda and others. All major maritime nations are represented at the IMO. It may be noticed that Bermuda, the 10th largest ship-owning country in terms of deadweight tonnage (DWT) according to the UN Conference on Trade and Development (UNCTAD 2018), is not an IMO member state. Bermuda is however a party to all major IMO conventions through the United Kingdom (UK), which is a member state and signatory to IMO conventions on its own account, of course, and its overseas territories. Bermuda is actually the largest UK overseas territory in terms of population.

Non-Governmental Organizations and Intergovernmental Organizations enter into agreements to work with the IMO in areas of common interest, only after securing approval from IMO authorities which consist of: the Assembly, the highest governing body of the IMO which includes all IMO Member States , the Council, which is elected by the Assembly and is known as the Executive Organization of the IMO, and five main Committees: The Maritime Safety Committee (MSC); the Marine Environment Protection Committee (MEPC); the Legal Committee; the Technical Cooperation Committee and the Facilitation Committee.

The main objective of the IMO is to facilitate international cooperation and develop international regulations to be adhered to by all shipping nations in order to promote and provide an efficient, safe, secure and sustainable shipping industry. This is achieved by implementing numerous rules to govern maritime safety, maritime security, oil pollution, environmental protection, implementation, compliance and cooperative legislative competence.

Since the establishment of the IMO, there have been over 50 international conventions and agreements and many protocols and amendments which have been adopted. These discussions focus on current and future developments in shipping and other related industries as well as the adoption of new conventions or the amendment of existing ones, all with the goal of meeting present and future demands of the shipping industry. There is also a voting process during these discussions, with each member only being allowed to vote once. Decisions are made by majority vote. Following the adoption of a convention and its formal acceptance by individual governments – expressing their consent to the convention using methods such as signature, ratification, acceptance, approval or accession – the convention enters into force within a specific time frame.

The International Convention for the prevention of Pollution from Ships (MARPOL)

First sign of the IMO's contribution to reduce pollution was through an important international Convention adopted in 1973, the International Convention for the Prevention of Pollution from Ships. The adoption of MARPOL came as a result of the Torrey Canyon disaster in 1967 where an accident in the English Channel resulted in the ship's entire cargo of 120,000 tons of crude oil being spilled into the sea. At that time, this was the largest oil pollution incident ever recorded.

Due to a series of increased tanker accidents in 1976 and 1977, MARPOL was subsequently amended by the adoption of the 1978 Protocol (National Oceanic and Atmospheric Administration). The 1978 Protocol was adopted in order to prevent and reduce pollution from ships due to the fact the 1973 MARPOL Convention had not yet entered into force. The MARPOL Protocol of 1978 ended up absorbing the parent Convention and entered into force in October 1983. There was a further amendment to MARPOL with the adoption of the 1997 Protocol which added to MARPOL its Annex VI on the Prevention of Air Pollution from Ships. The Annex entered into force in 2005. Also occurring in 1997, was the 1997 Kyoto Protocol - an international agreement linked to the United Nations Framework Convention on Climate Change (UNFCCC) - which entered into force in 2005, giving the IMO the mandate to reduce GHG emissions from the shipping industry.

MARPOL covers accidental and operational oil pollution, air pollution, and pollution from garbage, chemicals, sewage and goods in packaged form, as represented by the six Annexes below:

- Annex I - Regulations for the Prevention of Pollution by Oil (entered into force in 2nd October 1983)
- Annex II - Regulations for the Control of Pollution by Noxious Liquid Substances in Bulk (entered into force 2nd October 1983)
- Annex III - Prevention of Pollution by Harmful Substances Carried by Sea in Package Form (entered into force 1st July 1992)
- Annex IV - Prevention of Pollution by Sewage from Ships (entered into force 27 September 2003)
- Annex V - Prevention of Pollution by Garbage from Ships (entered into force 31 December 1988)
- Annex VI - Prevention of Air Pollution from Ships (entered into force 19th May 2005), (this will be examined as follows).

In 2011 the first ever mandatory global energy efficiency resolution for international shipping was adopted through resolution MEPC.203 on *the Inclusion of regulations on energy efficiency for ships* under MARPOL Annex VI. This added a new Chapter 4 to MARPOL Annex VI Regulations for the prevention of air pollution from ships which introduced mandatory energy efficiency regulations such as: The Energy Efficiency Design Index (EEDI) for new ships and the Ship Energy Efficiency Management Plan (SEEMP) for all ships. The goal of the EEDI and SEEMP is to outfit ships with higher energy efficiency, targeting the reduction of GHG emissions being released into the atmosphere.

EEDI and SEEMP entered into force on 1 January 2013. The EEDI aims to equip new ships with more energy efficient engines and equipment. It allows the industry to choose the best energy efficient technologies for their specific ship design as long as the required energy efficiency level is achieved. EEDI also requires a minimum energy efficiency level per capacity mile (for instance, tonne mile) for ships of different types and sizes.

According to the IMO, for the EEDI process, the CO_2 reduction level (grams of CO_2 per tonne mile) is currently set at 10% for new ships. This amount will be tightened every five years to ensure that it keeps abreast with new technological developments for reduction and efficiency measures. The EEDI was initially developed for the largest and more energy intensive new ships such as: bulk carriers, tankers, general cargo ships, gas carriers, container ships, refrigerated cargo carriers and combination carriers .However, in 2014, MEPC adopted amendments to EEDI in order to include newer ship types such as: ro-ro cargo ships (vehicle carriers), LNG (liquefied natural gas) carriers, ro-ro passenger ships, ro-ro cargo ships and cruise passenger ships which have non-conventional propulsion. Thus, ship types which are responsible for approximately

85% of CO_2 emissions from international shipping are now included under the international regulatory regime.

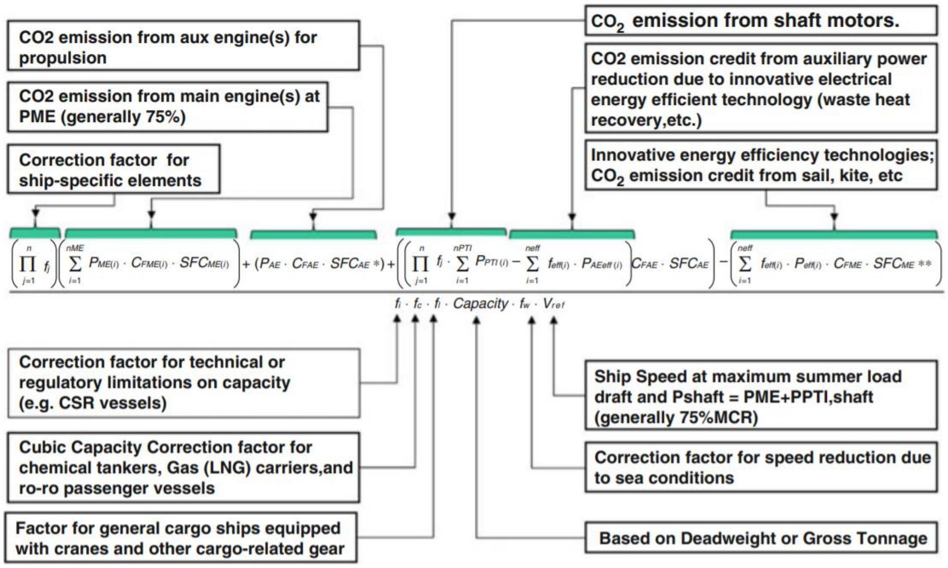

Figure 2.4: The EEDI calculation formula input parameters

The SEEMP (for new and existing ships) is a management plan that allows ship operators to monitor the operational energy efficiency of their ships in a cost-effective manner. This can be done by the use of an Energy Efficiency Operational Indicator (EEOI) as a monitoring tool. SEEMP also incorporates best practices for fuel efficient ship operations and it provides the voluntary use of the EEOI guidelines. The EEOI allows operators to measure the fuel efficiency of a ship, allowing them to consider any changes during the ship's operation which could have an effect on fuel efficiency. Operational changes which are frequently used include cleaning propellers, improved voyage planning, installing waste heat recovery systems, frequent cleaning of the underwater part of the ship and technical measures such as fitting a new propeller. Some other operational measures include slow steaming, weather routing and trim optimization.

In October 2016, further amendments were made to MARPOL Annex VI with the adoption of resolution MEPC.278 – entering into force on March 1, 2018 - which introduced the data collection system for fuel oil consumption of ships, making it now mandatory to record and report the type of fuel oil consumed by ships. Under this amendment, on or before December 31, 2018, ships with 5000 gross tonnage and more have to collect data on every type of fuel oil used along with information on proxies for transport work.

In 1988, an Intergovernmental Panel on Climate Change (IPCC) was created by the World Meteorological Organization and the United Nations Environment Programme (UNEP), which issued a first assessment report in 1990 which reflected the views of 400 scientists. The report stated that global warming was real and urged that something be done about it.

IPPC is a scientific intergovernmental body which provides comprehensive assessments of current scientific, technical and socio-economic information worldwide about the risk of climate change caused by human activity, its potential environmental and socioeconomic consequences, and possible options for adapting to these consequences or mitigating the effects. Thousands of scientists and other experts contribute on a voluntary basis to writing and reviewing reports, which are reviewed by representatives from all the governments, with summaries for policy makers being subject to line by line approval by all participating governments. Typically this involves the governments of more than 120 countries. The IPCC does not carry out its own original research, nor does it do the work of monitoring climate or related phenomena itself. A main activity of the IPCC is publishing special reports on topics relevant to the implementation of the UN Framework Convention on Climate Change (UNFCCC).

The Panel's findings spurred governments to create the United Nations Framework Convention on Climate Change (UNFCCC), which was ready for signature at the 1992 United Nations Conference on Environment and Development.

The Kyoto Protocol is a protocol to the United Nations Framework Convention on Climate Change, aimed at fighting global warming. The Protocol was initially adopted on 11 December 1997 in Kyoto, Japan, and entered into force on 16 February 2005. As of September 2011, 191 states have signed and ratified the protocol. Under the Protocol, 37 countries ("Annex I countries") commit themselves to a reduction of four greenhouse gases (carbon dioxide, methane, nitrous oxide, sulfur hexafluoride) and two groups of gases (hydrofluorocarbons and perfluorocarbons) produced by them, and all member countries give general commitments. The Kyoto Protocol contains provisions for reducing GHG emissions from international aviation and shipping and treats these sectors in a different way to other sources due to their global activities. Emissions from domestic aviation and shipping are included in national targets for Annex I countries. .

2.4 The Paris agreement

At Conference of the Parties (COP) in Paris, on 12 December 2015, Parties to the United Nations Framework Convention on Climate Change (UNFCCC) reached a landmark agreement to fight against climate change and to accelerate and strengthen the actions and investments demanded for a sustainable low carbon future. The Paris Agreement builds upon the Convention and – for the first time – brings all nations into a common cause to undertake ambitious efforts to combat climate change and adapt to its effects, with enhanced support to assist developing countries to do so. As such, it charts a new course in the global climate effort. Some of the key aspects of the Agreement are set out below:

- Long-term objectives aimed at maintaining the average increase in global temperature below 2°C compared to pre-industrial level
- Strategic plans: aimed at maintaining these values preferably close to 1.5°C Attention to developing countries: more benefits for this countries and a general willingness to reach the maximum values of global emission as soon as possible
- Research and innovation: in order to continue with rapid successive reductions, after reaching this maximum value, using the most advanced scientific and technological solutions
- Cooperation: obligation for richer countries to subsidize poor ones with a "green climate fund" of $100 billion a year, starting in 2020, to help them reduce emission
- Monitoring five-year checks starting from 2023.

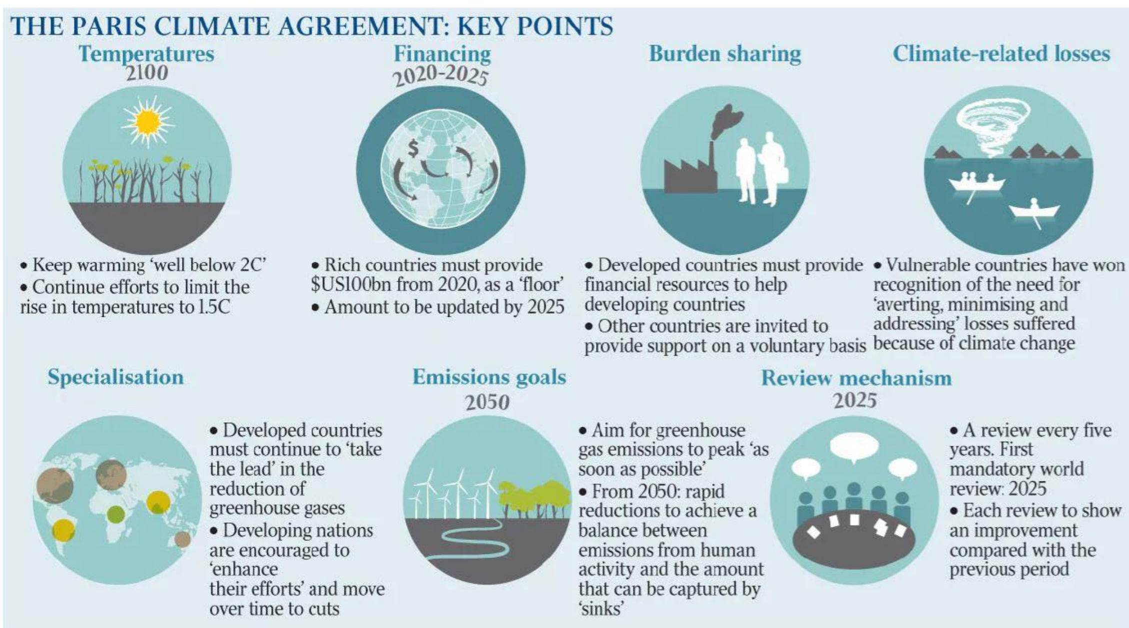

Figure 2.5: The Paris Climate Agreement key points

Air pollutants have direct adverse health impacts and those effects increase with proximity of the population to their release. Greenhouse gases, on the other hand, have the same impact regardless of where they are emitted. In other words, health-based air pollutant effects are generally local and climate-related pollutant effects are global.

MEPC 69 (April 2016) welcomed the Paris Agreement and acknowledged the major achievement of the international community in concluding the agreement, recognized and commended the current efforts and those already implemented by IMO to enhance the energy efficiency of ships, widely recognized and agreed that further appropriate improvements related to shipping emissions can and should be pursued, and recognized the role of IMO in mitigating the impact of GHG emissions from international shipping.

IMPACT OF COVID-19

In addition to the pandemic causing a drop in energy related emissions of approximately 8% in the near term, it will also result in lower emissions throughout the entire forecast period due to delayed growth and because some activities, like air travel, will undergo lasting changes. The cumulative reduction in CO_2 emissions to 2050 is estimated to be 75 GT CO_2, compared with a non-COVID situation. This represents about two years' worth of present emissions and will not significantly change the long-term temperature increase. In order to achieve the ambitions of the Paris Agreement, the world needs emissions reductions that are equivalent to those associated with the pandemic to happen every single year, from now until 2050.

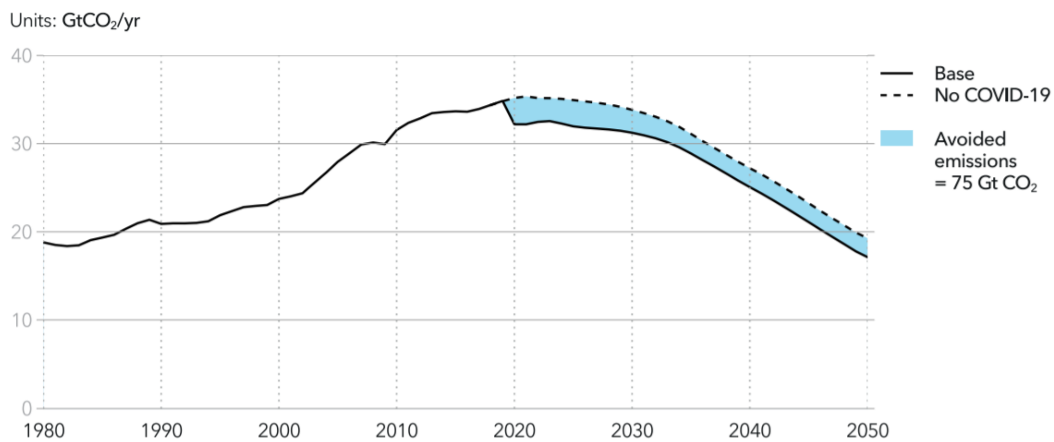

Figure 2.6: World energy- related CO_2 emissions- with and without Covid- 19

2.5 IMO INITIAL STRATEGY

In 2018, IMO adopted an initial strategy on the reduction of GHG emissions from ships, setting out a vision which confirms IMO's commitment to reducing GHG emissions from international shipping and to phasing them out as soon as possible. The initial GHG strategy envisages, in particular, a reduction in carbon intensity of international shipping (to reduce CO_2 emissions per transport work, as an average across international shipping, by at least 40% by 2030, pursuing efforts towards 70% by 2050, compared to 2008); and that total annual GHG emissions from international shipping should be reduced by at least 50% by 2050 compared to 2008.The Initial Strategy is aimed at:

- Enhancing IMO's contribution to global efforts by addressing GHG emissions from international shipping. International efforts in addressing GHG emissions include the

Paris Agreement and its goals and the United Nations 2030 Agenda for Sustainable Development.

- Identifying actions to be implemented by the international shipping sector, as appropriate, while addressing impacts on States and recognizing the critical role of international shipping in supporting the continued development of global trade and maritime transport services.
- Identifying actions and measures, as appropriate, to help achieve the above objectives, including incentives for research and development and monitoring of GHG emissions from international shipping.

IMO remains committed to reducing GHG emissions from international shipping and, as a matter of urgency, aims to phase them out as soon as possible in this century. Levels of ambition:

- Carbon intensity of the ship to decline through implementation of further phases of the energy efficiency design index (EEDI) for new ships to review with the aim to strengthen the energy efficiency design requirements for ships with the percentage improvement for each phase to be determined for each ship type, as appropriate;
- Carbon intensity of international shipping to decline to reduce CO_2 emissions per transport work, as an average across international shipping, by at least 40% by 2030, pursuing efforts towards 70% by 2050, compared to 2008.
- GHG emissions from international shipping to peak and decline to peak GHG emissions from international shipping as soon as possible and to reduce the total annual GHG emissions by at least 50% by 2050 compared to 2008 whilst pursuing efforts towards phasing them out as called for in the Vision as a point on a pathway of CO_2 emissions reduction consistent with the Paris Agreement temperature goals.

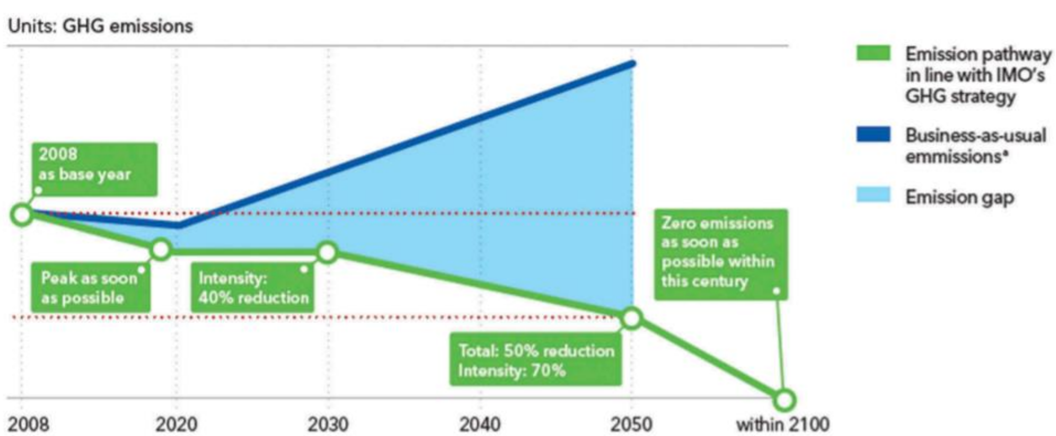

Figure 2.7: GHG emission gap between IMO GHG strategy and BAU emissions

In October 2018 (MEPC 73), IMO approved a follow-up programme, intended to be used as a planning tool in meeting the timelines identified in the initial IMO strategy. The streams of activity identified in the programme of follow-up actions include:

- Candidate short-term measures (Group A) that can be considered and addressed under existing IMO instruments;
- Candidate short-term measures (Group B) that are not work in progress and are subject to data analysis;
- Candidate short-term measures (Group C) that are not work in progress and are not subject to data analysis;
- Candidate mid-/long-term measures and action to address the identified barriers;
- Impacts on States;
- Fourth IMO GHG Study;
- Capacity-building, technical cooperation, research and development;
- Follow-up actions towards the development of the revised Strategy – set to be adopted in 2023.

2.7 KEY FINDINGS FROM THE FOURTH IMO GHG STUDY

The Fourth IMO GHG Study, which was published in 2020, is the first IMO greenhouse gas study published since the adoption in April 2018 of the Initial IMO Strategy on reduction of GHG emissions from ships. This landmark strategy is aimed at enhancing IMO's contribution to global efforts to combat climate change by addressing GHG emissions from international shipping.

The fourth IMO GHG study's results are surely worthy of note. First of all, the study found that total maritime GHG emissions, both international and domestic including CO_2, CH_4, and N_2O, and expressed in CO_2 equivalent emissions (CO_2e), have increased from 977 million tonnes in 2012 to 1076 million tonnes in 2018 (a 9.6% increase). More specifically, in 2012, 962 million tonnes were CO_2 emissions, while in 2018 this amount grew 9.3% to 1,056 million tonnes of CO_2 emissions. The share of shipping emissions in global anthropogenic emissions has increased from 2.76% in 2012 to 2.89% in 2018.

Year	Global anthropogenic CO_2 emissions	Total shipping CO^2	Total shipping as a percentage of global	Voyage-based International shipping CO_2	Voyage-based International shipping as a percentage of global	Vessel-based International shipping CO_2	Vessel-based International shipping as a percentage of global
2012	34,793	962	2.76%	701	2.01%	848	2.44%
2013	34,959	957	2.74%	684	1.96%	837	2.39%
2014	35,225	964	2.74%	681	1.93%	846	2.37%
2015	35,239	991	2.81%	700	1.99%	859	2.44%
2016	35,380	1,026	2.90%	727	2.05%	894	2.53%
2017	35,810	1,064	2.97%	746	2.08%	929	2.59%
2018	36,573	1,056	2.89%	740	2.02%	919	2.51%

Table 2.1: Total shipping and voyage-based and vessel-based international shipping CO_2 emissions 2012-2018 (million tonnes)

According to the Initial IMO Strategy GHG emissions by 2050 need to be at least 50% lower than what they were in 2008, which is considered as a base year. According to the Third IMO GHG study, in 2008, GHG emissions were 940 million tonnes, of which 921 million tonnes were attributed to CO_2.

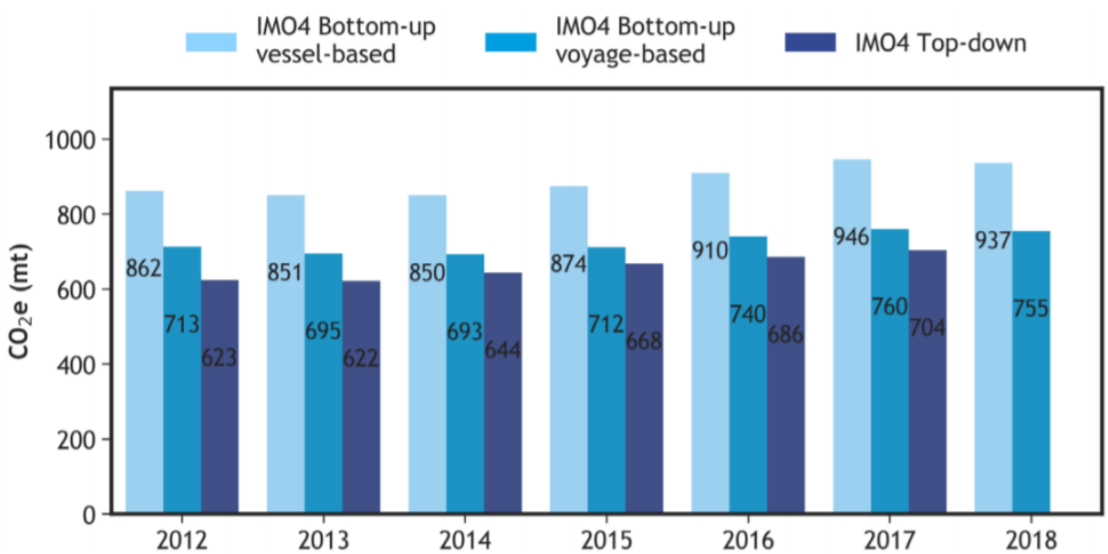

Figure 2.8: Annual greenhouse gas emissions (in CO_2e—excluding Black Carbon) **for international shipping**

Figure 2.8 (all GHG emissions in CO_2e, excluding black carbon (BC)) presents the detailed results for the inventory of international shipping emissions for the period of this Study (2012-2018), considering the CO_2e impact of N_2O and CH_4. Over the period, bottom-up international shipping CO_2-equivalent emissions increased by 5.7% and 8.3% by voyage-based and vessel-based allocation, respectively. Including BC, represented with a global warming potential (GWP) of

900, the voyage-based international GHG emissions for shipping in 2018 would be 7% higher, totalling 810 million tonnes CO_2e.

- A carbon dioxide equivalent or CO_2 equivalent, abbreviated as CO_2-eq is a metric measure used to compare the emissions from various greenhouse gases on the basis of their global-warming potential (GWP), by converting amounts of other gases to the equivalent amount of carbon dioxide with the same global warming potential.
- Global-warming potential, abbreviated as GWP, is a term used to describe the relative potency, molecule for molecule, of a greenhouse gas, taking account of how long it remains active in the atmosphere. The global-warming potentials (GWPs) currently used are those calculated over 100 years. Carbon dioxide is taken as the gas of reference and given a 100-year GWP of 1.

The Fourth IMO GHG study provided the results of three different approaches: bottom-up vessel based, bottom-up voyage based, and top down. The bottom- up voyage-based method defines international emissions as those that occurred on a voyage between two ports in different countries , whereas the bottom-up vessel-based method defines emissions according to ship types, as per the third IMO GHG Study. Both are calculated using an activity-based approach, according to which fuel consumption is estimated for all ships in the world fleet. The top-down method calculates emissions based on fuel sales data. There is about a 10– 15% difference between bottom-up and top-down, which is smaller than the equivalent gap in the third IMO GHG study, which was around 30–38%. This is an evidence of convergence between bottom-up and top-down results.

As mentioned, the Third IMO GHG Study did not use the same method for differentiating the international and domestic GHG inventories. In the Third Study, ship type and size characteristics were used to distinguish between international and domestic shipping. For instance, emissions from yachts, tugs, fishing vessels and ferries less than 2000 GT fell into domestic shipping .This method is based on assumptions and uniform behaviour within fleets of similar ship types and size. Nevertheless, in order to allow comparison with the Third IMO GHG Study and continued use to understand trends, wherever possible the results from both of these methods are included in the 4^{th} Study. The method as used in the Third IMO GHG Study is referred to as vessel-based (Option-1), the new method is referred to as voyage-based (Option-2).

The new approach uses AIS data to identify port calls, which allows for a distinction between international and domestic trips. The use of Automatic Identification System (AIS) data for the assessment of shipping emissions has substantially increased during the last few years. Activity data have substantially increased while the financial costs for acquiring the relevant AIS data have significantly decreased. The availability of the new data has made it possible to use refined methods that can significantly improve the quality of bottom-up ship emission inventories. The AIS system provides continuously automatic information on the vessel positions and instantaneous speeds of ships. If the required vessel characteristics are also known, the exhaust emissions can be modelled on very high temporal and spatial resolutions. The main advantage of such bottom-up emission inventories, compared to the top-down ones, is that these can describe the emitters in a more realistic manner, while maintaining the connection between single emitters and large scale inventories. In addition, it is possible to construct sophisticated emission scenarios and analyse in detail the spatial-temporal variation of emissions.

Figure 2.9 presents emissions, trade and carbon intensity trends as estimated across this Study and the two previous IMO GHG studies. Against a long-run backdrop of steadily increasing demand for shipping (growth in seaborne trade), the three studies approximately align with three discrete periods for international shipping's GHG emissions:

1. 1990 to 2008 – emissions growth (CO_2e) and emissions tightly coupled to growth in seaborne trade (UNCTAD).
2. 2008 to 2014 – emissions reduction (CO_2e) in spite of growth in demand (UNCTAD), and therefore a period of rapid carbon intensity reduction (EEOI and AER) that enabled decoupling of emissions from growth in transport demand.
3. 2014 to 2018 – a period of continued but more moderate improvement in carbon intensity (EEOI and AER), but at a rate slower than the growth in demand (UNCTAD). And therefore, a return to a trend of growth in emissions (CO_2e).

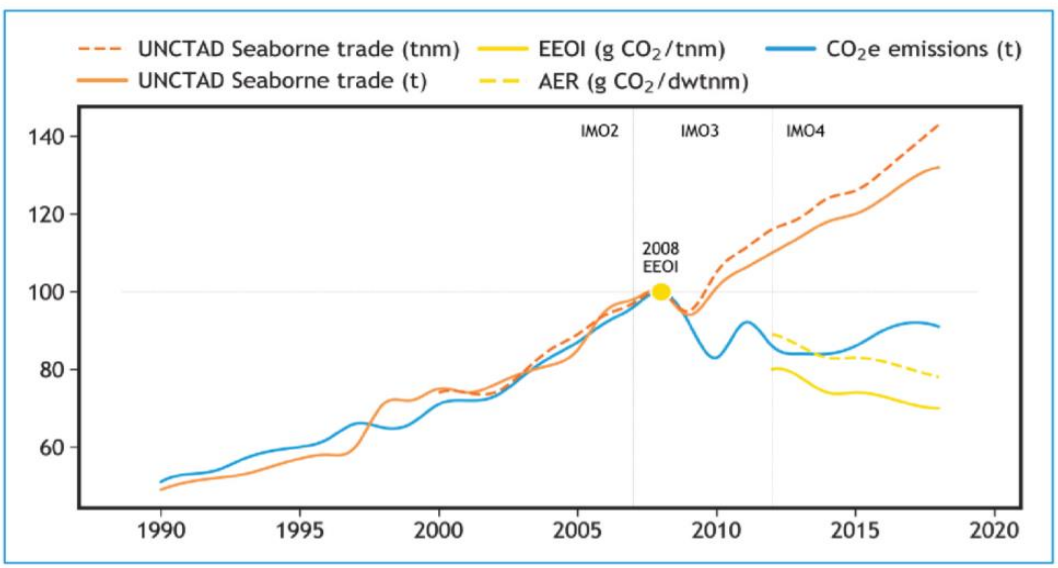

Figure 2.9: International shipping emissions and trade metrics, indexed in 2008, for the period 1990-2018, according to the voyage-based allocation1 of international emissions

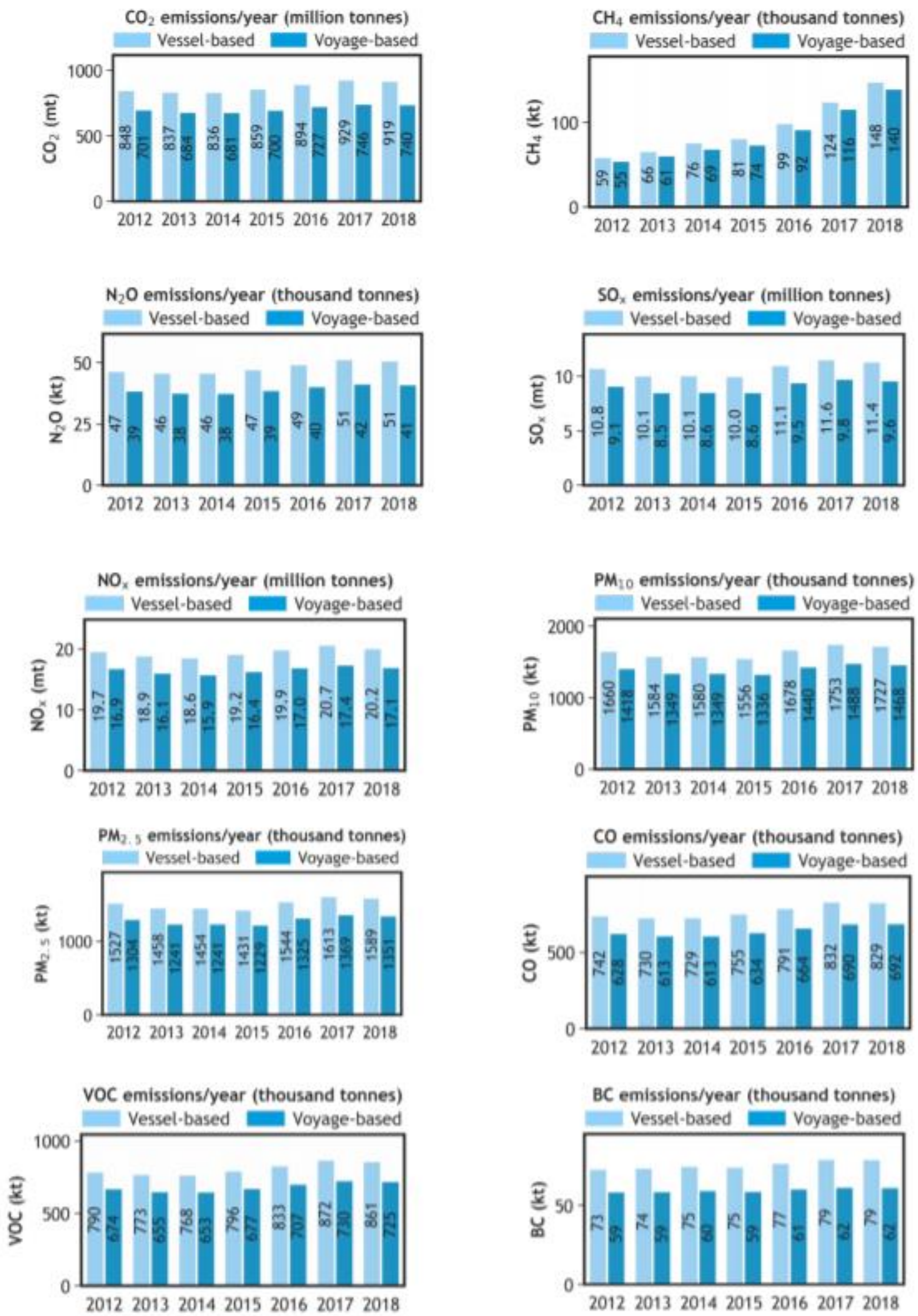

Figure 2.10: trends in a number of emissions species, both GHG and air pollutants.

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Figure 2.10 presents the trends in a number of emissions species, both GHG and air pollutants.

CH_4 trend saw an 87% increase over the period, which was driven by both an increase in consumption of LNG but the absolute increase is dominated by a change in the machinery mix associated with the use of LNG as a fuel, with a significant increase in the use of dual-fuel machinery that has higher specific exhaust emissions of CH_4.

SO_X and PM emissions increased over the period in spite of an overall reduction in HFO(Heavy Fuel Oil) use and increase in MDO(Marine Diesel Oil) and LNG(Liquefied Natural Gas) use (partly driven by the entry into force in 2015 of a number of Emission Control Areas associated with limits on sulfur content of fuels). The explanation is that the average sulfur content increase in HFO over the period exceeds the sulfur content reduction associated with the change in fuel use.

NO_X emissions saw lower rates of increase over the period than the trend in fuel consumption. This is consistent with the increased number of ships fitted with, and where appropriate operating with, NO_X Tier II and Tier III compliant machinery. In spite of these regulations, the overall trend in NO_X emissions was an increase over the period.

The study also reports on black carbon (BC) emissions—the first GHG study to do so. Black carbon, which is not a greenhouse gas, is a component of fine particulate matter and has a very strong warming effect. It reports an increase in BC emissions of approximately 12% from 2012 to 2018—this is actually higher than the reported CO_2 emissions increase.

According to the fourth IMO GHG study, the industry has already achieved a 29% reduction in carbon intensity (from 15.16 g CO_2/t/nm in 2008 to 10.7 g CO_2/t/nm in 2018). A further analysis of the voyage-based EEOI reveals that containerships and bulk carriers have already achieved a reduction of around 35%, and bulk carriers a remarkable reduction of 60%. On the other hand, LNG tankers show an increase of 7%. If AER is used as a proxy for carbon intensity, international shipping has achieved already a 21% reduction, versus the 40% reduction target of 2030.

The fourth IMO Study indeed demonstrates that whilst further improvement of the carbon intensity of shipping can be achieved, it will be difficult to achieve IMO's 2050 GHG reduction ambition only through energy-saving technologies and speed reduction of ships. Therefore, under all projected scenarios, in 2050, a large share of the total amount of CO_2 reduction will have to be achieved by more drastic means, like the use of alternative energy storage systems in ships.

Roel Hoenders, acting head of air pollution and energy efficiency (IMO) admitted: “It is likely that further measures will need to be adopted in the short and medium term to meet the targets set out in the Initial Strategy”.

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3. Historical Review of the Use of Electricity in Ships

3.1 ELECTRICITY ADOPTION IN SHIPS

The earliest attempt to apply electric propulsion to vessels dates back to the 1830s.In 1839, the German inventor Moritz Hermann von Jacobi with the financial assistance of Czar Nicholas, constructed a nine meter electric motor boat powered by battery cells, which carried 14 passengers on the Neva River, in Russia. The electric motor (about 1kW) was powered by a battery consisting of 69 Grove cells resulting in a speed of approximately 4 km/h. Due to the early motor design, which carried many imperfections, the invention was not adopted and used in any practical applications and was soon forgotten.

The first successful electrification of a commercial vessel occurred in the 1880s with the implementation of DC distribution onboard, when SS Columbia was fit with dc and light bulbs for illumination. After attending Thomas Edison's New Year's Eve lighting demonstration in Menlo Park, New Jersey, Henry Villard, president of the Oregon Railway and Navigation Company became enthusiastic of Edison's work. Villard subsequently ordered an Edison Lighting System to be installed on his company's new passenger steamer, Columbia. Although met with hesitation by Edison himself, the project moved forward, making the installation onboard Columbia Edison's first commercial order for the light bulb. Columbia would also be the first ship to utilize a dynamo. The success of Columbia's experimental dynamo system led to the system being retrofitted on to other vessels. Soon after, electric motors were installed in ventilation and gun firing circuits.

Figure 3.1: Passenger and cargo vessel SS Columbia (1880-1907)

The U.S. Navy first experimented with an installed electrical system aboard the USS Trenton, a steam frigate of 3,900 long tons. Trenton was commissioned in 1877 and featured two relatively new technologies, a steel hull and a steam propulsion system, in addition to the traditional sailing rig. After serving around the world for several years, Trenton was retrofitted with an electric lighting system, provided by the Edison Company for Isolated Lighting, at the New York Navy Yard in August 1883. This new technology was so well received that, in 1884, the Bureau of Navigation decided to light Atlanta, Boston, and Omaha, and electric lighting soon became a standard feature aboard both military and commercial vessels. The period can be considered to mark the birth of the marine vessel's power grid.

In 1896, the USS Brooklyn was fitted with an 80 volt dc electrical system to operate winches, deck machinery, and gun mounts. The lack of practical alternating current motors led to adoption of direct current as a standard to simplify the overall system. The same was true in many industrial applications until the early 1900s, as the available direct current motors were found to be more efficient than the alternating current designs of the day.

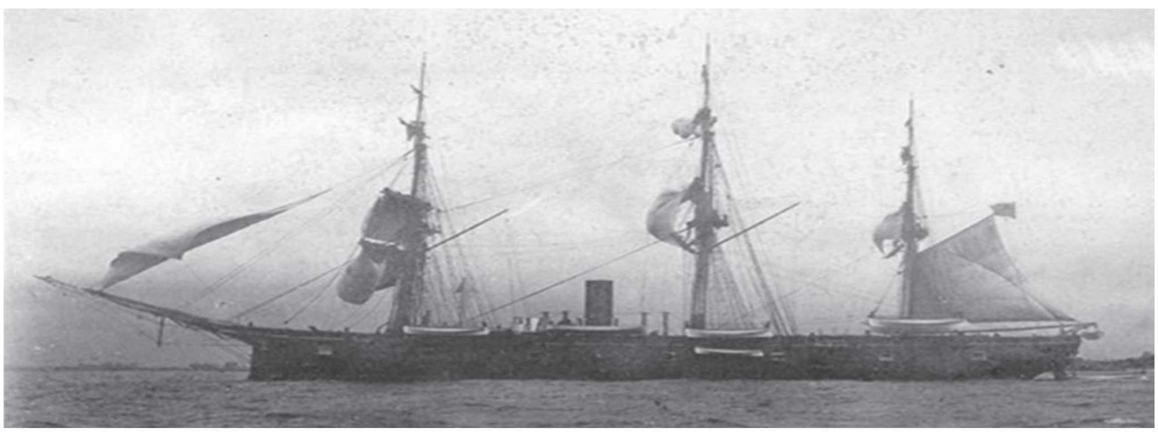

Figure 3.2: The USS Trenton River tanker Vandal (mechanical drawings, 1903)

3.2 FIRST DIESEL ELECTRIC PROPULSION SYSTEMS

In 1903, the Italian electrical engineer Cesido Del Proposto, made a significant progress in diesel-electric propulsion. He conceived and developed a new drive for ship screws.

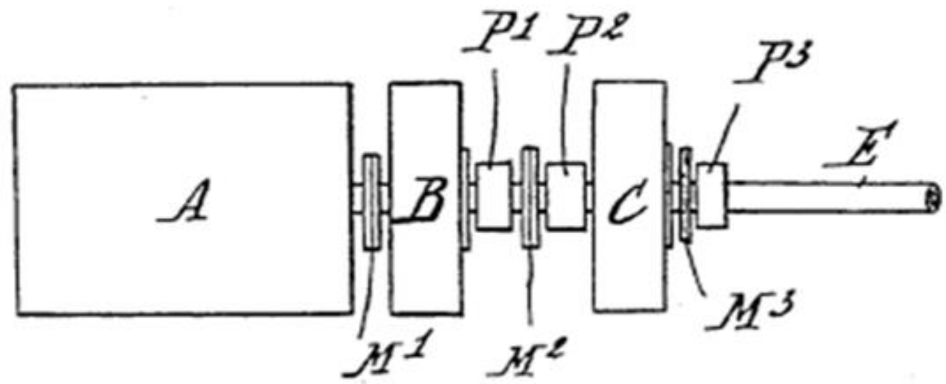

Figure 3.3: Proposto's engine drawings

The most crucial parts of this system were the propeller shaft (E) and the prime mover (A). Aside from these two parts the system consisted of a DC motor (C) and an engine-driven DC generator (B). The electrical energy, which is produced by the generator, was transferred to the motor via cabling. The electrical output of the generator was slightly higher than the electrical output of the motors. A coupling (M3) continuously connected the motor to the shaft. The generator and the prime mover were connected by a similar coupling (M1). Between the generator and the electric motor a magnetic clutch (M2) was located. The current delivered by the generator activated this clutch.

Russian Vandal and French Petite-Pierre, launched in 1903, were the world's first diesel-powered ships. Vandal was also the first equipped with fully functional diesel-electric transmission. The diesel engine and electric generator were placed in the middle, and the electric motors in the stern, driving the propellers directly. The holds were separated by longitudinal (rather than transverse) bulkheads running the length of the ship, a feature that became common on ocean-going tankers. The ship's power plant of three 120 hp(89KW) diesel engines was built in Sweden by Swedish Diesel (Aktiebolaget Diesels Motorer).The electrical transmission varied propeller speed from 30 to 300 revolutions per minute(RPM).

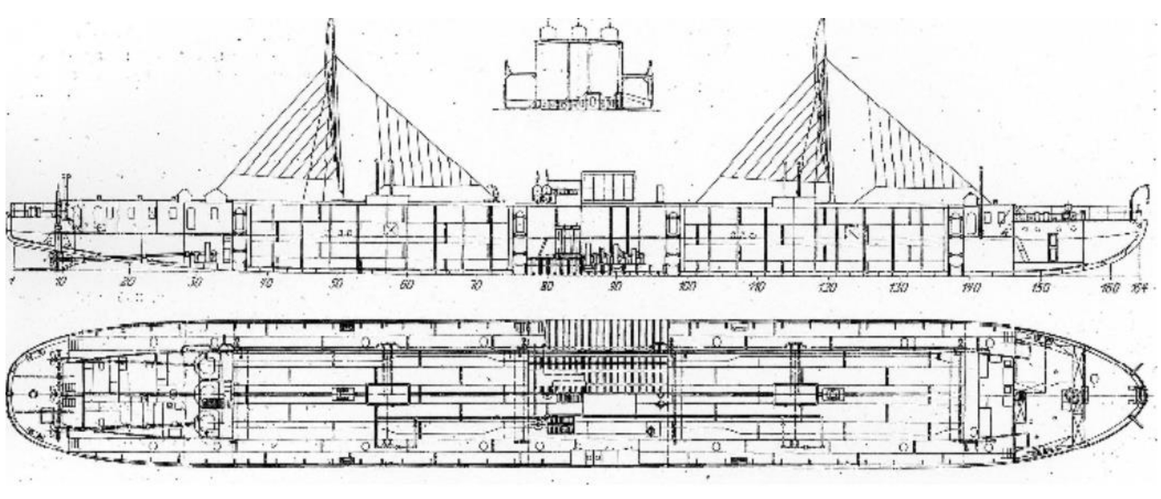

Figure 3.4: River tanker Vandal (mechanical drawings, 1903)

In the late 1880s, Nikola Tesla a former employee of Edison, Galileo Ferraris and Michael Osipowitch von Dilvio-Dobrowolsky each had discovered the benefits of two alternating conductors with 90◦ phase difference (or three conductors with 120◦ phase difference), which could be used to rotate a magnetic field. This led to the birth of the induction motor demonstrated independently by Ferraris and also by Tesla in the early 1880s and patented by Tesla in 1887. One of Edison's greatest rivals, George Westinghouse (Westinghouse Electric Co.), acquired these patents and with the help of Tesla the famous War of Currents began, with Edison on the dc side, and Westinghouse and Tesla on the ac side. The ac current had the ability to easily be transformed between different voltage levels, without rotating components as was needed for voltage transformation in dc, and could be transmitted at great distances by transforming the voltage to appropriate levels at relative low cost. An often neglected part of the history of alternating current is the Hungarian /research team known as ZBD (Zipernowsky,Blathy,Deri) , who invented the closed core shunt connected ac transformer in 1884, revolutionized the grid using parallel connections (instead of series connections) to a main distribution line, and also electrified the Italian city of Rome in 1886. Westinghouse adopted much of the Hungarian scientists' work to take up the fight with Edison's dc systems. Not only had the ac inventions had an effect on the mainland power generation and distribution grids, but the inventions also gave support to more advanced use of electricity in ships.

The passenger vessel Electric Arc built in 1908 as an experiment with alternating current. The vessel, which probably was the first experimental vessel with ac, originally featured a gas engine that was replaced by a petrol engine driving the alternator (4- and 6-poles winding). This vessel proved that electric drive with ac was feasible, and was followed by the cargo vessel Tynemount in 1913 with diesel-electric ac propulsion. The electrical system worked well for light loads, however, the propeller pitch was too coarse and needed more power than the generators were able to supply, resulting in failure of the engines.

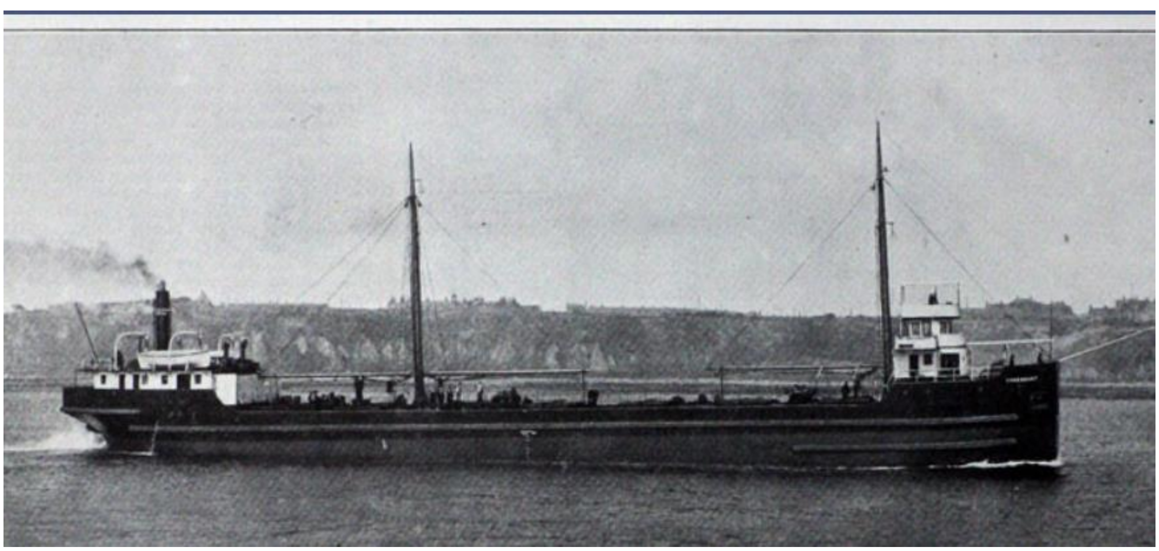

Figure 3.5: The Electric Motor Ship Tynemount

A key figure in the history of the Navy's adoption of electric drive is William Le Roy Emmet, a graduate of the Naval Academy Class of 1881 and a longtime engineer at General Electric. Working at Edison General Electric and then the General Electric Company after it shaped in 1892, Emmet was included in numerous of the company's challenging attempts, including building turbines for the first major hydroelectric power plant near Buffalo, New York.

In 1908, as reported by historian William McBride, Canadian inventor Reginald Fessenden submitted a proposal to the Navy for a turboelectric drive that was dismissed. Fessenden, however, was permitted to contact other companies that might be interested in the idea. Emmet at General Electric proved enthusiastic about the possibility of turboelectric drive and defined detailed drawings from Fessenden's proposal. Emmet outlined his ambitious plans in a lengthy paper in the Transactions of the Society of Naval Architects and Marine Engineers in 1909. Depicting two systems—the first being a hybrid electric/steam turbine combination, the other a pure turboelectric drive—Emmet advocated for the installation of electric drives in the Navy's battleships, even though he confessed in practice they had never been tested on anything bigger than firefighting boats in Lake Michigan. In Emmet's hands, the electric drive acquired a significant ally in Secretary of the Navy George von Lengerke Meyer. Leveraging an endorsement of turboelectric drive from the Navy's General Board, Meyer authorized the installation of electric propulsion in one of three new coal-hauling colliers that started construction in 1910.

In an endeavor to determine the most efficient and effective of the three types of propulsion, the Navy decided that each of the three colliers would have a different engine. Moreover, installing new equipment on these noncombatant vessels would avoid the risky step of evaluating them on expensive battleships. The three colliers were: USS Cyclops, which received reciprocating engines; USS Neptune, which received steam turbines; and USS Jupiter, the last of the three to be built in 1912, which was equipped with turboelectric drive. The decision was sensible as well as practical—although they were auxiliaries, the colliers' size (20,000 tons) was comparable to the battleships being laid down at the same time (22,000–26,000 tons). Once Jupiter underwent trials in 1913, the ship had a positive result and, according to a report by chief engineer S.M. Robinson, exceeded General Electric's economy predictions over the rival engines by eighteen percent. Emmet also triumphantly declared in his own report on the trials that, "If my first design for a warship made over four years ago (in 1909) had been accepted by the Navy Department, the vessel produced would have been very greatly superior in respect to economy, reliability, weight, simplicity, and cruising radius to any ship now afloat."

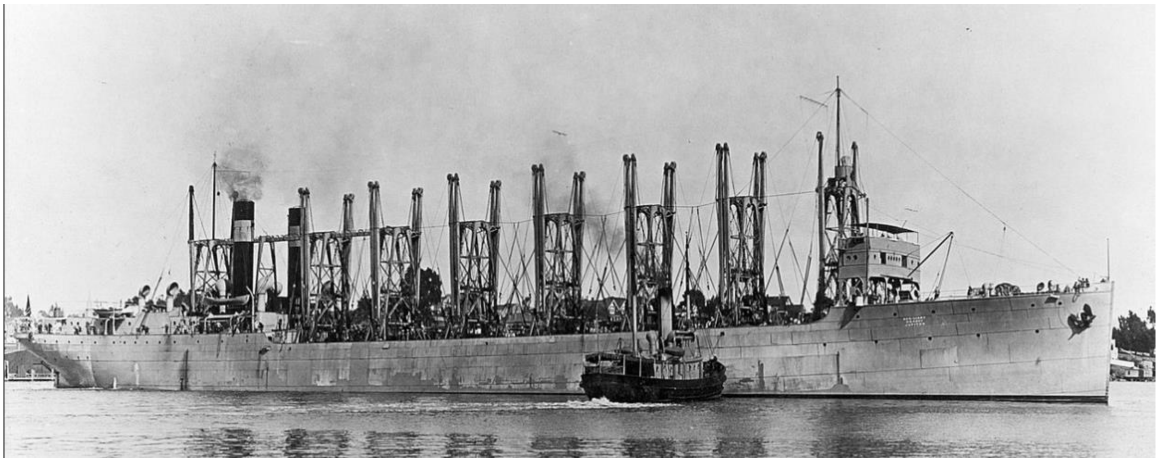

Figure 3.6: USS Jupiter (Navy Fleet Collier No. 3)

Emmet had the opportunity he was searching for in 1915 by ensuring that electric drive would adopt in the battleship USS New Mexico, the first important warship to be electrically driven. The New Mexico used two 11.5MW variable frequency ac generators that powered four 7,500hp induction motors, and was able to maintain a speed of 21 knots. The vessel also had six 300kW auxiliary turbo-generators for lighting and non-propulsion electrical machinery. The shaft alley was shorter and thus less of a target, and fuel economy was improved substantially. All that came at the expense of weight the electric motors and controls were heavy though reversal was accomplished easily by the switching of circuits with no need to change steam systems.

In 1916 and 1917, however, electric drive would be at the center of a major debate between the Navy and the nation's shipbuilders as both groups arranged plans for a host of new battleships proposed under 1916 legislation intended to make the Navy best in the world. One of the interesting features of the controversy was that it pitted the Bureau of Steam Engineering as the supporter of (apparently more progressive) turboelectric propulsion for the Navy's latest battleships, against many of the nation's biggest shipbuilders, which lobbied against the new technology as a threat to traditional propulsion (and higher profits). At first skeptical of electric drive, the bureau was convinced by Jupiter's success. Shipbuilders, however, balked at the increased costs of producing the new drives, which were more complicated than steam turbines or reciprocating engines.

With the help of vocal bureau spokesmen and prominent personalities such as Nicola Tesla who supported electric drive, public opinion swung toward acceptance of the new system and opposition from industry reduced. More specifically, Nikola Tesla, who was an early proponent of electric propulsion for ships wrote in the New York Herald, in February 25, 1917: "The ideal simplicity of the induction motor, its perfect reversibility and other unique qualities render it eminently suitable for ship propulsion, and ever since I brought my system of power transmission to the attention of the profession through the American Institute of Electrical

Engineers I have vigorously insisted on its application for that purpose.” Five other battleships—USS Tennessee , USS California , USS Colorado , USS Maryland , and USS West Virginia —would receive electric drives over the next five years, as would the battlecruisers USS Lexington and USS Saratoga , which would be retrofitted midway through their construction into aircraft carriers. (Consequently, from 1920—when Jupiter was converted into the first US aircraft carrier, USS Langley —until 1934, all US aircraft carriers had electric drive.)

The first generation of electric drives, however, never proved in practice as radically more efficient than their mechanical rivals as their supporters had theorized, and these were the last major ships to receive electric systems. However, USS Lexington proved the versatility of electric drive, when in late 1929 and early 1930 it provided power for the city of Tacoma, Washington, during a drought that had depleted the town’s power-generating reservoir.

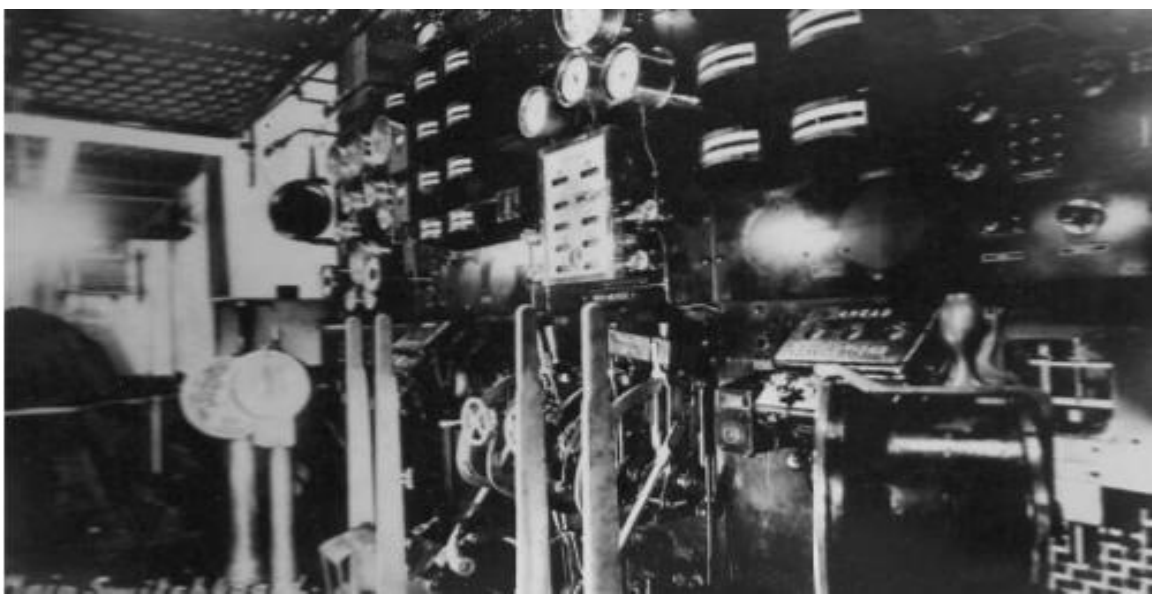

Figure 3.7: USS New Mexico’s main switchboard and control station. Change of speed and direction was done with manual levers

3.3 INTERWAR PERIOD AND T2 TANKERS

Following the end of World War I, the United States, Great Britain, and Japan all commenced large scale capital ship construction efforts, leading to a naval arms race. In an effort to prevent this from continuing, the Washington Naval Treaty was signed in 1922 by Britain, France, the United States, Japan, and Italy. The treaty established number and size limits on capital ship construction. Germany was prohibited from building any battleships under the Treaty of Versailles, which ended World War I. The Washington Naval Treaty also spelled the end of turboelectric propulsion for capital ships. In addition, the treaty also spelled the end of turbo-electric propulsion for war ships by prohibiting the reconstruction of ships, meaning a cancellation of any plans to rebuild existing US battleships with turbo-electric drives, and also prohibiting construction of new naval vessels. From this point on, most of the existing US vessels were powered by geared turbines.

As the treaty covered only naval vessels, the development of turbo-electric propulsion continued, but was not, however, used for naval surface vessels. Geared steam-turbine propulsion became predominant for large warships, however, electric propulsion was still being used, especially for passenger vessels and ice breakers with separate power systems supplying the propulsion loads and the ship's service loads.

The passenger vessel Cuba, originally built in 1894 as SS Yorktown, after being sold and renamed a couple of times, was wrecked in 1916 and rebuilt with turbo-electric propulsion in 1919 and was then the world's first passenger vessel with that propulsion system. The use of turbo-electric propulsion was not only taking place in the United States. In Europe the Swedish enterprise Rederiaktiebolaget Svea, which was located in Stockholm, started equipping ships that had steam machinery, with turbo-electric propulsion. In 1916, in the same period USS New Mexico was equipped with the new propulsion system, the Swedish company built two sister ships cargo ships. The one was fitted with triple-expansion engines while the other got two radial-flow reaction turbines, invented by the Swedish engineer Fredrik Ljungstrom, driving electric generators .The total power output from the turbines running at 9,200 revolutions per minute (rpm) was 800kW, with a voltage level of 500V. Two induction motors, one on each side, were running at 900rpm and drove the single propeller shaft through single-reduction gearing at 90 rpm. The first turbo-electric ship constructed in Great Britain was the cargo ship SS Wulsty Castle in 1918, which used the same type of machinery.

The battleship designs of the late 1930s did not feature turbo-electric propulsion systems despite its advantages. A major reason being vulnerability to electrical short-circuits that could result from battle damage increasing the likelihood to be knocked out of operation - survivability - and added weight which could instead be used more wisely, i.e. to carry more guns and armor. In fact no other nations at that time had naval surface vessels with turbo-electric propulsion.

One of the more important ships using turbo-electric propulsion built during World War II was the T2 tanker. The T2 tankers were critical for maintaining the upper hand in the war by transporting oil to the navy vessels around the world. The principal reason to use electric propulsion was to eliminate the need for large gearboxes, the manufacturing capability for which was limited. Between 1942 and 1945, 481 tankers of this type were built, with propulsion provided by a turbo-electric drive. The propulsion system consisted of a steam-turbine generator connected to a propulsion motor to drive the propeller therefore the need for a large main reduction gear was obviated.

4. Overview of Today's Electric Propulsion Systems

In diesel ships, the main engine takes full responsibility for producing and transmitting mechanical power to the thrust. In general, it does not contribute to generating electricity. Instead, the electrical load (generally for auxiliary systems and hotel facilities) is covered by independently arranged diesel generator sets.

Electric propulsion is defined as the type of propulsion in which the ship's shafts are driven directly (or less frequently by gearboxes) from electric motors and not from other engines such as diesel, gas turbines and turbochargers. Of course diesel engines, gas turbines and turbines are still present in power plants, but instead of moving the propeller axis directly, they drive electric generators, which in turn feed the electric propulsion engines. Ships with electric propulsion are designed to produce electrical power that can cover both propulsion and electrical loads.

After World War II and towards present time, new innovations and stringent requirements with regards to fuel efficiency, reliability, maneuverability (variable speed propulsion) and air pollution (emissions) led the way towards today's marine vessel power system solutions. With an increasing need for electricity, as a result of more electrical loads with different power requirements (i.e. voltage levels, dc/ac, etc.) the technical advances in power electronics found their way to the shipboard power system, with the result of the marine vessel power system slowly converting towards a fully electric Ship. During the period from 1950's to 1990s, the power electronics revolution triggered by innovative solid-state technology marked the start of a new era for marine vessels. With the development of semiconductor switching devices as thyristors and transistors for larger power applications, it became possible to control the rotational speed of electric motors by varying the electrical power input in terms of voltage and later on frequency. The first applications of variable speed motors were dc motors controlled by thyristor rectifiers. Further, the development of frequency converters made it possible to regulate speed also on ac motors. Either way, this opportunity to have variable speed control of propellers independent from the generator operation, opened new ways of applying electric propulsion. Multiple diesel generators (or gas turbine generators) could provide electric power at a fixed voltage and frequency. In this principle, the onboard power plant can be designed almost as any kind of land based industrial power plant with multiple generator sets, however without any external connection to a power grid. This means that the power plant operates as an island configuration, with short distances from producer to consumer. This opening for electric propulsion was initially welcomed in certain vessel types that have large variation in operation profile and/or other large electrical consumers onboard, as cruise vessels, icebreakers, offshore oil & gas exploration vessels.

Electric propulsion solutions today have many variants depending on vessel type, operational profiles, and available technology at the time of construction, a large flexibility of the design and many parameters that influence the optimal solution. Over the last ten years, the electrical propulsion fleet grew three times faster than the world fleet. Cruise vessels, Icebreakers, DP offshore vessels, and LNG carriers still accounts for the majority of vessels, but the technology is increasingly also used in other vessel types. LNG carriers were the last large group of vessels changing from mechanical steam propulsion to electric propulsion with the first vessels ordered in 2003. Further, other vessel types as dredgers, special construction vessel, pipe layers, cable layers, shuttle tankers, ferries, are vessel types that increasingly use electric propulsion, or partly electric propulsion. Some of this is due to special requirements as operation in ice, as we see more and more that the vessels themselves are constructed for icebreaking for travelling in the northern routes without additional icebreaking support. Another driver is Dynamic Positioning (DP) operation, which means that you need several propulsion and thruster units and by that benefit of centralized power production and distributed electric drive systems.

Except for these drivers, there are also now increasingly interests in looking into alternative propulsion systems also for vessel types that have traditionally been propelled by one or two main engines, due to the operational profile. One of the main benefits of electric propulsion is the ability to keep high propulsion efficiency for the whole operation range, while many of the vessels equipped with mechanical propulsion are designed and optimized for just one single operational point.

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4.1 TYPES OF ELECTRIC PROPULSION SYSTEMS

One of the most important advantages of using an electric motor for propulsion is that ship designers are not limited by the existence and placement of the necessary gearbox on the drive line and the very long shaft. Varieties of propulsion designs are available, but their applications depend on specific vessel requirements. The propeller shaft removal of electric propulsion facilitates the utilization of unconventional propulsors. Replacing mechanical components between the engine and propeller with an electrical network has multiple potential benefits including reduced fuel consumption, improved dynamic handling, increased reliability, reduced maintenance costs, and greater flexibility in the ship's layout. By selecting suitable motors, electric propulsion can make the gearbox redundant and significantly reduce the length or completely eliminate the shaft, as in the case of azimuth propellers. Figure shows the difference in the length of the drive shaft for the conventional mechanical system, the shaft propulsion and the azimuth propulsion with the electric motor outside the hull (pod).

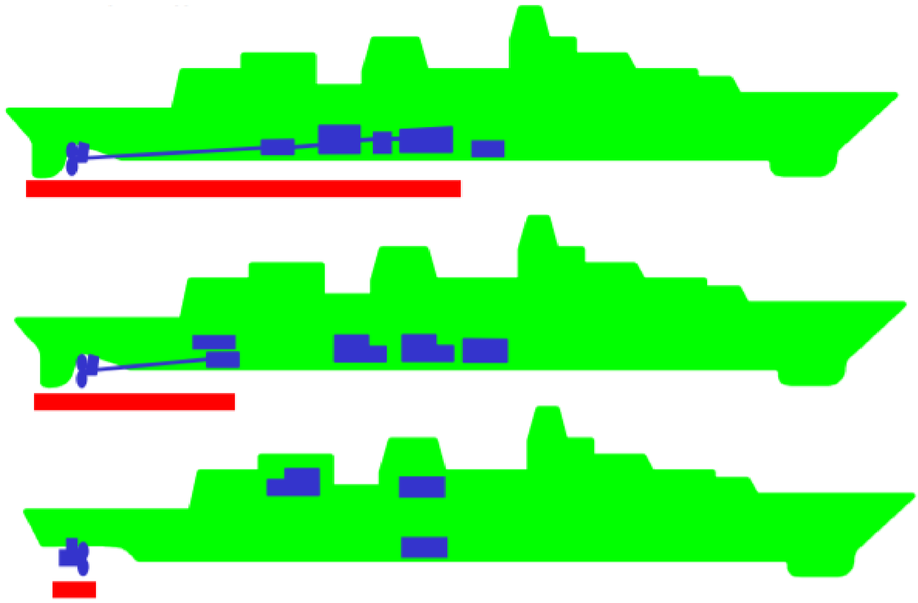

Figure 4.2: The length of the rotary shaft in conventional mechanical topology (top), in shaft propulsion (middle) and in pod propulsion (bottom)

Discussion in this section is limited to some of the most commonly used propulsion system, such as Shaft propulsion, Azimuth Propulsion and Podded Propulsion.

Shaft Propulsion

Shaft propulsion is very similar to conventional mechanical drive propulsion. Nevertheless compared to mechanical propulsion, a significant reduction in shaft length is possible due to the flexibility of the electric motor position. The engine is located in the hull of the ship and transmits torque, using a rotating shaft to the propeller which then converts the torque to forward or backward motion. Shorter shaft system can be possible by implementing frequency converter-based system. Maneuverability is a technical issue in shaft propulsion design, but this issue can be overcome by using rudder on each propeller. The shaft propulsion is available in wide power range and commonly used in shuttle tankers, research vessels, large anchor handler vessel and cable liners.

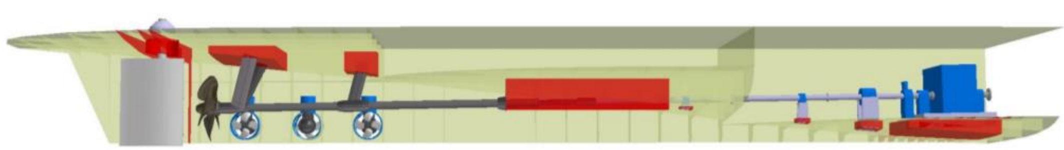

Figure 4.3: Shaft propulsion showing the electric motor (left), shaft, mechanical couplings and brackets.

Azimuth

Azimuth thruster is a type of propulsion device in which the propeller is placed on a bulb that can rotate in all directions in the horizontal plane so that the ship does not need a rudder. Therefore, the return of the ship is better than that of a fixed propeller and a rudder system. The engine can be diesel or electric-diesel. Depending on the shaft layout, the motorized rotary propeller can be classified into two types: L-drive and Z-drive. The L-shaped actuator has a vertical input shaft and a horizontal output shaft and a perpendicular gearbox. And the Z-type actuator has a horizontal inlet shaft, a vertical shaft, and a horizontal drive shaft and two perpendicular gearboxes. Electric drive, in which an electric motor located in the bulb, is directly connected to the propeller without gear. Electricity is provided by the diesel generator or gas turbine. The rotating propeller called ABB Azipod was invented by F.W. Pleuger and F. Busmann in 1955 and manufactured by ABB Group and was the first product to apply this technology. The rotating propeller combined with the steering system creates a propulsion system called the Apizod thrust system. In traditional propulsion systems, the engine is connected to the propeller shaft and the rear propeller and has a rudder behind the propeller. But in the Azipod propulsion system, the thrust system and steering system are combined into one. The system consists of a propeller-driven by an electric motor, this propeller on the bulb can rotate 360 degrees.

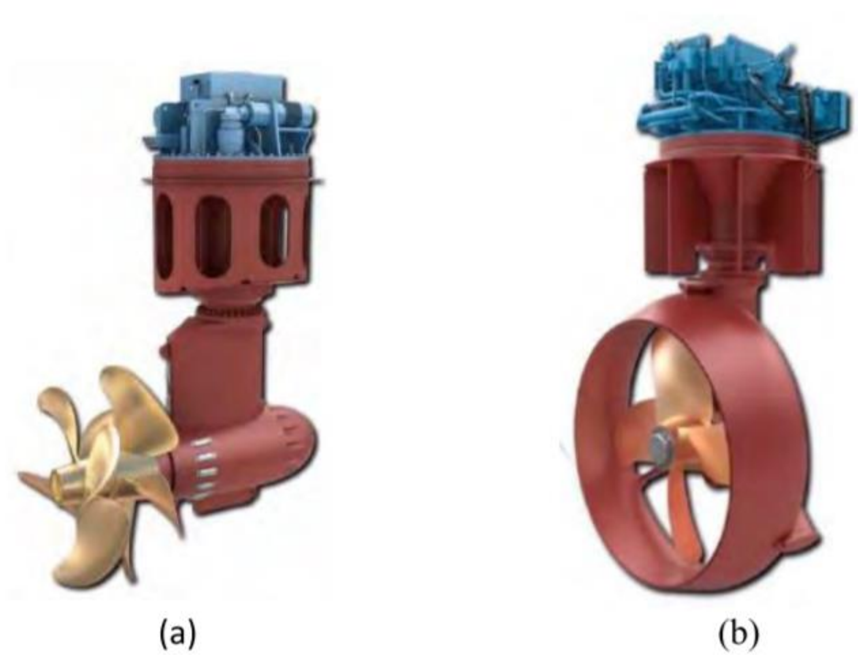

Figure 4.4: Azimuth Propulsion: (a) L-type and (b) Z-type

Podded

Podded Propulsion is a type of azimuth thruster, the only difference is that an integrated motor/propeller unit is mounted on the same shaft inside a sealed pod unit as shown in Figure. The podded propulsion was introduced in the early 1990s when the electric motor was installed directly on the fixed propeller shaft in a diving, rotating pod. While this concept was developed to enrich the performance of icebreakers, it was conceived early with the additional benefits of hydrodynamic and transmission performance. After the first application on the patrol passenger ship, "M/S Elation", its advantages confirmed that the shelled propulsion almost overnight became a new standard of passenger ships. In the direct driven pod, the engine is located outside the main hull of the ship inside the pod, which allows the propeller to be mounted directly on the engine. This type of power supply offers significant advantages in terms of efficiency, reliability and space saving. The system is designed to have a minimum number of mechanical parts, and therefore mechanical losses, and provides exceptional flexibility, which is necessary for navigation in shallow water and in the boarding / disembarking situations, with excellent hydrodynamic characteristics.

Figure 4.5: Cruise vessel "M/S Elation" (lower right) equipped with Azipod propulsion frees up space compared to sisterships (upper left) that can be utilized for other purposes, e.g. grey water treatment.

Figure 4.6: Podded Propulsion System

4.2 APPLICATIONS OF ELECTRIC PROPULSION IN SHIPS

Icebreakers

For icebreakers and other ice-going vessels the propulsion plant have to be dimensioned for navigation in ice, at different levels, but also need to have certain ocean going capabilities. In addition to specialized icebreakers, due to increased ship traffic in the northern Polar regions, other vessel types like container vessel, shuttle tankers, oil tankers, and now also LNG carriers are ordered with icebreaking capabilities. This means that the propulsion design need to tradeoff between a high bollard pull demand, propeller overtorque, and open water efficiency. For icebreaking operation, variable speed electric motor drives have proven to be superior to mechanical propulsion, due to high over torque capability and fast and accurate torque response of the electric motor drives.

Podded propulsion when introduced in the 1990s, were originally designed for icebreaking purpose and has proven its performance for this vessel type since. With the ability to combine full speed control of propeller in every direction, full 360 degrees steerable units, and direct transmission from motor to propeller the performance in ice is superior to shaft-line and other mechanical alternatives. This opened up possibilities for traditional ocean going vessels to be designed for icebreaking in stern direction and open water sailing in forward direction.

Figure 4.7: Icebreaker

Dynamic Positioning (DP) Drilling Vessels

While cruise vessels are mostly about sailing, maneuvering, and powering a small city, drilling vessels are designed to keep position and do required drilling operations. This gives different requirements to power and propulsion plant, and for these vessels, the safe and reliable operation is the key focus. These vessels are operated with a DP control system, in order to keep the vessel in correct position. This control system delegates required propeller speed and power to all the units in order to counteract the environmental forces from wind, waves and currents. The propulsion plant is therefore optimized for this application, giving maximum thrust force. The subsystems of a DP system are the power system, thruster system and DP control system. The design intend is that in occurrence of a single fault within the DP system the loss of the affected subsystem or component will not compromise the station capability of the vessel. Redundant components and system have to be immediately available with sufficient capacity to maintain the DP operation. In order for a vessel to keep position by use of DP control system, several thruster and propulsion units are equipped on the vessels both stern and bow. The propulsion plant is therefore optimized for this application, giving maximum thrust force. Each thruster is designed and constructed with a nozzle around the propeller in order to direct the water flow straight astern as much as possible. A nozzle creates additional resistance in sailing/ transit operation, and is therefore only used on vessels optimized for performance at vessel speeds around 0 knots, known as bollard pull. Besides the propulsion/thruster plant the biggest electrical consumer on these vessels is the drilling system, a fact that favors the use of an integrated power system for electricity production.

Figure 4.8: Dynamic Positioning Drilling Vessel

LNG Carriers

Liquefied Natural Gas (LNG) Carriers were one of the latest vessel types to make a distinct shift from mechanical propulsion to electrical propulsion. The operation profile of a classic LNG carrier with a long-term charter does not intuitively favor electric propulsion as they most of the time operates on design speed. However, these vessels used steam turbines as main propulsion as one of the last major vessel types because of the available boil-off gas from the cargo. LNG Carriers, as the name indicates, carries Liquid Natural Gas at a temperature of minus 163 C. The gas is kept liquid by insulated tanks, but is allowed to boil in order to avoid too big pressure built up. The simplest way to deal with this boil-off gas was to burn it and produce steam for propulsion demand. This is not as efficient power production as from combustion engines, meaning that when the technology made combustion engines available for operating with gas as fuel, this opened the way for electric power production from the boil-off gas, and thereby utilizing electric propulsion. The main motivation for the change was the increased efficiency and hence reduced fuel costs, and as the usage of Natural Gas as fuel on these ships are almost 100% the emissions are very low compared to traditional Heavy Fuel Oil (HFO) fueled ships. Another factor playing a role is that the LNG Carrier business has also changed the last years from only long term chartered vessels on fixed routes to more short term and even spot trading of LNG. This again favors electric propulsion with the flexibility and the capability to keep also high propulsion efficiency at lower vessel speeds. Most of the LNG Carriers with electric propulsion are utilizing the single propeller configuration as the conventional ships. The electric part is split into two separate systems giving a 50% redundancy on this part. Further redundancy is implemented in some key equipment.

Figure 4.9: LNG Carrier

Cruise Ships

Electric propulsion is nowadays applied most cruise ships, because it is by far the most economical approach to combine the requirements of high hotel load and variation in the load profile. As the cruising business has boomed and vessels have increased in size and passenger capacity, the requirements for comfort, safety and availability have gained notable importance. By shifting into electrical propulsion it is possible to reduce the space occupied by main propulsion systems and above all to place the different equipment in a way that the spaces reserved for passengers are maximized in terms of volume and quality. More specifically, the revenue is proportional to the number of passengers and therefore the less the volume used by machinery the highest the volume dedicated for passengers, both in terms of beds and in terms of recreational areas. This is not only related to the absolute volume occupied by machinery but also related to the quality of the volume (spaces above the water line come at a very high price). Consequently, cruise vessels adopted electric propulsion initially in order to optimize the machinery spaces by using a bigger number of smaller engines. Azimuthal thrusters are popular in the high-end cruisers, since they provide improved efficiency and maneuverability, low noise and vibration levels, and flexibility in the engine room design. Most of the cruise ships are configured for two (or three) propellers, mostly because of redundancy and feasible power limits of electric drives. Podded propulsion gained entrance to this market about 1995, and is today one of the most used propulsion variants on new cruise vessels.

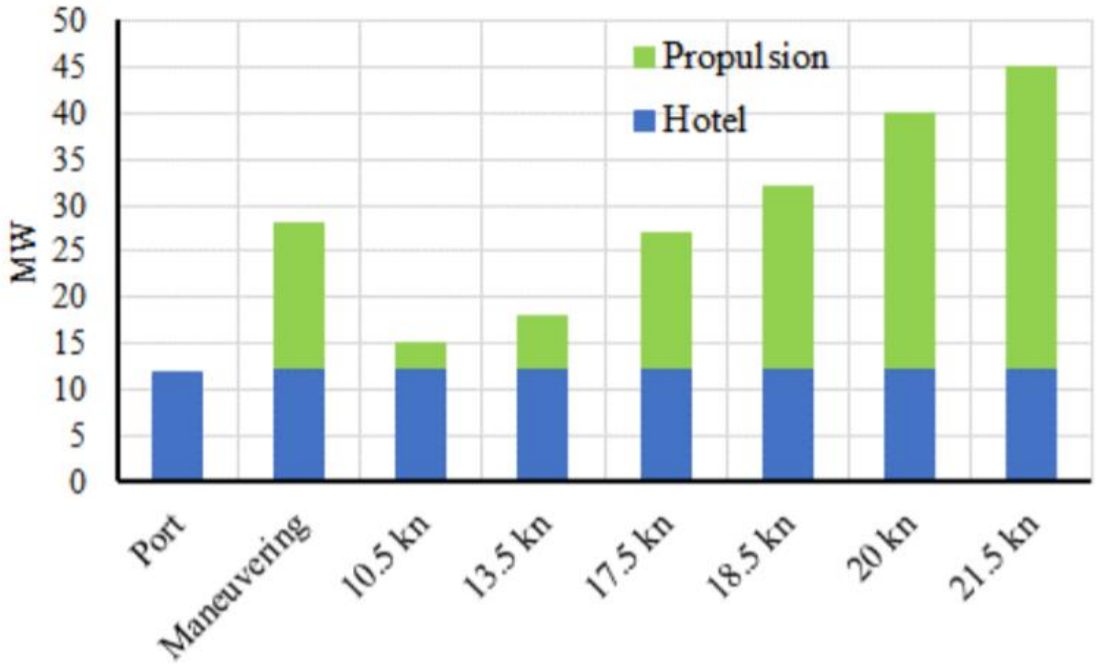

Figure 4.10: Typical electrical power distribution in a cruise ship.(''Turning the page in ship propulsion'', by switching to LNG- Wärtsilä 2008)

Among the first modern use of ac drives was the retrofit of ''Queen Elisabeth II'' in the early 1980s.They were the largest marine electric motors installed on cruise vessel (formerly transatlantic passenger liner).The ship was built in 1968 for Cunard Line, originally steam powered. After experiencing mechanical problems in 1983, and an electrical fire in 1984, Cunard decided to convert her from steam to diesel. The conversion to diesel-electric propulsion would improve the fuel efficiency and was expected to save Cunard £12 million a year in fuel costs. The vessel was fitted with 9 MAN B&W 9-cylinder engines, each weighting about 120 tons, all connected in a diesel-electric configuration, each driving a generator rated 10.5MW at 10kV. The electrical plant, in addition to powering the vessel's auxiliary loads (and hotel services) through transformers, drove two synchronous salient-pole 44MW propulsion motors (each weighting more than 400 tons), which, one on each propeller shaft, drove two five-bladed variable-pitch propellers. The vessel's service speed of 28.5 knots could be maintained using only 7 of the diesel-electric sets. At this speed the fuel savings were about 35% compared to the old machinery. The maximum power output from the power plant was 97,000 KW, in comparison with the old machinery's 82,000KW.

Figure 4.11: Queen Elizabeth II

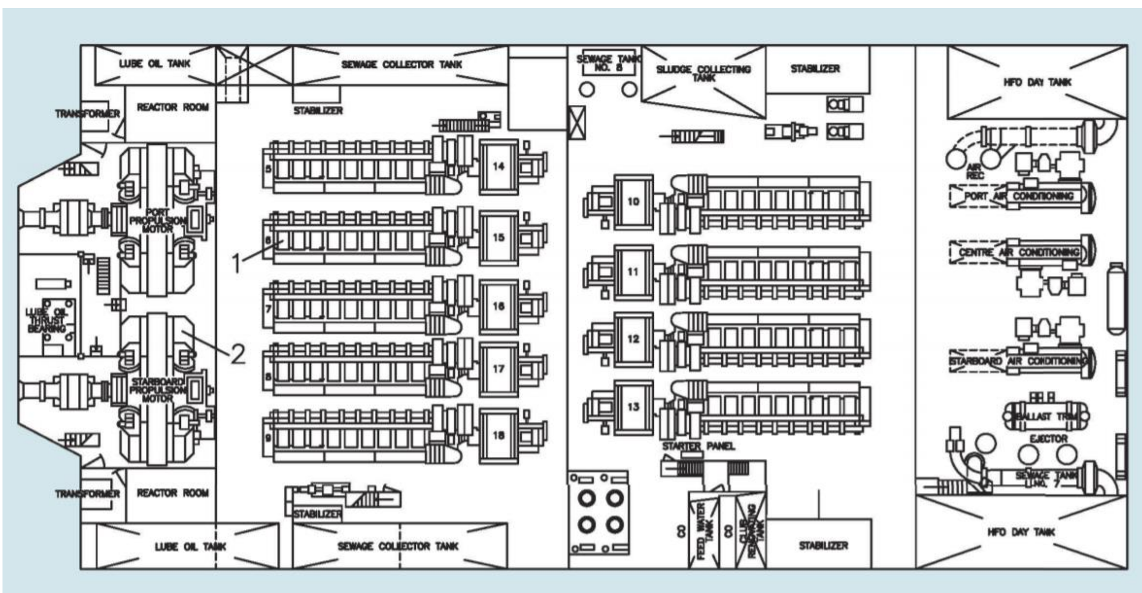

Figure 4.12: The Queen Elizabeth II propulsion layout 1: The diesel engine. 2: The electric motor

With this distributed configuration the power is fractioned, with the consequent advantage of operating the combustion engines at their rated condition or close to it. Furthermore that constant rotational speed gives several advantages:

- Maximum efficiency operation for the engines
- Reduce engine usage (20-25% with respect of a single engine unit)

- Gearbox stage elimination
- NOx emissions reduced together with a more efficient pollution abatement devices
- Redundancy and safety, in case of one or two engine failures, the rest of the system can produce enough energy for navigation
- Reduced volume of the electric motor, allowing ship hull designs with lower friction in water, thus improving the navigation speed

Queen Mary 2 is another distinctive example of a large cruise ship adopting electrical propulsion. It is the largest, longest, tallest, widest and most expensive passenger cruise vessel ever built. Its power plant includes two gas turbines and four diesel engines that produce 118 MW of electricity, enough to power a city of 300,000 people. More than two-thirds of this energy is used to power the propulsion system, as each of four electric motors draws 21.5 MW during full power. Queen Mary 2 is outfitted with four Rolls Royce Mermaid pod propulsors, two fixed and two azimuthing, i.e., rotating 360 degrees.

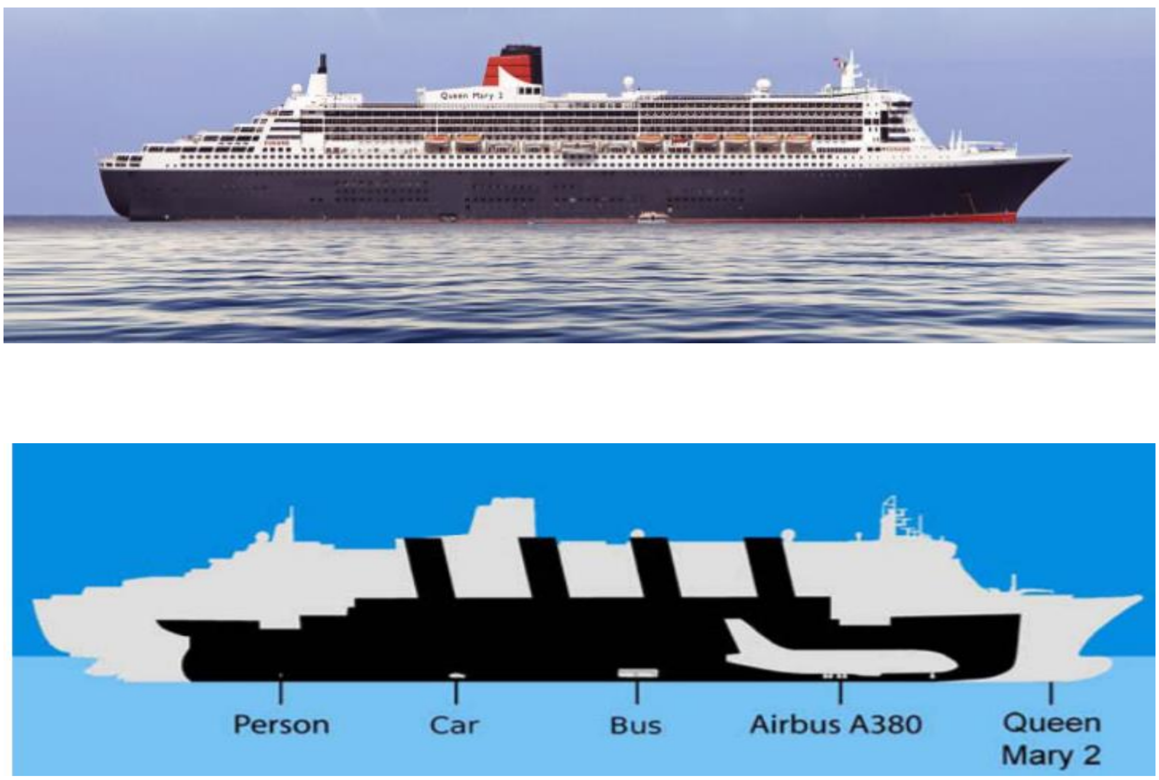

Figure 4.13: Queen Mary 2

5. ENERGY STORAGE SYSTEMS FOR SHIPS

Energy costs and environmental concerns are placing greater importance on marine industries. To reduce exhaust emissions and save fuel, many kinds of solutions have been proposed. Energy storage (ES) and associated technologies have received a substantial increase in attention in recent years, not least in the maritime industry. Used either as main power source or in parallel operation (hybrid) with combustion engines ES contributes to improve safety, efficiency and performance of future electric propulsion vessels.

5.1 Flywheel Energy Storage System

A mass which rotates about an axis is called flywheel. Energy can be stored mechanically in angular momentum of the rotating mass in the form of kinetic energy.

The flywheel in its simplest form used in machines is a large wheel with all its mass concentrated in the periphery. This helps all points to have the same high moment of inertia. A special feature of flywheels and at the same time their main advantage, is their ability to resist changes in their rotational speed, due to their high inertia. This property helps to maintain their rotational-kinetic energy for long periods of time, making them ideal for any kinetic energy storage system.

As shown in Fig. , the structure of a typical flywheel system is composed of several critical parts which can be divided as explained in the followings:

- Rotor: the main part of flywheel storing energy while rotating.
- Bearings: components that support axis of the rotor to spin remaining on a fixed position.
- Generator/motor: transforms the kinetic energy stored in the rotor to electrical energy which should be consumed by the power grid and vice versa.
- Power electronics interface: tunes and controls the out-put/input voltage and frequency of the generator/motor.
- Instrumentation and monitoring: monitor the state of flywheel to make sure that it is operating within design boundaries.
- Housing: a chamber around the flywheel which maintains vacuum around the flywheel and protect against hazardous mechanical destructions and failures.

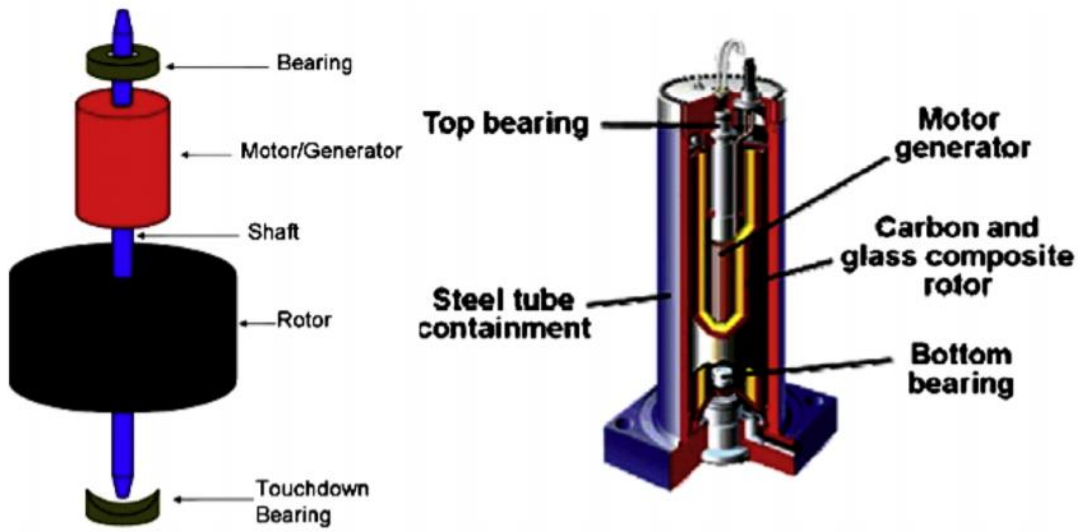

Figure 5.1: Critical components of a typical flywheel storage system and its cross-sectional view

Basically, the operation of flywheel is divided in two parts. First, when the energy should be stored in the flywheel mass, it accelerates through a motor which is connected through its shaft. Second, during the deceleration, the rotational mass speed declines and the motor operates in generator mode discharging the stored energy back into the power grid. According to above mentioned definitions, flywheels are always operating between these two modes to balance supply and demand keeping tuned the power grid at its nominal frequency of operation.

The flywheels are capable of switching from the full generation mode to full absorption mode in a few seconds. This advantage enables them to deliver the electrical energy at least twice as much as the electrical energy which is produced by a typical natural gas-fired power plant while reducing the carbon emissions to half. Also, this rapid response nature of flywheel systems brings the ability of resolving the problem of short-term transients caused by sudden changes in power system loads. For example, the problems such as voltage drop which may lead to a power outage.

As compared to ultra-capacitors, flywheel provides intermediate characteristics in terms of power and energy density. Flywheel technology caters with many shortcomings of prior energy storage technologies by having limited temperature sensitivity, chemical hazardless, similar rate of charge and discharge cycle, higher life cycle, reduced space, and weight.

Some possible advantages and disadvantages in vessels applications follow below.

Flywheel advantages:

- Potentially high efficiency of cyclic operation
- High cycle life
- No reactive chemicals or gassing characteristics

- Charge and discharge rates have parity, determined by motor generator torque No safety risks when motionless

Flywheel disadvantages:

- Complex designs for support, cooling, vacuum, and protection
- Safety containment, particularly for metallic flywheels operating at high rotational speeds

5.2 Super Capacitors

Super capacitors technology is a type of energy storage device, which is increasingly used in industry and automotive applications, such as cars, buses and high speed trains. Different from the conventional capacitors, SC (super capacitors) have a larger area for storing the charge and closer distance between the electrodes, that is why they achieve much greater capacitance within the same volume.

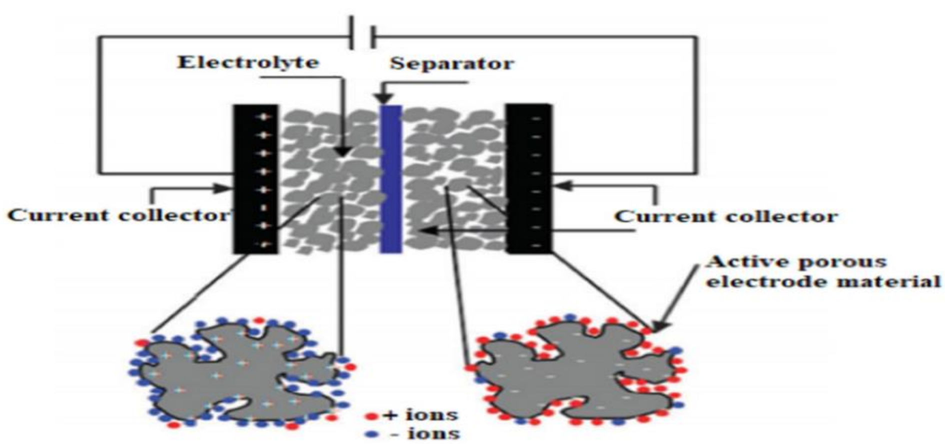

Figure 5.2: Schematic illustration of a super capacitor

The electric double-layer (EDL) phenomenon was firstly described by Helmholtz in 1853, and patented by General Electric Company in 1957, which used porous carbon material with high specific area as electrodes for double-layer structure formation. Nippon Electric Company (or NEC) licensed a SC product as a memory backup device that marked the first commercial application in 1971. Structurally, the SC consists of two electrodes, a membrane separator, and electrolyte as shown in Fig.

The two electrodes are insulated by the membrane separator and impregnated to the electrolyte. The membrane separator only permits the ion mobility but prevents electric contact. SCs store electrical energy mainly through the formation of the double-layer capacitor structure at the interface between the electrodes and the electrolyte. This energy storage mechanism involves no chemical phase or composition changes, apart from fast and reversible Faradaic reactions existing on the electrode surface, which also contribute to the total capacitance. The characteristic of electrostatic charge transfer results in a high degree of recyclability. Compared to conventional capacitors, the high capacitance of SCs originates from the high specific area of the electrodes, which is largely determined by the used electrode materials and their physical properties (e.g. conductivity and porosity). Advanced electrode materials have been the area of intensive study.

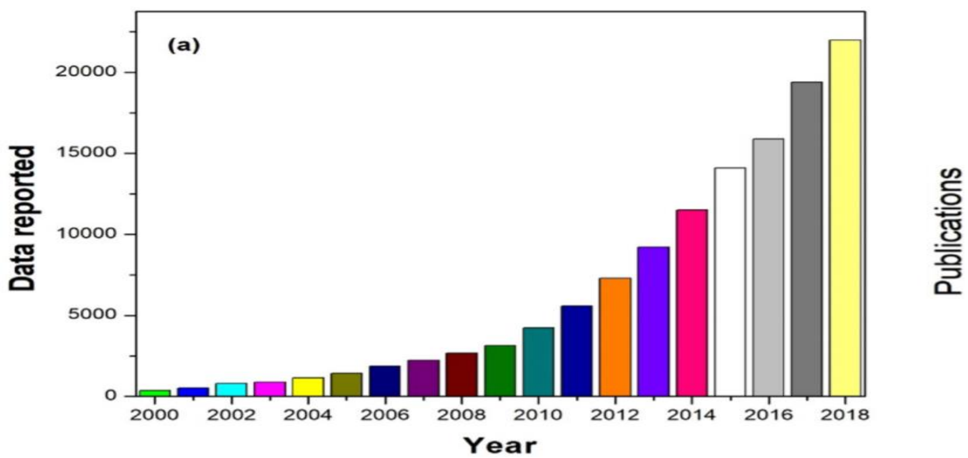

Figure 5.3: Statistical survey on the research activities toward supercapacitor: a) presents the number of publications including articles, books, and other authentic open literature (2000–2018) from a search using supercapacitor as a keyword in Google Scholar.

In line with recent technical advances in electric-powered devices in terms of cycle life, charge time, and specific power, SCs have become promising candidates in diverse fields that require high energy throughput (hybrid electric vehicles) and stable energy throughput (sensitive automation, computer chips, and portable electronic devices) . SCs can already be used in power systems that require high-power throughput, but not necessarily at the maximum level of energy storage capacity. SCs cannot store the maximum level of energy, which restricts their use in energy backup devices.

In 2017 American Bureau of Shipping (ABS) published a Guide for use of Supercapacitors in the marine and offshore industries. This proves that marine industry recognizes the application of supercapacitor technology in support of the hybrid initiatives and its benefits for improving energy efficiency of the onboard power plant. The Guide outlines the types of supercapacitors, including electrochemical capacitors and lithium ion capacitors, and defines requirements for design, construction and installation of supercapacitors in marine and offshore applications. It is emphasized that supercapacitors, as a commercialized energy storage device, exhibit beneficial characteristics such as high power density, a fast charging/discharging process, no thermal runaway characteristics, and wide operating-temperature range. The maritime industry is increasingly interested in using supercapacitors as an energy storage solution when quick energy delivery is required during a peak loading condition. In particular, offshore supply vessel owners are focusing on supercapacitors to provide energy supply during high-load operations, such as using power thrusters for dynamic positioning while station keeping according to ABS.

The supercapacitor technology has been operating in applications around the world for many years, and has a proven track record in cranes and vessels. The power is steady and can be precisely targeted, which promotes fast work and therefore saves time.

Interest in this advanced, reliable technology is growing. Particularly in times of expensive fuels, electrification with this dynamic component as a 'hard worker' offers economic advantages that make savings and cost reductions possible. The sustainable aspect is also key, especially when this becomes a requirement – for example, at emission-free and engine-free port entrances.

A 2020 report by Allied Market Research valued the global supercapacitor market at a modest $3.27 billion in 2019, but predicted that would reach $16.95 billion in 2027—a five-fold increase in just a few years.

5.3 Fuel Cells

The use of the fuel cell as an electricity generator was invented by William Grove in 1842.Fuel cells work like batteries, but they do not run down or need recharging. They produce electricity and heat as long as fuel is supplied. A fuel cell consists of two electrodes—a negative electrode (or anode) and a positive electrode (or cathode) — and an electrolyte. A fuel, such as hydrogen, is fed to the anode, and air is fed to the cathode. In a hydrogen fuel cell, a catalyst at the anode separates hydrogen molecules into protons and electrons, which take different paths to the cathode. The electrons go through an external circuit, creating a flow of electricity. The protons migrate through the electrolyte to the cathode, where they unite with oxygen and the electrons to produce water and heat.

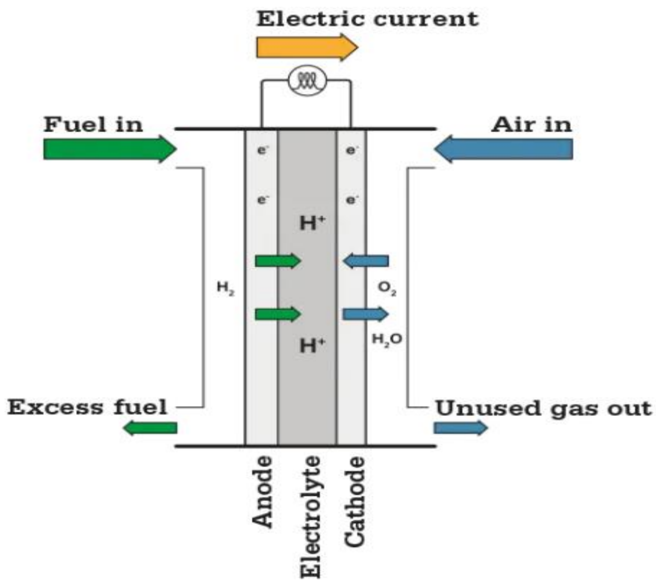

Figure 5.4: A fuel cell creates electric energy from using hydrogen as a fuel and air, with only water as a by-product

Several unit cells are arranged in a so-called fuel cell stack to match voltage and power levels required in different applications. A fuel cell power pack consists of a fuel and gas processing system and a stack of fuel cells that convert the chemical energy of the fuel to electric power through electrochemical reactions. Different fuel cell types are available, and can be characterized by the materials used in the membrane.

Due to the success and efficiency of combustion engines, fuel cells have not been widely considered for general use, and, until recently, fuel cells have been applied only for special purposes, such as space exploration and submarines. However, rising and fluctuating fuel prices and a strong focus on reduction of global and local emissions have led to an increasing focus on the development of fuel cells for application in other areas as well. Market studies (Fuel Cell Today, 2013) have revealed that fuel cells should no longer be considered as a technology for the future; they are already commercially available today for a diverse range of applications (e.g. portable electronics, power plants for residential use, and uninterruptible power supply). When looking at the maritime industry in particular, a wide range of maritime fuel cell projects are ongoing, and the application of the fuel cell in commercial shipping projects is increasing.

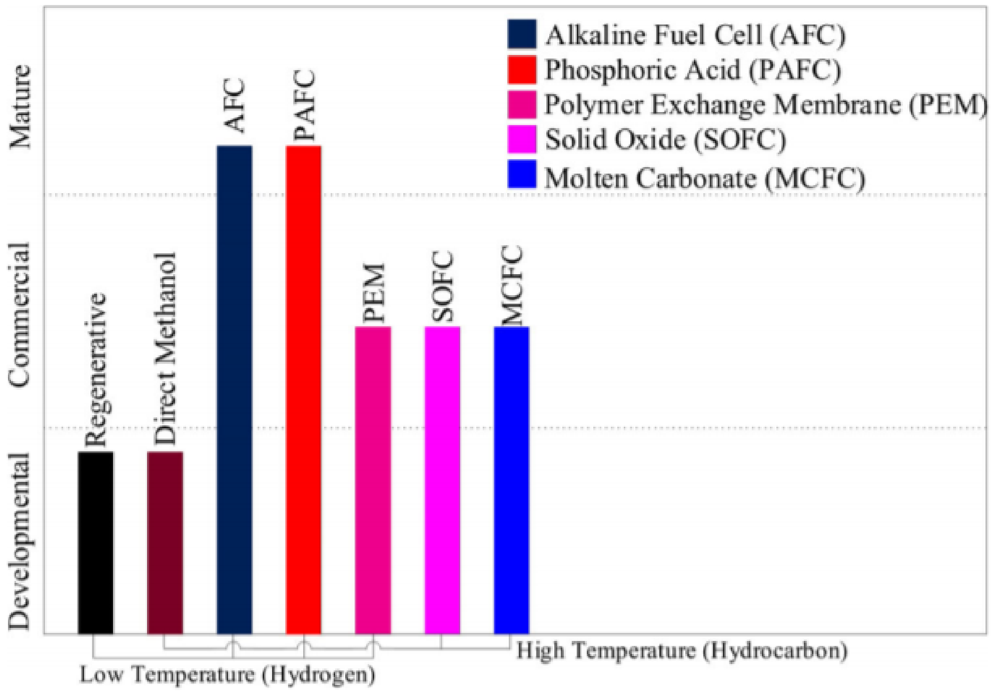

Figure 5.5: Different types of fuel cell and their technical maturity

Projects with Fuel Cells

Australian Global Energy Ventures and Ballard are to start experimenting with a new fuel cell-powered ship called C-H2. Some key specifications of the C-H2 ship:

- The design for the containment system is made up of two large (20 metres diameter) tanks, contained within the hull of the ship, that will store ambient temperature hydrogen at an operating pressure of 3,600 psi (250 bar) and will have a combined storage capacity of 2,000 tonnes of hydrogen.
- The design of the C-H2 ship will also allow for the evaluation of smaller capacity ships for demonstration or pilot scale export projects.
- One of the key considerations in designing a steel tank for storing hydrogen is that the hydrogen molecule is so small it can enter the steels molecular structure and over time can cause the steel to suffer from embrittlement.
- Technical requirements for such a large tank mean that it needs to be constructed in layers. Stainless steel will be used as the innermost layer, being resistant to hydrogen embrittlement, with six surrounding layers of ductile high-strength alloy steel to meet strength and fatigue requirements.

All American Marine and SWITCH Maritime completed the aluminum construction and outfitting of a 85-passenger zero-emissions, hydrogen-powered, electric drive (e-ferry) named Sea

Change, that will operate in the California Bay Area (referred to as the 'Water-Go-Round' project).When launched in 2021 the Water-Go-Round will be the first fuel cell vessel in the US and the first commercial fuel cell ferry in the world.

The 20 metres, high-speed Zero Emissions Ferry will be the flagship for a planned future fuel-cell powered fleet, transporting commuters around the bay. The Sea Change is powered 360 kW of Hydrogenics fuel cells and 100 kWh of lithium-ion batteries on board and can reach speeds up to 22 knots for short bursts. With just the fuel cells, it can run continuously at 14 knots. The fuel cells are supplied with hydrogen from storage tanks creating electricity to run the electric motors and turn the vessels propellers, generating the ferry's movement. With the ship only producing water and electricity as a by-product, it is 100% emissions free.

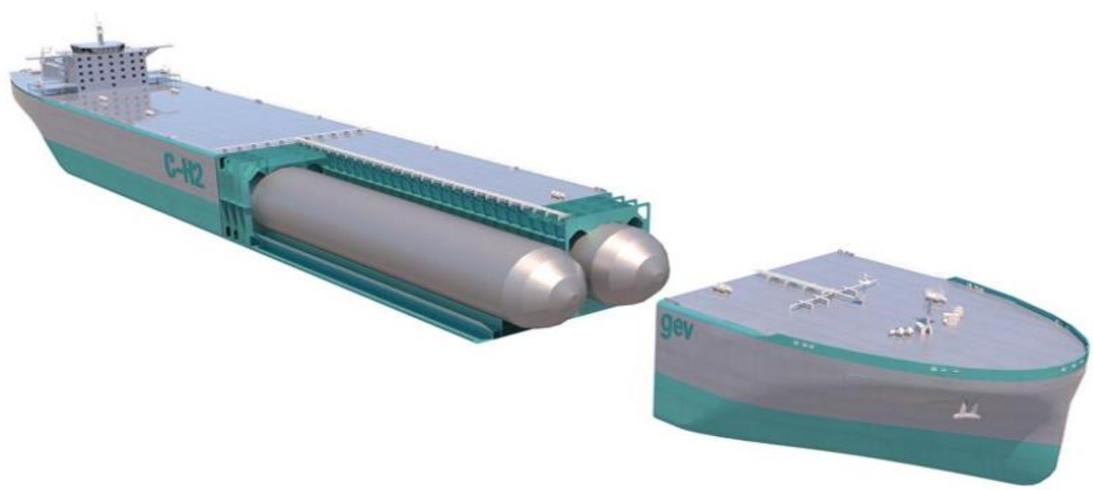

Figure 5.6: is an illustration of GEV's C-H2 general arrangement.

Figure 5.7: Sea Change

5.4 Batteries

Batteries are by far the most common used energy storage system for vessels. Battery technology development is primarily driven by consumer electronics and automotive markets. For shipping applications, the use of batteries can be separated in two main categories. The batteries can be used to create either an all-electric vessel - where batteries are used much the same way as diesel(as we can see below) or a hybrid vessel – where the role of the batteries is to supplement the other fuel and enable the system to operate as optimally as possible. In this section we will analyse how batteries can improve shipboard power systems and overall system efficiencies and operation through the use of batteries in hybrid configurations. In these cases, it is important to think of the batteries in a different way than just as adding another diesel with an amount of power that can be supplied to the power system. The battery enables a whole new approach to power system design and operation – and the benefits from battery implementation will be maximized when it is considered in this way. Below are some of the most important reasons for using batteries in hybrid ships, the precursors of fully electric ships.

Running Fewer Engines (Power Redundancy)

Several ship types have requirements for power redundancy for certain types of operations. This is particularly relevant for ships with dynamic positioning (DP) systems. The requirements for DP do not allow for the start of generators, and the redundancy requirements must therefore be ensured by the machinery in operation at any time (the spinning reserve). Running engines at low loads generally leads to higher specific fuel oil consumption, higher specific emissions, and increased maintenance costs. This enables fewer running engines, leading to reduced fuel consumption, emissions, engine running hours, and maintenance costs (Figure).

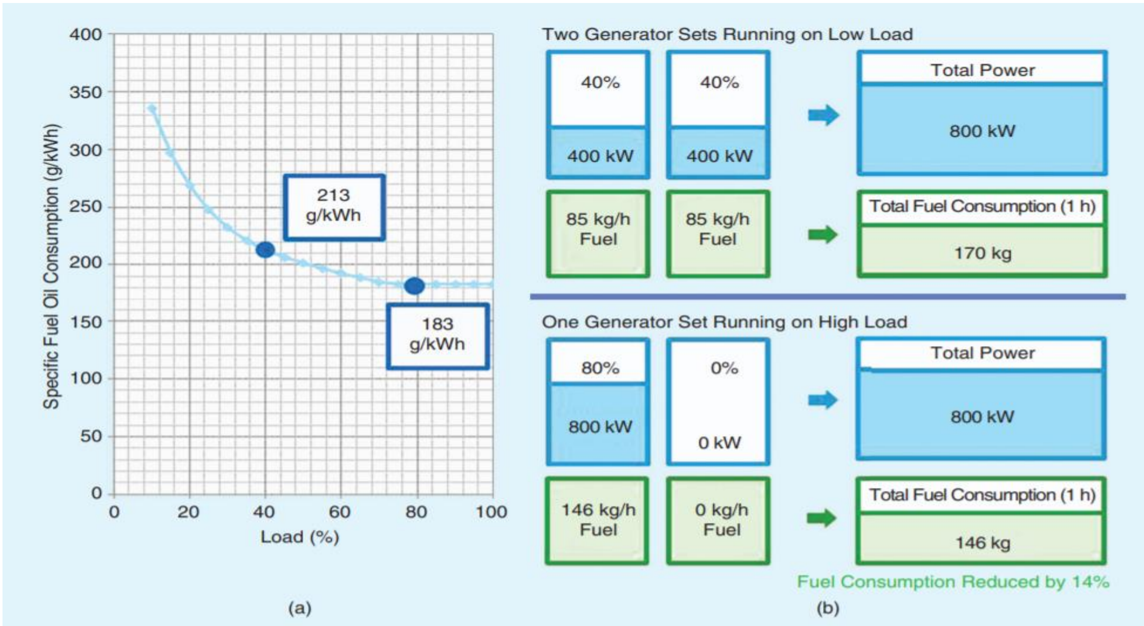

Figure 5.8: (a) The specific fuel oil consumption at different loads for a typical four-stroke diesel engine. (b) An example of the fuel savings achieved through running fewer engines at more optimal loads.

Running Engines at Optimal Loads

The specific fuel oil consumption and the emissions from an internal combustion engine are dependent on the engine load. Typically, engines are calibrated for optimal performance at 60–85% of the engine load. For ship types that experience large load variations during operation, the introduction of batteries may allow the engines to operate at an optimized point with respect to fuel oil consumption and/or emissions. This can be achieved by selecting the size of the engines such that they operate at optimal loads for most of the time, with additional power obtained from the battery when required. Furthermore, when the power requirements are low, the battery can be charged because of the excess energy production resulting from running the engine at the optimal load. Additionally, under operating conditions requiring very low loads, the ship may be able to operate on battery power alone for a certain period.

Avoiding Transient Engine Loads (Peak Shaving)

The fuel oil consumption and emissions are also affected by engine transients in the form of rapid increases or decreases in engine speed and/or load. The effects of the transients depend on the type of engine, the magnitude of the load variations, and the rate of change of the engine load. Introducing a battery may eliminate the engine load transients by ensuring a steady engine base load and covering additional transient loads through the energy storage device. Introducing a battery may eliminate the engine load transients through the energy storage device. The fuel savings achieved will depend on the engine used. Peak shaving is also expected to result in reduced engine wear and consequent lower maintenance costs.

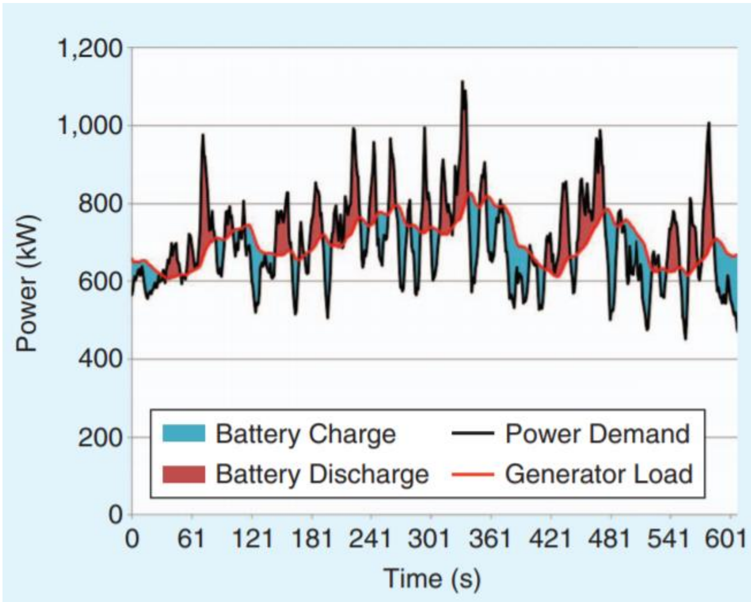

Figure 5.9: An example of peak shaving, which significantly reduces generator load variations in operations where large load transients are experienced.

Cold Ironing

The term cold ironing refers to the use of shore power to operate a marine ship when it is in a harbor. Cold ironing first came into use when all ships had coal-fired engines. When a ship was tied up in port, there was no need to continue feeding the fire and the iron engines would cool down, eventually going completely cold—hence, the term cold ironing. Recently, cold ironing has been considered as a means to mitigate local air pollution by significantly reducing and, in some cases, completely eliminating, harmful emissions from diesel engines.

6. Fully Electric Battery-Powered Ships

Fully electric is the term used in this thesis to refer to a vessel that gains all of its power from batteries and has no other power source on board. As mentioned earlier, a hybrid ship still uses an electric motor to turn the propeller, but the power is drawn from both batteries and diesel engines.

6.1 Lithium Battery Technology

A battery cell is an electrochemical device that converts electrical energy to chemical energy. The conversion is electrically driven through chemical reactions. A Li-ion battery is composed of two electrodes (a cathode and an anode) separated by an electrolyte (a good Li conductor but poor electron conductor). Upon discharge, lithium ions travel through the electrolyte from the high lithium chemical potential present at the anode to the low lithium chemical potential present at the cathode. The electron traveling in the external circuit can be used to perform external work. During charge, an external electrical potential is applied, and the process is reversed. On the cathode, Li ions are stored by “intercalation” in the crystal structure of a material. The chemical potential of cathode for lithium sets the voltage: the lower the chemical potential of lithium, the higher the battery voltage. The capacity is determined by how much lithium can reversibly enter the crystal structures and re-emerge. The amount of lithium stored per unit weight and per unit volume is a key issue, as is keeping the cathode material stable for the hundreds or thousands of cycles required from the battery. The faster the lithium and the electrons move in the cathode, the higher the power density out of the battery.

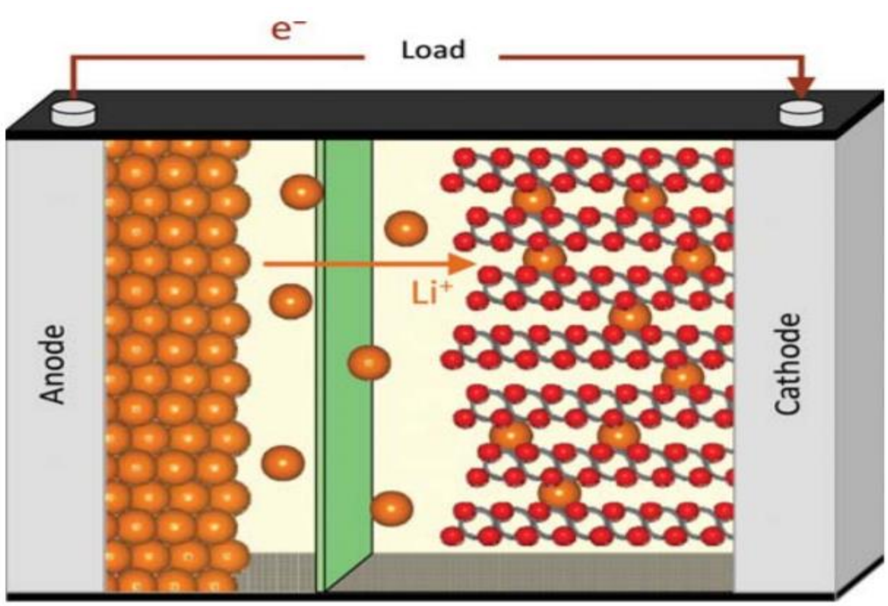

Figure 6.1: Schematic representation of a rechargeable lithium battery

Today, lithium ion batteries dominate the electromobility market. A combination of variables makes lithium extremely unlikely to be displaced. Firstly, it has the highest electrochemical potential of any element in the Periodic Table, which means that no other element can generate such a high battery voltage. Secondly, it is the lightest metal, which works with its voltage to give it the highest theoretical specific energy of any battery anode. Thirdly, it is now a mature technology that continues to benefit from mass production economies. The cost of lithium ion battery storage has dropped significantly over the last ten years and continues to do so. Fourthly, despite some battery fires incidents, public acceptance is generally good, which makes introducing new types of lithium ion battery much easier than introducing an entirely new kind of battery to the market. How it all started with Lithium ion Battery?

6.2 Lithium Battery History

A key driving force for lithium battery development in the 1970s was the diffusion of consumer electronics that brought into the market a series of popular devices such as electronic watches, toys, and cameras. These devices required batteries capable of providing a good powering operation with a small volume size and a contained price.

All the batteries fabricated in the initial stage of the lithium battery technology were of the primary type. The success of these batteries stimulated an obvious interest for moving to secondary, rechargeable systems. The breakthrough was obtained in 1978 by the development of the so-called “insertion” or “intercalation” electrodes. These are typically based on compounds that can reversibly accept and release lithium ions in and out their open structure. To allow the ongoing of the electrochemical reaction, as well as of the cycle life, the material must assure a reversible evolution of both the electronic structure (to balance the positive charge of the inserted lithium ions) and of the crystal structure (to prevent the lattice to collapse). By exploiting this type of cathode materials, the first commercial rechargeable lithium batteries appeared in the late 1970s to early 1980s, one manufactured by the Exxon Company in the USA with a TiS_2 cathode and one by at that time Moli Energy in Canada with a MoS_2 cathode, both using liquid organic electrolytes.

However, some operational faults, including fire incidents, led to the rapid conclusion that there were some problems that prevented the safe and long operation of these lithium batteries. These were clearly associated with the anode; due to its very high reactivity, lithium metal easily reacts with the electrolyte with the formation of a passivation layer on its surface. The layer, usually called solid electrolyte interface (SEI) is permeable to lithium ions, thus allowing the ongoing of the discharge process. However, irregularities on the SEI surface may lead to uneven lithium deposition upon charge with dendrite formation that eventually grew to short the cell. In extreme cases, these uncontrolled events gave rise to overheating effects with thermal runaway and explosions.

The route for the development of the rechargeable lithium battery had to pass through the replacement of the lithium metal with another more reliable electrode. The happy medium was that of relying on a totally new concept that considered the combination of two insertion electrodes, one capable of accepting lithium ions, operating as the anode, and the other, capable of releasing lithium ions, operating as the cathode. During charge, the negative intercalation electrode acts as a “lithium sink” and the positive one as “lithium source” and the total electrochemical process of the cell involved the transfer of lithium ions between the two intercalation electrodes. The process is then reversed upon discharge and cyclically repeated.

Actually, the concept of this type of battery dates back to the late 1970s and practically demonstrated in the early 1980s .However, more than 10 years had to pass before the concept could reach a practical application as demonstrated by a battery introduced by the Japanese Sony manufacturer in 1991. The distinctive feature of the Sony battery was in the definition of proper electrode materials, identified in graphite as the “lithium sink” anode and in lithium cobalt oxide as the “lithium source” cathode. Particularly important is the role of the cathode that must be capable of providing the lithium ions to assure the electrochemical process, as well as to accept them back in a reversible matter to assure the life of the battery. These characteristics were provided by $LiCOO_2$, a material disclosed by Goodenough in 1980.

The work of Sony triggered interest worldwide and, presently, many battery manufacturers, mainly located in Asia, are producing lithium ion batteries. The success of these batteries was, and still is, outstanding. Due to their specific properties, mainly in terms of relatively high energy densities, lithium ion batteries power the lives of millions of people each day. From laptops and cell phones to hybrids and electric cars and vessels, this technology is growing in popularity due to its light weight, high energy density, and ability to recharge.

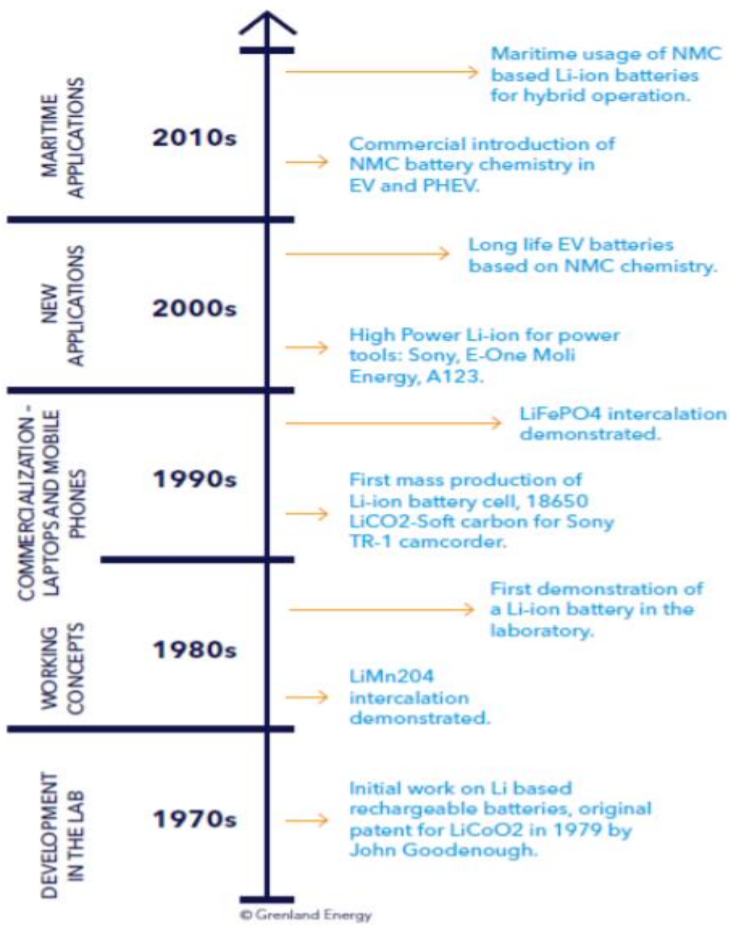

Figure 6.2: Milestones of lithium-ion battery technology

The Nobel Prize in Chemistry 2019 was awarded to three scientists, John B. Goodenough, M. Stanley Whittingham, and Akira Yoshino, for their work in developing this battery. According to the official Nobel Prize organization, “this lightweight, rechargeable and powerful battery is now used in everything from mobile phones to laptops and electric vehicles. It can also store significant amounts of energy from solar and wind power, making possible a fossil fuel-free society.”

Most of the researchers throughout the world are now concentrating on developing and modifying the lithium ion chemistry to achieve better performance considering the costs and other physical effects. The challenges for the management of battery charging and discharging within the ideal operating range of State Of Charge have become more important topics for advanced research and technology. Now, the advancement of Li-ion battery production and application is growing beyond expectation. The volume of research publications is shown in Fig, specifically in engineering and physics research areas, on Li-ion battery technology and applications from the Web of Science database over the last decade. The research has progressed dramatically throughout the world, though it was limited to a few Asian countries such as Japan, South Korea and China. Moreover, the research publications of Li-ion battery have been increasing over the years, as shown in Fig.

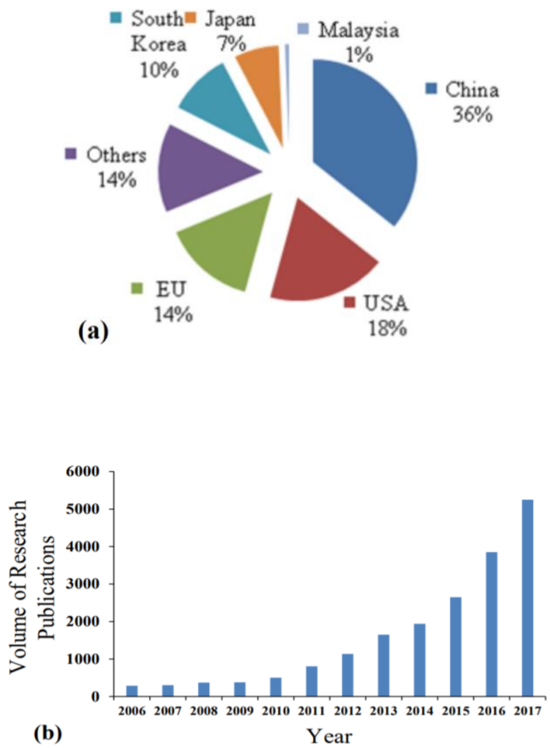

Figure 6.3: a) Research percentage on Li-on battery by country, b) Volume of research publications per year

6.3 Future Promising Battery Technologies

Solid State Battery

The co-founder of the Li-Ion battery, and recent Nobel prize laureate, John B. Goodenough, together with fellow researcher Maria Helena Braga, published a paper in 2017 on their development of a low-cost battery based upon a glass electrolyte that is non-combustible and has a long cycle life with a high volumetric energy density and fast rates of charge and discharge: the solid-state battery.

These batteries use a solid-state electrolyte, rather than the liquid which is used in conventional lithium ion batteries. Nominally then, the cathode and anode are the same materials used in typical lithium-ion batteries now (for instance NMC and carbon/graphite). A solid-state battery has the potential to improve most of the concerns with present-day Li-ion batteries. The glass solid-state battery can have three times higher energy density by using an alkali-metal anode (lithium, sodium or potassium) that increases the energy density of a cathode and delivers a long cycle life. A solid-state electrolyte is presumed to be non-combustible or at least resistant to self-ignition. The non-combustible nature of solid-state batteries also reduces the risk of thermal runaway, allowing for a tighter packaging of the cells and consequently improving the design flexibility and volumetric density.

However, solid-state batteries are currently on a low technology readiness level and basic research is still ongoing, with consequent uncertainties and concerns related to high production cost and scalability. The challenges in development are converting the insertion or deposition of the solid electrolytes to a process that is compatible with today's manufacturing practices, all without affecting the durability or cost of the final product while adding benefits such as better energy & power density, increased safety, and higher throughput.

Some accounts claim that in the initial phase of development, solid-state technology is estimated to have high cost varying in the range of ~$800/kWh to ~$400kWh by the year 2026. The comparatively high cost may significantly hinder production and uptake of solid-state batteries. However, with improved power density and lower cost, our Energy Transition Outlook forecasts that 50% of all new passenger vehicle sales in 2032 will be electric8. With a market breakthrough of solid-state batteries, it's likely that these numbers will grow even further.

Despite its promises of performing for longer and without bursting into flames, the chances of solid-state taking over conventional Li-ion batteries number one spot will depend largely on a broad range of factors, from EV industry demand to overcoming initial costs.

Metal Air Battery

Metal-air battery is considered one of the most disruptive technologies that is likely to be implemented into multiple applications by 2050. A metal-air battery is one that uses a metal anode and air as the cathode. There are several types of metal-air batteries, but only Li-air, Na-air K-air and Zn-air are considered rechargeable. Rechargeable Al-air and Mg-air have been reported, but with very limited cyclic ability. Metal-air batteries are composed of four parts: metal anode, electrolyte, separator and air cathode. When discharged, the metal anode is oxidized and dissolved in the electrolyte. The metal ions are transferred as energy carriers through the electrolyte and separator to the air cathode. Here a reduction reaction occurs with the air. In most cases, it is oxygen that reacts with the metal-ion, but reactions with lithium and CO2 has also been reported.

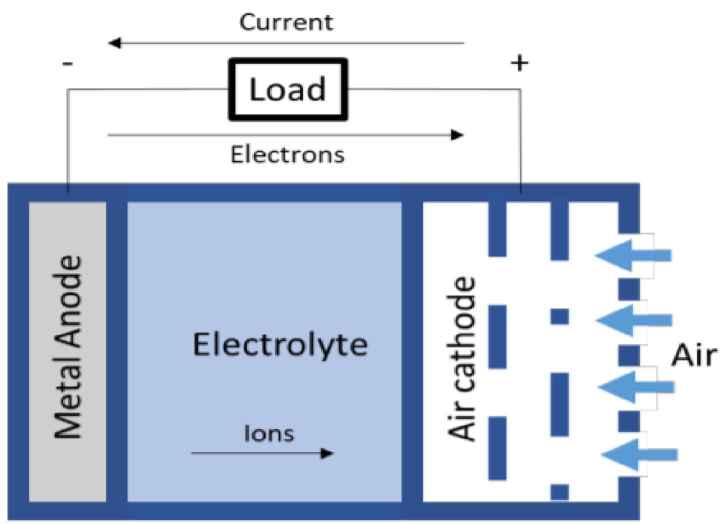

Figure 6.4: Principle of a metal- air battery

Metal-air batteries with both liquid and solid state electrolyte are a topic for research. There are still several obstacles to overcome before these batteries can be applied. When liquid electrolyte is used, dendrites and sei (solid electrolyte interphase) layers are formed at the anode, increasing the risk for internal short circuit and affect the performance respectively. Replacing the metal anode with an ion inserting material could improve these issues, but this will limit the specific energy of the battery. Furthermore, volatility of electrolyte and sluggish kinetic processes in the cathode are troubling the researchers.

The use of solid-state batteries will avoid the volatility of electrolytes and suppress the growth of dendrites. The conductivity of solid state electrolyte is very low, and needs to be improved to utilize the specific energy potential in metal-air batteries. Ceramic and polymer electrolytes are promising candidates to improve this aspect. If these challenges are solved, the solid-state metal air battery has the potential of both achieving high specific energy, energy density and can improve safety. Thus, this technology has the capability of inducing huge switches for battery powered vessels. Solid state combined with Li-air is regarded as the most promising option for ultra-high energy density.

There are still several obstacles to overcome before these batteries can be applied. We also should not forget that when looking so far into the future, the actual results of what we will see in the market have a non-negligible uncertainty in them.

6.4 Lithium Battery Manufacturing

The majority of global Lithium-ion cell manufacturing is in China, the United States, Asia, and Europe, as shown in Figure. China dominates today with nearly 80% of the global manufacturing capacity (~525 GWh); additionally, it has over 60% of near-term (2025) 1,400 GWh, which is either planned or under construction (Figure 16). For comparison, the Rocky Mountain Institute projects a 2023 global Li- ion manufacturing capability of 1,300 GWh with half of that in China.

The United States is the second-largest manufacturer of battery cells at 8% of current global capacity, primarily due to the Tesla-Panasonic plants in Nevada. The United States also has 6% (~90 GWh) of the facilities planned/under construction. With aggressive new legislation and government-backed financing, manufacturing in Europe is expected to grow significantly.

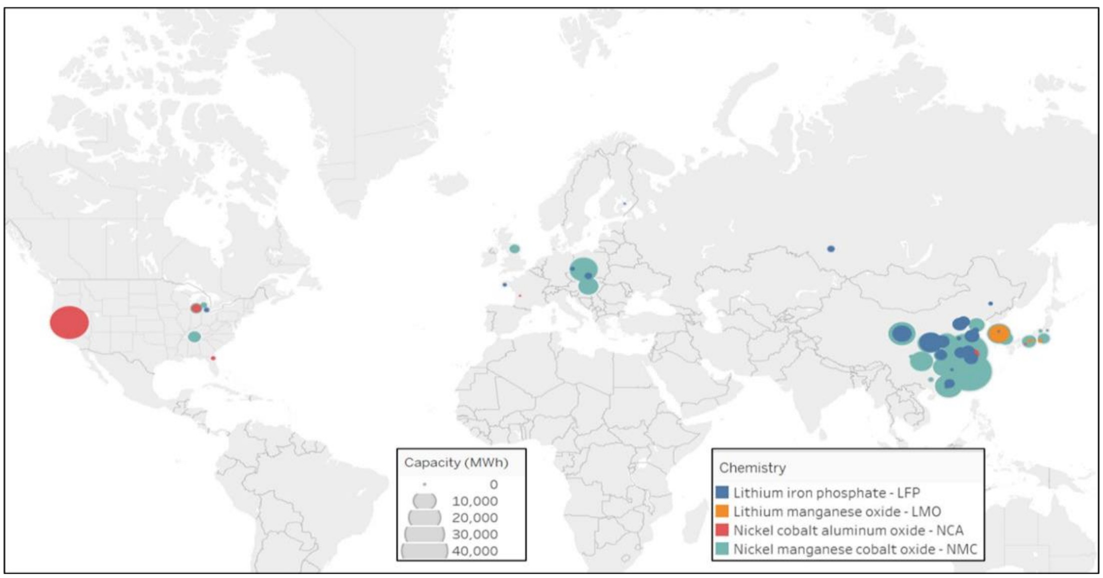

Figure 6.5: Global Li-ion battery cell manufacturing

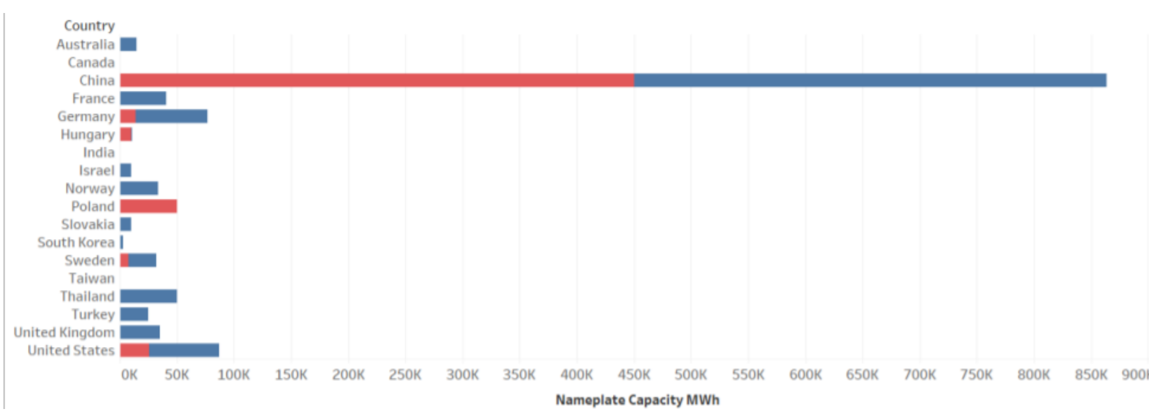

Figure 6.6: Li-ion battery manufacturing planned (blue) or under construction (red)

Although China's dominance in manufacturing today is well-established, mobility-fueled growth may change the global footprint in the future. Europe has enacted strong policies and incentives for local and regional growth that supports Electric Vehicles (EVs).

The European Battery Alliance (EBA) was created to build a globally competitive, innovative and sustainable European battery value chain. The Commission's approach, in establishing the EBA in 2017, was unusual at the time as it focused on supporting the whole value chain from research to access to raw materials, but also all aspects of battery production, second life of batteries and recycling. In recognition of the fact that battery development and production is capital intensive and requiring very high technological industrial processes, the Commission identified a range of existing and planned EU policies and financing to support six priority areas:

- Securing access to raw materials
- Supporting European cell manufacturing
- Strengthening industrial leadership through accelerated research and innovation programmes
- Securing a highly-skilled workforce along the value chain
- Supporting a sustainable EU battery cell manufacturing industry and
- Ensuring consistency with broader frameworks.

Currently, two gigafactories—plants that will produce enough batteries for over one million EVs—are planned in Dourvin, France, and Kaiserslautern, Germany, with French and German public investment of €1.5 billion and €3.5 billion, respectively, from private investors.The European Battery Alliance projects that the market for European-manufactured batteries could be €250 billion by the mid-2020s

6.5 Batteries Terms

Primary Cell/Battery. A cell or battery that can only be discharged once. It is not designed to be rechargeable and is usually protected from a charging current.

Secondary Cell/Battery. A cell or battery that is intended to be subjected to numerous charge and discharge cycles in accordance with manufacturer's recommendations.

Battery Management System. Electronic system associated with a battery module/pack that has functions to cut off in case of overcharge, overcurrent, over-discharge, and overheating. It monitors and/or manages its state, calculates secondary data, reports that data, and/or controls its environment to influence the battery's safety, performance, and/or service life.

Battery Cell. The basic functional electrochemical unit containing an assembly of electrodes, electrolyte, and terminals that is a source of electrical energy by insertion/extraction reactions of lithium ions or oxidation/reduction reaction of lithium between the negative electrode and the positive electrode. It is not ready for use in an application since it is not yet fitted with its final housing, terminal arrangement, and electronic control devices.

Battery Module. A group of cells connected together in a series and/or parallel configuration with or without protective devices and monitoring circuitry.

Battery Pack. Energy storage device that is comprised of one or more cells or modules electrically connected. It has a monitoring circuitry that provides information to a battery system.

Battery System (Array). System comprised of one or more cells, modules, or battery packs. It has a battery management system to cut off in case of overcharge, overcurrent, over-discharge, and overheating.

Battery Space (Compartment). The space in which the battery system is physically located.

Battery String. A number of battery cells or modules are connected in series to produce the same voltage level of the battery system.

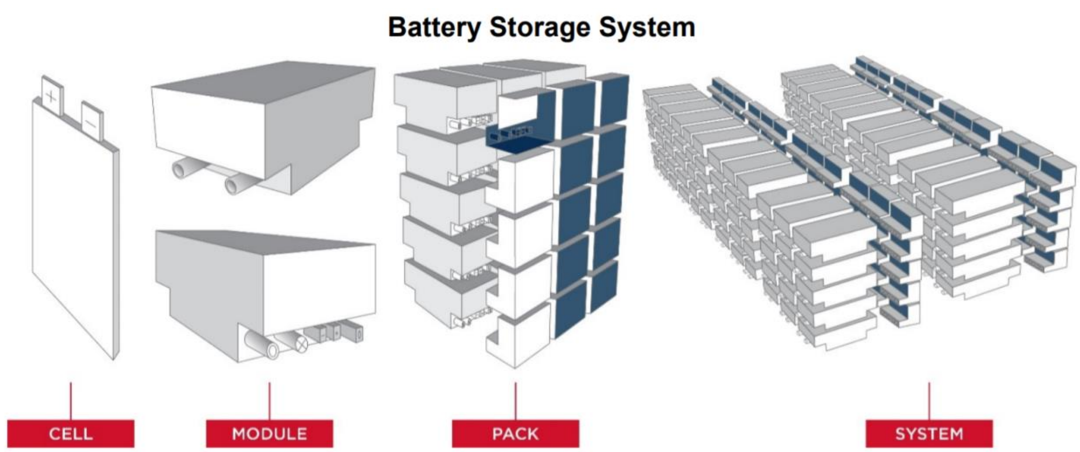

Figure 6.7: Battery storage system illustration

Cell Balancing. The mechanism of forcing all battery cells within a battery module to have identical voltages. Cell balancing is achieved by means of a "balancing circuit" (usually implemented as part of the Battery Management System). In the absence of a balancing circuit, one or more cells (as a result of ageing differently over its lifetime) may become under-charged or overcharged, either of which can lead to a failure of the battery module. Cell balancing is not an instantaneous process and requires some time for its completion.

Power Management System (PMS). A complete switchboard and generator control system controls power generation and distribution including multiple switchboards and ring bus systems. The PMS on board a vessel is responsible for functions such as load sharing among different power sources, load shedding when generated power is insufficient, etc.

Rated Capacity. The capacity value of a cell or battery determined under specified conditions and declared by the manufacturer.

State of Charge (SOC). Available capacity in a battery expressed as a percentage of rated capacity.

State of Health (SOH). An indication of the general condition of a battery compared to its ideal conditions (i.e., a new battery). The unit of SOH are percent points (100% = the battery's conditions match the battery's specifications).

Thermal Runaway. The condition where the rate of heat generation within a battery component exceeds its heat dissipation capacity. Thermal runaway can have many causes, such as overcharging, high ambient operating temperatures, etc., and can lead to a catastrophic or destructive failure of the battery cell.

6.6 Battery System Cost

The costs of batteries depend mainly on two factors, the choice of battery cells and of the battery system. Figure 6.8 shows an estimation of the cost components for a lithium-ion cell. This is an average estimation and will vary depending on the specific cell chemistry, design and manufacturer. Material costs are by far the highest expense at an estimated 60% of the total costs.

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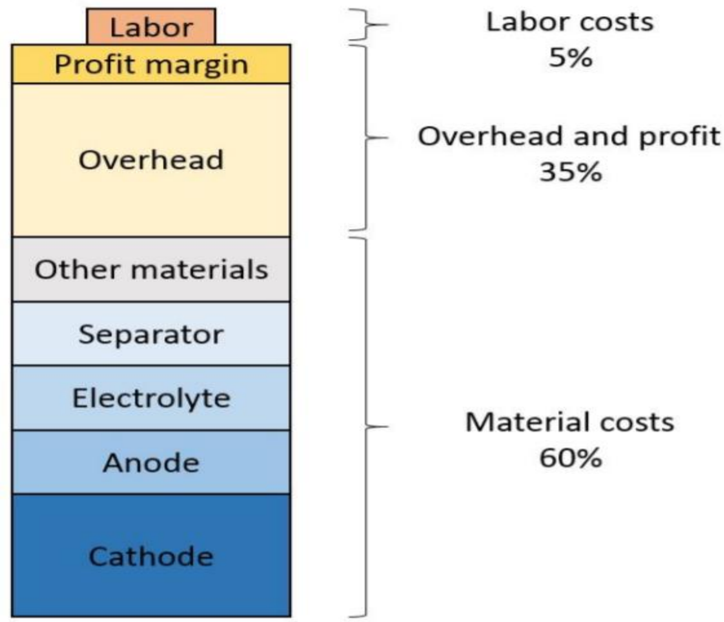


Figure 6.8: Cost components for lithium-ion battery cells

Over recent years, high scale production and capital investment into the battery production process made lithium-ion battery packs cheaper and more efficient. Today, over a decade of investments has produced factories that are scaled for continuous roll-coating processes to produce Li-ion batteries cost effectively. The infrastructure investments have been made, economies of scale are being achieved, and the optimization of the coating and reduction of mass of materials are occurring incrementally year over year. This demonstrates a staggering demand for energy storage worldwide and could be attributed to the fact that the world is moving towards a renewable energy-based economy where transport based on electricity plays an increasingly large role.

Depending on the application, the system can include multiple monitoring and safety systems. The main factors that influence the total costs for battery systems are safety, performance and reliability. Especially for marine battery systems, safety is a key factor. The first safety feature is the battery management system (BMS). The BMS measures the state of the cells to make sure certain limits in for instance voltage and temperature are not exceeded. In case of an internal short circuit or thermal runaway, the system must provide for protection of the other cells. System housing and internal cell support also needs to provide for an extra level of safety. Controlling the temperature of the battery cells is very important for safety as well as performance. Cooling the batteries is important to avoid them from overheating, which can lead to thermal runaway, or affecting the life expectancy of the batteries. Thermal management can be done by active or passive air-cooled or liquid-cooled systems, varying in costs, performance, size and energy requirements. Power electronics, wiring and connectors are also depending the overall costs of the system.

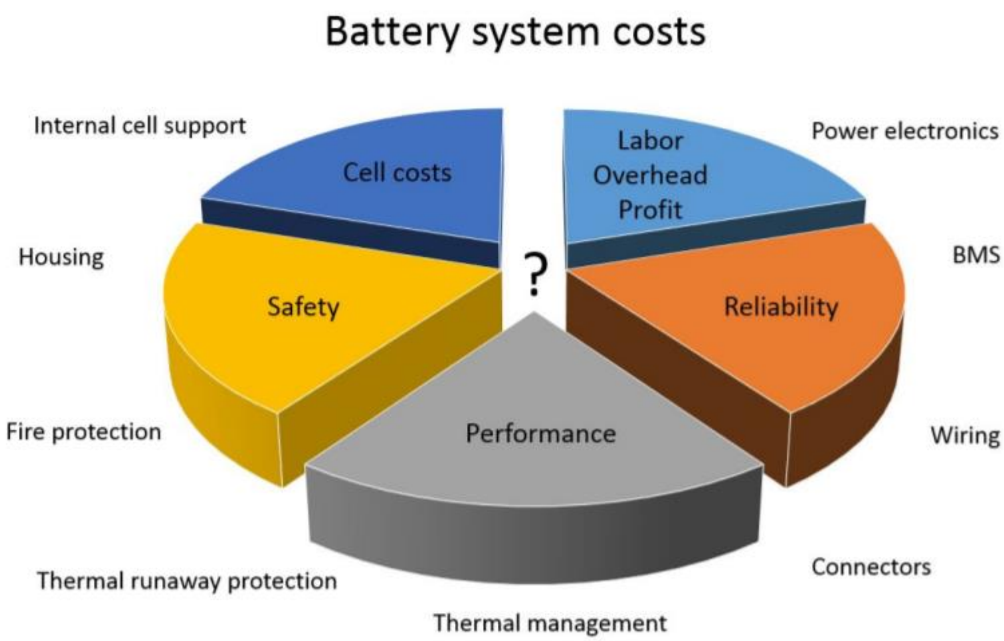


Figure 6.9: Cost determining factors for battery systems

A common misunderstanding on battery costs is that people read the news about electric cars and the battery cost dropping to 100-200 USD/kWh. It is important to understand that then they are usually talking about the battery cell, or maybe a module, for a mass-produced system for cars. Ships require more custom-made systems with higher requirements for the battery, particularly with regard to safety, as mentioned before. The “marinization” of the system means that maritime battery systems become significantly more expensive than car batteries. Nevertheless, marine battery systems costs are projected to be reduced following the exponential decrease in cost that applies to other packs of lithium ion batteries. This makes the perspective for fully electric vessels even better in the future, as the battery is the major contributor of the high initial cost of an electric ship.

Figure 6.10 shows the representative cost of a 4.065 MWh marine battery installation (the initial cost in 2015, and then the cost for replacing the battery if it becomes exhausted at various points from 2020 onwards) from the electric ferry Ellen which operates in Denmark.

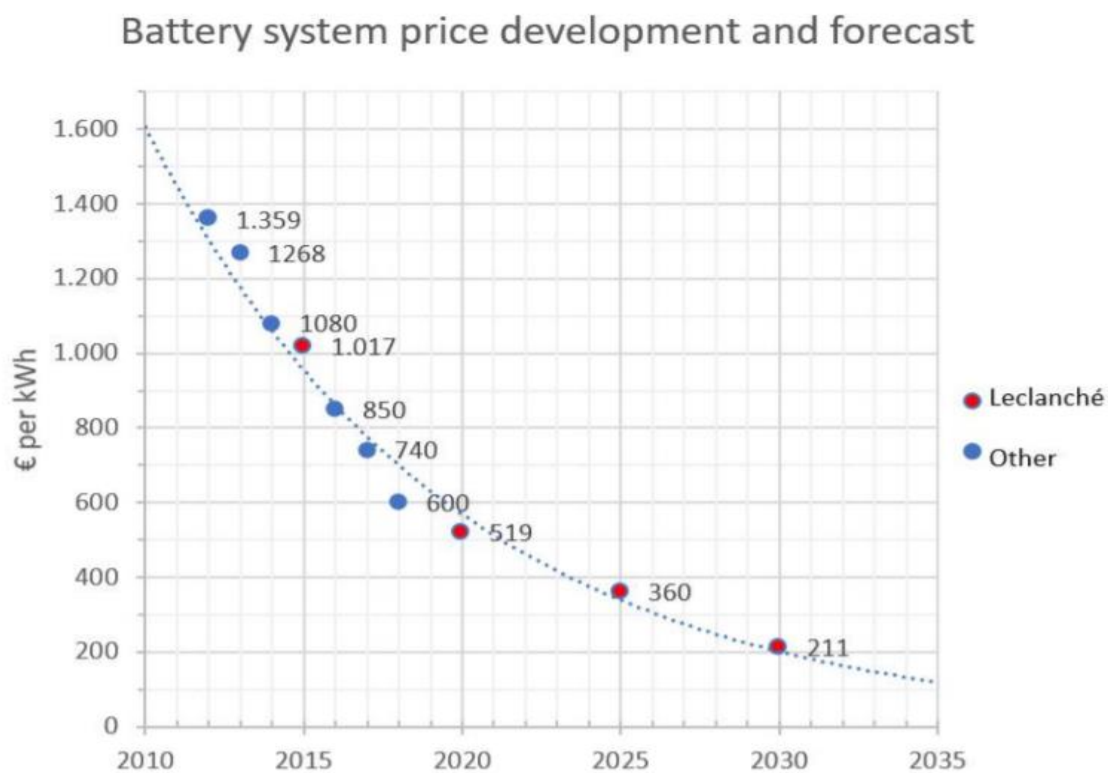


Figure 6.10: Battery system price development and forecast

This is despite the rising cost of lithium (Figure 6.11). The reason for the reduced cost of lithium ion batteries is entirely due to intense focus on efficient mass manufacture for the automotive industry, in facilities such as the gigafactories.

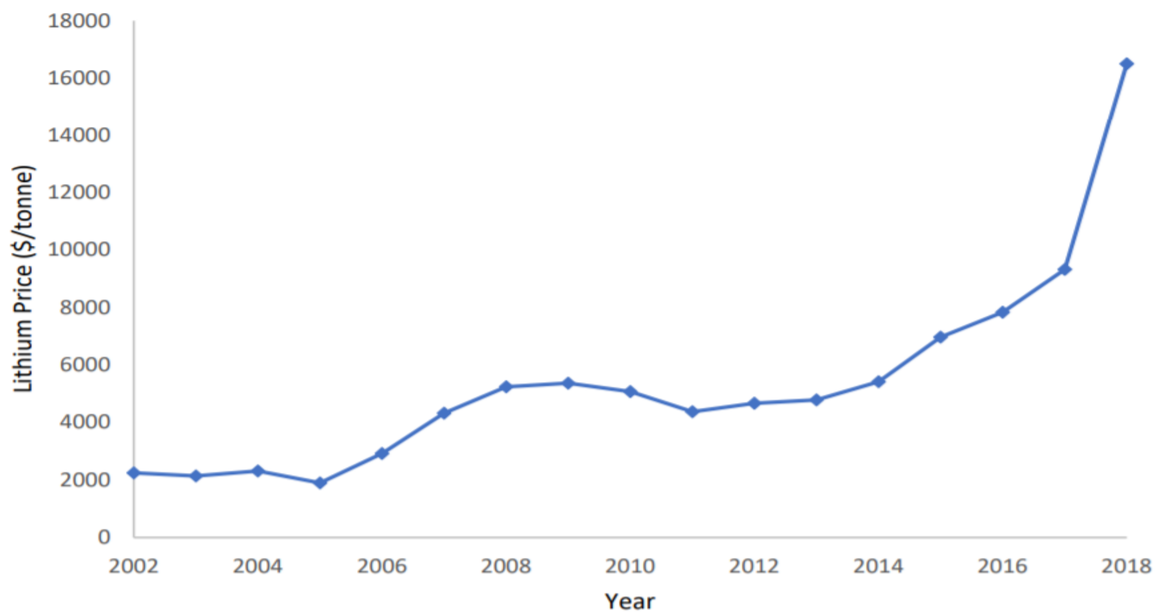


Figure 6.11: Lithium price per year

6.7 Battery ships augmentation

There is clearly an uptake of ships with batteries according to data retrieved from Maritime Forecast to 2050—Energy Transition Outlook (DNV) for year 2018, as merely 0.15% of the entire world fleet (by number of ships) were on battery (fully electric or hybrid), but 3.07% were on order; These numbers are however rapidly growing in line with IMO's ambitions for emission reductions by year 2050 (see IMO targets above).

The Maritime Battery Forum maintains an online ship database, providing insight in the current market of vessels with batteries. According to their statistics per 2019, there are more than 300 vessels that either have batteries installed on board already or are on order (see Figure). Norway and Europe are in the lead when it comes to the area of operation for vessels with batteries, as shown in Figure.

As the statistics show, the largest segments in terms of maritime batteries are car/passenger ferries, other activities (i.e. research vessels, patrol vessels and yachts), and offshore supply and other offshore vessels. Figure shows the battery application distribution, where hybrid is the most common choice.

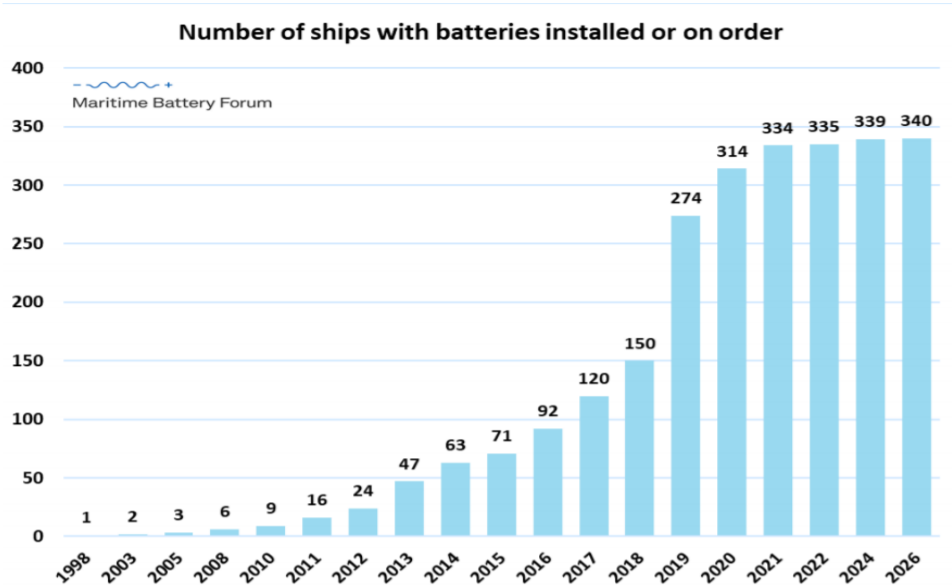


Figure 6.12: Total number of ships with batteries (installed and on order-Maritime Battery Forum 2019)

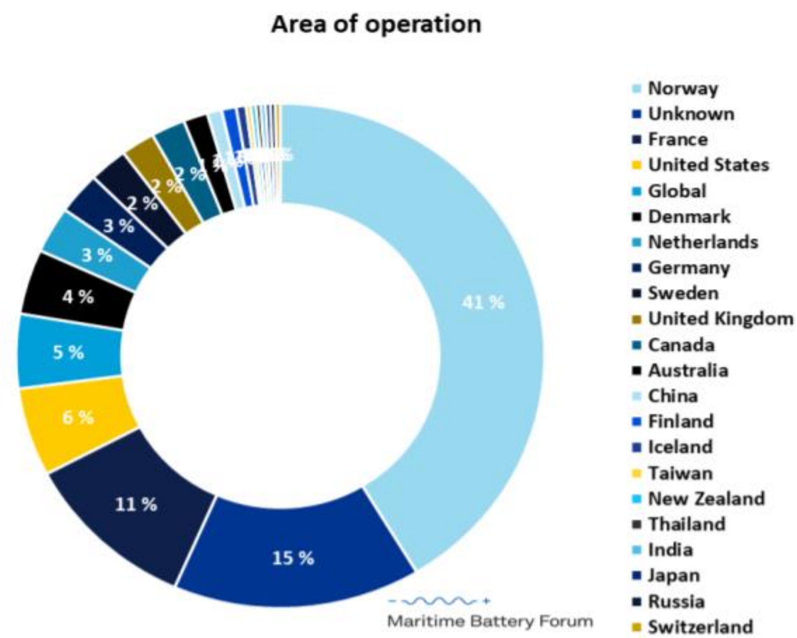


Figure 6.13: The area of operation for the vessels with batteries installed or on order (Maritime Battery Forum 2019)

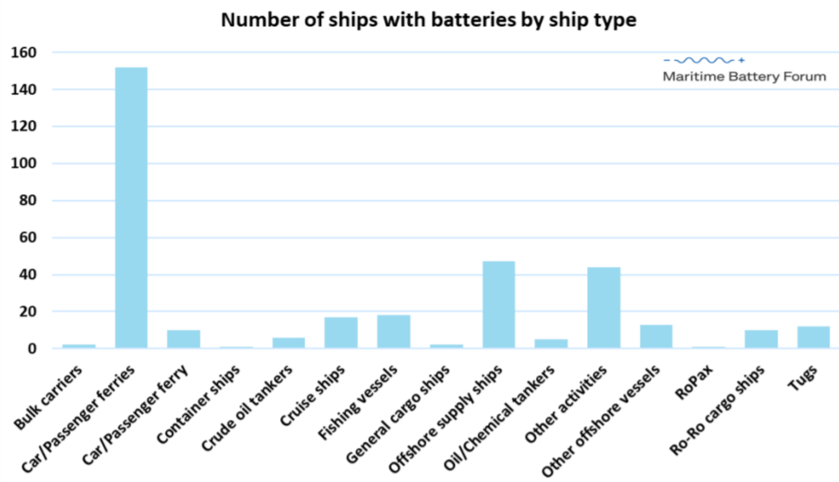


Figure 6.14: Number of ships with batteries by ship type (Maritime Battery Forum 2019)

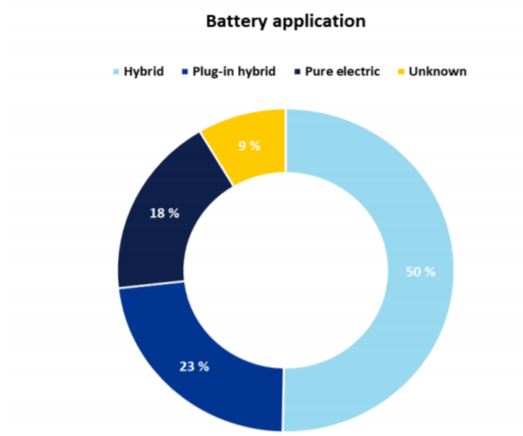


Figure 6.15: Number of ships with batteries by battery application (Maritime Battery Forum 2019)

In Norway, significant governmental incentives and corresponding industrial development efforts have been recently dedicated to reduce emissions from domestic marine transportation. It is a specific focus in Norway to cut the emissions in its world heritage fjords, as recognized by the UNESCO, pushing for zero emission vessels for passenger and car transportation across the fjords. Norway is, therefore, at the forefront of electrification of ferries and other vessels for short-distance transportation. As an example, it is expected that the country will have 70 battery-electric ferries by 2022. Moreover, around 98% of generated electricity comes from renewable energy sources, mostly hydropower, and charging from shore is therefore providing green electric energy to the onboard batteries.

6.8 NOTABLE BATTERY-POWERED SHIPS

Stena Jutlandica

Ferry operator Stena Line is planning to add a 1,000kWh battery system to its Stena Jutlandica ferry, which operates between the cities of Gothenburg, Sweden and Frederikshavn in Denmark. The project involving Stena Jutlandica, which operates on the Gothenburg-Frederikshavn route, is being carried out in steps.

Step one, which is presently underway, is about switching to electrical operation to reduce the use of diesel generators, as well as for maneuvering and powering the bow thrusters when the ship is in port. In the second step, battery power will be connected to two of the four primary machines, which means that the Stena Jutlandica will be able to run on electrical power for about 10 nautical miles inside the Gothenburg archipelago out to Vinga Lighthouse. In step three, all four primary machines will be connected to the batteries and the ship will be able to cover the 50 nautical miles between Sweden and Denmark solely on electrical power.

The reason for execution in multiple steps is to enable testing and assessment while the project is underway. If the project is successful, battery power can be considered for other vessels within the Stena Line fleet. Work with step two has begun and the goal is for implementation within about three years, according to Stena Line.

Figure 6.16: Stena Jutlandica ship

ELLEN E-FERRY

In 2015 the European Commission announced a project to build the world's first fully-electric ferry, able to travel more than 20 nautical miles, thanks to what would be one of the biggest batteries in the world, in a maritime setting at least.

Able to carry 31 cars or five trucks, and as many as 198 passengers at capacity, Ellen will sail between Søby on the island of Ærø, and Fynshav in Denmark, operated by the Municipality of Aeroe (Ærø Kommune). At almost 59.5 metres long and 13 metres wide and with a top speed of between 13-15.5 knots, it will cut the travel time of a single trip to 55 minutes, down from the 70 it takes a fuel-powered vessel currently operating on the route.

A significant part of the design specification was to use lightweight materials, ensuring the ferry uses as little power as possible. The use of steel was restricted to just the specially-designed hull, with the bridge constructed of aluminum instead. Deck furniture is constructed from recycled paper rather than wood.

The ship has two battery rooms, both below deck in the middle and towards the stern. Each contains 10 battery strings – made up of 42 unique modules – offering a total capacity of 2,150kWh per room. When fully charged the vessel boasts 4.3MWh of power, more than enough to complete its 22 nautical mile round-trip between charges. As well as having one of the largest known maritime battery capacities, the ferry is one of the first in the world to have no emergency generator. According to E-ferry project coordinator a certain amount of energy is reserved in each battery room, so if a battery room is lost or has to be shut down for a reason, there will always be enough energy left on the other room to sail back to harbour or to make all the emergency procedures.

Another notable feature is that Ellen is injected with the surplus from wind turbines on Ærø, which produce 100% of the electricity needed on the island.

Figure 6.17: Ellen e-ferry

First Fully Electric Cargo Ship

In 2017, a 2000 metric tonne all-electric cargo ship launched in Guangzhou (China).It is considered as the first of its kind to be fully powered by a lithium battery. As reported by, the 70m-long and 14m-wide tanker built by Guangzhou Shipyard International Company Ltd (Guangzhou Shipyard) ,has a battery system made up of more than 1,000 lithium-ion batteries and supercapacitors, giving the vessel the autonomy to travel up to 80km on one two-hour charge. The ship has battery energy of approximately 2400 kilowatt hours and is capable of speeds of up to 12.8 kilometres per hour. The zero-emission level vessel transports coal for the generation of electric power, down the Pearl River in Guangdong Province.

Figure 6.18: first all-electric cargo ship

AIDAperla

The cruise ship AIDAperla had a generating 10MWh lithium-ion battery system installed in 2020.It will be the largest battery storage system to be installed on a passenger ship and the first for a ship from Corvus Energy's new production facility in Norway. The ship can carry more than 4000 passengers and cruise members. The battery systems can be charged with shore power and during sea operation (peak load shaving). In addition to pure battery operation, the systems may also contribute for an extended period of time, e.g. during port mooring or during ship maneuvers.

AIDAperla was delivered by Mitsubishi Heavy Industries in 2017. The 125,000 gross ton vessel has a length of 300 meters, breadth of 37.6 meters and a maximum draft of 8.2 meters. Her power system includes three Caterpillar M 43 C diesel units and a Caterpillar M 46 DF dual-fuel marine engine. She has two ABB Azipod thrusters and is equipped with Mitsubishi’s air lubrication system.

Corvus Energy's new battery factory in Bergen will supply the company's largest market, the growing European market. The factory comprises a robotized and digitized production line with nine robotic stations and a capacity of up to 400 megawatt hours (MWh) per year. From unpacking incoming parts to testing the finished battery module, the entire factory is completely automated. The company's Vancouver facility will continue to supply North American and Asian markets, where demand for hybrid and zero-emission solutions is emerging and expected to grow rapidly.

Figure 6.19: AIDAperla cruise ship

MV Ampere

Ampere is a groundbreaking ferry constructed for Norled by the Norwegian Shipyard Fjellstrand in Omastrand in collaboration with Siemens and Norled. It is the world’s first electric-powered car ferry and generates zero emissions and minimum sound. The ferry was delivered in October 2014 and commercial operations began in May 2015. This marked the end of an innovation project that had started as a feasibility study in the shipyard Fjellstrand in 2010, but also a change towards green public ferry procurement in Norway. The tendering process for Ampere started after the Norwegian Public Roads Administration (NPRA) issued a development contract in 2011, with the aim of stimulating to zero or low emission technology in the developmental, yet commercial, tendering process. The contract was won by the shipping company Norled, which in 2012 offered to build a battery ferry.

Ampere's novelty lies in the combination of existing technology used in its construction. However, the infrastructure underpinning Ampere was quite novel. In order to provide Ampere with electricity, charging towers were built on both sides of the fjord. Although Ampere encountered difficulties before and after launch, the project has generally been considered a resounding success and has received vast publicity in both regional and national papers, and won several awards: Næringslivets klimapris 2014 (Norwegian industry's climate award), as well as the international 'Ship of the Year' award (2014), the Environmental Technology Award as one of the 'Ship Efficiency Awards 2015', and GreenTec Award (2016). Additionally, as the world's first fully electric car ferry, Ampere quickly seemed to find appeal among Norwegian policymakers, who set various climate goals in the National Transport Plan 2014–2023.

The advanced vessel operates on a 5.7km crossing in the Sognefjord between the villages of Lavik and Oppedal. It makes approximately 34 trips a day, each trip requiring approximately 20 minutes, excluding the 10 min of loading and unloading time for cars and passengers.

Technical details	Unit	MF Ampere
Ship type	-	RoPax
Capacity	cars, pax	120, 350
Length	m	80.8
Beam	m	20.8
Battery storage capacity	kWh	1000
Cell chemistry	-	NMC

Table 6.1: Main technical details of the all-electric ferry, MF Ampere

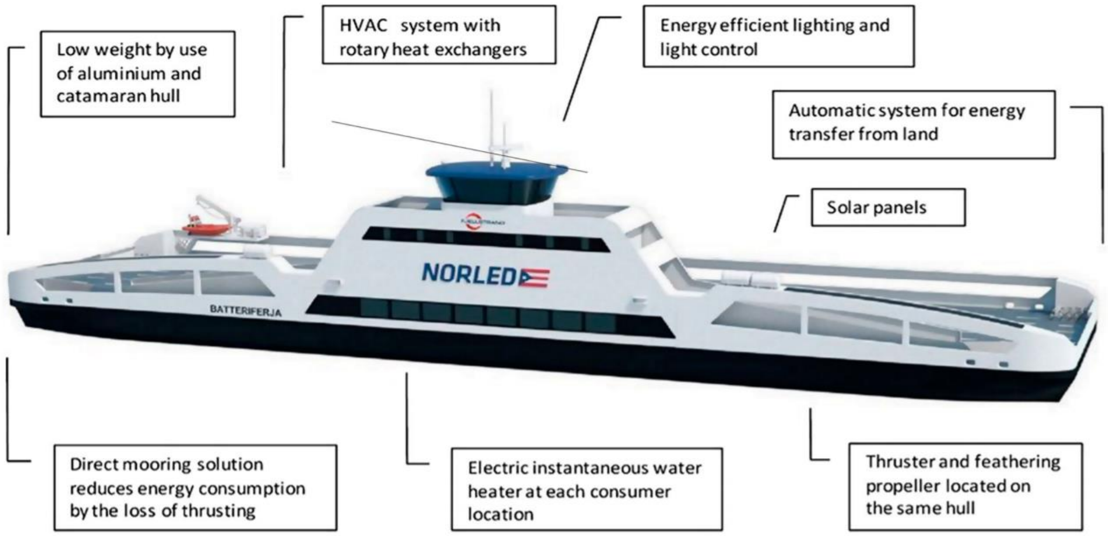


Figure 6.20:The Ampere ferry

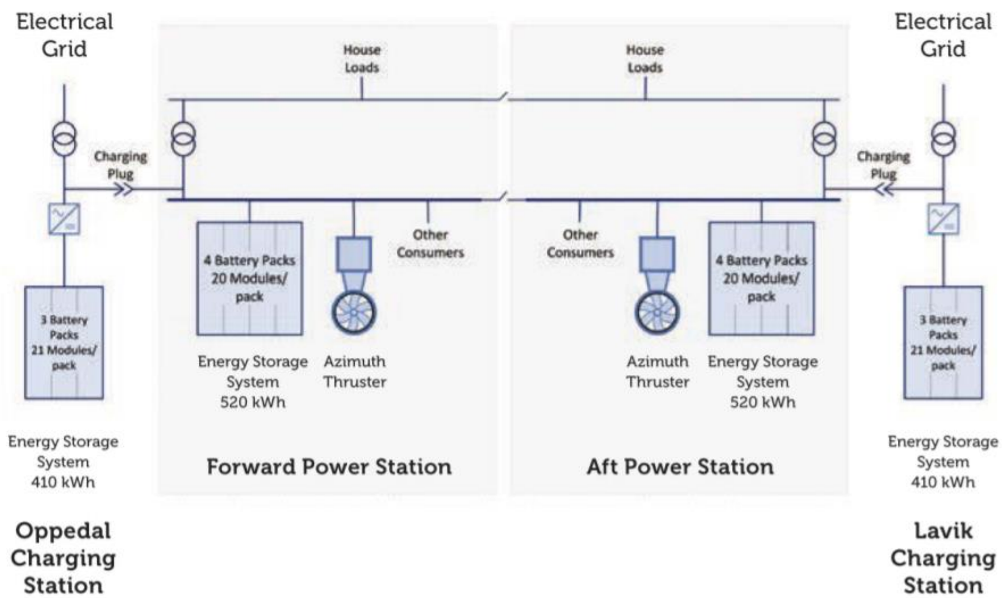


Figure 6.21: MF Ampere Single Line Diagram (Corvus Energy, 2016)

BASTO ELECTRIC SHIP

The world's largest all-electric ferry yet has gone into service in Norway on a route across the Oslo Fjord. Bastø Electric is the first of three battery-powered ferries operated by the shipping company Bastø Fosen to enter Norwegian waters with two more constructing in Turkey.

The Bastø Electric is 139.2-metre-long and 21-metre-wide and was built by the Turkish Sefine Shipyard and has room for 600 passengers and 200 cars or 24 trucks. The battery and fast-charging systems for all three ferries are supplied by Siemens Energy from the battery factory in Trondheim. Bastø Electric uses batteries with a capacity of 4.3 MWh. The fast-charging system has a capacity of 9 MW, according to the shipping company. When docking, the ferry is always “charged at lightning speed”.

The approximately ten-kilometre-long ferry route between Moss and Horten is Norway’s busiest ferry connection, according to Bastø Fosen. Annually, 3.8 million passengers and 1.8 million vehicles are transported on this route. “During 2022, emissions on this ferry route will be reduced by 75 per cent,” the shipping company says. Two other ferries are also to be converted from diesel to electric operation shortly. According to the company, each ferry docks and departs 20 to 24 times a day. The crossing takes around 30 minutes.

Figure 6.22: Bastø Electric ferry

Medstraum catamaran vessel

A European Union project called TrAM (Transport: Advanced and Modular) was launched in September 2018 aiming at developing, designing and demonstrating the feasibility of zero-emission, battery driven, fast vessels for coastal/river/inland waters transport services.

In 2021, the construction of the world’s first fully electric passenger fast ferry commenced at the Fjellstrand shipyard on the west coast of Norway.

Equipped to carry around 150 passengers, the catamaran vessel will be 31 metres long with a nine-metre beam. It will be equipped with two electric motors and a 1.5MWh capacity battery with charging power of more than 2MW. This will be the world's first fully electric and zero emission fast ferry classed in accordance with the International Code of Safety for High-Speed Crafts (HSC Code). As the TrAM project's demonstrator vessel, it will begin a trial passenger service between the city of Stavanger and surrounding communities and islands in spring 2022 to test and validate the project findings. The vessel has been designed for a service speed of 23 knots and has been named Medstraum (literally 'with electricity' and 'co-current 'in Norwegian).

National Technical University of Athens is amongst the consortium members responsible for R&D, simulation and testing of the project.

Figure 6.23: Medstraum vessel

6.9 Selection criteria for batteries of vessels

The most important part of a ferry retrofit into a battery-powered one is of course the choice of the battery chemistry. Although each application has different demands, for most cases there are six main selection criteria. Three are based on the operational performance: capacity, power and longevity. The other three are costs, safety and dimensions (size and weight). Which factors weigh more than others in the selection process depends on the application. From a maritime point of view, the capacity and power rating of the battery relate to the range and speed of the ship. The longevity and costs will determine the installation and operational costs of the ship. The safety and dimensional characteristics of the selected battery will have an influence on the location and integration of the battery in the ship. Each selection criteria is influenced by several parts of the battery. Figure 6.24 shows a schematic representation of a rechargeable battery and the parts that are of main influence on the battery selection criteria. The parts of the battery that have the largest influence on the six selection criteria are the electrodes, electrolyte, separator, container, terminals and the vent.

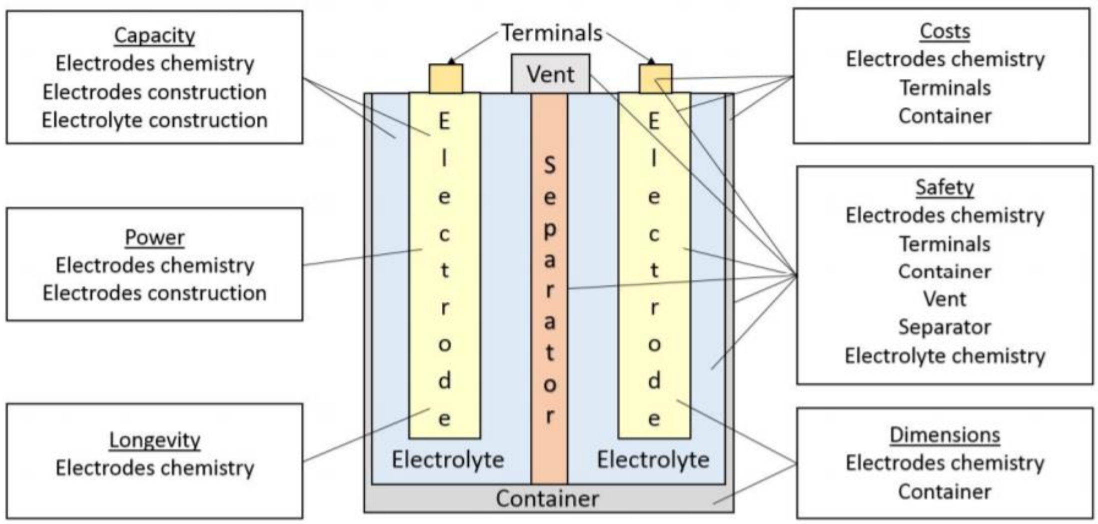


Figure 6.24: Main influences on battery selection criteria

Capacity

The capacity of a battery is the maximum usable energy it can store and is often measured in Watt-hours (Wh). To compare different batteries or battery materials the energy density is more commonly used. The energy density can be gravimetric (Wh/kg) or volumetric (Wh/L). The energy density of a battery can typically be between 40 Wh/kg and 250 Wh/kg. Figure 6.24 shows the three main influences on the capacity: the chemistry and construction of the electrodes and the structure of the electrolyte. The capacity is determined by the amount of energy that can be stored in the electrode, therefore, a thicker electrode or an electrode with more mass results in a higher capacity. Different materials have different energy storage characteristics. This is dependent on the molecular structure of the electrode materials. Materials that provide a better binding opportunity for lithium-ions, increase the energy storage capabilities of the electrodes. The last part of the battery that is a main influence on the capacity is the structure of the electrolyte. The electrolyte transfers lithium-ions from the anode to the cathode, enough transferring capability needs to be available to make use of the total energy storing capacity of the battery.

Power

The power rating of the battery is the ability to charge and discharge with high current rates and is usually measured in Watts (W). To compare different batteries on their power rating usually the power density is used. The power density is expressed in gravimetric density (W/kg) or in volumetric density (W/L). The power density of a battery lies typically between the 50 W/kg and

3000 W/kg. In order to achieve fast charging speeds, which is required for a lot of applications, a high power battery cell is required. For a high power rating the chemical reactions inside the cell need to have as little resistance as possible. A low internal resistance can be achieved by having thin electrodes resulting in a larger active surface area. This is the opposite as required for a high capacity. Therefore, always a balance has to be found for the right combination of capacity and power. A larger active surface area can also be achieved by choosing the right chemistry with this characteristic. A higher power rating is also connected to a higher charging rate. The speed of charging and discharging a battery is described by the C-rate. A C-rate of 1C stands for a full charge or discharge in approximately 1 hour. So a 1 kWh battery discharged at 1C should deliver a current of 1 kW for 1 hour. Discharging the same 1 kWh battery at 2C should deliver a current of 2 kW for half an hour. Discharging the battery at 0.5C it should deliver a current of 0.5 kW for 2 hours. Increasing the C-rate means increasing the current and decreasing the time. Increasing the charge or discharge current also increases the internal losses and decreases the efficiency of a battery.

Longevity

The longevity of a battery is determined by two different characteristics, the calendar life and the cycle life. The calendar and cycle life are determined by the aging of the battery. Calendar aging is the decrease in capacity and power over time. Cycle aging is the decrease in capacity and power due to the usage of the battery. There is one part of the battery that is most determining for the longevity of the battery and that is the chemistry of the electrodes. The reactivity of the electrodes is determined by the material that is used. A high reactivity is required for a good battery performance, but this also increases the aging rate. Materials are added to the electrodes to make them more resistant to aging, but this usually leads to a loss of performance. Choosing the right material for the electrodes is finding the right balance between the performances on capacity, power and longevity.

Safety

The safety of the battery cell depends on all parts of the cell. The constructional parts like the 86terminals, container and vent need to be designed for optimal safety. The separator, electrodes and electrolyte are in constant interaction with each other and need to be selected for their combined safety. The most important factors for safety are the electrode and electrolyte chemistry. All the energy of the battery is stored in the material and this must be resistant to for instance thermal runaway. Thermal runaway is the venting of hot gases and flames by a battery cell. Some battery materials have a low temperature limit where thermal runaway starts taking place, other materials are less vulnerable. Usually, more safety means less capacity.

The two principal cell chemistries used in maritime lithium-ion batteries are: nickel manganese cobalt oxide (NMC) and lithium iron phosphate (LFP).

NMC BATTERY

Lithium nickel manganese cobalt oxide (NMC) battery is the most popular type of cathode for automotive applications and is being used in a lot of marine applications as well. NMC contains both manganese and cobalt. The manganese has poor structural stability but good chemical stability, and the cobalt has the opposite. When combined in a cathode, they complement each other. Nickel has intermediate properties. The cathode combination is typically one-third nickel, one-third manganese and one-third cobalt, also known as 1-1-1. Because manganese and nickel are also more environmentally benign and abundant, the current trend is to include as little cobalt as possible in modern NMC batteries. The three active materials can easily be blended to suit a wide range of applications for automotive, marine and energy storage systems (EES) that need frequent cycling. Today, the NMC battery is growing in its diversity.

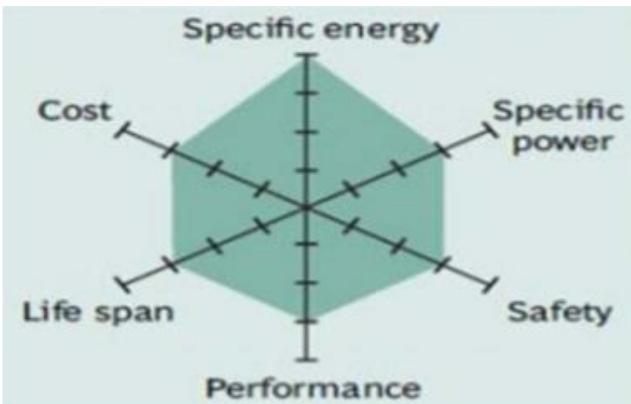


Figure 6.25: Typical NMC characteristics. NMC has good overall performance and excels on specific energy.

LFP BATTERY

In 1996, the University of Texas found that phosphate could be used as a cathode material for lithium batteries. This cathode is steady in the overcharged condition and can tolerate high temperatures without breaking down thus the cathode material in the lithium iron phosphate battery (LFP) is more dependable and more secure than other cathode materials. Phosphates exhibits cell operating temperature range of -30°C to +60°C and cell packing temperature range of -50°C to +60°C that deteriorates thermal runaway and prevents from burning out. It has less impact on the life cycle for overcharging and undercharging, although the specific energy is diminished marginally. The key benefits of this chemistry are high current rating and long cycle life, besides good thermal stability, enhanced safety and tolerance if abused. Li-phosphate is more tolerant to full charge conditions and is less stressed than other lithium-ion systems if kept at high voltage for a prolonged time. As a trade-off, the lower voltage of 3.2V/cell reduces the specific energy to less than that of NMC battery.

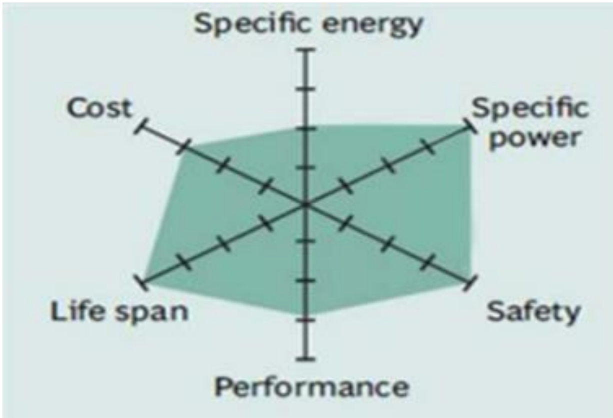


Figure 6.26: Typical Li-phosphate battery characteristics. Li- phosphate has excellent safety and long life span but moderate specific energy and elevated self-discharge

For our retrofit, we choose a Valence U24-24XP battery, which is a high-performance, twenty four volt battery, built on lithium iron phosphate chemistry, thus providing a safe, reliable and mobile energy solution. The LFP batteries have less specific energy compared to NMC batteries which translates to increased weight, but they are more economical and have a longer lifespan. Finally, on account of the high temperatures during the summer in Greece, NMC batteries would be a risky choice because of their higher potential for explosion, which is not the case with the corresponding LFP batteries.

Fig: U24-24 XP LFP battery

	UEV-18XP	18 V	75 Ah	14.9 kg/ 32.8 lbs	10.6” x 5.83” x 9.65” 269mm x 148mm x 245mm	-	120 A	21.9 V	1440 Wh
	U24-24XP	24 V	59 Ah	16.3 kg/ 35.8 lbs	10.2” x 6.77” x 8.86” 260mm x 172mm x 225mm	Group 24	118 A	29.2 V	1510 Wh
	U27-24XP	24 V	72 Ah	19.2 kg/ 42.2 lbs	12.0” x 6.77” x 8.86” 306mm x 172mm x 225 mm	Group 27	144 A	29.2 V	1843 Wh

Fig: Mechanical and Electrical specifications of U24-24XP battery

7. Legal and Regulatory Framework

A maritime battery might be up to several hundred times larger than a traditional electric vehicle battery. The high energy content, combined with extreme charging and operational patterns, represents new challenges in relation to safety, integration and service life. To avoid accidents and unwanted incidents that may have significant safety and cost implications – and potentially halt the development of these technologies – it is important that the battery related systems are verified and validated strictly.

In the following chapters describe we will describe the technical design of the battery system and its arrangement in the vessel, based on the following publications:

- DNV-GL : Rules for classification, Part 6, Additional Class Notations (Oct.2015)
- DNV-GL : Guideline for Large Maritime Battery Systems (Mar. 2014)
- Lloyd’s: Battery installations, Key hazards to consider and Lloyd’s Register’s approach to approval (Jan. 2016)
- DNV-GL : Tentative Rules for Battery Power (Jan. 2012)
- IEC61508 : Functional Safety
- SOLAS: ChII-1: Electrical installation
- SOLAS: ChII-2: fire protection
- IEC 62619 9.2.3
- IEC 62620
- IEC 61508 : Functional Safety
- IEC 62619
- IEC/ISO/IEEE 80005 : Utility Connections Reports (– Shore Connection High Voltage)
- IEC/ISO/IEEE 80005-1: The onshore power supply standard high voltage

- IEC/ISO/IEEE 80005-2: Communication protocol

7.1 Battery System

Battery system is the most important part of the project, because the ferry depends on it. Its role is to provide the energy for every operation of the ship. It consists of the cells, the hardware required to manufacture the battery units, sub-arrays and arrays, safety features as contactors and fuses, the required components of thermal management, bus-bars (collect the electric power at one location) and high voltage cabling, electronics, voltage and temperature sensors and low voltage cabling and connectors.

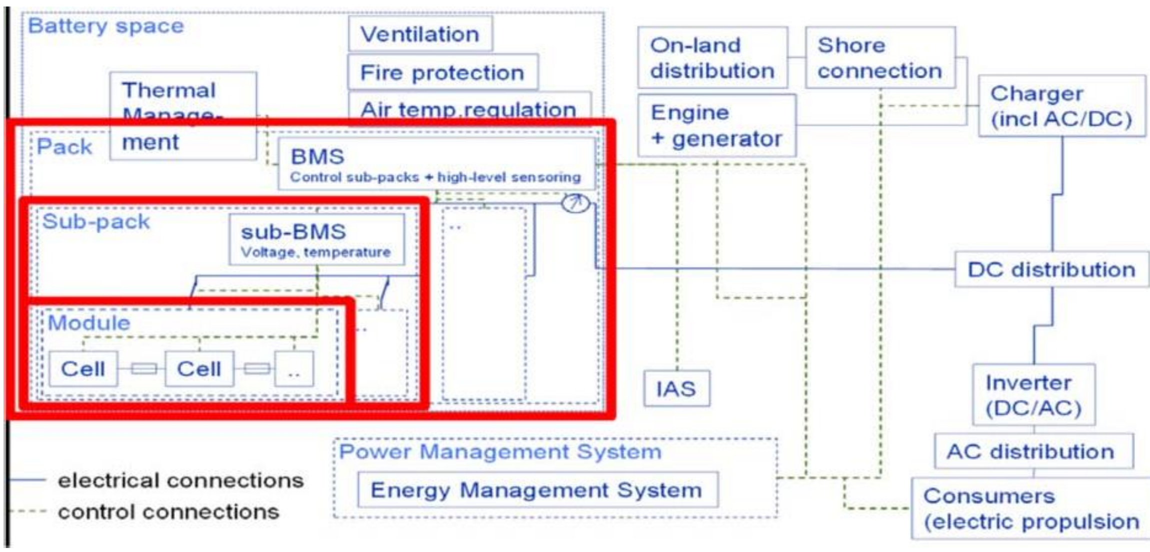


Figure 7.1: Battery system and related sub-systems (DNV, 2014)

A cell is the smallest electro chemical unit. An assembly of cells including some level of electronic control forms the module.

The modules are connected into series and parallel to form a sub-pack. Sub-Pack is the smallest unit that can be electrically isolated. Depending on the system architecture, each sub-pack can have internal relays/contactors which can interrupt main power connection.

The sub-packs (or modules if there are no sub-packs). A battery pack consists of several parallel sub-packs. The battery system may consist of several battery packs. The electrical connections between the different aggregate levels of the battery system may be connected using cables, bus bars or a combination of these.

The battery system consists of one or more battery strings including all required systems that can work for the intended purpose as a standalone unit.

All the components of the battery system need to be carefully and placed and interconnected and surveilled because many dangers which can lead to hazardous situations may arise in all aggregated levels as follows:

CELL'S DANGERS:

- High Impedance
- Internal short circuit
- Insulation fault
- Electrolyte leakage

MODULE'S DANGERS:

- Short circuits
- Control Failure
- Temperature Sensor failure, Voltage sensor failure
- Internal open circuit, high impedance
- Internal Short Circuit
- Insulation fault
- Cooling system leakage
- Loss of Cooling

SUBPACKS' DANGERS:

- Contactor does not open/close when required
- Current sensor measurement error
- Connector high impedance
- Leakage of cooling connector
- Sub-pack enclosure leakage/damage
- Mishandling of battery system.

PACKS' DANGERS:

- High level sensor failure
- Voltage and temperature imbalance
- Battery life too short
- Contactor does not open/close when required
- Reverse polarity protection
- Emergency shutdown

If the electrical architecture of a sub-pack contains independently controllable parallel strings, each single string shall include independent current measurement.

Low contact impedance for the electrical connections is crucial to avoid over-heating and control the fire risk, as well as maximum efficiency. Several parallel strings will decrease the risk of overheating from increased contact impedance. It can also ease the detection of elevated levels of contact impedance in the electrical connections resulting in increased safety of the system. The battery casing, covering modules and cells, shall be made of a flame-retardant material.

The outgoing circuits on a battery system shall in addition to short circuit and over current protection be provided with a switch disconnector for isolating purposes so that isolating for maintenance is possible.

It is recommended that it is possible to disconnect the battery system in an emergency situation. This should be done by implementing an emergency shutdown circuit that disconnects the battery contactor/breaker. This emergency shutdown should be arranged as a separated hardwired circuit. It should be possible to shut down the battery locally and from the bridge.

7.2 Battery System Capacity

The required installed capacity (Ah) depends on the vessel’s operational profile and the safety regulatory framework.

Battery sizing must ensure redundancy. Reliability and safety of the system must be at least at the same level as a conventional vessel with internal combustion engines.

At least two independent battery packs/systems shall be installed. The usable energy of each battery system should be adequate for a return trip with one battery pack inoperative. The system's capacity shall be sufficient to cover the energy needs of the vessel for the predicted operation conditions. Charging will be possible at the port during embarkation/disembarkation and should be adequate to provide the necessary power for the planned route, before departure. Battery capacity installed shall be designed for contingencies due to weather conditions and consequent increased power consumption with at least 10% margin. Conditions that differ from the usual operational condition that the vessel will encounter will not be accounted for. Such cases could be the maintenance trip. In that case, extra mobile power packs could be used.

Emergency generator can be omitted if national flag authorities agree.

Single failure of critical modules shall not compromise the integrity of the vessel, for non-propulsion cases loss of battery power shall not affect critical vessel functions.

Battery system installed, at normal daily operation, is not discharged to deep, also at worst time of season, ensuring that number of daily recycles of batteries is kept within calculated limits, allowing a long battery life-span.

Capacity deterioration (ageing) rate for the battery is to be documented, considering actual modes of operation.

The total battery capacity installed is sufficient to absorb charging and discharging powers according to the electrical balance sheet, including hotel power, without exceeding recommended temperatures generated within batteries from battery loads as deviations would lead to lower life-span of batteries.

The battery capacity installed is reasonably balanced in relation to the chosen maximal charging powers in port thus higher charging powers will save battery weight but vice versa also result in high investment cost of the shore charging connection station as its price depends mostly on maximum power capacity.

The battery pack installed should be increased to exploit the lower night rates of electricity (at certain times spot rates are negative).

For unscheduled deviation is of course not an option. In case of emergencies the EU regulation concerning ferry operation for operational areas of category D requires only a capacity for the ferry to fight a fire for at least three hours by own means, the emergency fire pumps.

Since our subject is the retrofit, battery system's weight and volume must be adequate from a stability point of view.

Battery lifetime shall be such that the business case is economically reasonable (optimally higher than 7 years, which is the period we assume the change of battery).

7.3 Arrangement

Arrangement of the battery spaces must be such that the safety of passengers, crew and vessel is ensured.

Because the battery system is the main source of power (replaces one of the required main sources of power) it shall be located in the machinery space. A battery space contiguous to the machinery space may be considered.

The arrangement of the battery spaces must be so that a hazardous situation that may be caused by a breakdown of the batteries (e.g. gassing, explosion, fire) cannot lead to loss of propulsion or auxiliary power for essential or important users.

The battery space shall not be located without adequate protection from heat, ignition sources, dust, oil pollution or other potential harmful environmental influence to the system and its components. If possible, a battery space should be a dedicated room.

Battery spaces shall with reference to SOLAS Reg. II-2/3.30 be defined as a machinery space. With respect to structural fire protection as given in SOLAS Reg. II-2/9.2.2.4 the battery room shall be defined as other machinery spaces.

Fire integrity of battery spaces shall be enclosed by A-0 fire integrity and have additional A-60 fire integrity towards:

- machinery spaces of category A as defined in SOLAS Reg. II-2/3
- enclosed cargo areas for carriage of dangerous goods
- muster stations and evacuation stations

Battery systems within the battery space shall be arranged with sufficient protection (partition plates or sufficient distance in accordance with maker recommendation) to prevent escalation between battery modules in case of a thermal runaway.

Battery space shall not contain other systems supporting essential vessel services, including pipes and cables serving such systems, in order to prevent loss of propulsion or steering upon possible incidents (e.g. thermal runaway) in the battery system.

Battery space shall not contain heat sources or high fire risk objects. High fire risk objects are objects similar to those listed in SOLAS Reg. II – 2/3.31 (Heat sources are sources with temperature higher than 220 ºC as used in SOLAS Reg. II-2/4.2.2.6.1).

Battery space shall be adequately arranged so that access for repairs and substitution of defected parts is facilitated.

Battery space shall demonstrate robustness for long term exposure in a marine environment (temperature, moisture, list, trim, roll, etc.) and shall provide protection against external hazards (e.g. fire, mechanical impact, water ingress, pipes leakage).

7.4 Operational Environment

During battery system's operation for optimal efficiency, battery space must establish the appropriate ambient conditions. Within the battery space various hazards may arise and we must take into consideration the following requirements in order to eliminate those risks.

The battery system shall not be located without adequate protection from heat, ignition sources, dust, oil pollution or other potential harmful environmental influence to the system and its components. Therefore, specified procedures should be followed, and relevant controls or alarms must be installed.

For optimal battery operation, battery space must ensure proper environment conditions related to:

- Air temperature regulation
- Ventilation
- Fire protection
- Thermal Management The following shall be monitored and presented at a manned control station:
- Ambient temperature of battery space
- Indication of ventilation running.

And accordingly shall give an alarm at the engine room control station and at the bridge in cases of:

- High ambient temperature in battery space
- Failure of ventilation.

Any abnormal condition in the battery system shall initiate an alarm in the vessel's main alarm system with individual or group-wise indication. For vessels without a centralized main alarm system, battery alarms shall be presented at the bridge.

Battery systems shall be arranged within a space with ventilation that can provide air with temperature control of the ambient temperature. The temperature control (max/min temperature) shall follow recommendations given by the battery maker. For liquid cooled battery system, such ventilation system is not required.

The ventilation system for battery spaces shall be independent ducting system from any other heat and air condition system (HVAC) serving other spaces and arranged with mechanical air supply.

If temperature sensors are arranged in close vicinity within the battery module so that loss of functionality of a broken sensor element or circuitry will be mitigated by a neighboring sensor, the sensor element/circuitry can be common for indication, alarm, control and safety functions. Such arrangements shall still be designed with single fault tolerance in CPUs and other electronic parts of the system. The objective is that no single failure shall cause loss of both safety and alarm functions at the same times.

Depending on the chemistry of the batteries as defined by the safety description it may be needed to classify the battery space, where flammable gas may arise, according to the zones definitions given in IEC 60079-10-1. This classification shall be used as a basis to support the proper selection and installation of equipment for use in the hazardous area. The hazardous area plan for the battery space, shall be a part of the complete hazardous area plan for the vessel.

If liquid cooled batteries are used, independent mechanical exhaust ventilation system is required for extracting possible battery vapour in an abnormal situation.

If a failure/damage of the batteries can lead to release of flammable gases, then gas detection shall be arranged. Also, an additional emergency mechanical exhaust fan and emergency inlet direct from open air shall also be arranged.

Battery spaces are considered as not normally manned and access to the space shall be through normally closed doors with alarm or self-closing doors.

Battery spaces shall be protected by a water-based fixed fire extinguishing system approved for use in machinery spaces of category A as given in SOLAS Reg. II-2/10 and the FSS Code. Though, cell chemistry is the most important consideration when choosing fire suppression. Using water on a lithium battery will result in the production of hydrogen. However, a fire could be safely extinguished using salt. The one best placed to determine such requirements is battery manufacturer.

As a general fire extinguishing medium (heavy) foam could be, also, be considered. Its advantages are:

- Longer lasting cooling effect since heavy foam might form a “wall” around and between battery sub- packs with a good cooling effect (depending on layout).
- Potential off-gas which is warmer than air can be ventilated from a high position in the battery space while foam can be injected from the top and spreading slowly downwards.
- Surrounding foam can bind potentially flammable solid or fluid off-gas products while gases can be ventilated out.

Battery spaces shall be monitored by conventional smoke detection within the spaces. Smoke detection shall comply with the international code for Fire Safety Systems (FSS Code) and battery space fire alarm shall be given at the bridge.

- Emergency disconnection of the battery system shall be arranged at the following locations: adjacent to (outside of) the battery space
- navigation bridge

7.5 Battery management system, Controls and Alarms

Vessel’s operation should be as simple and as similar to conventional system as possible, requiring an (automated) energy management system in addition to power management; this is the role of BMS. Battery Management System is the electronic regulator that monitors and controls all functions and parameters of the battery system. It is responsible for communicating with vessel’s general power management system, and providing all key battery information to ensure an efficient operation. It must be designed for monitoring battery system’s state and keeping it within allowed limits, calculating secondary data, reporting that data, controlling its environment, authenticating it and / or balancing it. It should, also, have an override function to prevent the power management system to perform tasks outside its safe boundaries In such a way that failures in the protective safety system shall be detected, alarmed, but not cause shutdown of the battery system. Finally, BMS shall have sufficient protection mechanisms against intrusion by software and unwanted calibration access to the battery system.

More specifically, The Battery Management System (BMS) shall:

- Provide limits for charging and discharging to the charger
- Protect against overcurrent, over-voltage and under-voltage)
- Protect against over-temperature
- Control cell balancing.
- Protect against over-pressure

The following parameters shall be measured:

- Cell voltage
- Cell temperature
- Battery string current.

The following parameters shall be monitored and indicated for the operator at local control panels or in remote work stations:

- System voltage
- Max, min and average cell voltage
- Max, min and average cell temperature
- Battery string current
- Ambient temperature
- Electrical insulation resistance.

The following parameters shall be calculated and be available for the Energy Management System (EMS):

- state of charge of the batteries (SOC)
- state of health of the batteries

8. Retrofit Methodology & Case Study

The most important part of the electrification process is the design of the battery system itself. The battery system will be the primary source of power for our vessel, so its capacity should be planned in order to be able to provide energy for the required trips, while being charged during berth time. The expenses for the battery system cover the biggest percentage of the whole investment.

The size of the battery system is determined by mainly two factors. The first one is its energy requirements and the second is the time available for the charging process. In order to calculate the energy requirements we have to take into account the energy required for the vessel's propulsion and hoteling loads during the daily operation of the vessel.

The emergency generator will not be changed, due to lack of legislation framework. Although this issue is not discussed, it is an important part of the electrification process. The new systems that are installed on the vessel such as the ventilation, cooling and control systems of the batteries are very important for the safety of the vessel and their normal operation must be guaranteed even during emergencies.

The required energy is mainly based on the propulsion requirements for the service speed ($V_{SERVICE}$) at specific loading configuration and correlated draft (T). For our case DWT is the number of passengers and vehicles on board the vessel. There are several distinct ways to make these estimations, depending on the desired accuracy and the data availability, such as CFD modeling and energy consumption, but both methods are unreliable due to lack of relevant data and incorrect sheets.

Charging procedure and routine will affect decisively, as well, the outcome. Choices upon the available charging frequency, charging currents applied and time needed to plug-in/off and start charging from grid are translated into alternations of provided quantity of energy to the system, therefore suggesting smaller or larger battery system, more or less lifecycles.

8.1 Model inputs

Marine-electrical is a computation program and that was developed by Nikos Ntokos and Marios Prapas, to satisfy the need for a way to calculate the cost of retrofit conversion for a current vessel. In addition, a report form is designed, through which the user can visualize the results of each analysis and compare different ships and scenarios.

The required data to calculate our energy balance sheet and create the battery-ship's operation scenarios are the following:

Concerning vessel's current characteristics, following data inputs are required:

- No of Main Engines for propulsion and their nominal output
- No of Operating Main Engines for propulsion
- Main Engine Load Factor
- No of Electric Generators and their nominal output
- Electric Generators Load Factors
- Electrical Load Balance at Sea
- Electrical Load Balance at Port
- Electric Motors Diversity factor
- Electric Motors Efficiency number
- System's DC Voltage (V)

Concerning route characteristics, following data inputs are required:

- Cruising distance (nm)
- Time Cruising (min)
- Time at Berth (min)
- Required(max) no. of trips per shift

Concerning battery modules characteristics:

- V nominal (V)
- Dimensions (m)
- Capacity (Ah)
- Volume (m^3)
- Weight (kg)
- Nominal Charging/Discharging current for max lifecycles (A)
- C-Rate
- Nominal D.O.D.

Calculation of Installed Battery Energy

The investigation of battery systems' sizing is the most influential issue to be figured out. Batteries' cost will be the highest expense for this retrofit and they will be vessel's sole source of power and they are not light. We wouldn't want an expensive ship, carrying more batteries than needed (batteries are a steady weight, unlike fuel) nor a vessel being obliged to miss some voyages because it didn't have enough installed energy compared to time available for charging. Our choice must have balance, with many parameters to consider.

The energy demand for propulsion per voyage, is calculated by the formula:

$$E_{prop/voyage} = {(N_{M/E} \times P_{M/E\_Average} \times T_{CRUISING})}\Big/{(\eta_{EL_{MOTOR}} \times 60)} \text{ (kWh)}$$

The energy demand for hoteling/electrical loads, for one voyage is:

$$E_{hot/voyage} = N_{G/E} \times P_{G/E\_Average} \times T_{CRUISING}$$

$$P_{M/E\_Average} = {(\int_0^{T_{CRUISING}} P_{M/E\ moment}\ [kW]dt)}\Big/{T_{CRUISING}}$$

$$P_{G/E\_Average} = {(\int_0^{T_{CRUISING}} P_{G/E\ moment}\ [kW]dt)}\Big/{T_{CRUISING}}$$

$$E_{sea\_voyage} = E_{prop/\ voyage} + E_{hot/voyage}$$

$N_{M/E}$: Number of operating Main Engines

$N_{G/E}$: Number of operating Generators

P_{M/E_NCR} : Nominal continuous operating load of the main engine

$P_{M/E\_Average}$: Average load of main engine during the trip

$P_{G/E\_Average}$: Average load of generator during the trip

$P_{M/E\ moment}$: Load of Main Engine at a given moment

$P_{G/E\ moment}$: Load of Generator Engines at a given moment

$T_{CRUISING}$: Time cruising (min)

η_{EL_MOTOR} : Electric Motors Efficiency

For the calculation of the energy required, the average operating load during the voyage is used. This is calculated considering that the ship's power demand as a function of time is linear until it reaches the service speed and respectively when it approaches the port it also reduces power in a linear way. It is assumed that the ship reaches the service speed at the normal continuous rating of the engine (NCR).

At the same time, the efficiency of the electric motor is taken into account, which will be installed after the conversion, considering that the motor requires from the batteries energy increased from what the propeller requires, because of the losses from the conversion of electricity into rotary movement and which are expressed by the rate of efficiency of the electric motor.

Power required during the stay in the port:

$E_{port/voyage} = (P_{Gen\_port} \times T_{port}) / 60$ (kWh)

T_{port} : Time at birth (min)

Total energy required for one voyage:

$E_{voyage\_total} = E_{sea\_voyage} + E_{port/voyage}$ (kWh)

Charging Scenarios

The choice of charging scenario significantly determines the size of installed power on board. More specifically, along with the factor of the maximum Depth of Discharge (DOD), they are the most important factors that determine how much energy it should be installed on board, so that the final installed capacity is sufficient to cover the energy requirements of the ship without, however, exceeding the value of the maximum DOD.

Scenario 1: Charging after a number of routes

In this scenario it is considered that the ship's batteries should meet the ship's energy requirement for N_x voyages without charging and at the same time the maximum battery discharge rate does not exceed the maximum DOD value. Then, after the N_x voyages the ship will be fully charged up to 100% of the battery capacity.

(1 trip = 2 voyages)

Calculation of Installed Energy on board:

$E_{min} = E_{voyage} \times N_x / DOD$ (kWh)

N_x: The number of voyages without charging

$N_y = (2 \times N_{trips}) / N_x$: Total number of charges during the day

$E_{Total\_day} = N_x \times E_{Voyage}$ (kWh)

N_{trips} : Number of trips per day

Number of battery modules

As previously analyzed, two battery packs will be installed on the ship which will have the same number of batteries. Each package will include batteries in series voltage and in parallel.

$$N_{Bt.\ Series} = roundup\left({V_{Syst}}/{V_{nom\_bat}} \right)$$

V_{Syst} : System's Nominal Voltage (V)

V_{Bt_nom} : Battery module's nominal voltage (V)

$$N_{Bt\_parallel} = roundup\left({(1000 \times E_{min})}/{(N_{Bt\_Series} \times V_{Bt\_nom} \times Bat\_Capac)} \right)$$

$$E_{energy\_installed} = {(N_{Bt.Series} \times N_{Bt\_parallel} \times V_{Bt\_nom} \times Bat\_Capac)}/{1000} \text{ (kWh)}$$

Bat_Capac: Battery module's nominal capacity (Ah)

New Maximum DOD (because of the rounding):

$$DOD_{real} = {(N_x \times E_{VOYAGE})}/{E_{energy\_installed}}$$

$$Cycles_{Daily} = {(DOD_{real} \times 2 \times N_{Trips})}/{N_x} = {E_{Total\_day}}/{E_{energy\_installed}}$$

Calculation of the time for fully charging the batteries for a given value of charging current:

$$T_{Charging} = T_{port\_voyage} = 60 \times {(DOD_{real} \times Bat\_Capac)}/{Current_{charg}} \text{ (min)}$$

Scenario 2: Intermediate Charging

In this scenario we assume that the ship is charging after each voyage for as long as it remains in the port. At the same time, the energy absorbed by the batteries after each charge in combination with the initial energy of the batteries (100%) before the ship starts its voyages, is sufficient to meet the energy requirements of the ship without the battery exceeding the maximum depth of discharge which has been defined. The maximum depth of discharge occurs when the ship completes its last voyage, the value of which will be equal to the defined DOD.

$$E_{Total\_day} = N_{Trips} \times E_{Trip}$$

$$E_{Total\_charg\_day} = E_{min} \times f \times (2 \times N_{Trips} - 1)$$

$$f = {(Cur_{Charging} \times (T_{Charging} - T_{Plug}))} / {Bat\_Capac}$$

f is a parameter to estimate the impact of different charging current and time needed to connect the system to the grid on charging load transferred on board (%)

T_{Plug}: Total time needed to plug-in/off vessel to the grid

$2 \times N_{Trips} - 1$: The total number of intermediate charging during the day

The total energy consumed by the ship at the end of its last voyage during the day is the aggregate of the total energy given from intermediate charging and the product between State of Charge (SOC) at the end of the day and energy installed in the ship.

$$E_{Total\_charg\_day} + E_{min} \times DOD = E_{Total\_day} =>$$

$$=> E_{min} = E_{Total\_day} \times {1} / {((2 \times N_{Trips} - 1) \times f + DOD)} \text{ (kWh)}$$

Number of battery modules

The methodology for the calculation of the battery modules is the same as in the previous charging scenario.

$$N_{Bt.\ Series} = roundup\left({V_{Syst}} / {V_{nom\_bat}} \right)$$

$$N_{Bt\_parallel} = roundup\left({(1000 \times E_{min})} / {(N_{Bt\_Series} \times V_{Nom\_Bt} \times Bat\_Capac)} \right)$$

$$E_{energy\_installed} = {(N_{Bt.Series} \times N_{Bt\_parallel} \times V_{Bt\_nom} \times Bat\_Capac)} / {1000} \text{ (kWh)}$$

New Maximum DOD (because of the rounding):

$$DOD_{real} = {E_{Total\_day}} / {E_{min}} - ((2 \times N_{trips} - 1) \times f)$$

$$Cycles_{daily} = f \times (2 \times N_{trips} - 1) + DOD_{real} = {E_{total\_day}} / {E_{energy\_installed}}$$

8.2 CASE STUDY: ARGOSTOLI-LIXOURI

Kefalonia is the largest of the Ionian Islands in western Greece and the 6th largest island in Greece. Argostoli is the capital city of Kefalonia while Lixouri is the second largest city of Kefalonia.

In 1758, Republic of Venice decided to make Argostoli the capital city of Kefalonia .Habitants of Lixouri, which was at the time the most thriving city in the island, could not accept this situation and the infamous dispute between the two cities began. Ioannis Kapodistrias had to intervene to end successfully the hostilities in the 1800s. The intense situation gradually normalized and since the middle of the 19th century trade relations replaced the rivalry.

Today, Lixouri and Argostoli are connected with a ferry line. The ferry makes the trip a maximum number of 8 times per day during summer.

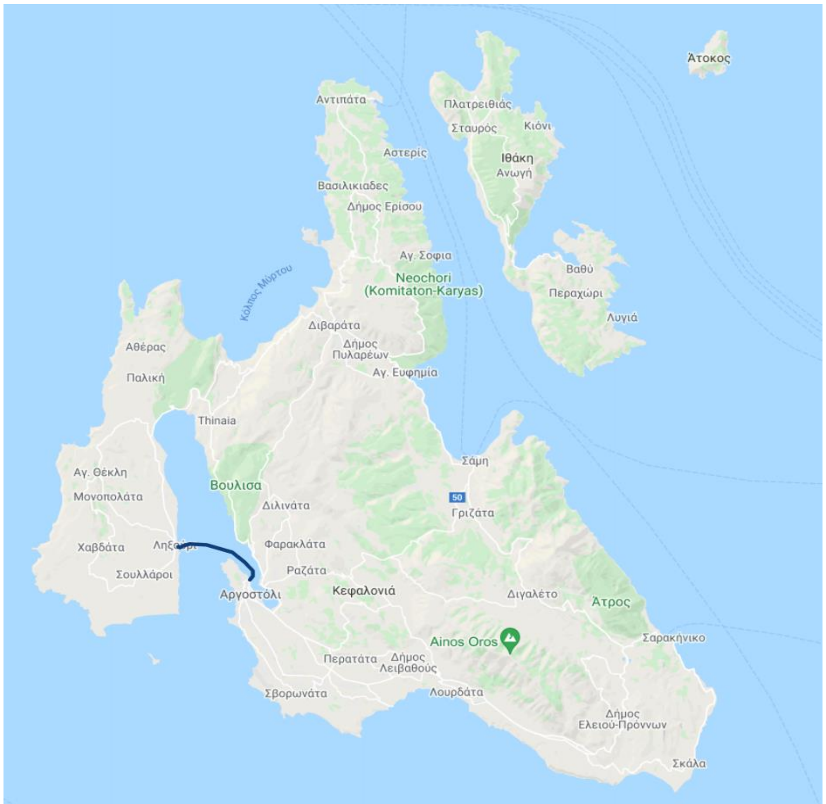


Fig:Route of the vessel(Blue Line) :Argostoli(Αργοστόλι)Port-Lixouri(Ληξούρι)Port –Distance: 4 nautical miles-Time:00.30min

The Ship

Fig: Vasos K. Ship

Vessel's characteristics

L_{OA}	57m
L_{wl}	48m
B	15m
T_{DESIGN}	2.6m
Year built	2007

Argostoli-Lixouri route's characteristics

Distance	**4 nm**
$T_{CRUISING}$	20 min
$T_{AT\ BERTH}$	15 min

The viability of the investment will be examined for the first 7 years after the conversion. This option is based on the fact that according to the manufacturers, the batteries will begin to have a noticeable loss of capacity after this time. The manufacturers give 7000-10000 cycles of battery operation without its capacity being reduced below 70% of the original. Generally, when considering real ships, the number of daily battery life cycles will be a key parameter to consider, with emphasis on ensuring that batteries do not exceed the operating cycles recommended by the manufacturers for a total of seven years. At the same time, it is considered that at the end of the seventh year there will be an additional income from the replacement of the batteries, which will result from their recycling. The batteries in some cases can be sold as they are as they are in fairly good condition. This will be due to the fact that the study of operating loads and the autonomy of the ship is strictly defined, with the result that the battery operates in the studied operating cycles, without too large discharge currents and discharge depths not exceeding 70%.

Purpose of this study is the investigation of the technological and economic viability of the replacement of the main and auxiliary engines with a battery system in the local ferry ship. For this reason we will examine two scenarios for the retrofit of the ship into a battery-powered one. In the first scenario we will consider that the vessel does an intermediate charging, namely that it charges in both ports of the route Argostoli-Lixouri. In the second scenario the ship charges only in one port per four routes. It should be noted that the difference between the two scenarios is the frequency batteries are charged, while the additional equipment used, (the power electronics, electric motors etc.) remain the same. Another difference is that we use higher current to charge the batteries in the second case so that the ship does not spend an excessive amount of time into the port, a scenario that obviously would not be tolerable from the shipowner.

Project's application on this route is consistent with European Union recent policy developments. It promotes smart growth with its research, technological development and innovation, employment, sustainable growth affecting environment and energy on transport sector and it certainly complies with EU's climate policy by protecting local and global environment.

Battery Modules specifications

Type	**LFP**
Maker	Valence
Name	U24-24XP
Nominal Module Voltage	25.6 V
Nominal Capacity	59 Ah
Charging Voltage	29.2 V
Energy	1510 Wh
Maximum Recommended Current	59 A
Dimension	0.260 x 0.172 x 0.172m
Weight	16.3 kg
Price(BMS included)	460 $/kWh
Specific Energy	92.66 Wh/kg
Cycles range	7000-10000

Naturally, the most important aspect during the electrification process of a vessel is the sizing of the battery packs. Battery packs are going to be the sole power source of the vessel for both its electrical and propulsive power needs. Considering this, the battery sizing has to ensure redundancy and sufficiency for the intended operation of the vessel. Reliability and safety of the system must be at least the same as a conventional vessel counterpart. Another fact that must be taken into account is the expenses of purchasing such equipment and retrofitting it into a conventional vessel. Batteries cost will be the highest expense for this retrofit so finding a golden rule between reliability and economic viability is of the utmost importance.

Batteries are expected to require far less maintenance than conventional combustion engines and turbines. However the cost of installing battery systems onboard, including replacing them after typically seven to eight years, is significantly higher than for traditional diesel engines.

Benefit from fuel and Operation&Maintenance costs may be considered as the revenues in the analysis (in order to make a comparison of running the vessel on batteries).

As stated before, the replacement of the emergency accumulators of the vessel will not be investigated by the present thesis. This thesis is focused on the technological and economic viability of the replacement of the main and auxiliary engines with a battery pack.

Battery system's size depends on its energy consumption and available time for charging during its shift. In order to determine vessel's daily energy requirements, power needed for propulsion and electrical loads must be calculated according to its operational profile.

A very important parameter that affects the revenue from the conversion is the specific fuel consumption (gr/kWh) of the main engines and generators, as it determines the amount of fuel emitted from the engine. Generally, the values of the specific fuel consumption of marine engines range from 160 - 220 (gr/kWh) depending on the type of engine (2X or 4X). The lowest prices of special consumption correspond to large 2X engines which have higher efficiency than the corresponding 4X engines. Usually, the main engines used in these types of ships are 4X engines. Below are diagrams showing the change in specific fuel consumption as a function of operating load for both the 4X marine engine and the generator.

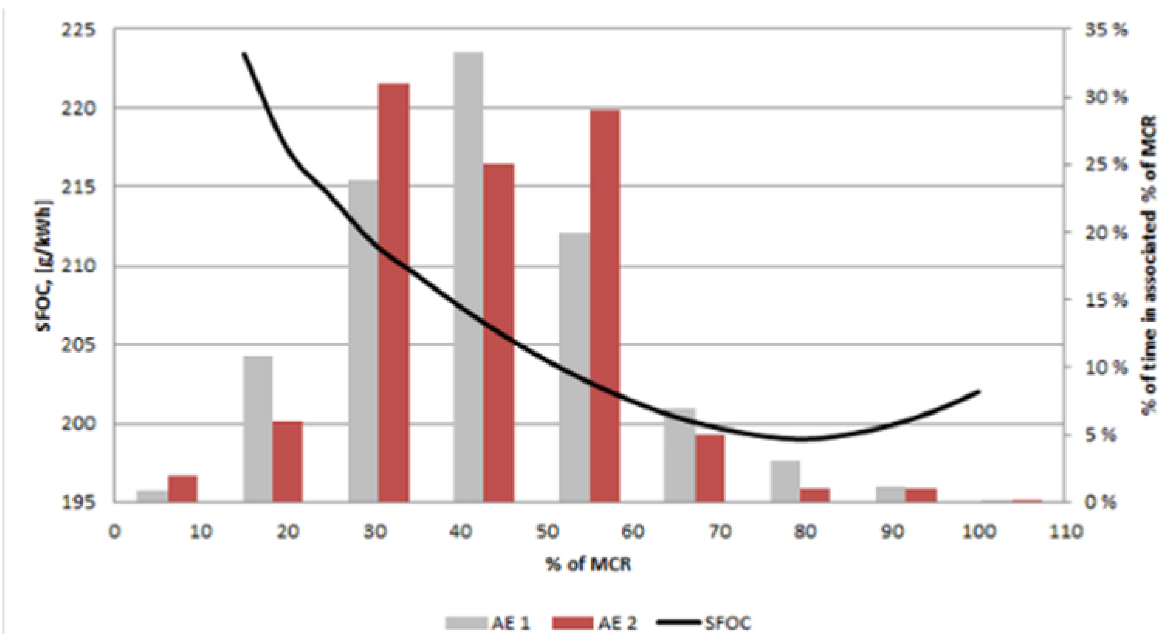


Figure: SFOC diagram for Generator Engines

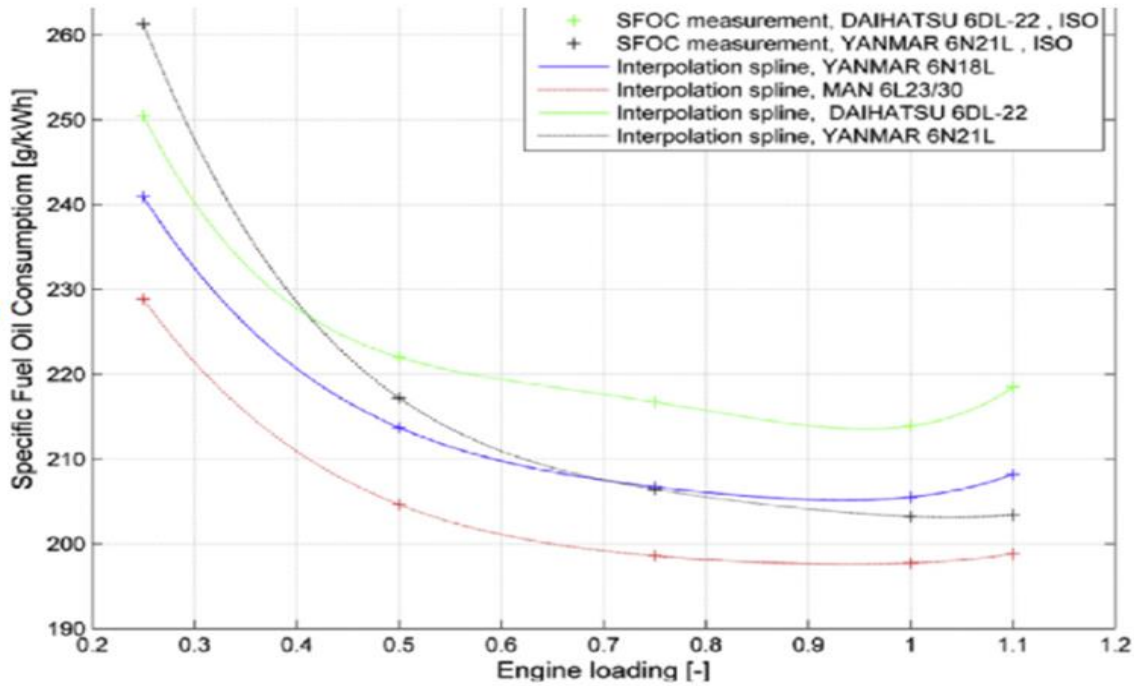


Figure: SFOC diagram for Main Engines

Operational characteristics

Main Engines (M/Es)	
No of Operating M/Es	1
M/E MCR	760 kW
M/E NCR	500 kW
M/E NCR Consumption	205 gr/kWh
M/E Efficiency Factor	0.4
Generator Engines (G/Es)	
No of G/Es	3
No of Operating G/Es	2 (one emergency generator)
G/E MCR	60 kW
G/E NCR	27.5 kW
G/E Port Load (for all Operating G/Es)	49 kW
G/E NCR Consumption	206 gr/kW
G/E Port Consumption	207 gr/kWh
G/E Efficiency Factor	0.4
DC Voltage	500 V

Assumptions for the calculations:

- Oil growing price 3.5%
- Electricity growing price 1%
- Contingencies costs are estimated 10% of project value

The financial analysis will be held for a seven year period time according to battery manufacturers' guidelines concerning the degradation of batteries to 70% of its nominal capacity.

8.3 INTERMEDIATE CHARGING SCENARIO

In this scenario we will take three different charging currents, in order to find the optimal solution for our retrofit based on energy installed, real depth of discharge and life expectancy of the battery system.

Intermediate Charging				
$Current_{charging}\,(A)$	DOD_{real}	$E_{installed}$(kWh)	$Cycles_{daily}$	$Life_{expectancy}$
35	0.61	1450	2.254	9.86
40	0.59	1329	2.459	9.04
45	0.60	1208	2.705	8.22
50	0.67	1087	3.006	7.39

We will choose 50A as the charging current because compared to the other charging currents it has less installed energy requirement (which translates to less cost and less battery system weight) and the battery has a satisfying life expectancy.

Total Energy per day	**3269 kWh**
Energy installed	1087 kWh

Battery Arrays	**2**
No.of Modules Series	20
No.of Batteries Parallel	36
Total No. of Batteries	720
Charging Time	11 min
C Rate(During Charging)	0.85
New DOD	0.667
Total Weight of Batteries	11,736 kg
Total Volume of Batteries	7.27 m^3
Daily Cycles	3.006
Life Expectancy	7.39 years

Battery	**500,244$**
Inverter (1)	207,000$
Motor (1)	37,800$
Buying Cost	745,044$
Selling Cost	36,700$
Total Cost after Sell	745,000$

Pre-Retrofit Fuel Costs	**124,734$/year**
Battery Fuel Costs	57,201$/year
Fuel Costs Benefit	67,532$/year

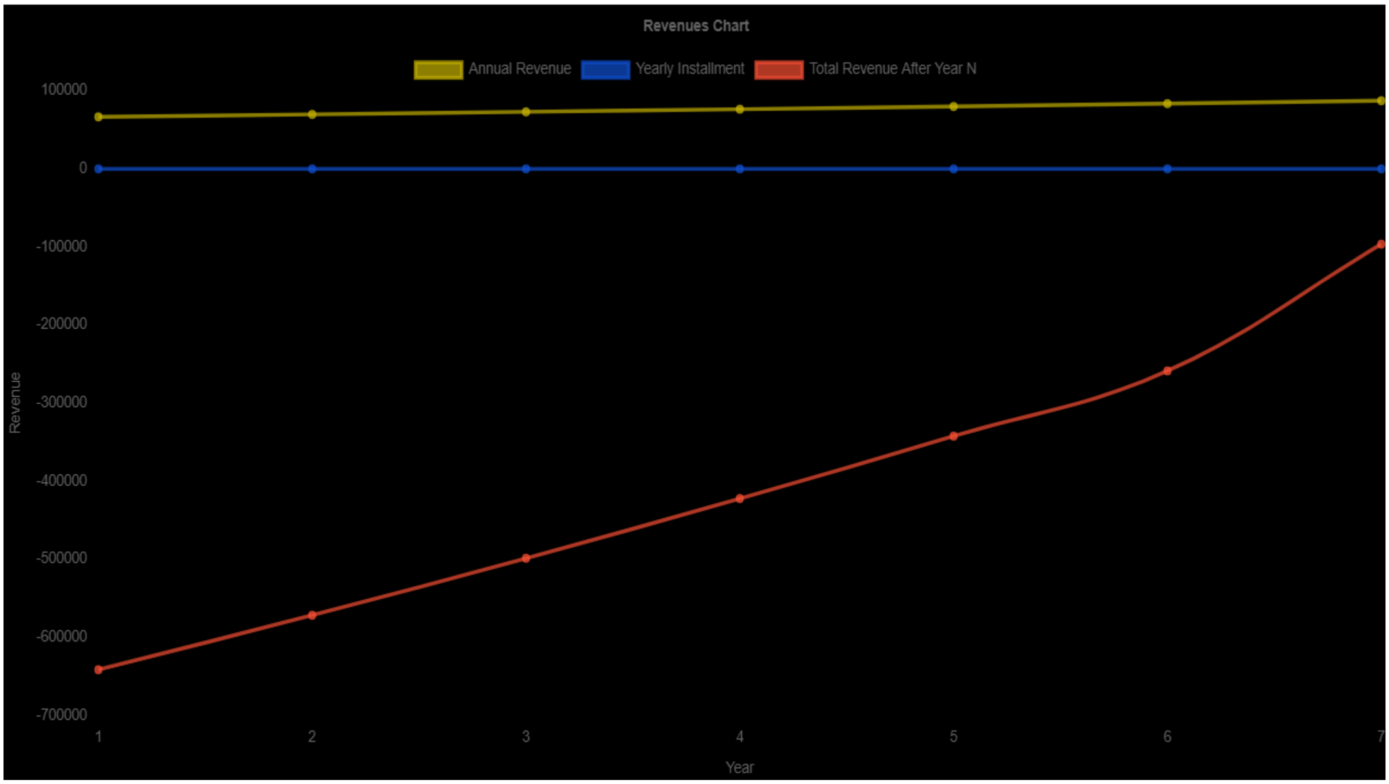
Pre-Retrofit Maintenance Costs	**11,280$/year**
Battery Maintenance Costs	12,179$/year
Maintenance Costs Benefit	-900$/year

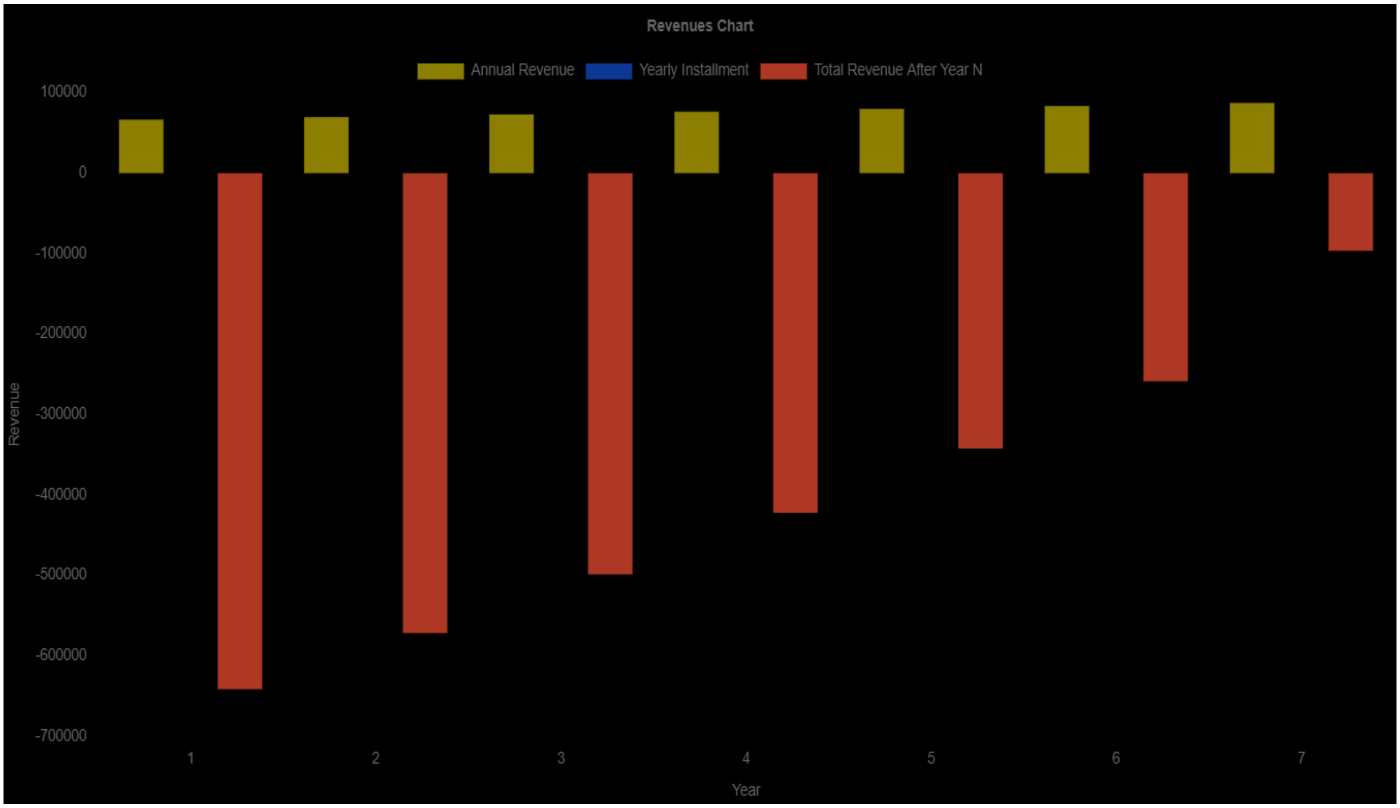
Total Benefits	**66,632$/year**

Financial Calculation

Years	Initial Cost	1	2	3	4	5	6	7
Annual Benefit ($)	-708344.48	66632.93	69801.8	73077.2	76462.4	79960.8	83576	87311.5
Benefit selling the battery equipment (Recycling)								75036.672
Cost by replacing the battery equipment								
Loan / Yearly Installment ($)	0	0	0	0	0	0	0	0
Total Revenue After Year N ($)	-708344.48	-641711.55	-571909.75	-498832.55	-422370.15	-342409.35	-258833.35	-96485.178
NPV		-302816.7 $		IRR		0 %		

INTERMEDIATE CHARGING CHARTS



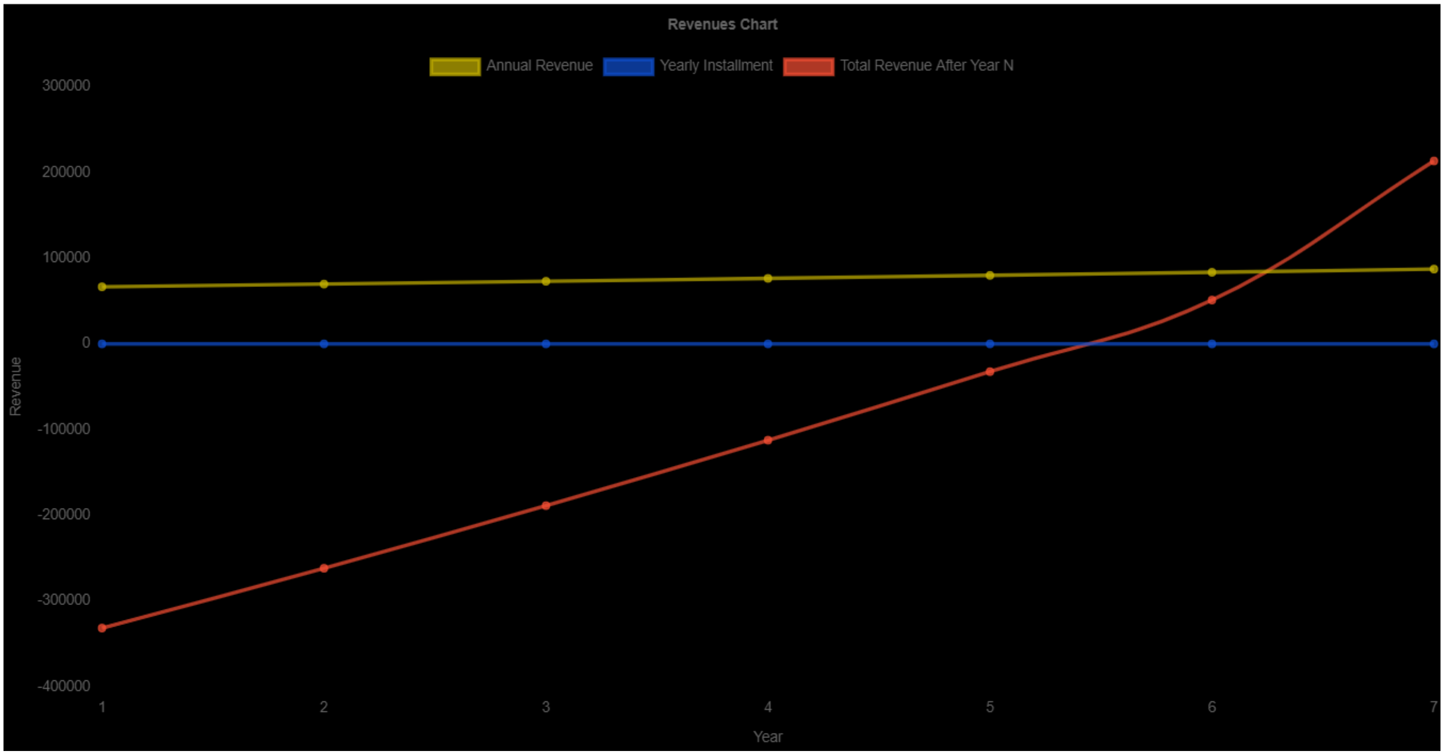


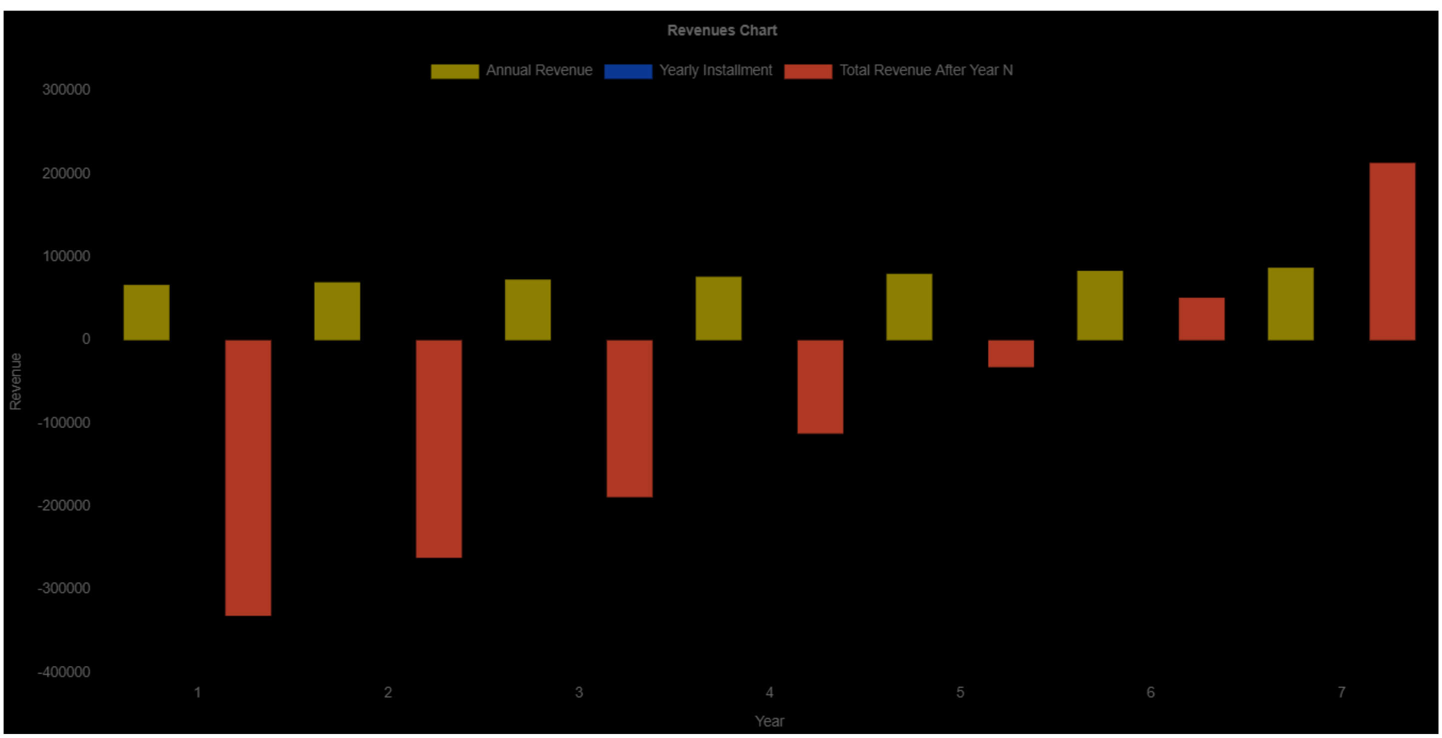
$NPV = -303{,}000\ \$$: Grant is required for the fulfillment of the project

Assuming 310,000 $ grant:

Financial Calculation								
Years	Initial Cost	1	2	3	4	5	6	7
Annual Benefit ($)	-398344.48	66632.93	69801.8	73077.2	76462.4	79960.8	83576	87311.5
Benefit selling the battery equipment (Recycling)								75036.672
Cost by replacing the battery equipment								
Loan / Yearly Installment ($)	0	0	0	0	0	0	0	0
Total Revenue After Year N ($)	-398344.48	-331711.55	-261909.75	-188832.55	-112370.15	-32409.35	51166.65	213514.822
NPV	7183.3 $			IRR	10.5 %			

CHARTS WITH GRANT





8.4 WITHOUT INTERMEDIATE CHARGING FOR N VOYAGES SCENARIO

In this scenario the ship does not charge per N voyages .We use a higher current for charging (59A) otherwise the ship would stay into the port for an intolerant amount of time. We examine three, four and five voyages without intermediate charging in order to find the optimal choice for our retrofit.

Without Intermediate Charging for N voyages					
N	DOD_{real}	$E_{installed}$ (kWh)	$Cycles_{daily}$	$Life_{expectancy}$(years)	$T_{charging}$(min)
3	0.68	906	3.607	6.16	42
4	0.67	1208	2.705	8.22	41
5	0.67	1510	2.164	10.27	43

We can notice that we have significantly less energy requirement for three voyages without intermediate charging. In this case though, the battery has a life expectancy of 6.16 years which can be a problem because we want to make the analysis for seven years. It is a common that battery manufacturers consider the life expectancy in more severe conditions than the ones the battery is actually going to meet, thus this difference in years is not so important and it is relatively safe to consider that the battery will live up to seven years. Nevertheless, we will also examine the case without intermediate charging per four voyages in order to be sure that we will not need a change of batteries before the seven years period.

THREE VOYAGES WITHOUT INTERMEDIATE CHARGING

Total Energy per day	**3269 kWh**
Energy installed	906 kWh

Battery Arrays	**2**
No.of Modules Series	20
No.of Batteries Parallel	30
Total No. of Batteries	600
Charging Time	41 min
C Rate(During Charging)	1
New DOD	0.676
Total Weight of Batteries	9780 kg
Total Volume of Batteries	6.06 m^3
Daily Cycles	3.607
Life Expectancy	6.16 years

Battery	**416,870$**
Inverter (1)	207,000$
Motor (1)	37,800$
Buying Cost	661,670$
Selling Cost	36,700$
Total Cost after Sell	624,970$

Pre-Retrofit Fuel Costs	**124,734$/year**
Battery Fuel Costs	57,201$/year
Fuel Costs Benefit	67,532$/year

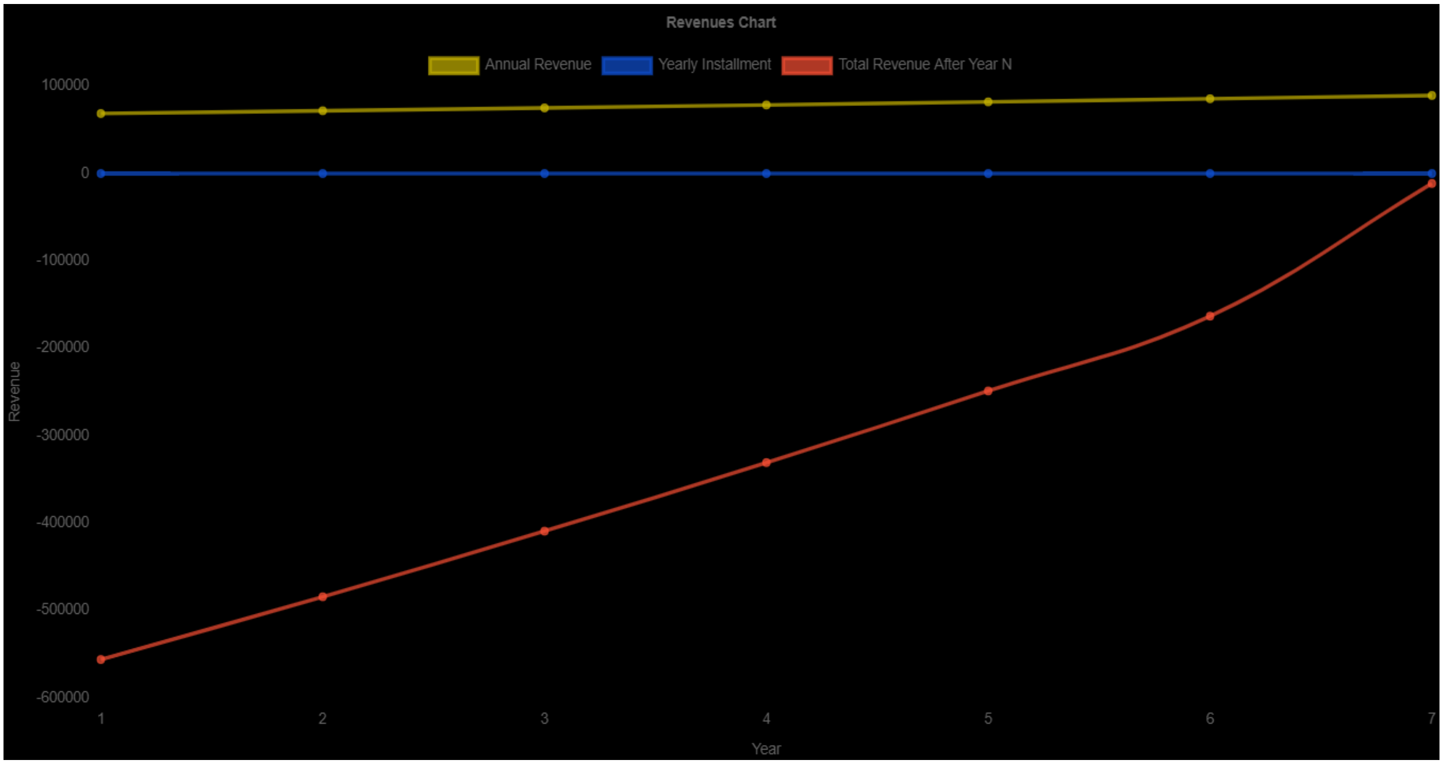
Pre-Retrofit Maintenance Costs	**11,280$/year**
Battery Maintenance Costs	10,149$/year
Maintenance Costs Benefit	+1130.11$/year

Total Benefits	**68,663$/year**

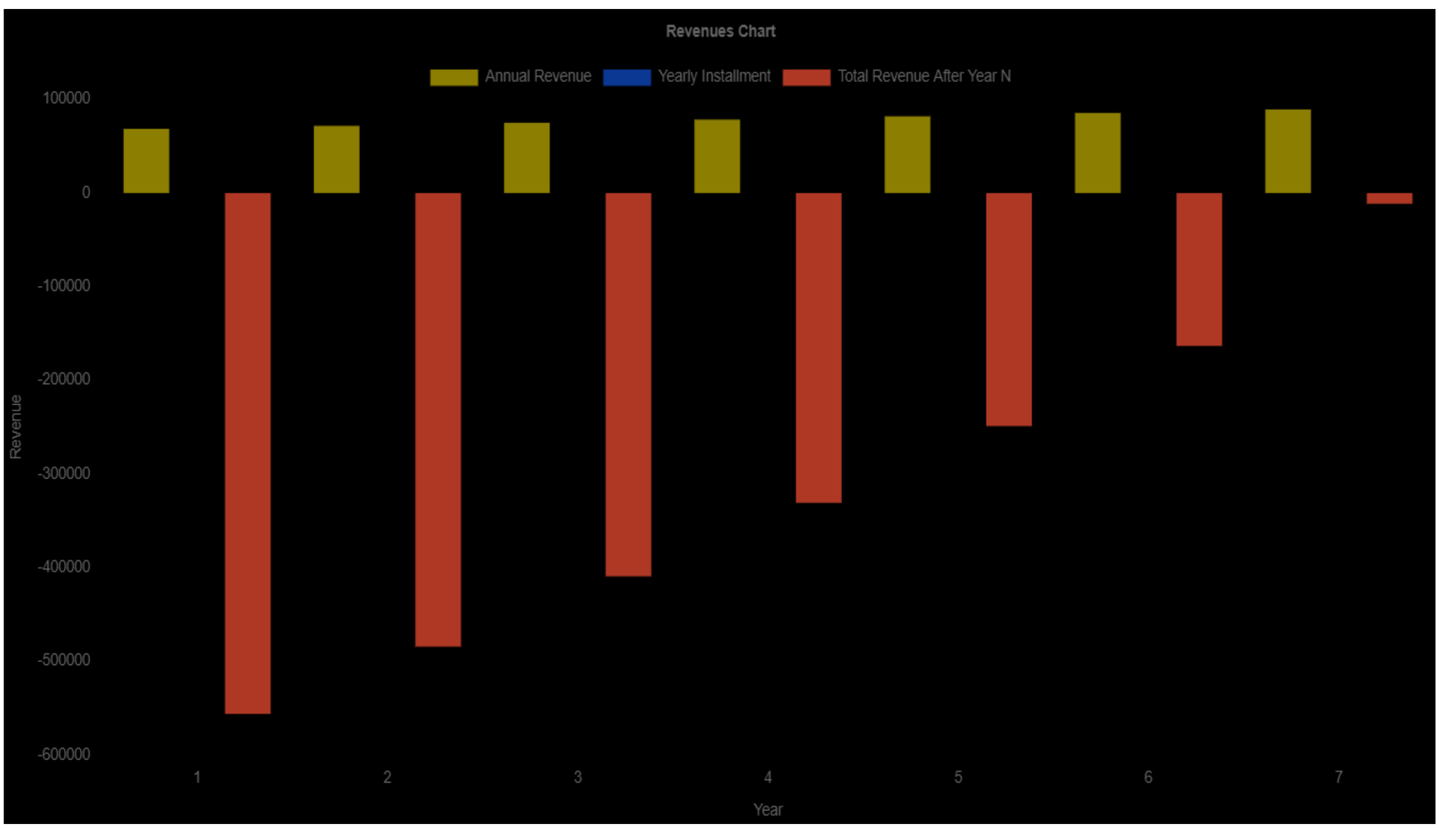
Financial Calculation

Years	Initial Cost	1	2	3	4	5	6	7
Annual Benefit ($)	-624970.4	68662.91	71831.8	75107.2	78492.4	81990.8	85606	89341.5
Benefit selling the battery equipment (Recycling)								62530.56
Cost by replacing the battery equipment								
Loan / Yearly Installment ($)	0	0	0	0	0	0	0	0
Total Revenue After Year N ($)	-624970.4	-556307.49	-484475.69	-409368.49	-330876.09	-248885.29	-163279.29	-11407.23
NPV		-215977.4 $		IRR		0 %		

CHARTS WITHOUT GRANT



Revenues Chart
Annual Revenue
Yearly Installment
Total Revenue After Year N
100000
0
-100000
-200000
-300000
-400000
-500000
-600000
Revenue
1
2
3
4
5
6
7
Year



Revenues Chart
Annual Revenue
Yearly Installment
Total Revenue After Year N
100000
0
-100000
-200000
-300000
-400000
-500000
-600000
Revenue
1
2
3
4
5
6
7
Year

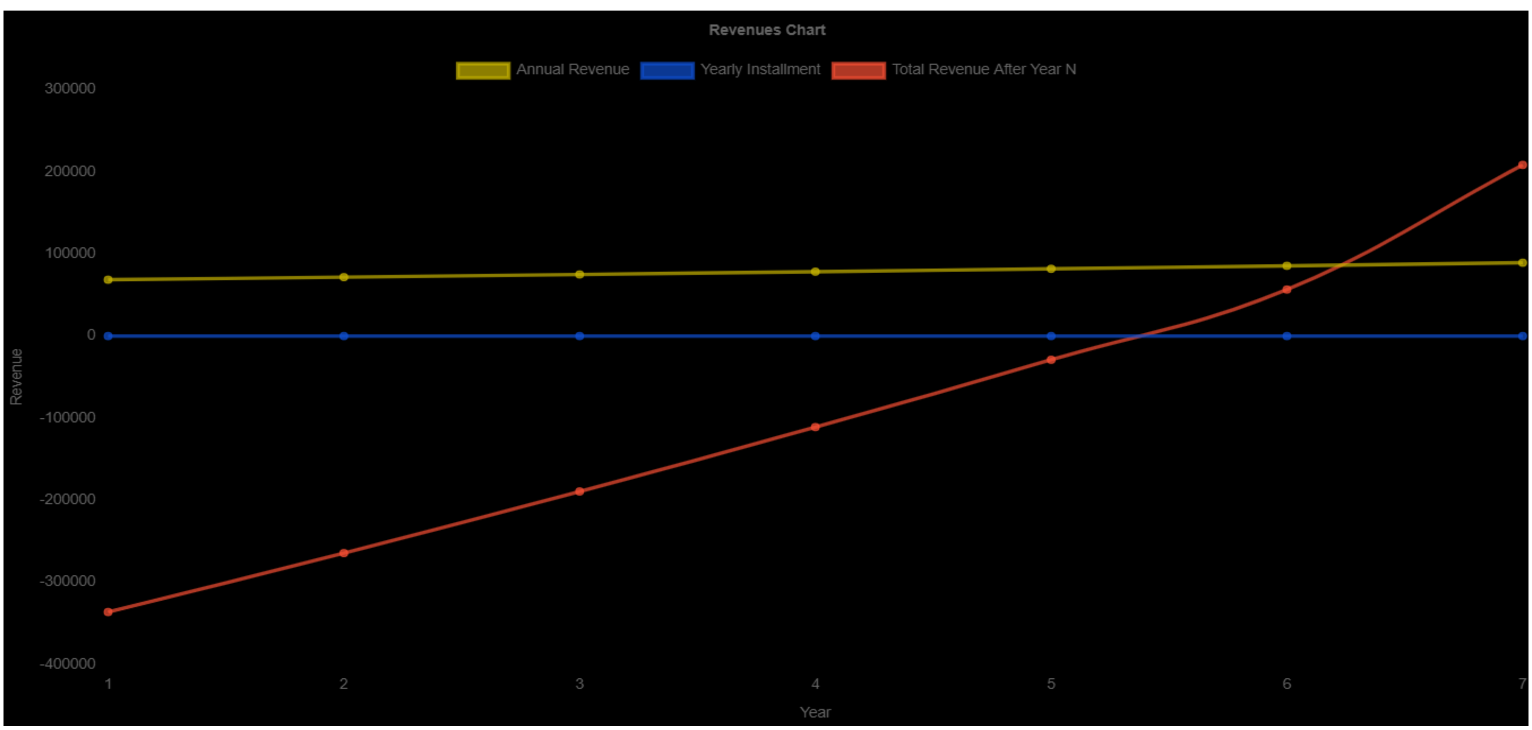
$NPV = -216{,}000\ \$$: Grant is required for the fulfillment of the project

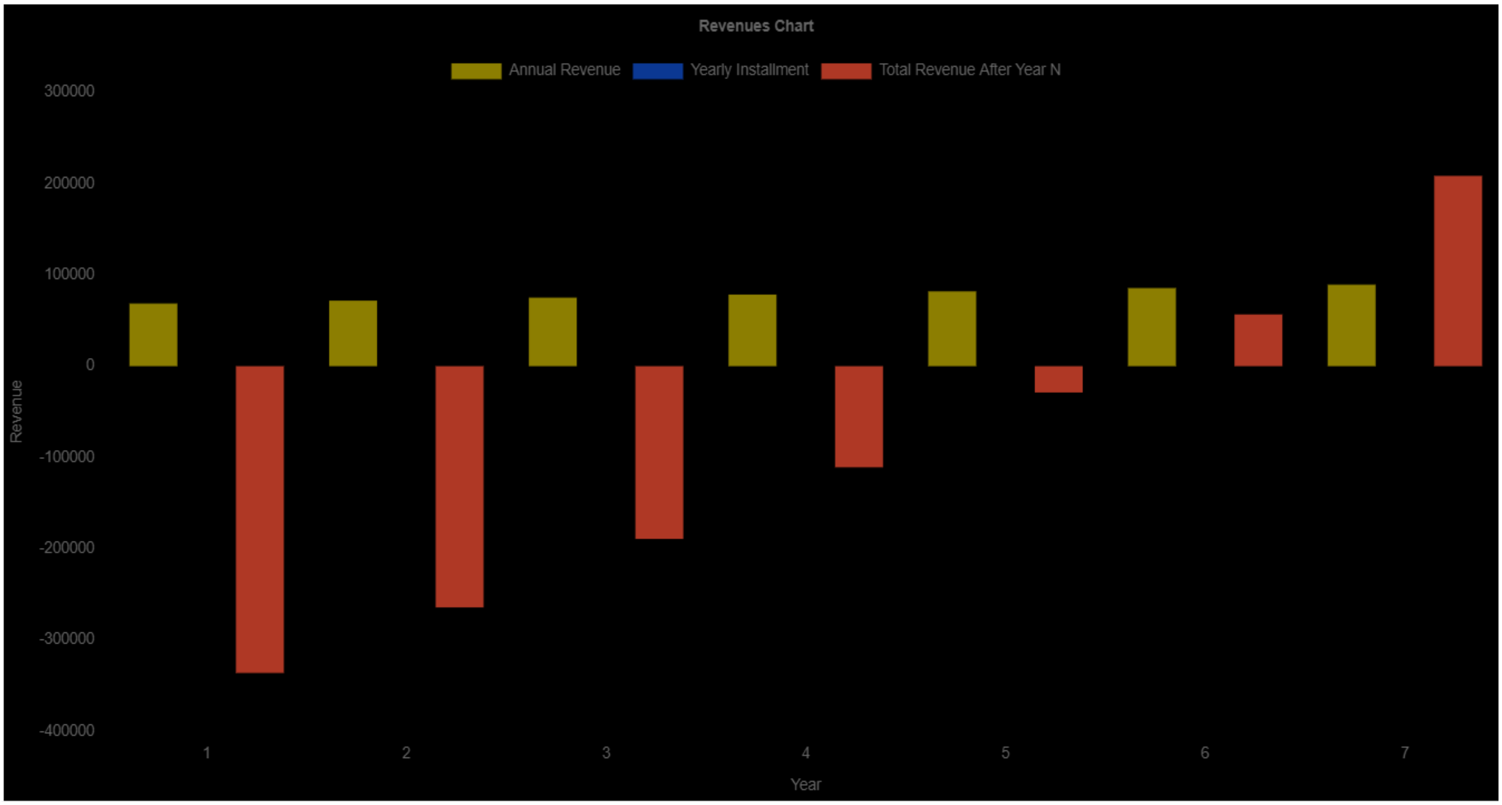
Assuming 220,000 $ grant:

Financial Calculation

Years	Initial Cost	1	2	3	4	5	6	7
Annual Benefit ($)	-404970.4	68662.91	71831.8	75107.2	78492.4	81990.8	85606	89341.5
Benefit selling the battery equipment (Recycling)								62530.56
Cost by replacing the battery equipment								
Loan / Yearly Installment ($)	0	0	0	0	0	0	0	0
Total Revenue After Year N ($)	-404970.4	-336307.49	-264475.69	-189368.49	-110876.09	-28885.29	56720.71	208592.77
NPV	4022.6 $			IRR	10.3 %			

CHARTS WITH GRANT





FOUR VOYAGES WITHOUT INTERMEDIATE CHARGING

Total Energy per day	**3267 kWh**
Energy installed	1208 kWh

Battery

Battery Arrays	**2**
No.of Modules Series	20
No.of Batteries Parallel	40
Total No. of Batteries	800
Charging Time	47 min
C Rate(During Charging)	1
New DOD	0.676
Total Weight of Batteries	13040 kg
Total Volume of Batteries	8.08 m^3

Daily Cycles	2.704
Life Expectancy	8.22 years(>7)

Financial Analysis

Equipment Cost

Battery	**555,827$**
Inverter (1)	207,000$
Motor (1)	37,800$
Buying Cost	800,0627$
Selling Cost	36,700$
Total Cost after Sell	763,927$

Fuel Costs

Pre-Retrofit Fuel Costs	**124,681$/year**
Battery Fuel Costs	57,177$/year
Fuel Costs Benefit	67,504$/year

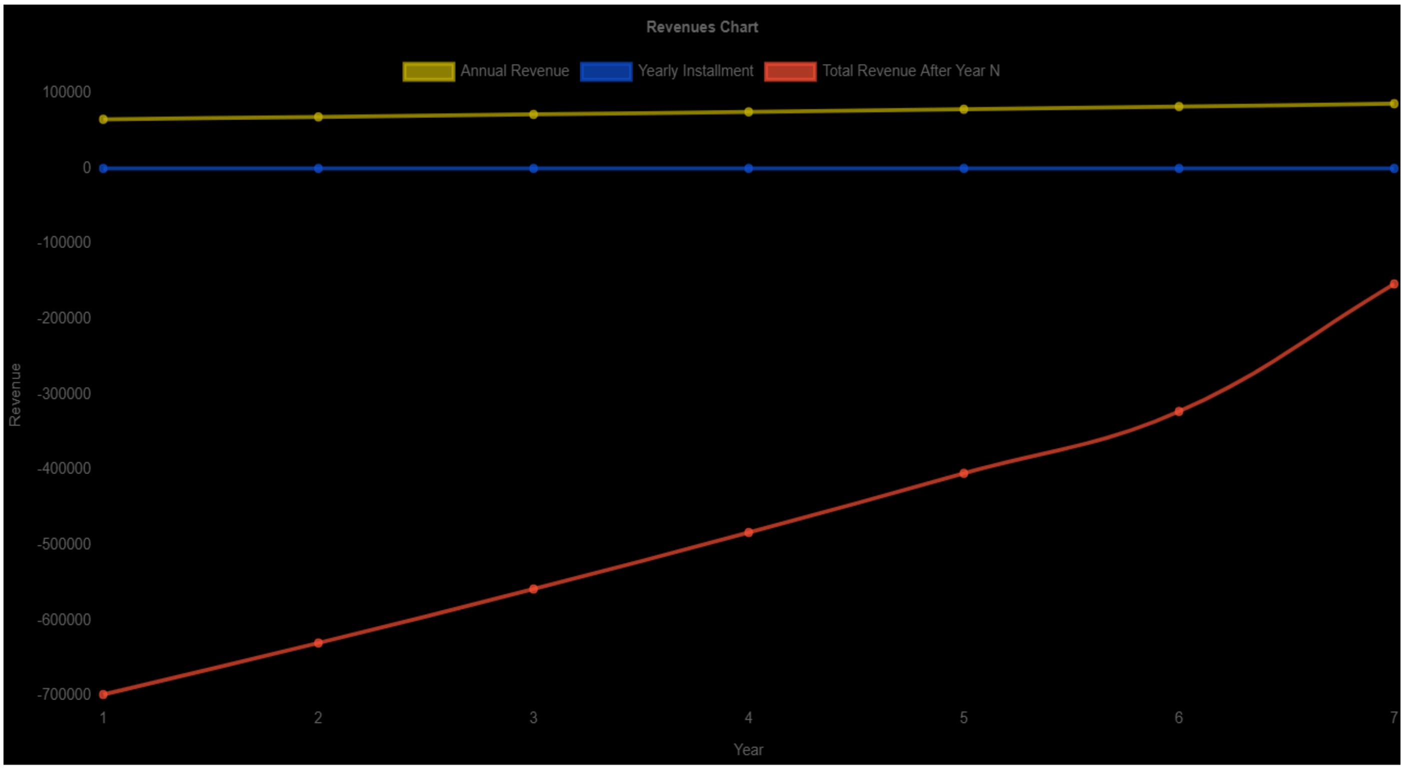
Pre-Retrofit Maintenance Costs	**11,280$/year**
Battery Maintenance Costs	13,533$/year
Maintenance Costs Benefit	-2,253$/year

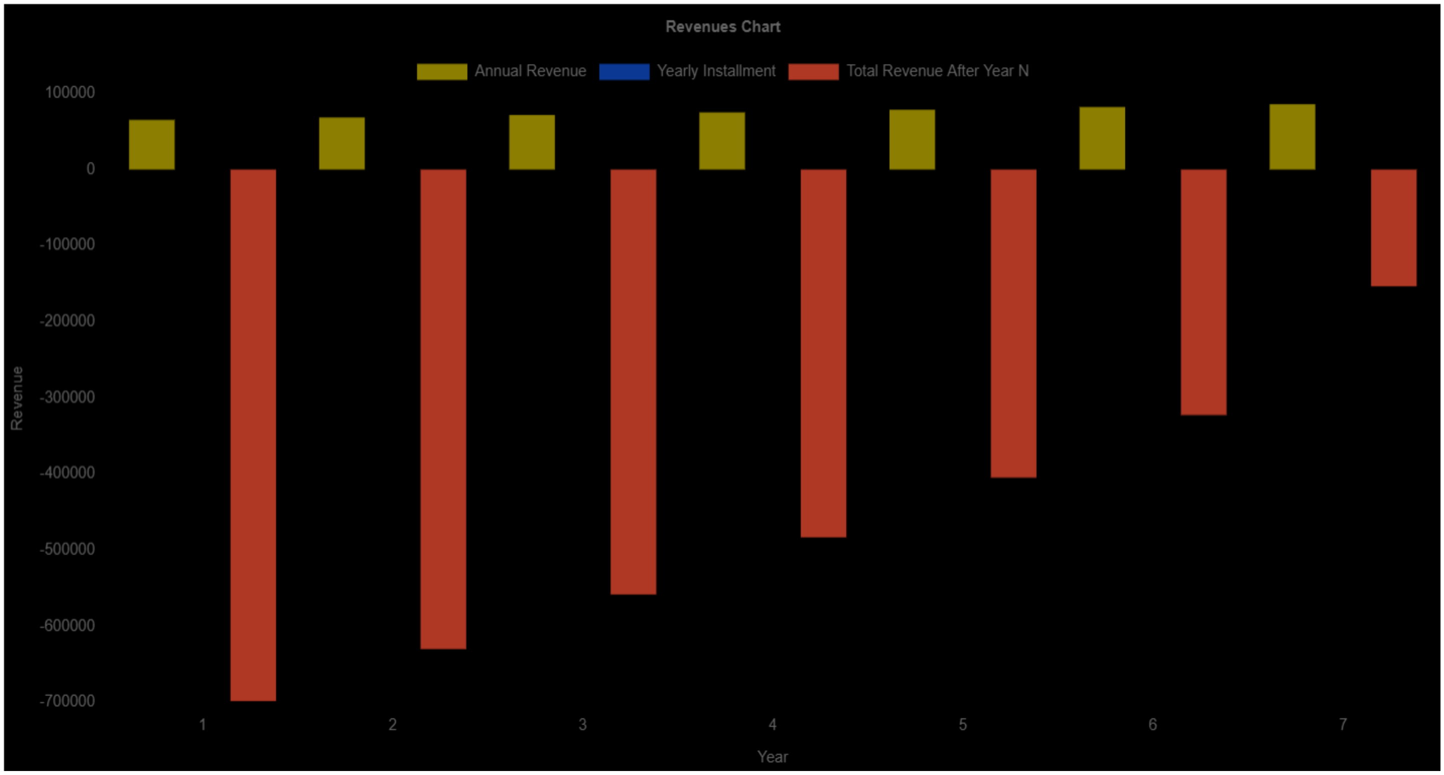
Total Benefits	**65,250$/year**

Financial Calculation

Years	Initial Cost	1	2	3	4	5	6	7
Annual Benefit ($)	-763927.2	65279.62	68448.5	71723.9	75109.1	78607.5	82222.7	85958.2
Benefit selling the battery equipment (Recycling)								83374.08
Cost by replacing the battery equipment								
Loan / Yearly Installment ($)	0	0	0	0	0	0	0	0
Total Revenue After Year N ($)	-763927.2	-698647.58	-630199.08	-558475.18	-483366.08	-404758.58	-322535.88	-153203.6
NPV	-360709.5 $			IRR	0 %			

CHARTS WITHOUT GRANT





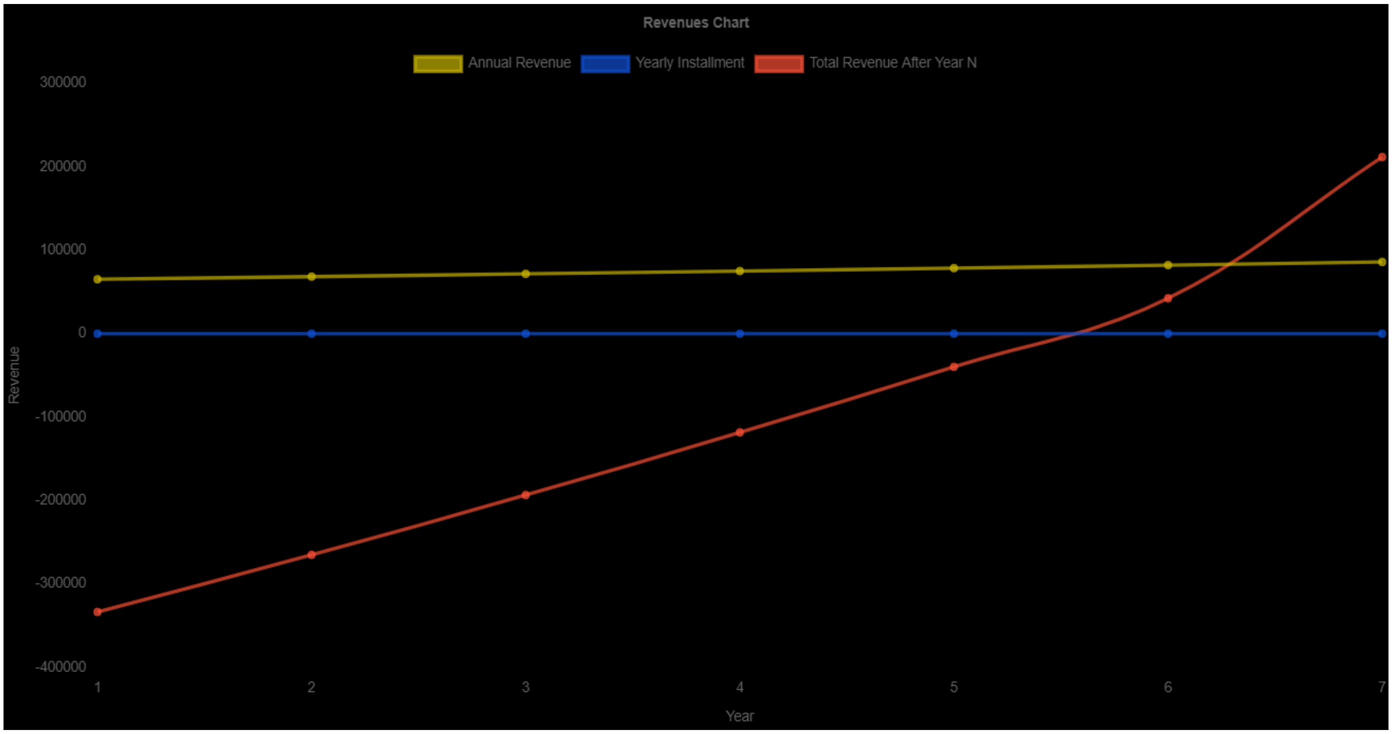
$NPV = -360{,}000$ $: Grant is required for the fulfillment of the project

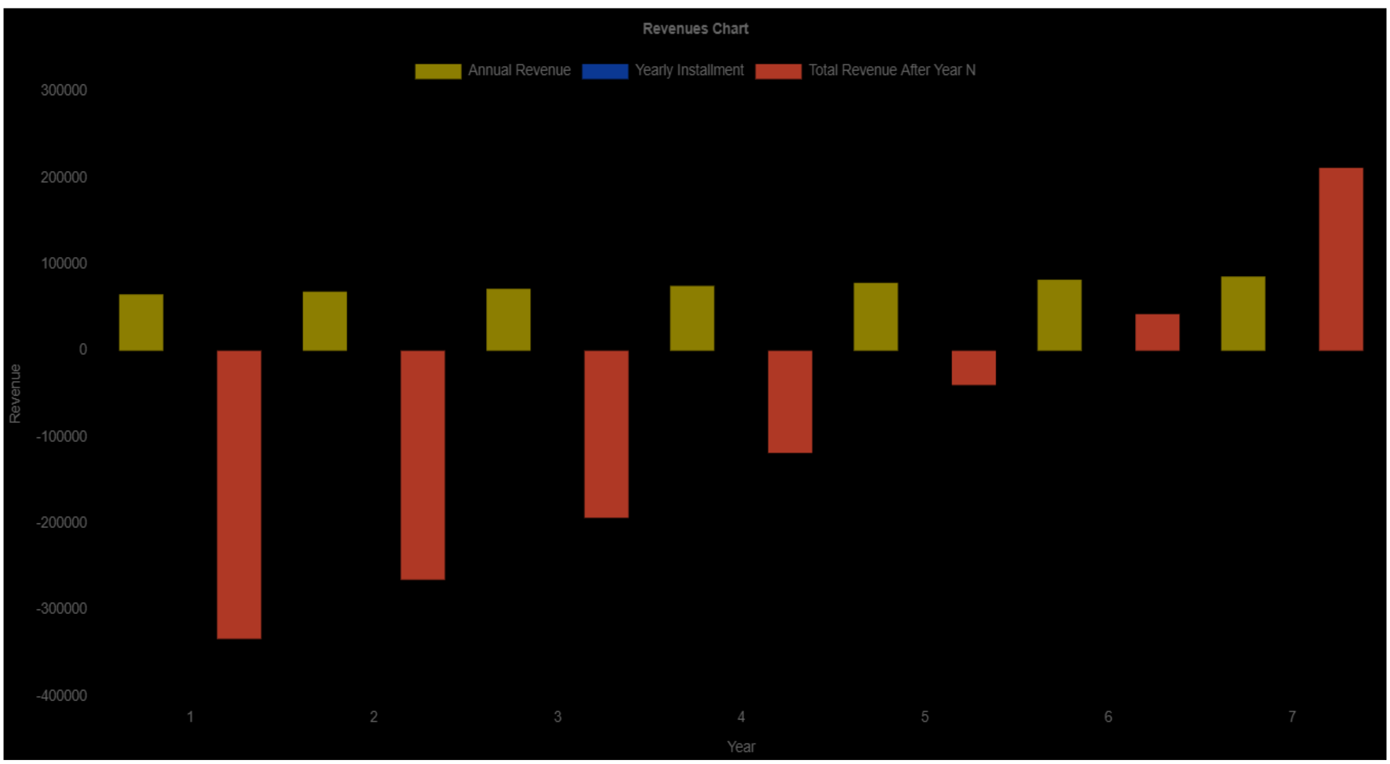
Assuming 365,000 $ grant:

Financial Calculation

Years	Initial Cost	1	2	3	4	5	6	7
Annual Benefit ($)	-398927.2	65279.62	68448.5	71723.9	75109.1	78607.5	82222.7	85958.2
Benefit selling the battery equipment (Recycling)								83374.08
Cost by replacing the battery equipment								
Loan / Yearly Installment ($)	0	0	0	0	0	0	0	0
Total Revenue After Year N ($)	-398927.2	-333647.58	-265199.08	-193475.18	-118366.08	-39758.58	42464.12	211796.4
NPV	4290.5 $			IRR	10.3 %			

CHARTS WITH GRANT





8.5 Results Analysis

For the retrofit we examined two different charging scenarios. In the intermediate charging scenario we chose 50 amperes as the optimal charging. In this case we must install a 1087 kWh battery system of 11.7 tonnes with a life expectancy of 7.4 years. The batteries must be charged for 11 minutes in every port of the trip with 4 additional minutes in order to plug in/off the vessel. The total retrofit cost is 745,000$ (considering the sale of the engines). Savings from fuel costs will be 68,000$ per year.

In the second scenario without intermediate charging, we examined the cases for 3 voyages and 4 voyages. As for 3 voyages the required energy is 906 kWh with a life expectancy of 6.16 years, compared to 1208 kWh and 8.22 years 4 voyages respectively. We chose the maximum recommended current of 59 amperes to charge the batteries for both cases, at 40 minutes approximately. The total weight of the batteries is 9.8 tonnes for 3 voyages and 13 tonnes for 4 voyages. The total savings from fuel costs would be 69,000$ and 65.000$ for 3 and 4 voyages respectively. The retrofit will cost 625,000$ for 3 voyages without intermediate charging and 763,000$ for 4 voyages without intermediate charging.

The Net Present Value of the project is negative in both scenarios. This means that a grant is necessary for the accomplishment of the retrofit. From financial point of view the case without intermediate charging for 3 voyages seems like the optimal scenario since it has by far the smaller negative Net Present Value ($-216{,}000\$$).The other two cases are though safer from the perspective of the battery life expectancy for the desirable seven years analysis.

9. CONCLUSION

The battery-powered vessel that is presented in this paper is directly addressing the urgent need of reducing the increasing CO_2 emissions from waterborne transportation. Ferries are very popular in Europe, where more than one third of the world fleet operates. However, the European Union ferry fleet is old and in need of newer, more energy efficient and less emitting CO_2 and polluting types.

The new fully electric concept aims to become a game changing approach to short and medium range ferry connections. The concept goes beyond a sustainable transport solution targeting also cost effectiveness. Changing to the fully electrical ferry is a typical case of higher investment cost against lower operational cost. However, the operational cost should also be seen in a broader sense including external cost and taking into account derived improvements in transport quality (expressed through cost, comfort and environmental quality). The concept considers the cost balance in this broader perspective taking into account impacts to economic, environmental and social balances. Fortunately, despite of obsolete maritime and energy regulations, in many cases the concept will be the most economically attractive choice. This means that, not only it does eliminate emissions and pollutants, it can present a cost-effective alternative.

The evaluation has concluded that the economic grounds for electrification are also there; the electric ferry is a valid commercial alternative from a purely economic aspect. Thus, while the retrofit of ships into battery-powered, has high costs, the operational costs, especially those dedicated to energy/fuel, are significantly lower for fully electric vessels.

Time is our ally. As also indicated in the economical evaluation, while battery systems have been a major cost contributor to the ship investment costs, the steady decrease in cost of €/kWh for marine applications makes the perspective for fully electric vessels even better in the future.

The cost-effectiveness of the innovative shift towards electrically driven short sea ferries would benefit from changes of current regulations (for example if quotas were to be imposed on shipping as for businesses on land). It could change the balance between up front finance cost and future running cost thus shortening the payback time and increasing the incentive for ship-owners to adopt battery-powered ships.

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