National Technical University of Athens

School of Naval Architecture and Marine Engineering

Division of Marine Engineering

Diploma Thesis

# Electrification of vessels covering small distances

Makariou Evangelos

February 2020

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# Abstract

Purpose of this thesis is to gather and keep a record of the technical characteristics of ferries covering small distances in Greek waters and these routes. As far as ferries are concerned their principal dimensions, service speeds, number of passengers and vehicles, power of main engines, generators and emergency generator are recorded. Concerning routes, distance, required cruising time, available time at port and frequency of routes are recorded.

Afterwards, a classification is made according to distance and frequency of routes. Further analysis is provided with the use of Retrocalc, a computational tool that Mr. Michail made, for each route and ferry separately. Input data for each route is presented analytically as well as output data and thus with the run of the program effect of the different characteristics of ferries and routes (variants of the program) are interpreted.

Comparisons between different routes and different scenarios of same routes are made, which also helps to interpret the effect of different variants (time at port, engine power etc.), leading to the selection of the desired characteristics of ferries to be electrified. Finally, the economic results are presented; taking into account all necessary technical details (e.g. required number of batteries) and the routes are classified according to their cost of retrofit-deadening.

Except these, a historical review is made of electric ships in the past as well as future projects and tendencies are presented. Technology of batteries is analyzed, including mechanisms and chemistries of all categories of batteries that are used on board. The retrofit procedure is developed thoroughly along with the necessary rules, regulations and legislations that shall be followed. All possible vessel to shore connection systems and designs of electrical topologies on shore and on board are presented.

An environmental study is carried out with the effects on human health, environment and economy mentioned. Regulations for the control of hazardous substances and possible ways to reduce emissions are presented as well as a targeted study for the production of electricity in Greece, to conclude that an all-electric ferry is an interesting and favorable choice from all perspectives (technical, economical and environmental) and shall be encouraged by Greek authorities.

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# Contents

# 1 Introduction

## 1.1 Background of study

In this day and age, it is widely accepted that not only the new generation of ships but also the already existing, must meet new challenges concerning the energy efficiency, the reliability and the environmental impacts.

The transport sector consumes about 25% of total commercial energy consumed in the world. [1]

Reducing energy consumption and emissions of transport systems are important issues because transportation sector have a strong impact on pollution and fuel consumption. It is estimated that 80% of cargo is carried by the sea, and maritime transportation is responsible for more than 30% of $CO_2$ emissions of the transportation sector and about 3% to 4% of the humanity $CO_2$ emissions. Greenhouse gas emissions related to ships are important and rapidly growing.

Without action, these emissions will be more than double by 2050, due to the expected growth of the global economy and the associated transport demand. This is why international regulations have been established or are in project concerning limitation of ship emissions.

In this context, minimization of fuel consumption and reduction of emissions is one of the main objectives for designing new generations of ships. [2]

To reduce exhaust emissions and save fuel, many kinds of solutions have been proposed. For example, the after-treatment system of exhaust gases, replacing alternative fuels, and using hybrid-propulsion types have been commonly applied to meet environmental regulations. However, these are not fundamental solutions for the de-carbonization in the marine industry.

An innovating solution could be the all-electric battery ship with zero greenhouse gas emissions-emission free with extremely energy efficient design, causing no damage to the environment and to the health of humans. This solution is especially beneficial for island communities, coastal zones and inland waterways, where ship emissions are the main cause of humans' disorders.

Technological evolution seems to allow us to use battery storage system for the marine propulsion. As technologies have been developed, the BESS (Battery Energy Storage System) has been widely regarded as an auxiliary or main power source because of the following benefits: Fast response and peak saving, reducing mechanical noise, less maintenance time and costs, low emissions and fuel saving, redundancy availability, more energy-efficient and easy to apply new and renewable power sources.

The environmental savings of battery-powered ships depends on the emissions creating by generating electricity. Norway, for example, is close to 100% renewable electricity generation, so the savings from all existing ferries are very important.

As far as Greece is concerned, there are no electric ships although the conditions are ideal. Primarily because there is no place in Greece that abstains more than 150 km from the sea, with 33% of population living not more than 2km from the coast and so the benefits are significant. Another ideal condition is the climate that could generate renewable electricity very easily with the many sunny hours and strong winds per year.

Greece has more than 150 vessels serving routes of short sea shipping, all of whom consume fossil fuels with bad consequences on the environment and on health of native people and tourists, and that is why electrification is necessary.

## 1.2 Problem statement and objectives

The purpose of this thesis is to fulfill some challenges concerning the electrification of ferries in the Greek seas and conclude whether or not the electrification process is appropriate for the Greek ferries taking into account all social and economic factors.

The first challenge is to analyze the electrification process: by accomplishing battery calculations, updating electrical studies, calculating the required installed capacity of the battery systems in order to ensure safety for passengers according to each vessel's profile, ensuring that the energy being provided from the battery storage system is enough to ensure that the electric ferry has an operational day and by designing a charging connection system between the ship and a coastal public electricity grid.

The second challenge is to gather the most important ferry lines in Greece (Location, distances, coverage times, number of ships, speeds, times of stay at each port, frequencies) and prioritize the routes depending on their distance and frequency. In addition, the technical characteristics of those ferries will be presented (general dimensions, speeds, number of passengers and vehicles, engine power, generator power, loads).

Last challenge will be the conversion cost estimation analysis for all those lines and their comparison so we can find out if the installation of all-electric vessel is economically feasible and reach to a conclusion which line is the most beneficial to be electrified first.

For this last challenge we will use a program named Retrocalc which Mr. Dimitrios Michail made in his diploma thesis and its purpose and operation will be analyzed.

## 1.3 Structure of study

Chapter Two
A historical review is presented of ships using the power of electricity which represent important milestones in evolution. Turbo-electric, diesel-electric, hybrid driven ships are presented with the last technology to be the fully electric driven, with many examples. Future tendency and projects are also presented.

Chapter Three
The mechanism of batteries is explained along with the most important categories and types of batteries and their technical characteristics. All needed terms explaining batteries are also presented and thus we can evaluate the appropriate battery chemistry for the all-electric ship.

Chapter Four
The range of the main characteristics of the vessels studied in next chapter is presented. An analytic presentation of the rules, regulations and legislations that shall be followed is included and a description of the retrofit procedure with all the necessary information is made.

Chapter Five
Designs of electrical topologies on shore and on board are presented for different scenarios (high-low voltage, AC-DC current). All possible vessel to shore connection systems are also presented.

Chapter Six
A presentation of hazardous substances and their effect on human health, environment and economy is made. Possible ways to reduce emissions and regulations for the control of hazardous substances are analyzed. Generation of electricity from shore side is compared to that on board and the generation of electricity in Greece is presented with its perspectives.

Chapter Seven
The retrofit design philosophy is presented while the program used for the estimation of the required battery capacity is analyzed. Analysis of the inputs variants, the calculation procedure and illustration of the output data is made.

Chapter Eight
In this chapter, 11 different routes are gathered and classified according to their distance and frequency. For each route a vessel is chosen for retrofit, so 11 different vessels with their characteristics in detailed are presented. Other input data of the program used is presented and the results from the program, too. The cases are compared between them so the importance of the different variants is estimated. Finally, for some routes, different scenarios and vessels are examined in order to see if we can have better economic results.

Chapter Nine
Final conclusion on vessels retrofit and recommendations are presented.

# 2 Electric ships: Past, Present and Future

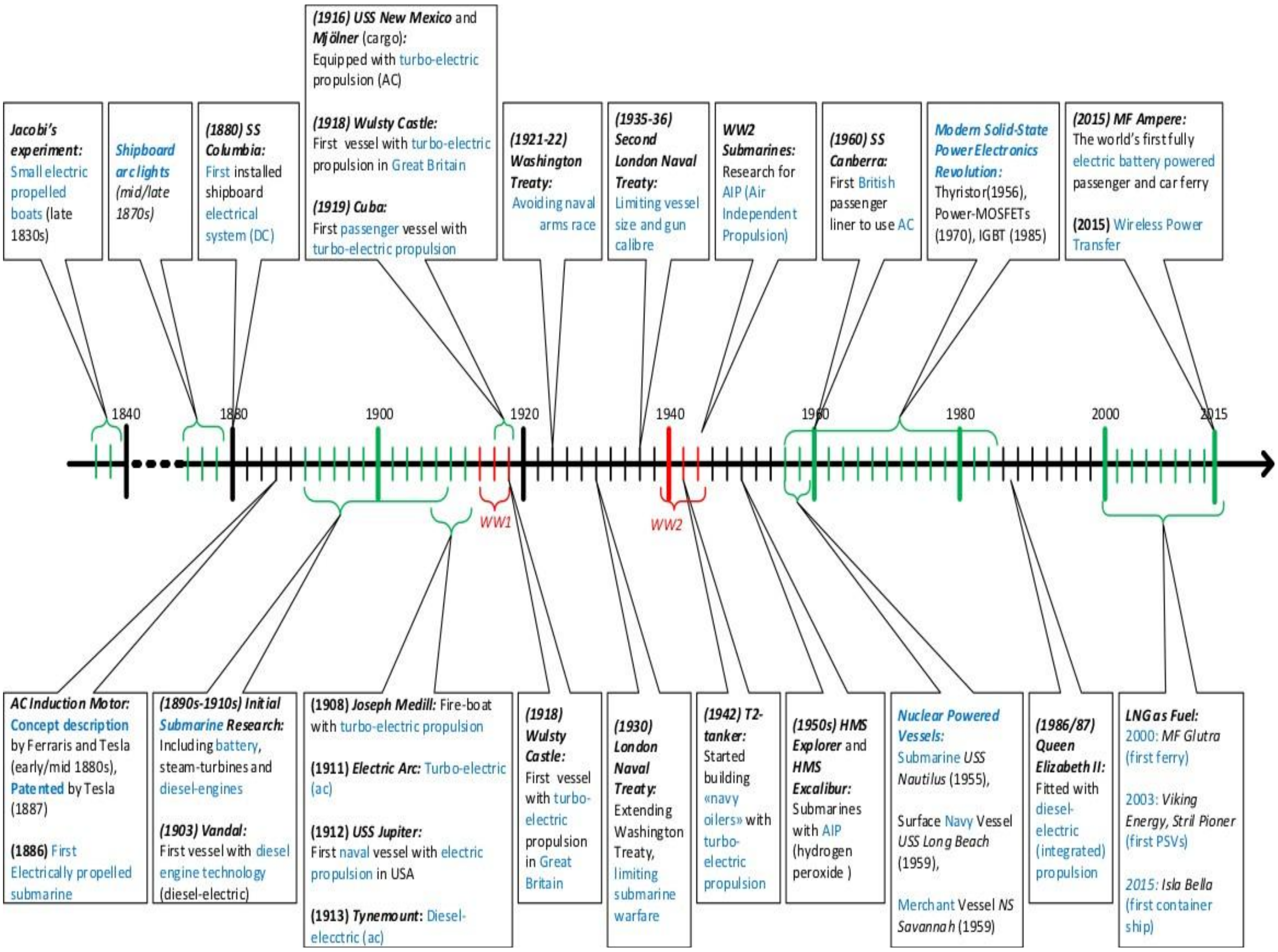



*Figure 1: Timeline of the history of electric ships [12]*

In the late 1830s, the German inventor Moritz Hermann von Jacobi (Yakobi [4]) invented a simplistic dc motor and conducted a couple of experiments with small boats able to carry about a dozen passengers with electric propulsion. The electric motor in his last experiment (about 1kW) was powered by a battery consisting of 69 Grove cells

(early electric primary cell-unrechearchable) resulting in a speed of about 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 [4], [5], [6].

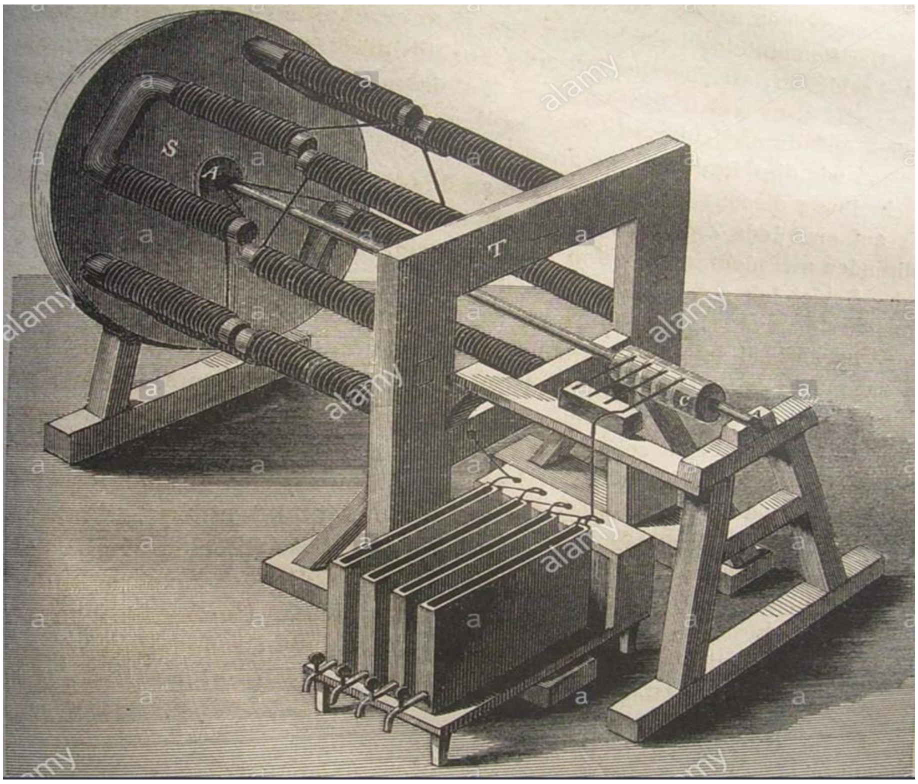


*Figure 2: Jacobi's electromagnetic motor, designed in 1834 (www.alamy.com)*

In August 1848, B.Hill constructed an electric boat propelled by a motor, using a Grove type battery, at Wales. However, these batteries were large, heavy, discharged unhealthy $NO_2$ fumes and as the cell was discharged the voltage was reduced.

In 1859, G. Planté invented the lead acid, the first commercial rechargeable electric battery, which led to the current batteries used in cars.

In 1886, “Elektra” was constructed, a test boat from Siemens & Halske. The City of Berlin in Germany tested it for local public transport. The boat had room for 25 passengers and sailed along the river Spree at 14 km/h.

During the last quarter of the 19th century, marine vessels with steam engines became more common. The early steam turbines were initially coupled directly with the propeller with poor results. That’s why in the early 1900s, marine reduction gears and electric propulsion systems were developed to improve the propulsion system powered by the high-speed steam turbine.

The United Kingdom was developing and perfecting mechanical-drive system employing reduction gears, while the United States focused on electric-drive systems [7],[8]. In 1908, the first merchant vessel Joseph Medill (a fire-boat) was built with a turbo-electric (dc) propulsion (400 SHP) [9], [10].

The first naval vessel with electric propulsion in USA was USS Jupiter in 1912. It included diesel engine propulsion, turbo-electric propulsion and direct coupled steam turbine propulsion. It was such a successful experiment that US decided to adapt the same propulsion system to all battleships.

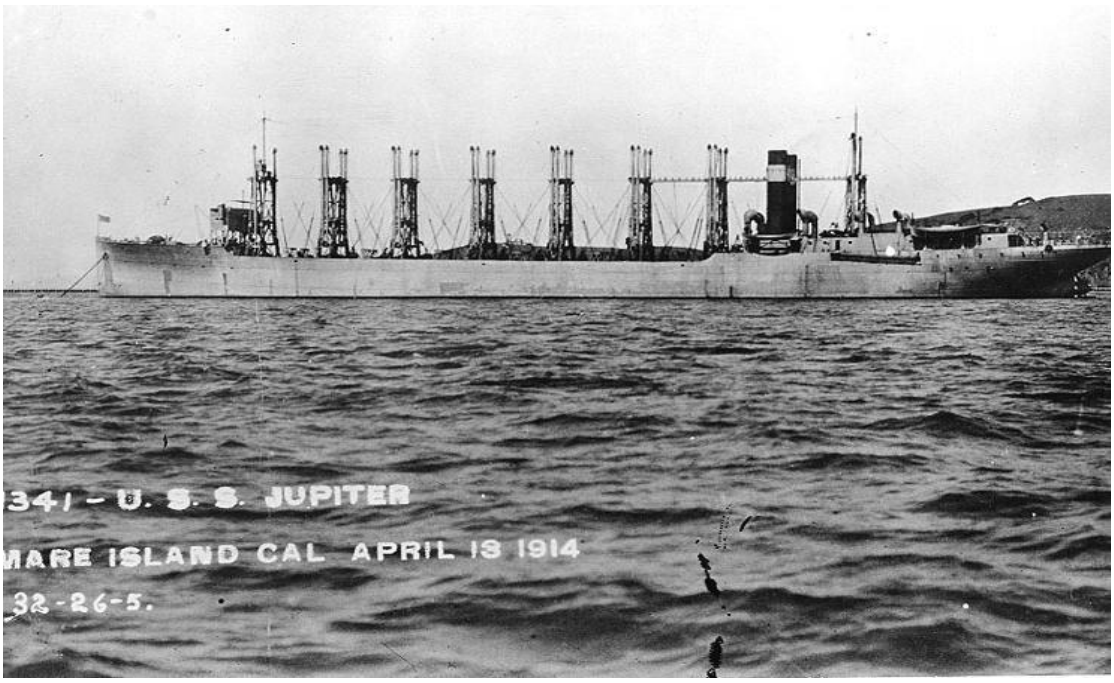



*Figure 3: The USS Jupiter, 1914(U.S. Naval History and Heritage Command Photograph)*

In 1914, USS New Mexico was the first vessel converted to turbo-electric propulsion. It is important to note that there were no power electronics in the early 1910s, hence; the vessel's speed was controlled through a complex combination of varying the frequency (speed), voltage of the generator sets and changes in pole configuration. The turbo-electric propulsion was a very effective system with a number of benefits and its main switchboard is shown on Figure 4. [11]

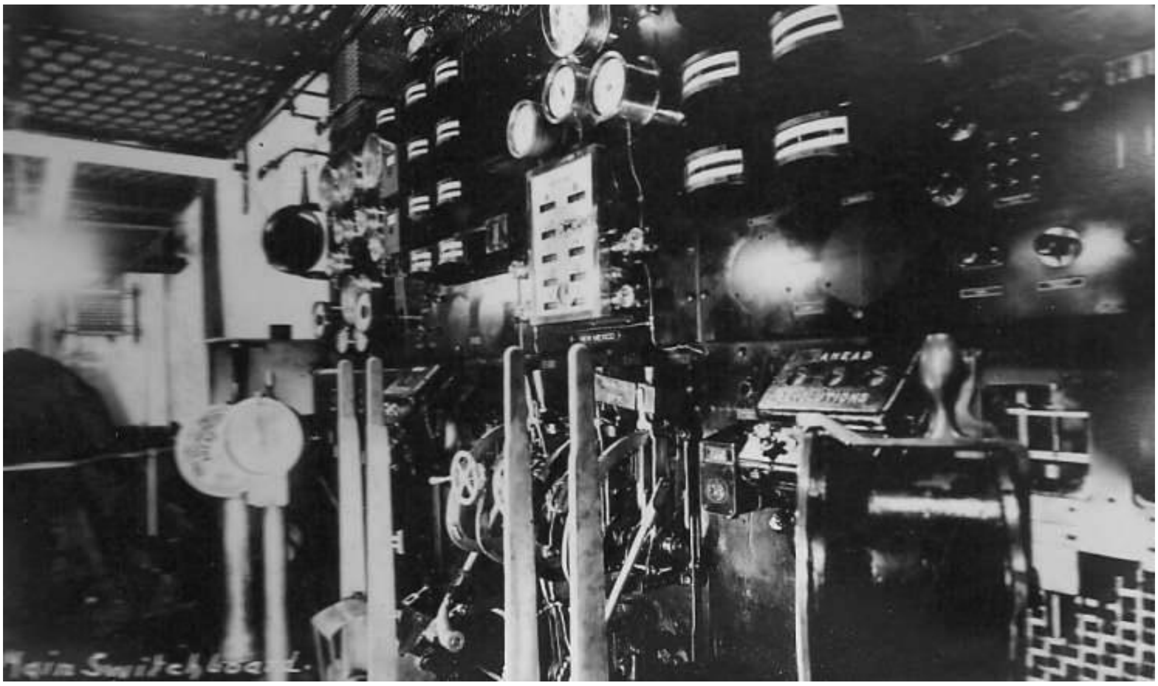



*Figure 4: USS New Mexico's main switchboard and control station. Change of speed and direction was done with manual levers.*

Turbo-electric transmission uses electric generators to convert the mechanical energy of a turbine (steam or gas) into electric energy and electric motors to convert it back into mechanical energy to power the drive shafts. Figure 5 shows a simplified drawing of the turbo-electric generation.

The passenger vessel Cuba was rebuilt in turbo-electric propulsion and was the first passenger vessel with that propulsion system. Its electric propulsion motor is presented on figure 6.

Concerning Europe, the Swedish enterprise Rederiaktiebolaget Svea, located in Stockholm, started equipping ships, which had steam machinery, with turbo-electric propulsion.

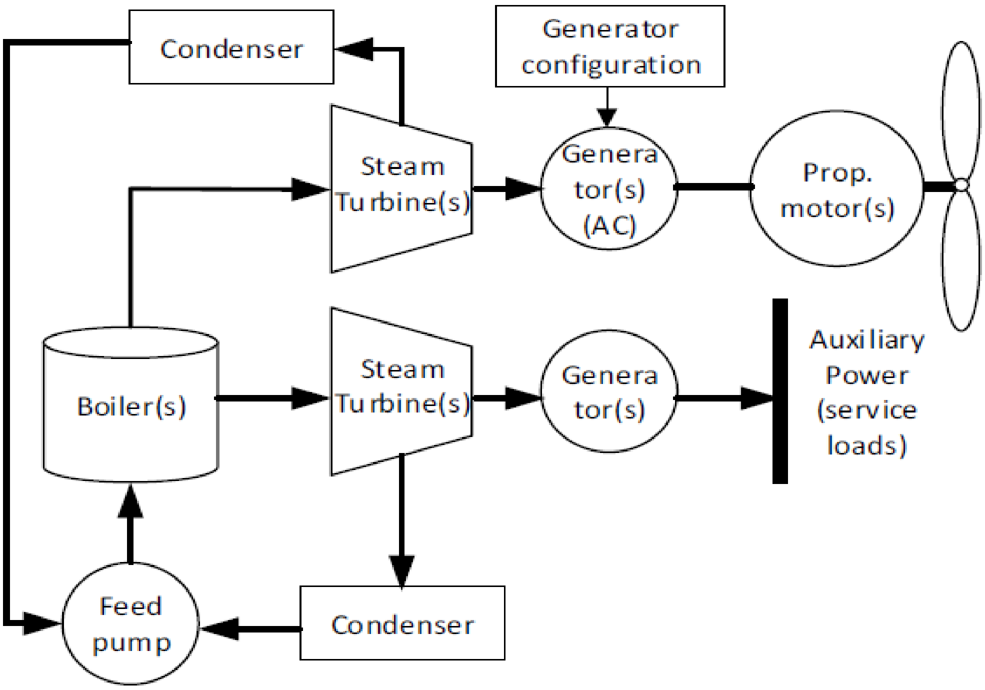



*Figure 5: Simplified drawing of the turbo-electric generation and distribution system installed in USS New Mexico, based on written description [12]*

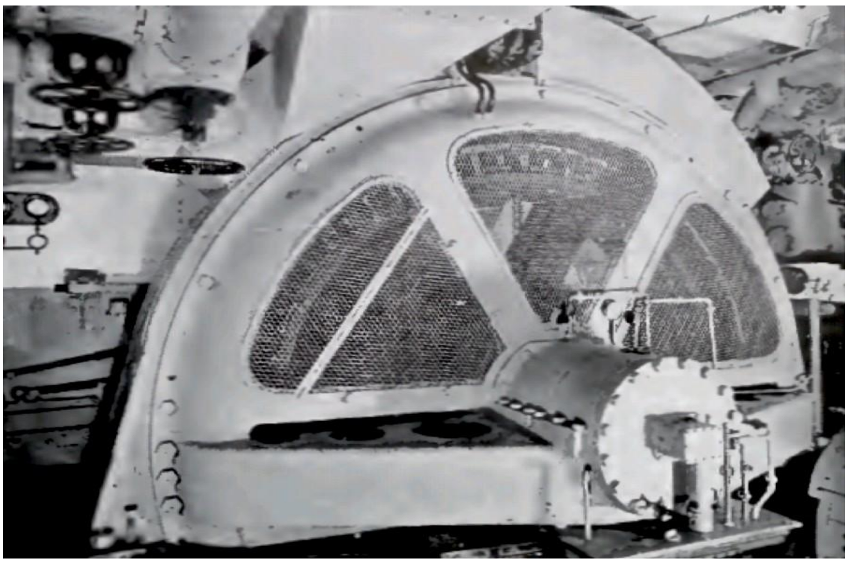


*Figure 6: Cuba's 3.000 horsepower, 1.150 volt, 1.180 ampere electric propulsion motor*

After the invention of diesel engines, Tynemount in 1913 was the first ship with diesel-electric ac propulsion. Two diesels of 300hp were running at 400rpm; the port side diesel drove a 6-pole alternator and its shunt-wound exciter, and the starboard diesel drove a generator which was wound for eight poles [4]. The electrical system worked well for light loads, however, the propeller pitch was too coarse and required more power than the generators were able to supply, resulting in a breakdown of the engines.

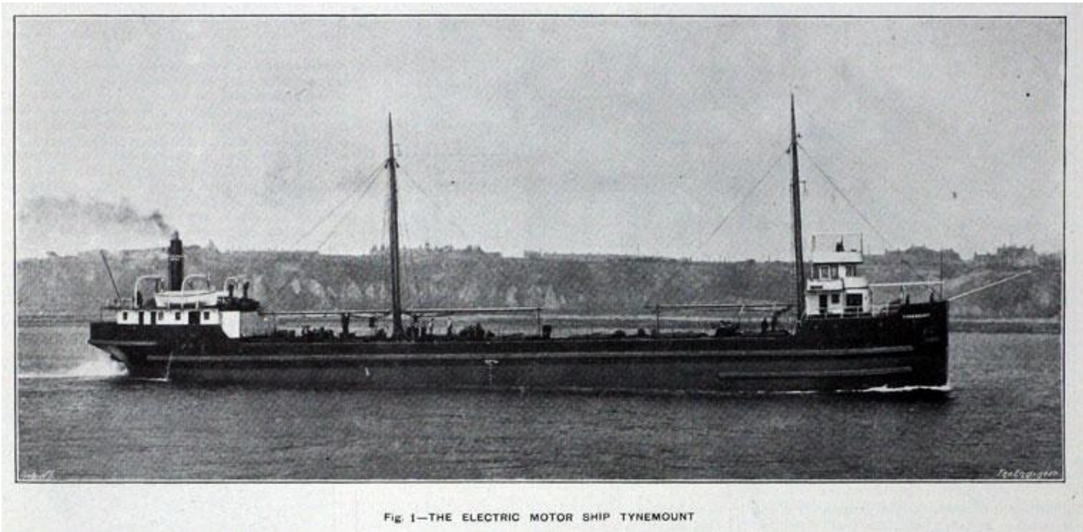



*Figure 7: The first seagoing vessel to be electrically propelled*

During World War 2, between 1942 and 1945, we have the rapid construction of 481 tankers known as “the navy oilers”, which were crucial for maintaining the upper hand in the war by transporting oil to the navy vessels around the world. The propulsion system consisted of a steam-turbine generator connected to a propulsion motor to drive the propeller; hence, the need for a large main reduction gear was obviated.

Another type of ship that is constructed rapidly and in an innovating way is the submarines using Diesel-Electric systems. The propulsion system consisted of a diesel-electric system to charge the main batteries (lead batteries) on the surface using the propulsion motors as generators. The batteries were solely used during submerged operations for both propulsion and service loads such as lights and instrumentation. Figure 8 shows a simplified sketch of such a configuration.

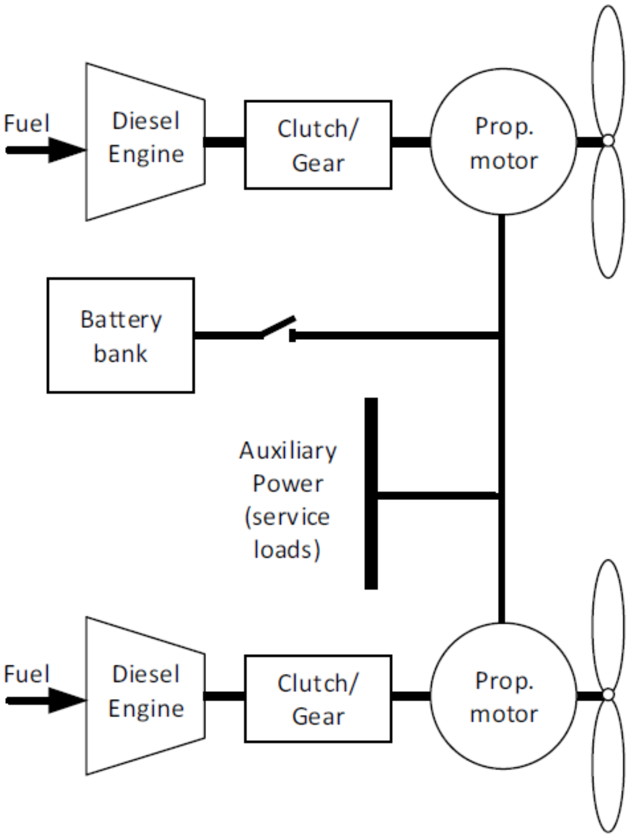



*Figure 8: Simplified drawing of a common diesel-electric configuration in World War I and II submarines. Propulsion motors acted as generators driven by diesel engines on surface.*

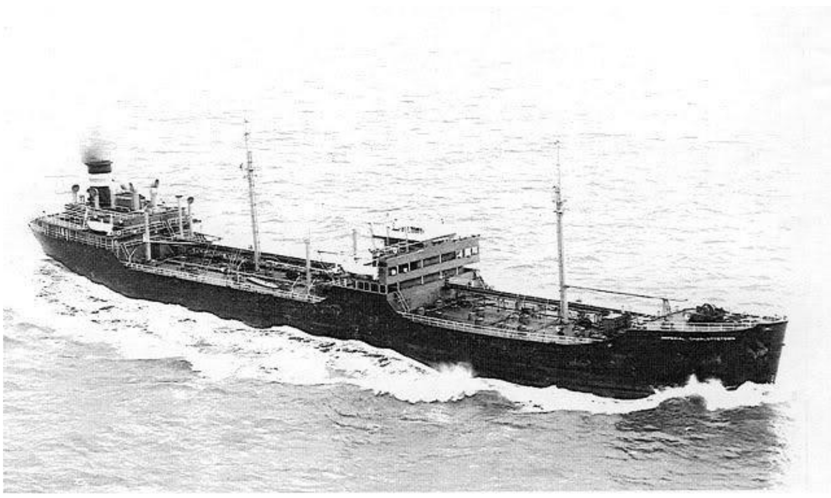


*Figure 9: The T2 tanker (World War II)*

After World War II and toward 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 (e.g. 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 an All-electric Ship (AES).[12]

In 1990s, a new era is created by the podded propulsion. In this arrangement, the electric motor is directly connected to a fixed pitch propeller and submerged, so it does not occupy space in the ship's main hull, further reducing the volume devoted to machinery within the ship. This pod is movable, so maneuverability is improved dramatically as well as the ship's efficiency. Presently, five companies manufacture pods in sizes ranging from a few hundred kilowatts to 25MW.

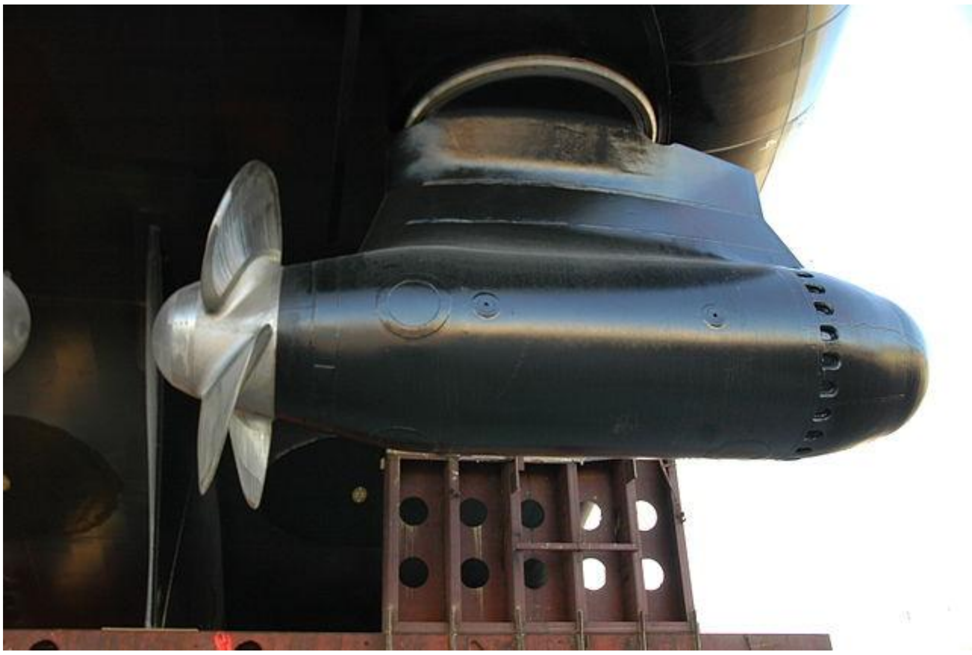


*Figure 10: Pod propulsion*

The last 10 years we have an explosion in the production of vessels using electrical propulsion and a fleet of new ships have been built with this new technology.

And that's because the shipbuilding industry realized the potential of the electric propulsion on improving fuel efficiency and reducing emissions. If we take into consideration the stricter legislation (The International Maritime Organization's (IMO) MARPOL Annex VI Tier III limits will cut $NO_x$ emissions from new engines by about 80 per cent relative to Tier I), the turn into this solution is a natural consequence.

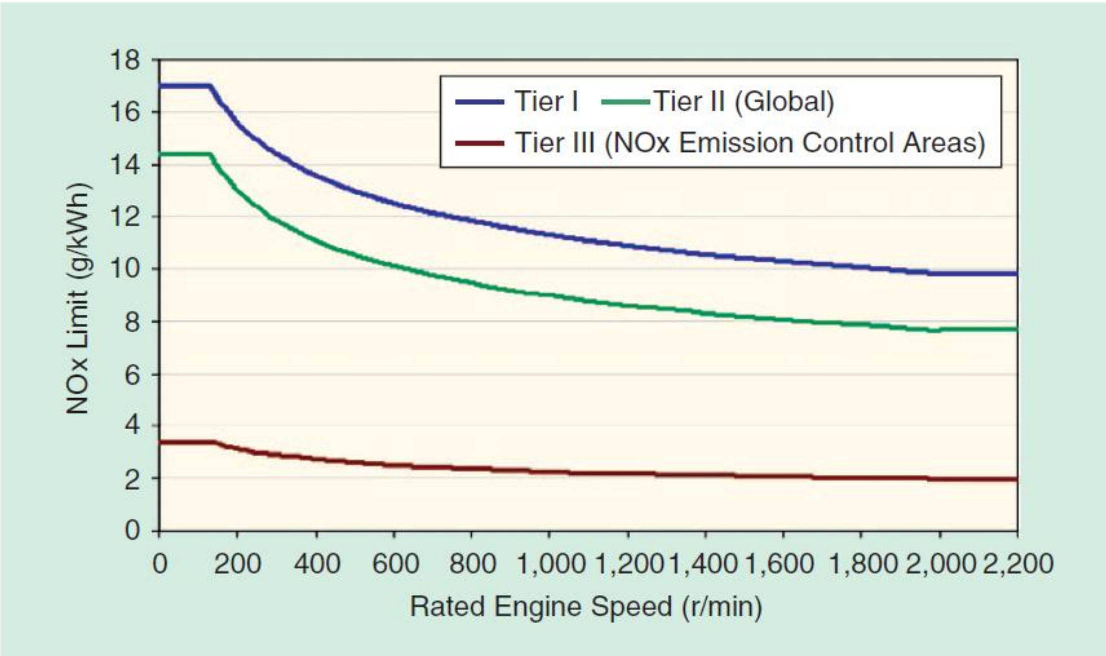



*Figure 11: MARPOL Annex VI $NO_x$ emission limits (www.dieselnet.com).*

The first LNG carrier with electric propulsion was constructed at Chantiers de l'Atlantique in France for the French owner Gaz de France in 2004.

In 2010, the "Turanor Planetsolar" was launched in Kiel and became the first solar powered electric boat to circumnavigate the planet in 2012. The vessel uses lithium ion batteries weighting 8.5 tons and it takes 48hrs for the batteries to get fully charged and make Turanor move operating for 72 hours without any sunlight.

*Figure 12: Turanor Planetsolar: World's largest Solar-Powered boat*

In January 2015, world's first fully electric battery powered passenger and car ferry, MF Ampere, was set in operation in Norway (commissioned and delivered in October 2014). The vessel was a joint development between the Norwegian ferry company Norled AS, the shipyard Fjellstrand and Siemens AS. The vessel, which was certified by DNV-GL, is powered by a lightweight Corvus Energy Storage System (ESS), weighting only 20 metric tons, and supplies all the vessel's power demands while at sea [13], [14].

The vessel, which is 80 meters long, can carry 120 cars and 360 passengers, and the ferry's crossing, which goes between Oppedal and Lavik, near Bergen, Norway, takes about 30 minutes. The ship's batteries, which are approximately 1MW combined, are charged on each side of the route using the villages' electric grids, which distribute hydro-generated power. Due to fast charging and to avoid overloading the electrical grids in the villages, the charging systems contain battery packs (battery energy storage systems), which are charged by the villages' electrical grid while the vessel is at sea. The vessel's hull is optimized to be energy effective, and each port is equipped with a docking system which uses vacuum mounts to keep the ferry at rest without using the vessel's propulsion. Figure 13 shows a simplified one-line diagram of the ferry's power system.

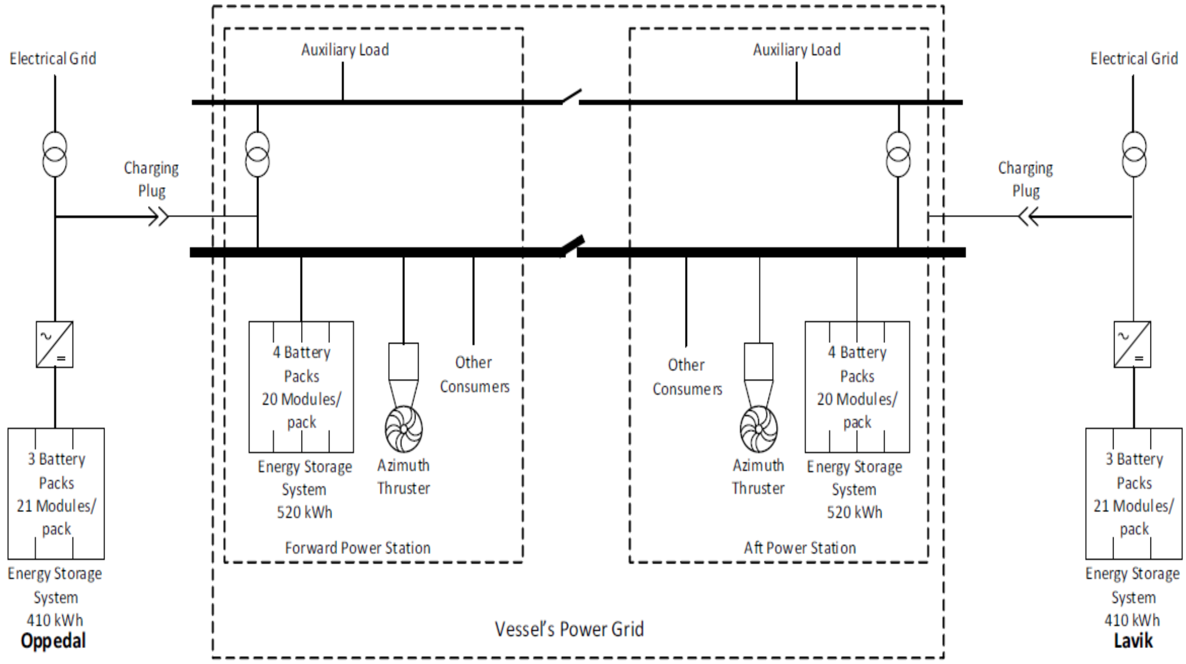



*Figure 13: Simplified one-line diagram of Norled's MF Ampere all-electric battery ferry [13]*

*Figure 14: Ampere Electric-Powered ferry*

What is more, in Stockholm, an all-electric ship named Movitz makes the route Solna Strand- Gamla Stan. Instead of a 250kW diesel engine using lots of tons diesel per year, omitting 130 tons of $CO_2$, 1.5 tons of $NO_x$ and 80 kg of particles, GreenCityFerry's boat has two 125 kW electric motors placed outside the hull in so-called PODs. The system is powered by super-advanced Nickel-Metal-Hybrid (NiMH) 180 kWh batteries from the Swedish company Nilar. NiMH batteries deliver high power instantly and can be charged very quickly. Boat needs around 90 kW to cruise at 9 knots. The ability to charge for 10 minutes and then operate for an hour is an extremely important development for the passenger ferry industry, which operates under a strict timetable.

Also, it reduces the need for large battery packs. The ferry can charge while passengers embark and disembark. Most important of all, the conversion is estimated to cut out 130 tons of $CO_2$, and 1.5 tons of $NO_x$ emissions annually, though the real bonus comes from operating costs. Echandia estimates that its electric ferry cuts costs by 30%, giving ferry operators a huge incentive to carry out an electric conversion.


*Figure 15: Movitz, Supercharged electric passenger ferry*

Two more ships Tycho Brahe and Aurora have been converted from diesel-powered to full electric propulsion with 4MWh batteries each, being recharged from land by a robot arm when docked. Two of the four diesel engines have been removed from each ship with the other two as a backup system, not for daily operation. These ships cover a distance of 5km between Helsingor in Denmark and Helsingborg in Sweden. The capacity comes to 1250 passengers, 260 tracks,240 cars and 9 passenger train coaches at one times.

*Figure 16: Tycho Brahe: world's largest emission-free electric ferry with the first automated shore-side charging station (www.abb.com)*

China has the first fully electric container ship – initially as a trial on Pearl River in Southern China. It is planned only for use on inland waterways, as the ship can travel a distance of just 80 kilometers. The 1000 lithium-ion batteries on board weigh 26 tons and achieve 2.400 kilowatt hours.

Norway is also working on an electric container ship: From 2020, the "Birkeland" will transport chemicals and fertilizer from the plants of manufacturer Yara to the port in Brevik. The company uses trucks for this at present – around 40.000 trips per year. The ship will transport 120 containers.

Dutch company Port-Liner is also building fully electric cargo ships. They will sail on inland waterways, including to Rotterdam port. They can travel for 34 hours on one battery charge. The batteries are in containers that are simply exchanged at the port, which means that they do not have to be charged immediately. Port-Liner plans to produce 15 electric ships for the Netherlands and Belgium in the coming years.

To sum up, the available technology of electricity comes to:

- Diesel-electric drive: Diesel generators generate the electricity. The electricity then drives the electric engine, which moves the ship's propeller.
- Hybrid drive: Batteries are on board in addition to the internal combustion engine. On the one hand, they can be switched on additionally for a short time when a power peak is needed. On the other hand, they can store surplus energy, such as from the diesel generator. This would allow the ship to sail using nothing but electricity for some time.
- Fully electric drive: There is no internal combustion engine on board, all the energy comes from batteries.

All those vessels presented already sail using nothing but electricity. That's because they sail shorter distances and can therefore use smaller batteries. Several boat builders are also planning hybrid cruise ships.

However, large cargo ships that sail the world's oceans electric drives are still a long way away. The batteries are still not efficient enough and are too heavy for ships that sail long distances on the high seas. Experts predict that it will be at least 20 years before we see the first fully electric oceangoing ships.

*There is a powerful agent, obedient, rapid, easy, which conforms to every use, and reigns supreme onboard my vessel. Everything is done by means of it. It lights, warms it, and is the soul of my mechanical apparatus. This agent is electricity.*

*—Jules Verne, 1870*

# 3 Technology of batteries

## 3.1 Basic Principles of batteries

Electricity is the flow of electrons through a conductive path like a wire. This path is called a circuit.

Batteries have three parts, an anode (-), a cathode (+), and the electrolyte. The cathode and anode (the positive and negative sides at either end of a traditional battery) are hooked up to an electrical circuit.

The chemical reactions in the battery cause a build-up of electrons at the anode. This results in an electrical difference between the anode and the cathode. The electrons are unstable and want to rearrange themselves to get rid of this difference. But they do this in a certain way. Electrons repel each other and try to go to a place with fewer electrons.

In a battery, the only place to go is to the cathode. But, the electrolyte keeps the electrons from going straight from the anode to the cathode within the battery (insulator). When the circuit is closed (a wire connects the cathode and the anode) the electrons will be able to get to the cathode. In the figure below, the electrons go through the wire, lighting the light bulb along the way. This is one way of describing how electrical potential causes electrons to flow through the circuit. However, these electrochemical processes change the chemicals in anode and cathode to make them stop supplying electrons. So there is a limited amount of power available in a battery.

When you recharge a battery (only for secondary batteries) you change the direction of the flow of electrons using another power source, such as solar panels. The electrochemical processes happen in reverse, and the anode and cathode are restored to their original state and can again provide full power.

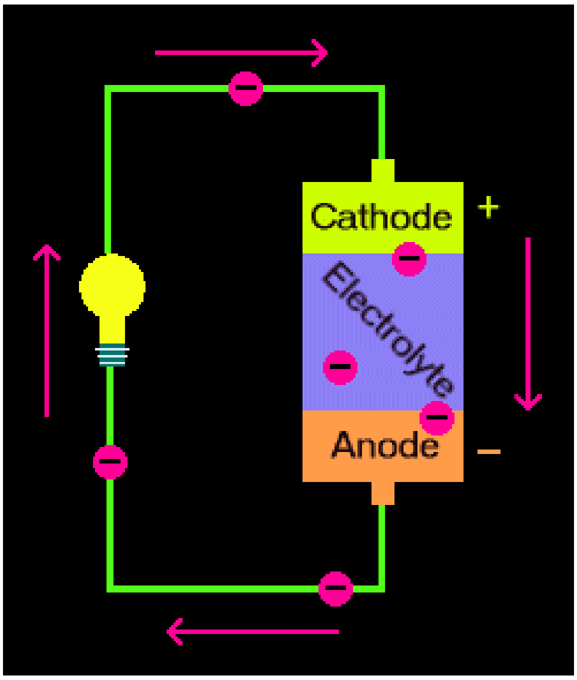



*Figure 1: Mechanism of battery [16]*

As far as chemical reactions are concerned, they are different for different electrodes and electrolytes. However, the general principal is electrons going around the circuit and ions reacting with the electrolyte. As a battery generates power, the chemicals inside it are gradually converted into different chemicals. Their ability to generate power reduces, the voltage falls until the battery runs out of energy. In other words, if the battery cannot produce positive ions because the chemicals inside have become depleted, it can't produce electrons for the outer circuit either.

During a discharge of electricity, the chemical on the anode releases electrons to the negative terminal and ions in the electrolyte through what's called an oxidation reaction. Meanwhile, at the positive terminal, the cathode accepts electrons, completing the circuit for the flow of electrons. The electrolyte is there to put the different chemicals of the anode and cathode into contact with one another, in a way that the chemical potential can equilibrate from one terminal to the other, converting stored chemical energy into useful electrical energy. "These two reactions happen simultaneously," says Antoine Allanore, a postdoctoral associate at MIT's Department of Materials Science and Engineering. "The ions transport current through the electrolyte while the electrons flow in the external circuit, and that's what generates an electric current."

## 3.2 Terminology of batteries

The most significant technical terms of battery technology are described below [17]:

**Accumulator** - A rechargeable battery or cell (Secondary battery).

**Ampere or Amp** - An Ampere or an Amp is a unit of measurement for an electrical current. One amp is the amount of current produced by an electromotive force of one volt acting through the resistance of one ohm. Small currents are measured in milli-Amps or thousandths of an Amp.

**Amp Hour or Ampere-Hour** -A unit of measurement of a battery's electrical storage capacity. Current multiplied by time in hours equals ampere-hours. One amp hour is equal to a current of one ampere flowing for one hour. Also, 1 amp hour is equal to 1.000 mAh

**Ampere-Hour Capacity** - The number of ampere-hours which can be delivered by a battery on a single discharge.

**Anode** - During discharge, the negative electrode of the cell is the anode. During charge, that reverses and the positive electrode of the cell is the anode. The anode gives up electrons to the load circuit and dissolves into the electrolyte.

**Aqueous Batteries** - Batteries with water-based electrolytes. The electrolyte may not appear to be liquid since it can be absorbed by the battery’s separator.

**Actual Capacity or Available Capacity** - The total battery capacity, usually expressed in ampere-hours or milliampere-hours, available to perform work. The actual capacity of a particular battery is determined by a number of factors, including the cut-off voltage, discharge rate, temperature, method of charge and the age and life history of the battery.

**Battery** - An electrochemical device used to store energy. The term is usually applied to a group of two or more electric cells connected together electrically. In common usage, the term "battery" is also applied to a single cell, such as an AA battery.

**Battery Capacity** - The electric output of a cell or battery on a service test delivered before the cell reaches a specified final electrical condition and may be expressed in ampere-hours, watt- hours, or similar units. The capacity in watt-hours is equal to the capacity in ampere-hours multiplied by the battery voltage.

**Battery Charger** - A device capable of supplying electrical energy to a battery.

**Battery-Charge Rate** - The current expressed in amperes (A) or milli amps (mA) at which a battery is charged.

**Cut-off Voltage or final voltage** - The prescribed lower-limit voltage at which battery discharge is considered complete. The cut-off or final voltage is usually chosen so that the maximum useful capacity of the battery is realized. The cut-off voltage varies with the type of battery and the kind of service in which the battery is used. When testing the capacity of a NiMH or NiCD battery, a cut-off voltage of 1.0 V is normally used. 0.9V is normally used as the cut-off voltage of an alkaline cell. A device that is designed with too high cut-off voltage may stop operating while the battery still has significant capacity remaining.

**C- Rate or Charge rate** - The definition of the charge rate or C-rate of a battery or cell is the charge or discharge current in Amperes as a proportion of the rated capacity in Ah. For example, in the case of a 500 mAh battery, a C/2 rate is 250 mA and a 2C rate would be 1A.

**Capacity** - The capacity of a battery is a measure of the amount of energy that it can deliver in a single discharge. Battery capacity is normally listed as amp-hours (or milli amp-hours) or as watt-hours.

**Cathode** - Is an electrode that, in effect, oxidizes the anode or absorbs the electrons. During discharge, the positive electrode of a voltaic cell is the cathode. When charging, that reverses and the negative electrode of the cell is the cathode.

**Cell** - An electrochemical device composed of positive and negative plates and electrolyte, which is capable of storing electrical energy. It is the basic “building block” of a battery.

**Charge** - The conversion of electric energy, provided in the form of a current, into chemical energy within the cell or battery.

**Charging** - The process of supplying electrical energy for conversion to stored chemical energy.

**Constant-Current Charge** - A charging process in which the current applied to the battery is maintained at a constant value.

**Constant-Voltage Charge** - A charging process in which the voltage applied to a battery is held at a constant value.

**Cycle** - One sequence of charge and discharge.

**Deep Cycle** - A cycle in which the discharge is continued until the battery reaches its cut-off voltage, usually 80% of discharge.

**Shallow Cycling** - Charge and discharge cycles which do not allow the battery to approach its cut-off voltage. Shallow cycling of NiCd cells lead to “memory effect”. Shallow cycling is not detrimental to NiMH cells and it is the most beneficial for lead acid batteries.

**Cycle Life** - For rechargeable batteries, the total number of charge/discharge cycles the cell can sustain before its capacity is significantly reduced. End of life is usually considered to be reached when the cell or battery delivers only 80% of rated ampere- hour capacity. NiMH batteries typically have a cycle life of 500 cycles;

NiCd batteries can have a cycle life of over 1.000 cycles. The cycle of a battery is greatly influenced by the type depth of the cycle (deep or shallow) and the method of recharging. Improper charge cycle cut-off can greatly reduce the cycle life of a battery.

**Direct Current (DC)** - The type of electrical current that a battery can supply. One terminal is always positive and another is always negative.

**Discharge** - The conversion of the chemical energy of the battery into electric energy.

**Depth of Discharge** - The amount of energy that has been removed from a battery (or battery pack). Usually expressed as a percentage of the total capacity of the battery. For example, 50% depth of discharge means that half of the energy in the battery has been used. 80% DOD means that eighty percent of the energy has been discharged, so the battery now holds only 20% of its full charge.

**Discharge, deep** - Withdrawal of all-electrical energy to the end-point voltage before the cell or battery is recharged.

**Discharge, high-rate** - Withdrawal of large currents for short intervals of time, usually at a rate that would completely discharge a cell or battery in less than one hour.

**Discharge, low-rate** - Withdrawal of small currents for long periods of time, usually longer than one hour.

**Drain** - Withdrawal of current from a cell.

**Dry Cell** - A primary cell in which the electrolyte is absorbed in a porous medium, or is otherwise restrained from flowing. Common practice limits the term “dry cell” to the Leclanch, cell, which is the common commercial type.

**Electrochemical Couple** - The system of active materials within a cell that provides electrical energy storage through an electrochemical reaction.

**Electrode** - An electrical conductor through which an electric current enters or leaves a conducting medium, whether it be an electrolytic solution, solid, molten mass, gas, or vacuum.

**Electrolyte** - A chemical compound which, when fused or dissolved in certain solvents, usually water, will conduct an electric current. All electrolytes in the fused state or in solution give rise to ions which conduct the electric current.

**Electropositivity** - The degree to which an element in a galvanic cell will function as the positive element of the cell. An element with a large electropositivity will oxidize faster than an element with a smaller electropositivity.

**End-of-Discharge Voltage** - The voltage of the battery at termination of a discharge.

**Energy - Output Capability** - expressed as capacity times voltage, or watt-hours.

**Energy Density** - Ratio of cell energy to weight or volume (watt-hours per pound, or watt-hours per cubic inch).

**Float Charging** - Method of recharging in which a secondary cell is continuously connected to a constant-voltage supply that maintains the cell in fully charged condition. Typically applied to lead acid batteries.

**Galvanic Cell** - A combination of electrodes, separated by electrolyte, that is capable of producing electrical energy by electrochemical action.

**Internal Resistance** - The resistance to the flow of an electric current within the cell or battery.

**Memory Effect** - A phenomenon in which a cell, operated in successive cycles to less than full, depth of discharge, temporarily loses the remainder of its capacity at normal voltage levels (usually applies only to NiCd cells). Note, memory effect can be induced in NiCd cells even if the level of discharge is not the same during each cycle. Memory effect is reversible.

**Negative Terminal** - The terminal of a battery from which electrons flow in the external circuit when the cell discharges.

**Nonaqueous Batteries** - Cells that do not contain water, such as those with molten salts or organic electrolytes.

**Ohm's Law** - The formula that describes the amount of current flowing through a circuit. Ohm's Law - In a given electrical circuit, the amount of current in amperes (I) is equal to the pressure in volts (V) divided by the resistance, in ohms (R). Ohm's law can be shown by three different formulas:

To find Current $I = V/R$

To find Voltage $V = I \times R$

To find Resistance $R = V/I$

**Open Circuit** - Condition of a battery which is neither on charge nor on discharge (e.g., disconnected from a circuit).

**Open-Circuit Voltage** - The difference in potential between the terminals of a cell when the circuit is open (e.g., a no-load condition).

**Oxidation** - A chemical reaction that results in the release of electrons by an electrode's active material.

**Parallel Connection** - The arrangement of cells in a battery made by connecting all positive terminals together and all negative terminals together. The voltage of the group remains the same as the voltage of the individual cell. The capacity is increased in proportion to the number of cells.

**Polarity** - Refers to the charges residing at the terminals of a battery.

**Positive Terminal** - The terminal of a battery toward which electrons flow through the external circuit when the cell discharges.

**Primary Battery** - A battery made up of primary cells.

**Primary Cell** - A cell designed to produce electric current through an electrochemical reaction that is not efficiently reversible. The cell, when discharged, cannot be efficiently recharged by an electric current. Alkaline and zinc air are common types of primary cells.

**Rated Capacity** - The number of ampere-hours a cell can deliver under specific conditions (rate of discharge, end voltage, temperature); usually the manufacturer's rating.

**Rechargeable** - Capable of being recharged; refers to secondary cells or batteries.

**Recombination** - State in which the gases normally formed within the battery cell during its operation, are recombined to form water.

**Reduction** - A chemical process that results in the acceptance of electrons by an electrode's active material.

**Seal** - The structural part of a galvanic cell that restricts the escape of solvent or electrolyte from the cell and limits the ingress of air into the cell (the air may dry out the electrolyte or interfere with the chemical reactions).

**Secondary Battery** - A battery made up of secondary cells.

**Self Discharge** - Discharge that takes place while the battery is in an open-circuit condition.

**Separator -** The permeable membrane that allows the passage of ions, but prevents electrical contact between the anode and the cathode.

**Series Connection -** The arrangement of cells in a battery configured by connecting the positive terminal of each successive cell to the negative terminal of the next adjacent cell so that their voltages are cumulative.

**Shelf Life -** For a dry cell, the period of time (measured from date of manufacture), at a storage temperature of 21 degrees C (69 degrees F), after which the cell retains a specified percentage (usually 90%) of its original energy content.

**Short-Circuit -** A condition that occurs when a short electrical path is unintentionally created. Batteries can supply hundreds of amps if short-circuited, potentially melting the terminals and creating sparks.

**Short-Circuit Current -** That current delivered when a cell is short-circuited (e.g. the positive and negative terminals are directly connected with a low-resistance conductor).

**Starting-Lighting-Ignition (SLI) Battery -** A battery designed to start internal combustion engines and to power the electrical systems in automobiles when the engine is not running. SLI batteries can be used in emergency lighting situations.

**Stationary Battery -** A secondary battery designed for use in a fixed location.

**Storage Battery -** An assembly of identical cells in which the electrochemical action is reversible so that the battery may be recharged by passing a current through the cells in the opposite direction to that of discharge. While many non-storage batteries have a reversible process, only those that are economically rechargeable are classified as storage batteries. Synonym: Accumulator; Secondary

Battery.

**Storage Cell** - An electrolytic cell for the generation of electric energy in which the cell after being discharged may be restored to a charged condition by an electric current flowing in a direction opposite the flow of current when the cell discharges. Synonym: Secondary Cell.

**Taper Charge** - A charge regime delivering moderately high-rate charging current when the battery is at a low state of charge and tapering the current to lower rates as the battery becomes more fully charged.

**Terminals** - The parts of a battery to which the external electric circuit is connected.

**Thermal Runaway** - A condition whereby a cell on charge or discharge will destroy itself through internal heat generation caused by high overcharge or high rate of discharge or other abusive conditions.

**Trickle Charging** - A method of recharging in which a secondary cell is either continuously or intermittently connected to a constant-current supply that maintains the cell in fully charged condition.

**Vent** - A normally sealed mechanism that allows for the controlled escape of gases from within a cell.

**Volt** - The unit of measurement of electromotive force, or difference of potential, which will cause a current of one ampere to flow through a resistance of one ohm. Named for Italian physicist Alessandro Volta (1745-1827).

**Voltage cut-off** - Voltage at the end of useful discharge.

**Voltage end-point** - Cell voltage below which the connected equipment will not operate or below which operation is not recommended.

**Voltage nominal** - Voltage of a fully charged cell when delivering rated current.

**Watt** - A measurement of total power. It is amperes multiplied by volts. 120 volt X 1 amp = 12 volts X 10 amps.

**Wet Cell** - A cell, the electrolyte of which is in liquid form and free to flow and move.

## 3.3 Categorization of batteries

There is a great variety of batteries of different sizes, shapes, voltages and capacities. Although they can be made from many different electrolytes and electrodes there are two basic types of batteries, primary and secondary.

### 3.3.1 Primary batteries

Primary batteries are disposable batteries of one use that cannot be recharged. The electrochemical reaction cannot be reversed, so when the chemical reaction is exhausted, the battery is dead. Primary cells can be connected in series to achieve the desirable voltage, but must not be connected in parallel because one cell is likely to try to charge the other. These are the following five basic batteries used on board:

**Zinc-carbon batteries**

They have a nominal voltage of 1.5V per cell. They are cheap, but lose about 15% annually when stored. When exhausted, they should not stay inside the instrument, as there may be leak of very corrosive chemicals that can destroy the equipment. If the battery runs out, it can extend its life by shutting down the machine and leaving the battery to “rest”. Continuous discharge reduces battery capacity.

**Alkaline Manganese batteries**

They are longer lasting batteries like "Duracell". They have a nominal voltage of 1.5V per cell. They are more expensive than Zinc-carbon batteries, but have three times the capacity and looses only 7% of their capacity annually when stored. This type of battery can also "rest" by shutting down the machine, and continuous discharge reduces battery's capacity.

**Mercury batteries**

They have a nominal voltage of 1.4V per cell. They are more expensive, but have eight times the capacity of zinc-carbon batteries while losing only 6% of their total capacity annually when stored. However they are not commonly used, due to their disposal problems, associated with mercury.

**Silver-oxide batteries**

They are the small silver batteries used on watches and calculators. They have a nominal voltage about 1.5V per cell. They have similar capacity to manganese batteries, losing only 4% of their total capacity annually when stored. However, the cost is much bigger.

**Lithium ion manganese oxide battery**

Li-$MnO_2$ are the most modern, powerful batteries with a nominal voltage of 3V. Their capacity is close to mercury batteries and their advantage that they lose only 2% of their total capacity annually when stored. They are ideal for backup batteries of some equipment such as EPIRB (Emergency Position Indicating Radio Beacon) and SART (Search and Rescue Transporter) due to their long life span.

## 3.3.2 Secondary Batteries

Secondary or Storage batteries can be recharged hundreds of times. Charging inverts the chemical process inside the battery so it can resupply electricity and can simply be achieved by passing current in the opposite direction that it would normally flow. This process is not available in primary cells and batteries.

In vessels they are used to power their electrical equipment, such as wireless VHF (Very High Frequency) and they are charged from the engine, the generator or a battery charger connected to the main source. All-electric ships have assigned the exclusive production of power to batteries, replacing the internal combustion engines.

Secondary cells can be used in series, in parallel or in combination, to achieve the necessary voltage and capacity. The only limitation is that each cell must have a similar voltage, capacity and chemical composition. The four types of secondary batteries used in vessels are explained below.

**Lead-acid batteries**

Lead-acid batteries are the oldest type of rechargeable batteries (similar to a car's battery). They are easy to install, low-cost with negligible maintenance. Self-discharge rates for this type of batteries are very low, around 2-5% of rated capacity per month, which makes them ideal for long-term storage applications. Disadvantages are low energy density and short service life. The typical energy density is around 30Wh/kg and the typical lifetime is between 1200 and 1800 cycles [18]. The cycle life is affected by depth of discharge and they are not suitable for discharges over 20% of their rated capacity [19]. The performance of lead-acid would also be affected by temperature: higher temperature (with the upper limit of 45°C) will reduce battery lifetime and lower temperature (with the lower limit of -5°C) will reduce the efficiency.

Each battery consists of separate cells each of which has a nominal voltage of 2V. Most batteries consist of three or six cells giving 6 or

12V respectively. The batteries are then grouped together to achieve the necessary voltage and capacity. Most vessels use 12 or 24V for their batteries.

When the cell is full discharge, then the anode is of lead peroxide ($PbO_2$) and a cathode is of metallic sponge lead (Pb). When the electrodes are connected through a resistance, the cell discharge and electrons flow in a direction opposite to that during charging.

The hydrogen ions move to the anode and reaching the anodes receive one electron from the anode and become hydrogen atom. The hydrogen atom comes in contacts with a $PbO_2$, so it attacks and forms lead sulphate ($PbSO_4$), whitish in color and water.

Each sulphate ion ($SO_4^{-2}$) moves towards the cathode and reaching there, gives up two electrons becomes radical $SO_4$, attack the metallic lead cathode and form lead sulphate whitish in color.

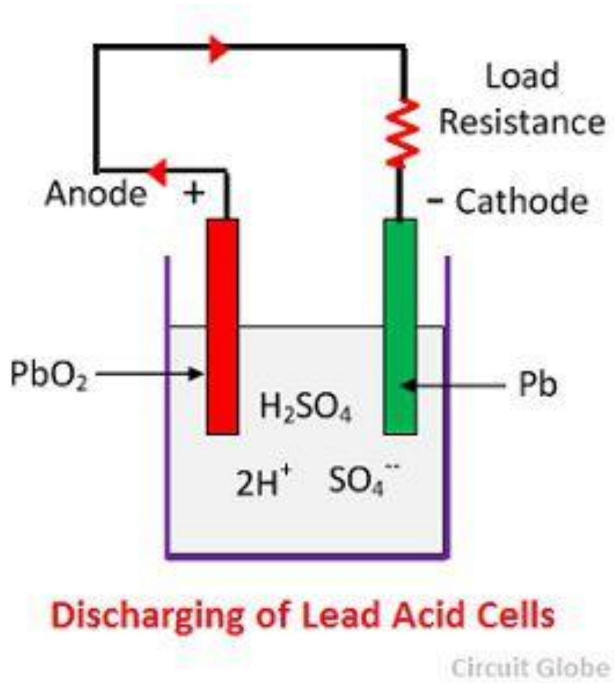



*Figure 2: Lead acid principle of operation [20]*

## Nickel-based batteries

In a nickel-based battery, nickel hydroxide is used on the positive electrode but for the negative electrode, different materials can be used. This fact explains the existence of various technologies. There are three kinds of nickel-based batteries namely the nickel-cadmium (NiCd) battery, the nickel-metal hydride (NiMH) battery and the nickel-zinc (NiZn) battery. The NiCd technology uses cadmium hydroxide, the NiMH uses a metal alloy and the NiZn uses zinc hydroxide. Nickel-based batteries have larger energy densities than lead-acid batteries, 50 Wh/kg for the NiCd, 80 Wh/kg for the NiMH and 60 Wh/kg for the NiZn.

NiCd batteries are now reaching the level of maturity as lead-acid batteries. NiCd batteries have a longer lifetime about 3000 cycles and can be fully discharged without damage [21]. As an example, this technology is used in the energy storage system of the Alaska Golden Valley project which provides a backup to an isolated electrical power system. This project is claimed to be the world's most powerful battery system with a rated power of 40 MW and with a discharge capability over 7 min [22]. However, two drawbacks limit future large-scale deployment of this technology. One is the high price, for the NiCd battery may cost up to 10 times more than the lead-acid battery. Another is the environment concerns about cadmium toxicity and associated recycling issues. [23]

NiMH batteries have high energy density which is over twice than lead-acid batteries. This type of batteries can be recycled and their components are harmless to the environment. They also can be used in large temperature ranges and high voltage operation. However, repeatedly discharged at high load currents would shorten the life of NiMH batteries to about 200–300 cycles and the memory effect reduces the useful SOC (State of Charge) of the battery.

NiZn batteries have the same advantages of NiMH batteries and have deep cycle capability as NiCd batteries, but they suffer from poor life cycle due to the fast growth of dendrites.

### Lithium based batteries

They are rechargeable batteries of ultimate cutting-edge technology with twice the capacity of nickel metal hydride batteries (NiMH) and low tendency of memory effect. They are expensive batteries (three times the price of NiMH batteries) and are ideal for applications where high power and low weight are combined.

Lithium-ion uses a cathode (positive electrode), an anode (negative electrode) and electrolyte as conductor. The cathode is metal oxide and the anode consists of porous carbon. During discharge, the ions flow from the anode to the cathode through the electrolyte and separator; charge reverses the direction and the ions flow from the cathode to the anode.

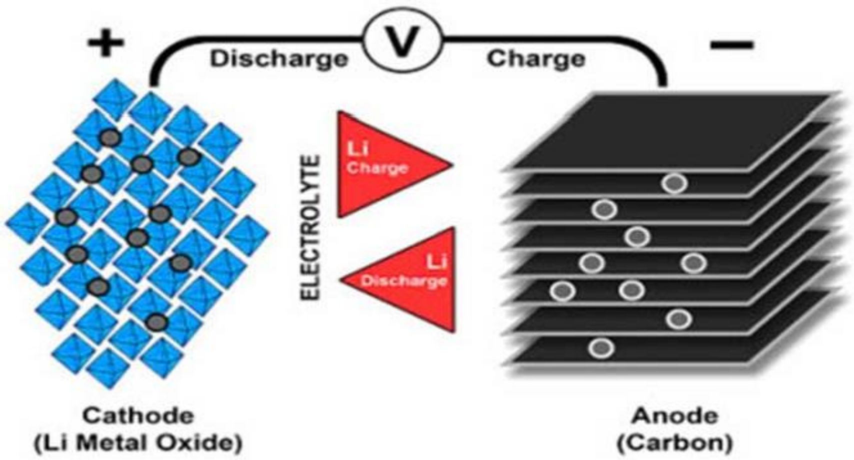



*Figure 3: Mechanism of lithium based batteries [24]*

### Lithium Cobalt Oxide ($LiCoO_2$)

The battery consists of a cobalt oxide cathode and a graphite carbon anode. During discharge, lithium ions move from the anode to the cathode. The drawback of Li-cobalt is a relatively short life span, low thermal stability and limited load capabilities. It cannot be charged and discharged at a current higher than its C-rating.

**Lithium Manganese Oxide ($LiMn_2O_4$)**

Li-manganese has a capacity one-third lower than Li-cobalt. Design flexibility allows the maximization of life span, load current or high capacity. Other good characteristics of this type of battery are high thermal stability and enhanced safety thanks to its architecture.

**Lithium Nickel Manganese Cobalt Oxide ($LiNiMnCoO_2$ or NMC)**

One of the most successful Li-ion systems is a cathode combination of nickel-manganese-cobalt (NMC). The cathode combination is typically one-third nickel, one-third manganese and one-third cobalt, also known as 1-1-1. Thanks to the combination of manganese, nickel and cobalt oxide there is an improvement in the life span, specific energy (capacity), specific power (load capability) and lower cost (less cobalt). Another successful combination is NCM with 5 parts nickel, 3 parts cobalt and 2 parts manganese.

**Lithium Iron Phosphate ($LiFePO_4$)**

In this type of battery, phosphate is used as a cathode material. Li-phosphate offers good electrochemical performance with low resistance, high current rating and long cycle life, besides good thermal stability, enhanced safety and tolerance. 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. Li-phosphate has a higher self-discharge than other Li-ion batteries.

**Lithium Nickel Cobalt Aluminum Oxide ($LiNiCoAlO_2$ or NCA)**

This type of battery is similar to NMC regarding high specific energy and power and a long life span. It is a further development of NCM with the aluminum giving greater stability. Disadvantages are safety and cost.

**Lithium Titanate ($Li_4Ti_5O_{12}$)**

Li-titanate replaces the graphite in the anode of a typical lithium-ion battery. The cycle lasts more than that of a regular Li-ion battery and Li-titanate is safe, with excellent low-temperature discharge characteristics. However, the battery is expensive and the specific energy is low, rivaling that of NiCd.

**Li-Polymer**

Lithium-polymer uses different electrolyte compared to other batteries. It uses a solid-dry polymer electrolyte that allows the exchange of ions and replaces the traditional porous separator that is soaked with electrolyte. The battery must be heated to 60°C and more otherwise the solid polymer has poor conductivity. With the addition of a gelled electrolyte, it can be used at room temperature. Most Li-ion polymer cells today incorporate a micro porous separator with some moisture.

Essentially lithium polymer is the same as lithium-ion, using the same cathode and anode material, and can be built on many systems (mainly cobalt based) and is not considered like unique battery chemistry as the only difference is the electrolyte. The cost is higher nevertheless it offers slightly higher specific energy, power and light weight.

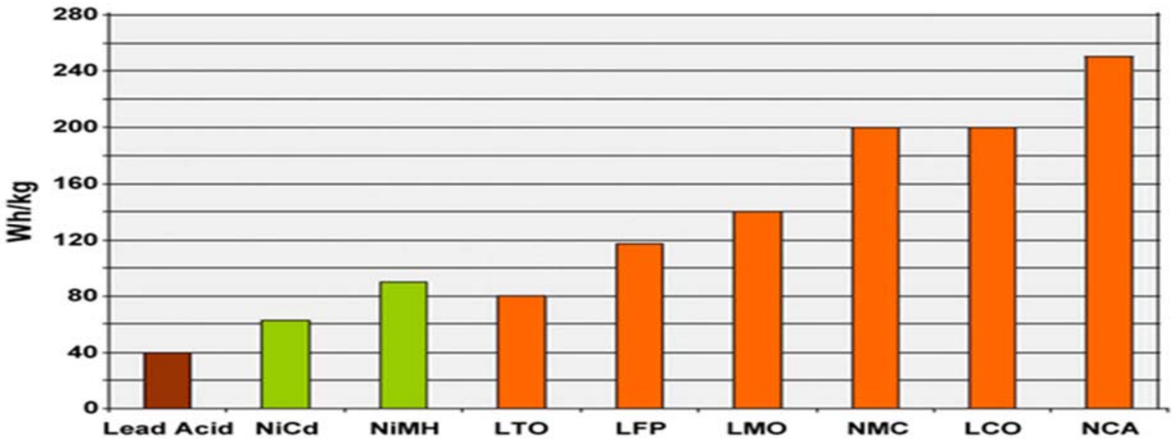



*Figure 4: Comparison of specific energy of lead-, nickel- and lithium based systems*

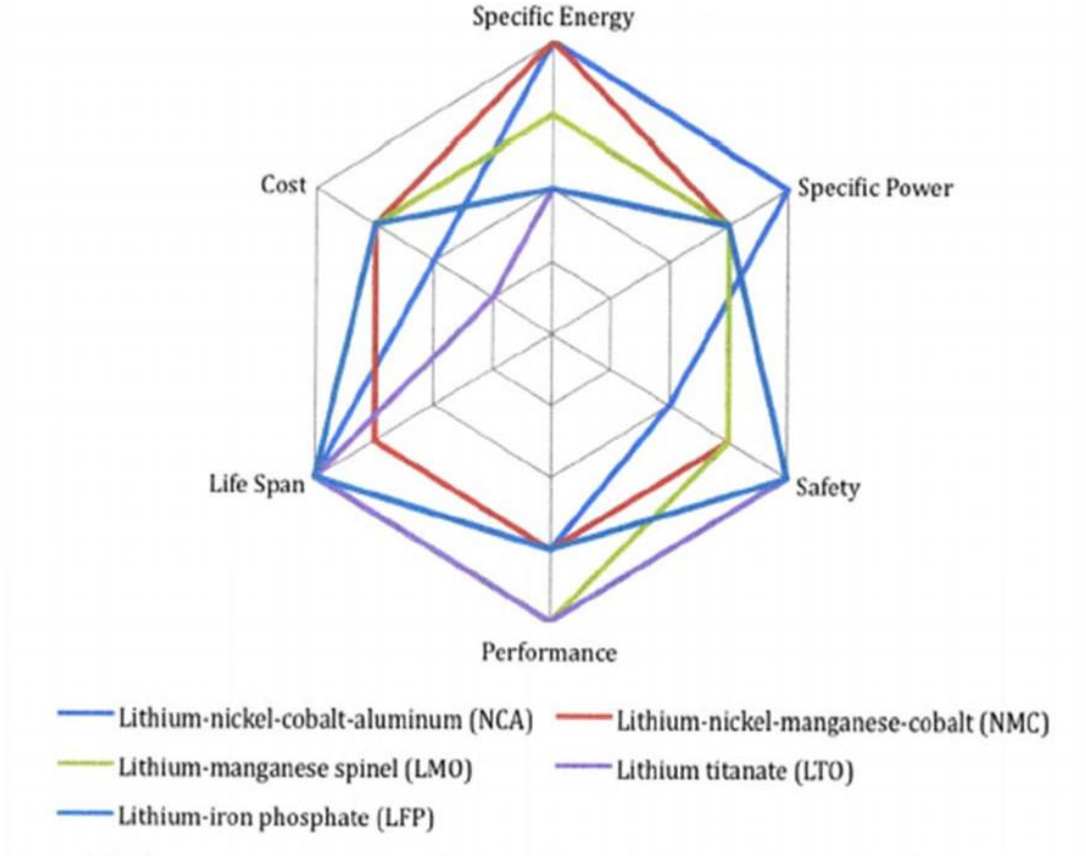



*Figure 5: Comparison of all the characteristics of lithium-ion batteries [24]*

Nickel Cadmium (NiCd) batteries are used where long life, high discharge rate and economical price are important. However, they have low energy density and they are environmental unfriendly. Nickel - Metal Hydride (NiMH) batteries have a higher energy density and does not contain any toxic metals.

Li-ion batteries are used in the naval sector and they are the fastest growing battery system. Especially, NMCs and Iron phosphate cover the requirements of maritime applications. Iron phosphate batteries have greater life span, power density and safer operation compared to the others Li-ion batteries, however they have a lower energy density.

Lithium-ion Polymer batteries offer additionally light weight and easy packaging, making them suitable for the maritime sector.

| Type | Anode material | Cathode material | Rechargeable | Year of commercialization | Cutoff voltage | Nominal voltage | 100% SOC Voltage | Energy density (Wh/kg) | specific power (w/kg) | Cost Wh/$ ($/Wh) | self discharge rate %/month | recharge cycles |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lead-Acid | Lead | Lead Dioxide | Yes | 1881 | 1.75 | 2.1 | 2.23–2. | 30–40 | 180 | 6.76–17.38 (58–148) | 3–20 | 500 typical 800 max |
| Nickel-Zinc | | Nickel oxide hydroxide | Yes | 2009 | 0.9 | 1.65 | 1.85 | | | | 13 | 100 to 50% capacity |
| Nickel-Iron | Iron | | Yes | 1901 | 0.75 | 1.2 | 1.65 | 19–25 | 100 | 4.11–5.48 (182–243) | 20–30 | 5000 |
| Nickel-Cadmium | Cadmium | | Yes | 1960 | 0.9–1.05 | 1.2 | 1.3 | 30 | 150–200 | | 10 | 500 |
| Nickel-metal hydride | Metal Hydride | | Yes | 1990 | 0.9–1.05 | 1.2 | 1.3 | 100 | 250–1000 | 3.29 (304) | 30 | 300-800 |
| Lithium titanate | Lithium | Lithium manganese oxide or Lithium nickel manganese cobalt oxide | Yes | 2008 | 1.6-1.8 | 2.3-2.4 | 2.8 | 60–110 | 3,000-5, | 0.49 (2043) | 2-5 | 6000–10000 to 90% capacity |
| Lithium Cobalt Oxide | Graphite | Lithium cobalt oxide | Yes | 1991 | 2.5 | 3.7 | 4.2 | 195 | | 2.74 (365) | | 500-1000 |
| Lithium Iron Phosphate | | Lithium iron phosphate | Yes | 1996 | 2 | 3.2 | 3.65 | 90–130 | 2 | | 4.5 | 7000 to 80% |
| Lithium Manganese Oxide | | Lithium manganese oxide | Yes | 1999 | 2.5 | 3.9 | 4.2 | 150 | | 2.74 (365) | | 300-700 |
| Lithium nickel cobalt aluminum oxide | | Lithium nickel cobalt aluminum oxide | Yes | 1999 | 3.0 | 3.6 | 4.3 | 220 | | | | 1000-1500 |
| Lithium nickel manganese cobalt oxide | | Lithium nickel manganese cobalt oxide | Yes | 2008 | 2.5 | 3.6 | | 205 | | | | 5000 |

*Figure 6: Technical characteristics of all batteries [25]*

# 4 Methodology’s delimitation

The purpose of the present study is to develop a general methodology that could convert Passenger Ferries from diesel-propelled to fully electric. Economic analysis will follow on next chapter for 11 different ships that cover 11 different lines in the Greek seas. The technical analysis in this chapter will be general and could be applied to all 11 ships with similar characteristics. All the reconstruction aspects will be covered, including the necessary land-based adjustment (ports).

An electrification methodology has been developed to assess the options for reconstruction. Environmental benefits have been taken into account. A lot of concern must be given because the electrification will turn the ship dependent on its batteries and the accompanied infrastructure.

For the delimitation process, data has been collected from Mr. Bakirtzoglou and last regulations of DNV (Jan. 2018).

## 4.1 Conversion project

In this project, we will examine ferries that cover 11 different lines of distances between 1.5 and 18 nautical miles (2.78-33.34km). Many of the lines examined are covered by both closed type and open type (double ended) ferries. The first ones cover the larger distances and the second the smaller. However, at all lines studied there are either both types or just closed type, that’s why the project will focus on closed type ferries (ferries with a traditional design with one or two engines).

These ferries have a typical construction of a ship with one bow and serve routes from and to islands, and according to their transportation capacity, routes and distance are calculated. This kind of ferry, which will be examined on next chapter, is Mare Di Levante and is shown below.

Their propulsion system usually consists of one or two propellers on the stern of the ferry, connected to diesel engines, which produce the required power. The typical design includes a machine room, at the stern and the fuel tanks inside or near of it.


*Figure 1: Mare Di Levante a typical ferry serving the route Zakinthos-Killini [38]*

Closed-type ships are designed to use all installed main engines and the propellers they are paired with in order to achieve their service speed. However, many times in cases where the ports are close and the frequency is high, they cruise at lower speeds, using even half of the Maximum Continuous Rating (MCR) installed on board.

On routes from more than half an hour, a small delay of 5 minutes is not something important for the passengers but for the ship-owners means a huge profit. In case of emergency, all the installed power can be used. The size of the battery system should be installed driven to cover power needs but also be economical.

On the following table, the range of the basic characteristics of the ships studied in chapter 8 is presented:

| Range of technical characteristics of ferries in Greek coastlines | | |
|---|---|---|
| **Average main dimensions** | | **Main Machinery** |
| L (Length) | 45 – 120 (m) | 1 or 2 medium speed main engine, 500-9000 HP in total |
| B (Beam) | 12– 21 (m) | 2 or 3 electric generators, 160-550 kW each |
| T (Draft) | 1.8-5.5 (m) | 1 emergency generator, 50-90 kW |
| $V_S$ (Speed) | 7-19 (knots) | |
| Passengers | 300 –1140 | |
| Cars | 65-350 | |
| Trucks | 10 –40 | Year of building: 1975-2018 |

*Table 1: Range of technical characteristics of ferries studied, in Greek coastlines*

The electricity distribution network of these ships works with Alternating current (AC) at 60 Hz.

For the electrification of a conventional ship, it is necessary to install the appropriate number of batteries so the ship can satisfy the needs in propulsion and hoteling only with its batteries. The batteries will be recharged while the ship is loading and unloading at the port and changes are needed both at the ship and at the harbor.

Concerning ship's side electrification the following are demanded:

- In the place of fuel tanks, installation of groups of batteries
- Proper arrangement of battery packs, to ensure the required Voltage and Capacity (Ah).
- Install a Battery Management System (BSM)
- The battery system must be installed in accordance with national and international regulations.
- Replacement of existing main diesel engines with the same power and speed motors, which will be responsible for powering the propellers.
- Modifications to the shaft and propeller to connect them to new

electric motors.

- Modification of the ship's distribution network.
- Uninstall existing electric generators, since the required electrical power will be supplied directly from the battery system.
- Install a point on board that will be able to connect to shore side.

Concerning shore side electrification, the following are demanded:

- Underground cables
- At least one substation containing: (a) frequency converters and rectifiers, (b) power transformers, (c) all necessary protection and safety equipment.
- Interface equipment containing: (a) plugs and sockets, (b) cables with their rollers, (c) crankshafts and (d) mooring system.

The conversion process is a problem with many variants that has to be taken into consideration both from the technical view and from the operational view. But the main priorities are safety of passengers and of the vessel and the satisfactory life span in order to be economically feasible.

## 4.2 Legal and regulatory framework

In order to proceed to the technical design of the conversion of the ferry into an all-electric ship and the necessary port infrastructure, it is important to study the rules and the guidelines that are published by flag state authorities, IMO (International Maritime Organization) and by the class, which will survey the ship and will be responsible for its certification.

According to the regulation of IMO (EUROSOLAS-Directive 98/18/EC), with which Greece complies as a Member state and as a flag authority, the following are mentioned for ferries under retrofit, belonging to "Class C":

- Passenger ships operating inland waterways where probability of exceeding 2.5 meters of significant wave height is less than 10% over a one year period.
- During the itineraries, they never get further than 15 miles from a refuge or more than 5 miles from the coastline.

Legislation by IMO or from Greek state regarding all-electric ships does not exist and is in progress. After conversion, the vessel must have the same safety and integrity levels as before, when powered with conventional internal combustion engines. SOLAS (International Convention for Safety of Life at Sea) chapters for electrical installation and fire protection are the most suitable for our retrofit.

Concerning emergency generator and its firefighting capabilities, no action will be taken and will be left as it is, since it has been already dimensioned and approved. Since there are a huge variety of different batteries, it is impossible to have a standard regulatory framework for all of them.

Next step is to pick a classification society, in order to approve the ship as "battery-ready" which means ready for use with batteries. The following points are taken by different classification societies and are related to our design:

- DNV-GL : Rules for classification, Part 6, Additional Class Notations (Jan.2018)
- 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

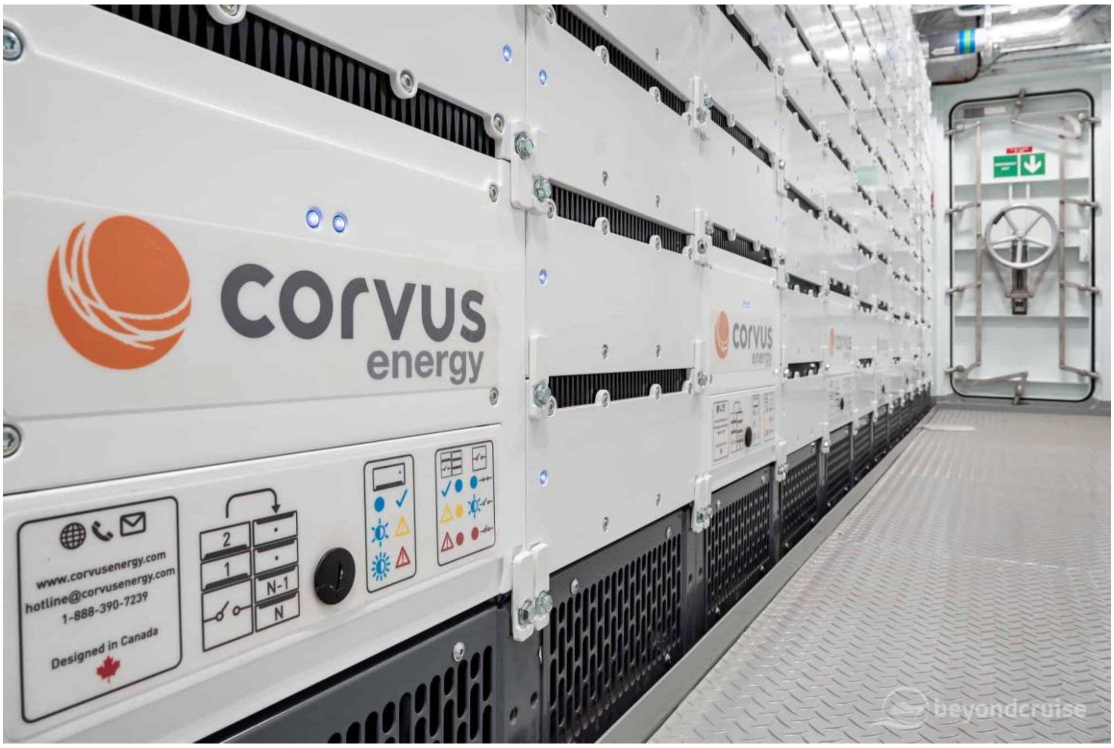



*Figure 2: A view of the battery room aboard the MS Roald Amundsen*

## 4.3 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.

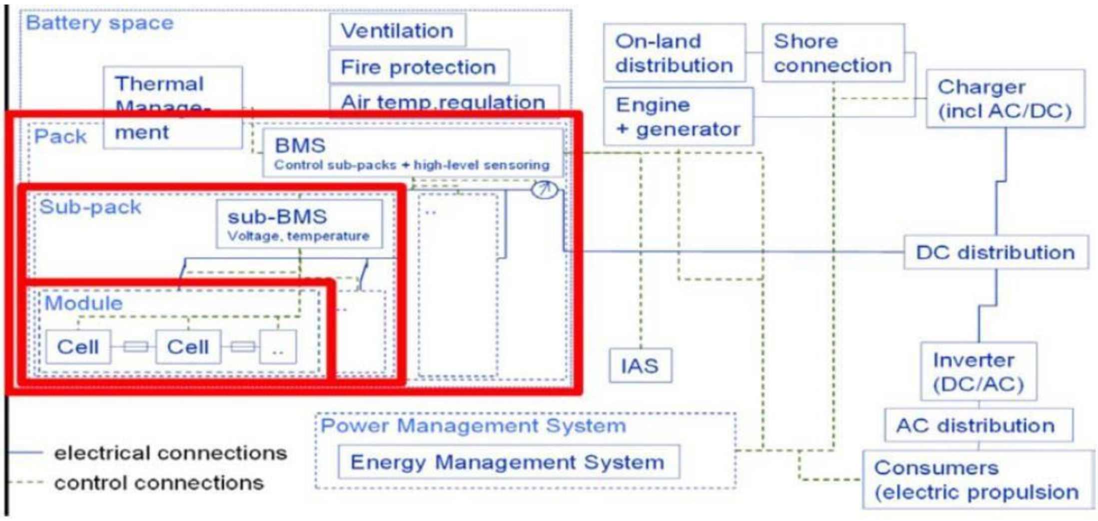



*Figure 3: Battery systems and related sub-systems [14]*

As mentioned in chapter 3, the cell is the smallest electrochemical unit. By combining a number of cells, we make a battery assembly and put it into a frame to protect the cells from external shocks, heat or vibration. This is called a Battery module.

Modules are connecting in series and in parallel to form a sub-pack. Every sub-pack includes switches that can block the main power connection.

By assembling sub-packs in parallel and various control/protection systems including a BMS (Battery Management System), a cooling system etc., we make a Battery Pack. Battery system consists of some battery packs, assembled with cables and bus-bars.

Maintenance of all the components of the system is very important, because the dangers that can appear in every level of the system are many, the most important of which are [24]:

**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

Some proposals for battery's system safety are:

- If a sub-back is consisted of parallel rows of modules, then each of them must include an independent current measurement.
- Low contact impendence for electrical connections is vital to prevent overheating and to control the risk of fire. Using multiple parallel rows can reduce the risk of overheating from increased contact resistance. It can also make easy the detection of high levels of contact resistance within the electrical connections, resulting in increased system security.
- Battery casing, covering modules and cells, shall be of a flame-resistant material.
- The requirements for Ingress Protection (IP) rating of the batteries depends on the location. As a minimum, IP 44 is required.
- 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.
- In an emergency situation, it should be possible to disconnect the battery system. 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.

## 4.4 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.

The emergency generator could not be installed if this is approved by the national authorities.

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

The system while on daily normal operation should be discharged/charged at the normal calculated rate in order to allow for long life span. The system's capacity will be deteriorated after several cycles of charging/discharging and due to aging. This deterioration should be monitored, in order not to affect the vessel's proper function.

The total installed capacity of the batteries should be sufficient to absorb the charge and discharge power according to the electrical balance of the vessel, including the power (hotel loads), not exceeding the recommended temperatures produced inside the batteries due to electric loads, as temperature differences will lead to a lower battery life.

The battery capacity installed should be balanced in relation to the chosen maximal charging capability in port thus higher charging powers will save battery weight while the use of maximum power capacity could lead in high costs, because the station's price depends mostly on maximum power capacity. [24]

The installed battery pack should be increased in order to take advantage of the lower electricity bills during nights. For ships of class C, the EU regulation, in case of emergency, requires the ship to be able to fight at least for three hours alone the fire by its own means.

The weight and volume of batteries must be sufficient in terms of stability. Lifespan of batteries should be long enough, so the project can be economical feasible.

## 4.5 Battery system installation area

Battery space should include all necessary stuff to maintain the battery system within a predetermined space with specific environmental conditions (e.g. temperature, moisture etc.). In order to achieve the optimum performance, appropriate controls and alarms must be installed.

All possible dangers must be assessed from the beginning and should be faced in order to protect the passengers and the vessel. The biggest danger is overheating, which can cause a fire or a gas leak. Therefore, the guidelines below, regarding the handling of the battery space and the relevant alarms and controls, should be followed strictly.

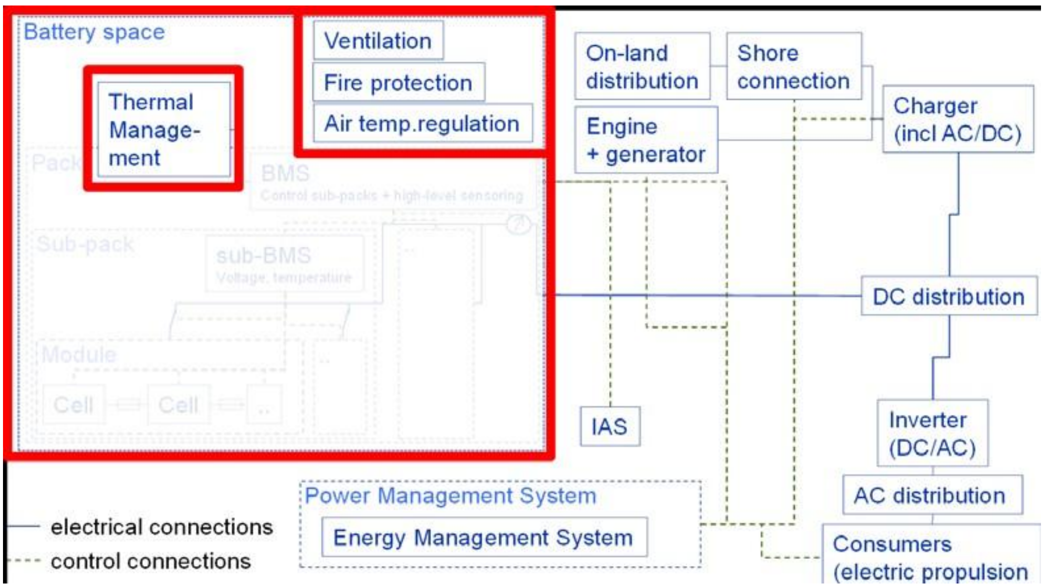



*Figure 4: Illustration of a battery system controlling batteries' temperature [14]*

### 4.5.1 Space arrangement

In order to assure the safety of passengers, crew and vessel batteries' space arrangement should follow some points:

First of all, battery spaces should be put aft collision bulkhead. Boundaries of battery spaces shall be part of vessels structure or enclosures with equivalent structural integrity.

Given that the system of batteries is the only power source, it should be placed at the engine room, where the previous diesel engines were. A successive battery space after the engine room can be examined.

In case of emergency (fire, gases, explosion etc.), the architecture of battery spaces should be capable of maintaining the vital functions of the vessel and the power for propulsion.

Battery space should be a dedicated room and always with adequate protection from heat, dust, oils or any other potential environmental influence. With respect to structural fire protection according to SOLAS Reg. II-2/9.2.2.4, the battery room shall be defined as other machinery spaces.

Fire rating of battery spaces shall be enclosed by A0 class with additional A60 class at:

- 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 modules within the battery space shall be arranged in such way to prevent aggravation of a possible thermal runaway between battery modules. This protection could be achieved by using partition plates or installing the modules keeping sufficient distance in accordance with the manufacturer instructions.

The battery space shall not contain other essential systems and everything related to them (pipes or cables).

The battery space shall be free of any heat sources or high fire hazard objects, as listed in SOLAS Reg. II – 2/3.31 (Heat sources are sources with temperature higher than 220°C as used in SOLAS Reg. II-2/4.2.2.6.1).

The battery space shall be arranged in such way to be accessible for repairs and replacement of failed parts.

### 4.5.2 Operational environment

For optimal battery performance, the battery space environment shall meet certain environmental 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 the battery room and the correspondent alarms in case of increased temperature
- Indication of operating ventilation system and alarm in case of any malfunction

Afterwards, alarm must be activated at the control station and at the bridge in cases of high temperatures and lack of ventilation in the operational environment of batteries. Any other abnormal condition should activate the main alarm system. Vessels without a centralized alarm system, battery alarms should be presented at the bridge.

Battery systems shall be arranged within a space with ventilation that can provide temperature controlled air that will be within the minimum/maximum limits specified by the manufacturer. For liquid cooled battery system, such ventilation system is not required, but an undependable ventilation system is required for extracting possible battery vapor.

The ventilation system for battery spaces shall be an independent from any other air conditioning system serving the vessel's spaces, ducting system.

The sensors should be arranged in such a way that a reliable indication could be provided in case of failure of one sensor by a nearby 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 in order to prevent simultaneous failure of safety and alarm functions.

Depending on the chemistry of the batteries used, certification of battery spaces, where flammable gases exist, maybe needed according to zones specified in IEC 60079-10-1. This certification should be used as a basis for the correct choice and installation of the equipment in the hazardous area. In that case, gas detection systems shall be installed too, along with an emergency mechanical exhaust fan and emergency inlet direct from open air.

In case of malfunction of the ventilation, the use of relief valve is obligatory, so the explosive atmosphere will be avoided. Air at the exhaust should be monitored and activate an alarm (at the bridge also) at 30% or higher LEL (Lower Explosive Limit), that will certify the automated disconnection of batteries and of every other electric circuit.

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 category A machinery spaces according to SOLAS Reg. II-2/10 and the FSS Code. Though, cell chemistry is the most important consideration when choosing fire extinguishing agent. Using water on a lithium battery for example, will lead in the production of hydrogen. However, a fire could be safely extinguished using salt. The battery's manufacturer shall give instructions to cope with fires in the system.

As a general fire extinguishing agent (heavy), foam could be considered, as well. 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 spread 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

## 4.6 Battery management system

Vessel’s operation should be as simple and as similar to conventional system as possible. It requires a BMS (Battery Management System) which monitors and controls all the system's functions and parameters. It is responsible for the communication with the general power management system and provides all the basic information of the batteries in order to ensure their efficient performance. It should also have an override function to prevent the power management system to perform tasks outside its safe boundaries, in way that failures in the protective safety system shall be detected and indicated, but will not cause shutdown of the battery system. Finally, it must be designed for monitoring the system and keeping it within permissible limits, calculating and reporting secondary data, controlling its environment, authenticating it and/or balancing it.

The battery management system (BMS) shall:

- provide limits for charging and discharging to the battery converter
- protect against over-current, over-voltage and under-voltage
- protect against over-temperature
- provide cell and module balancing

The following parameters shall be measured:

- cell voltage
- cell or module temperature
- battery string current.

The following parameters shall be indicated at local control panels or in remote workstations:

- system voltage
- max, min and average cell voltage
- max, min and average cell or module temperature
- battery string current.

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 (SOH)

Important parameters should be recorded in a memory that doesn't lose its data with an electricity blackout.

## 4.7 Land-ship Interconnection System

There are two possible systems of interconnection:

- AC (Alternating Current) Interconnection System
- DC (Direct current) Interconnection System

IEC 80005-1 covers AC high-voltage shore connection systems while IEC 80005-3 covers AC low voltage shore connection system. Currently there is no standard or recommendation covering DC shore connection systems, therefore AC charging system is selected although the DC connection system may have some significant advantages. The next two chapters summarize the requirements of an AC interconnection system as described in IEC 80005.

These standards intend to establish the requirements for ensuring compatibility between ship and high voltage interconnection equipment at as many ports as possible. The standards guarantee a simple, direct connection, eliminating the need for ships to make adjustments to their equipment across the various ports. Ships that do not comply with the standards may encounter significant difficulties in interconnecting with compatible onshore stations. Standards also cover matters as power quality, electrical, environmental and mechanical requirements, safety, compatibility between land and ship equipment, plugs, sockets, testing and certification of ships.

### 4.7.1 Land Interconnection Equipment

The standards suggest similar configurations for both HVSC (High Voltage Shore Connection) and LVSC systems. The main difference between the two configurations is the grounding equipment used in high voltage systems to avoid the danger of electric shock. The main components of the LVSC system are listed and shown in the next figure:

1. shore supply system
2. shore side transformer and neutral resistor or/and IT system

3. shore side protection relay
4. shore side circuit-breaker
5. shore side feeders circuit-breakers
6. shore side control system
7. shore to ship connection and interface equipment
8. ship side control system
9. ship protection relay
10. on board shore connection switchboard
11. on board transformer (where applicable)
12. on board receiving switchboard.

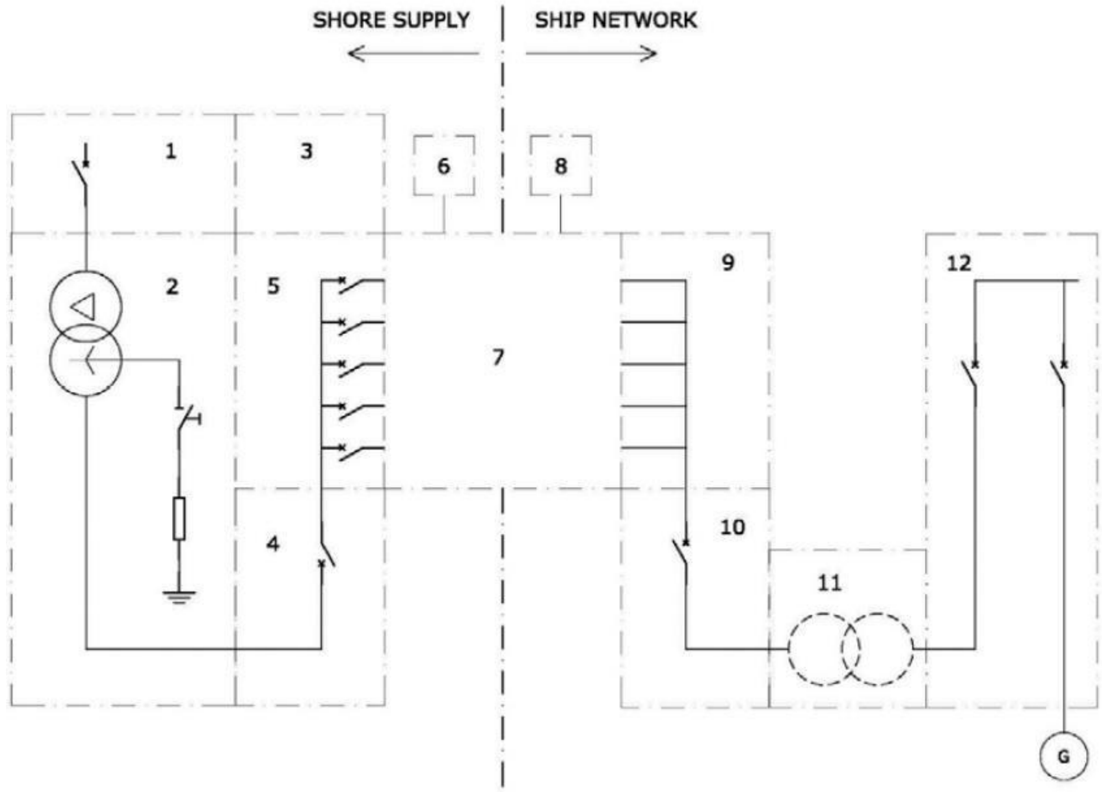



*Figure 5: port side configuration for a LVSC system presented in IEC/ISO/IEEE 80005-3*

Suggestions from these standards are listed below:

Firstly, the isolation transformer should be DYN type with the star configuration terminal attached to the side of the ship (D stands for delta configuration, Y for star; N means the neutral conduit is accessible to the star terminal).

The neutral point of the isolation transformer feeding the shore to ship power receptacles shall be earthed through a neutral earthing resistor. The neutral earthing resistor may be omitted when shore LVSC utilizes IT system. When frequency conversion of the shore supply is required a secondary delta winding of the transformer, in combination with an earthing transformer with resistor on the primary side, suitable to compensate for possible circulating currents, are permitted provided that the other requirements of the standard are fulfilled.

The continuity of neutral ground resistance must be constantly monitored. In case of continuity loss, the earth protection switch must be activated.

Equipment earthing conductors finishing at the shore power outlet box should be connected with the ship in order to create an equivalent connection between shore and ship. This may require bonding to the ship switchgear earthing bus and/or bonding to ship hull.

Another important topic that the IEC/ISO/IEEE 80005.3 standard covers is the number of cables that should be incorporated in a LVSC system. Table 2 shows the number of feeding cables as a function of the maximum power demand and the voltage of the connection, while Table 3 presents the maximum corresponding current per cable.

| ***kVA*** | **Connection Voltage** | | |
|---|---|---|---|
| | 400 V | 440 V | 690 V |
| *250* | 2 | 1 | 1 |
| *500* | 3 | 2 | 2 |
| *750* | 4 | 3 | 2 |
| *1000* | 5 | 4 | 3 |

*Table 2: Number of feeding cables as a function of the maximum power demand and the voltage of the connection. [24]*

| kVA | Connection Voltage | | |
|---|---|---|---|
| | 400 V | 440 V | 690 V |
| 250 | 180,4 A | 328,0 A | 209,2 A |
| 500 | 240,6 A | 328,0 A | 209,2 A |
| 750 | 270,6 A | 328,0 A | 313,8 A |
| 1000 | 288,7 A | 328,0 A | 278,9 A |

*Table 3: Maximum corresponding current per cable [24]*

### 4.7.2 Ship Interconnection Equipment

IEC / ISO / IEEE 80005-3 recommend the following actions to ensure the smooth and safe operation of the ship-side interface as well as to avoid errors:

First of all, for an AC connection with shore side, the vessel's system shall have its own battery charging system. The charging system and shore connection shall include temperature sensors that will be able to detect incidents of high temperature and resistance as early as possible. Charger should be designed in a way that high charge currents and voltages are avoided, while keeping the specified current level and voltage in the specified levels. Any failure shall give alarm at every control station.

Connection process shall be preferably an automatic procedure; otherwise a risk assessment for involving personnel shall be done. During the charging process, the system shall automatically stop the propulsion operation. However, some applications may still need propulsion power so unplugging of the charging interface must be avoided.

Where device settings are required to be changed during AC supply connection, means shall be provided for personnel to change them. The protection settings in use shall be clearly indicated at the control station.

The distance between the supply and reception point should be as short as possible. The shore connection switchboard should be in accordance with IEC 61439. The switchboard shall include a circuit breaker, meeting the requirement of IEC 60947.2., to protect the ship electrical equipment downstream. In no case shall the protection at the shore connection switchboard be omitted. In order to have the installation isolated before it is connected, a circuit breaker with built in disconnection function shall be provided. This circuit-breaker shall be in conformity with IEC 60947-2. The rated capacity of the circuit breaker shall not be less than the prospective peak value of the short circuit current (IP) calculated in compliance with IEC 61363.1. The rated short-circuit breaking capacity of the circuit-breaker shall not be less than the maximum prospective symmetrical short-circuit current (IAC (0.5T)) calculated in compliance with IEC 61363-1.

A motor operated circuit breaker shall be provided. The shore connection switchboard shall be equipped with voltmeter (for all three phases), short circuit devices (tripping and alarm), over current devices (tripping and alarm), earth fault, indicator alarm, unbalanced protection for systems with more than one cable.

The protection systems shall be provided with battery back-up adequate for at least 30 min, see IEC 60092-504:2001, 9.6.2.5. Upon failure of the battery charging or activation of back-up system, an alarm shall be activated to warn relevant duty personnel. Alarms and indications shall be provided at an appropriate location for safety and effective operation.

Galvanic separation between the shore and on board systems shall be provided on shore side.

An on board transformer may not be required if the ship’s network is designed for the shore supply voltage and the neutral point treatment is in line with the ship systems and the galvanic separation is done on shore.

When necessary, means shall be provided to reduce transformer current in rush and/or inhibiting the starting of large motors or the connection of other large loads, when a LV supply system is connected.

There shall be no flammable materials close to shore power connector in order to prevent fire spreading from the connector to the environment and the vessel.

# 5 Design of Electrical Topologies

The majority of modern passenger ships are equipped with 1 or 2 main engines (except some small ferries with 3 or 4), installed in the engine room, which are responsible for propulsion. For the supply of electric loads (lighting, air conditioning etc) there are usually 2 or 3 diesel generators. Adequate and reliable power supply is a critical success factor for all-electric ships. Ships require a constant voltage and specific frequencies. The land infrastructure must be the appropriate for the successful function of batteries on ships.

The electricity is supplied by the utility grid and distributed to the connection point or seaside terminal. When this electricity is generated from renewable power plants near the port, such as wind or solar parks, then a zero-emission all-electric ship is possible. The mechanism of transfer of electricity from land to ship is not simple, but a complex system equipped with automation and alarms to meet security requirements. All equipment designed to manage and monitor the LV (Low Voltage) and HV (High Voltage) flexible cables and their connecting devices is called Cable Management System (CMS).

## 5.1 Topologies on vessel

This chapter presents the one-dimensional diagrams of the energy grid configurations for the retrofit of a ferry. The design philosophy was based on a ferry with a two-engine room, with two independent battery packs, installed in two different parts of the engine room for greater safety. The outgoing circuits on a battery system shall, in addition to short circuit and over current protection, be provided with switchgear for isolating purposes so that isolating for maintenance is possible. DNV GL suggests an isolated system for grounding purposes (isolated positive/negative terminal).

A DC distribution system offers many advantages (e.g. less number of cables) in comparison with an AC system, but it is suitable for new-built electric ships. Existing ships use already an AC system the modification of which would greatly increase the cost.

In the figure below it is presented the one line diagram of the power network with a DC distribution system and could be applied in a shipbuilding of a new all-electric ferry.

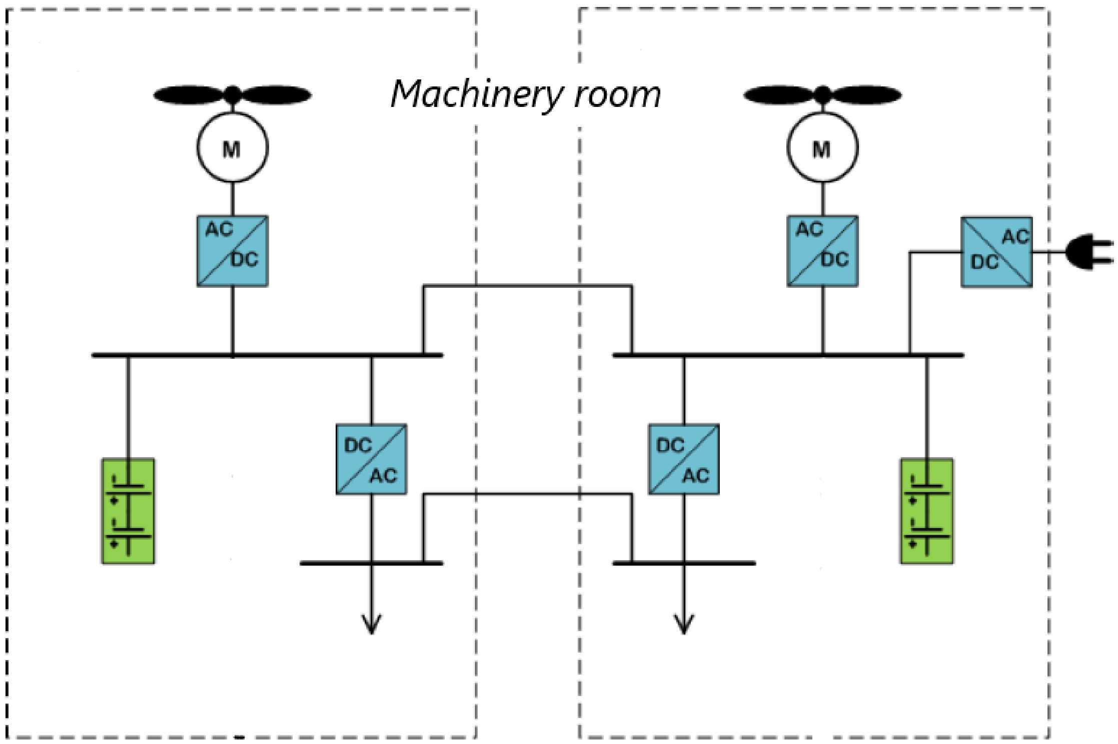



*Figure 1: Electric ferry DC distribution system topology [24]*

The main components of this configuration are:

- Two inverters (DC/AC) for the control of the induction propulsion motors of nominal power equal or greater to the nominal power of the motor.
- Two inverters for the supply of the existing AC electrical loads (lighting, air condition etc.)
- One rectifier (AC/ DC) for the charging of the batteries while at berth
- 2 DC cables (2 conductors) for the interconnection of the machinery rooms.
- 2 DC buses

When DC distribution system is used on board rectifier could be omitted, as the same onshore frequency converter could be used to charge more than one ferries, and as a consequence the cost would be lower.

Figure 2 presents the one line diagram of the power network with an AC distribution system, which is the most suitable of the retrofit of the existing diesel-powered vessels into battery-powered ones.

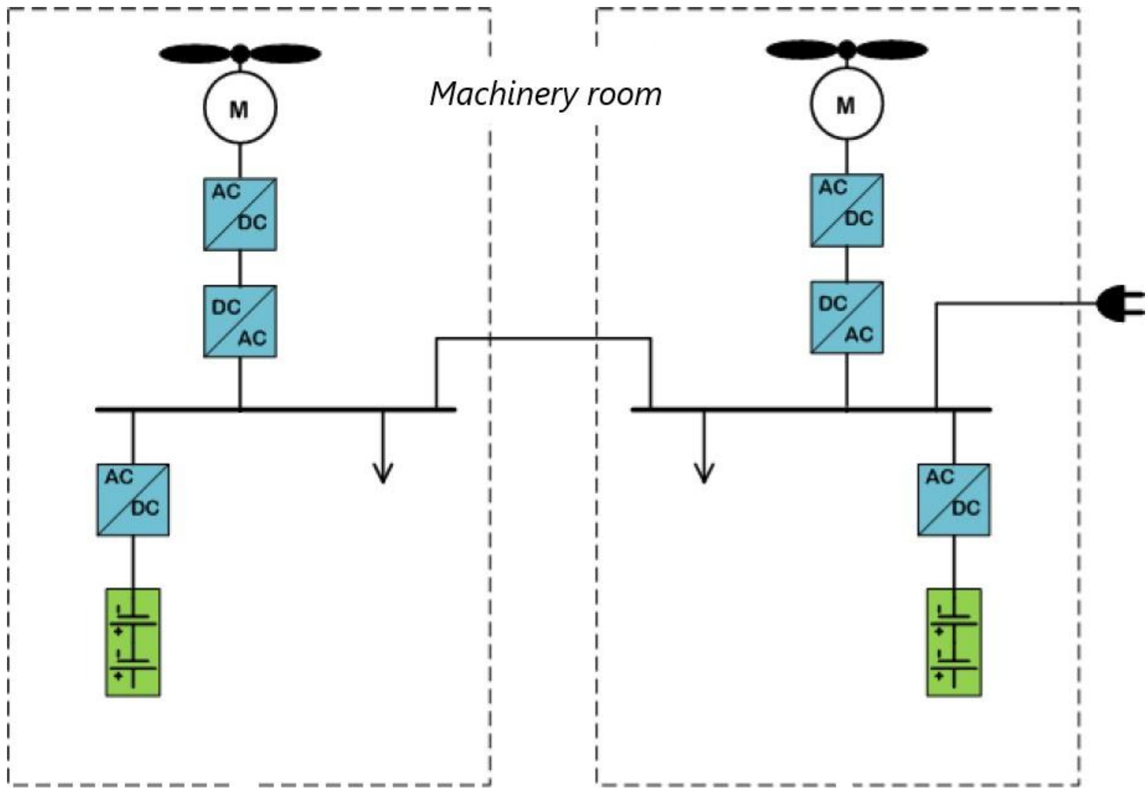



*Figure 2: Electric ferry AC distribution system topology*

The AC configuration consists of:

- 2 AC/DC inverters (one for each battery). The inverters will convert the DC current from the batteries to AC to the ship's grid.
- 2 back-to-back converters (AC/DC/AC) of nominal power equal to or greater than the motor's nominal power, to control the propulsion motors.
- 2 three phase AC cables to connect the battery rooms.

According to IEC/IEEE/ISO 80005 a HV (3.3/6.6/11kV) shore side connection must be installed when the max charging power exceeds 1 MW and the vessel should be equipped with a step down transformer to convert the voltage to voltage suitable for use on the vessel (380/400/440V).

On the next figure, an alternate configuration is presented with the system of double bus-bar, which could be used in case of the retrofit of a diesel-powered ferry with its distribution system functioning at 60Hz, while on shore system functions at 50Hz (or vice versa). With this system there is no need for an onshore or offshore frequency converter in order to cover the hoteling loads while being in charging phase at the port. One battery pack could be charged while the other will supply the required loads for air conditioning, lighting etc.

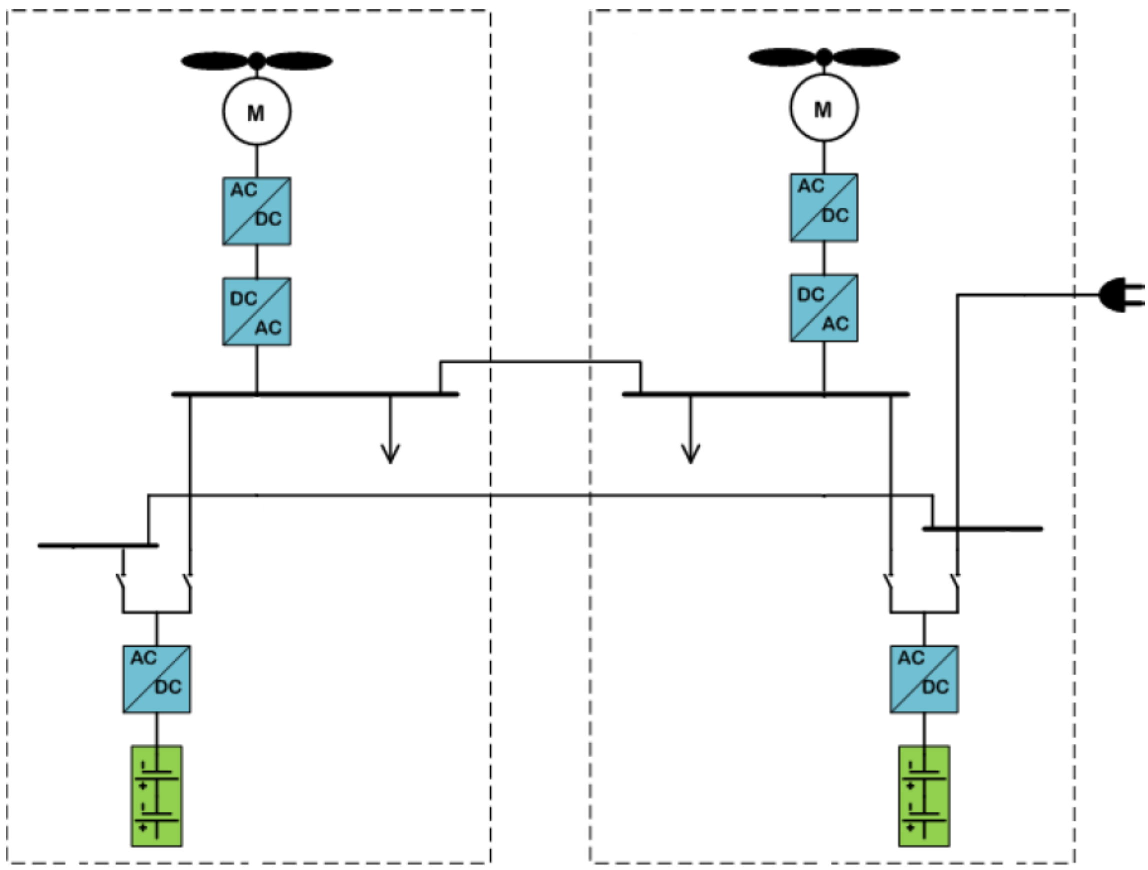



*Figure 3: Electric ferry AC distribution system with double bus-bar topology*

## 5.2 Topologies on shore

The charging process of the vessel's batteries with AC current is taking place using a main substation equipped with a MV switchboard supplying the shore side substations.

Shore side substations connecting the vessels with the grid are equipped with:

- An isolation transformer of DYN configuration which converts grid MV current to the connection voltage, with the neutral point grounded (possibly through a grounding resistance)
- The outgoing switchboard supplying the plugs for the connection between the port and the vessel.

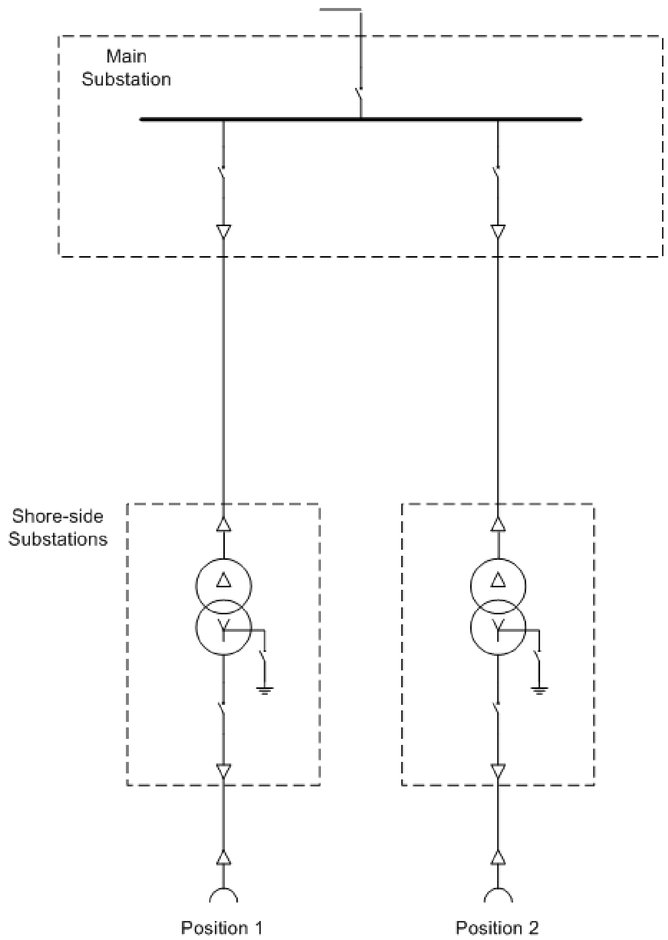



*Figure 4: AC LV shore-vessel connection [24]*

If the maximum charging power of the system is more than 1 MW a suitable HV connection should be installed instead of the LV connection. An earthing switch must also be added after the outgoing circuit breaker, as shown on the next figure:

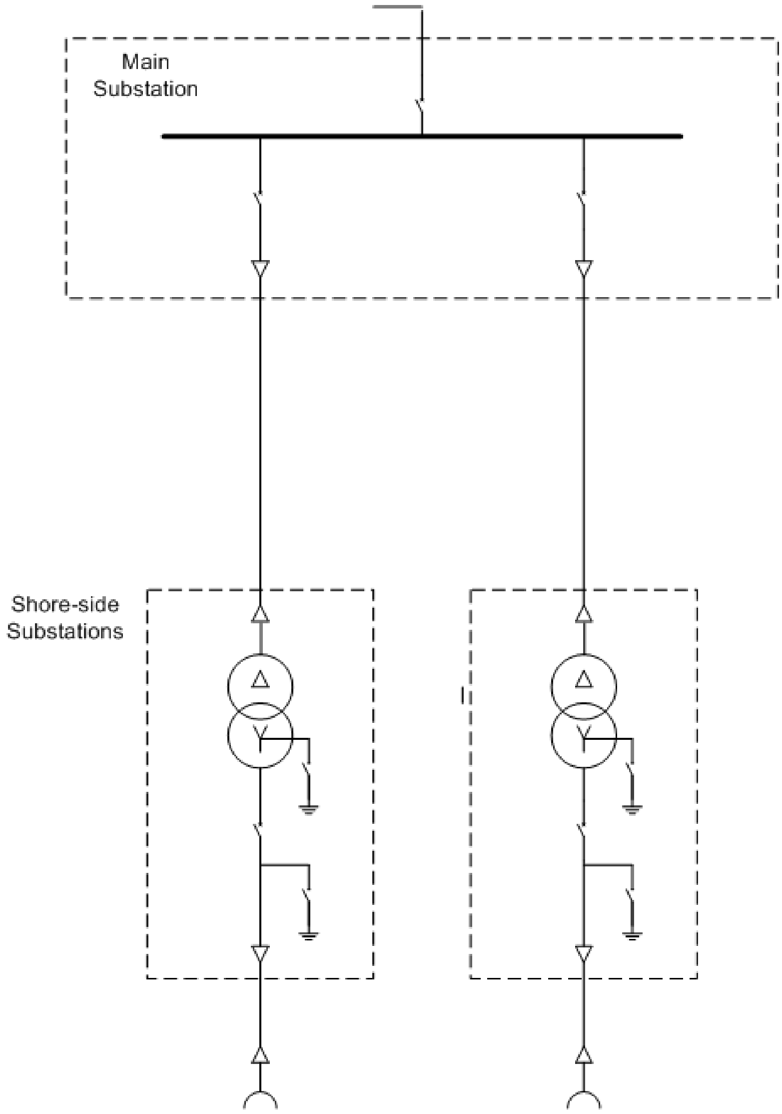



*Figure 5: AC HV shore-vessel connection*

Finally, in case of a DC connection a rectifier should be installed downstream the step down transformer to convert AC to DC current, as shown on the figure below:

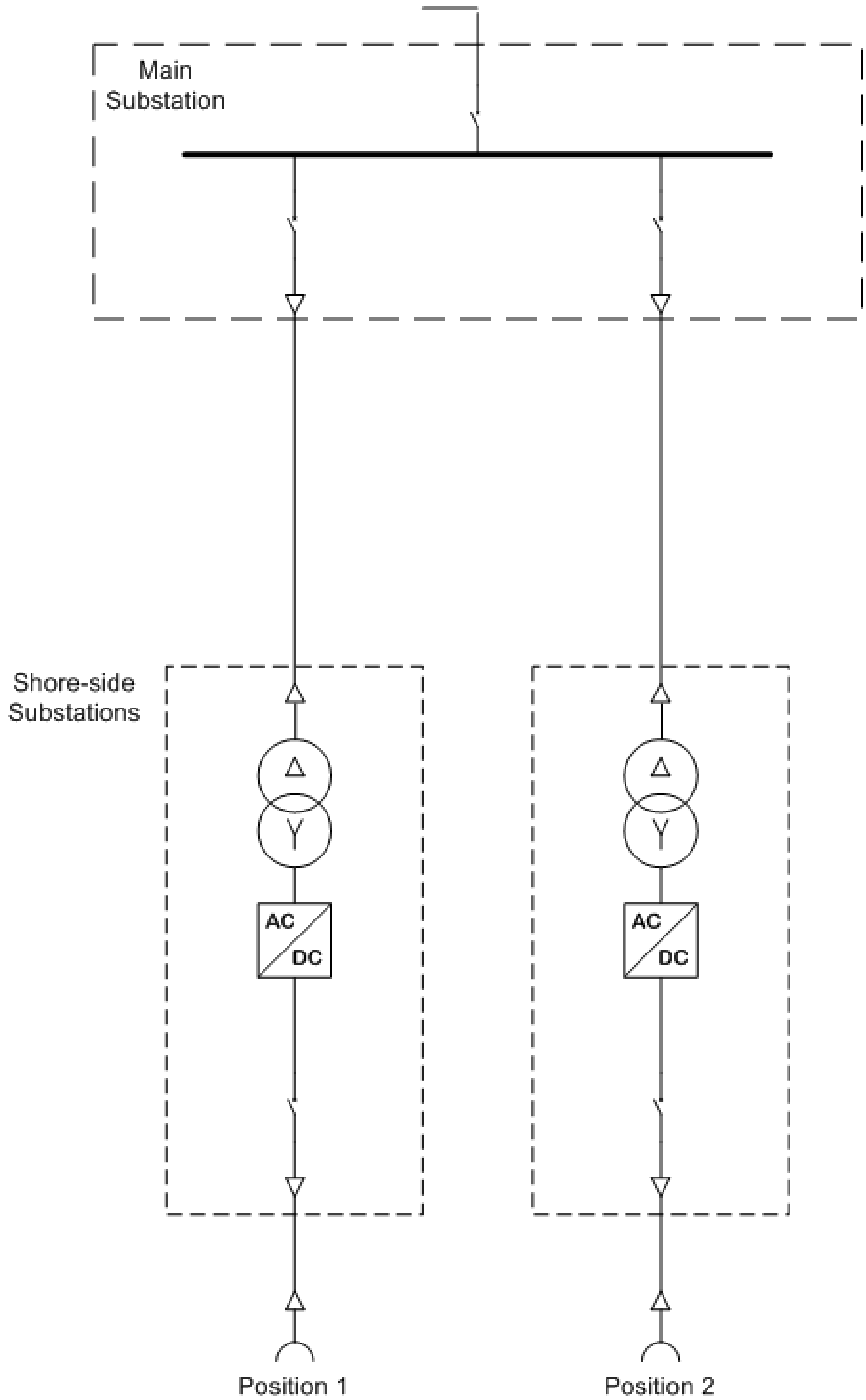



*Figure 6: DC HV shore-vessel connection*

## 5.3 Vessel to Shore Connection (SC)

Vessel to shore connection and interface equipment includes LVSC or HVSC systems, cables, earthing and communication systems. Cables should be installed in a way that assures proper movement compensation, cable handling and placement for normal operations. A hardwired circuit is required in case of emergency disconnection. The circuit should be separated from other cables, used for monitoring, control and alarm functions. CMS (Cable Management System) is splitted into shore based and ship based systems.

Concerning shore based systems they can be fixed, mobile or mounted to a special barge. The fixed shore based CMS is an integrated, unmovable part of the dock, whereas the mobile systems use an electrically driven unit to move the supply plug in a convenient position, in order not to restrict other vessel's movement at the port. The third alternative of shored based systems uses a barge equipped with cables, and the barge is maneuvered towards a ship which is docked away from the main station. These systems are presented below.

(a) (b)

*Figure 7: (a) Fixed based CMS in the Port of Los Angeles (b) Mobile shore based CMS in port of Shenzhen [26]*

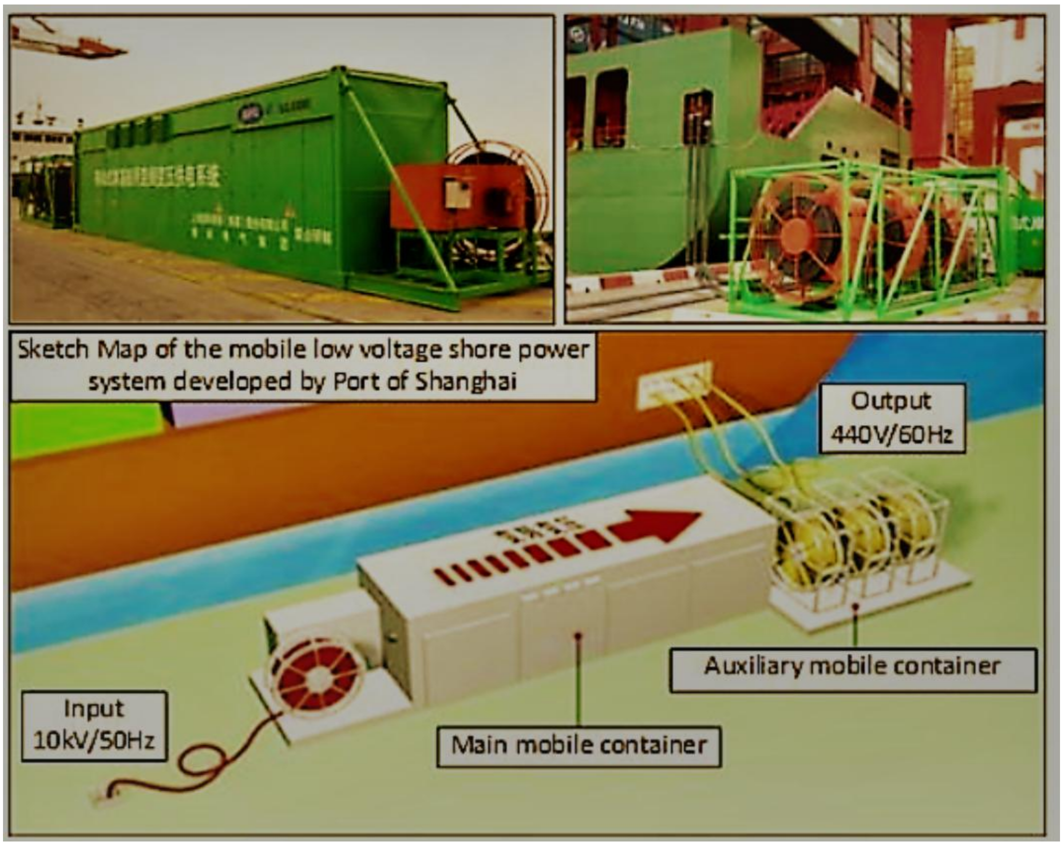



*Figure 8: The diagram and equipment of mobile low voltage shore power system [27]*

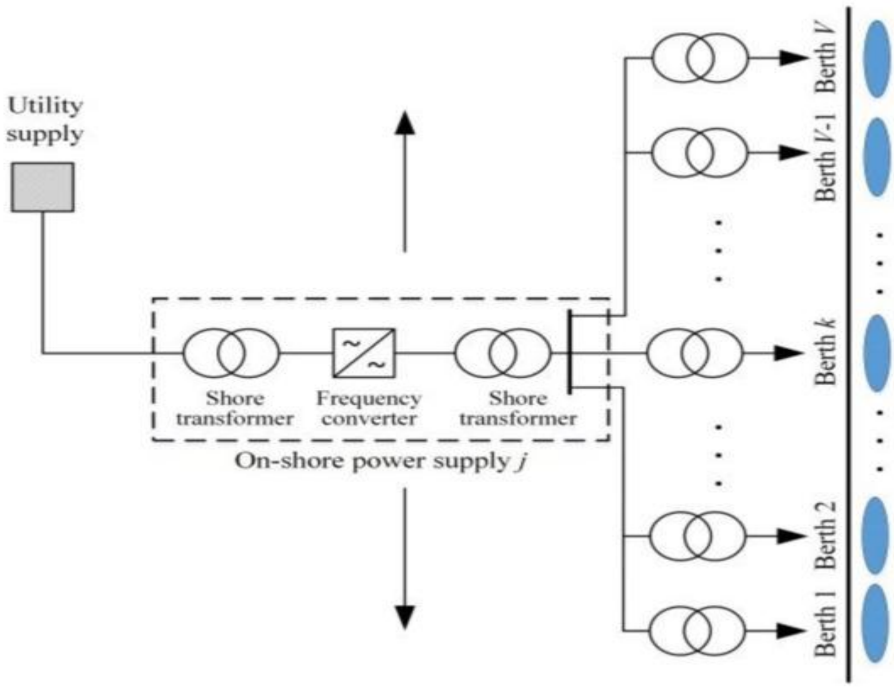



*Figure 9: Mobile pattern of OPS (On-Shore Power System) [26]*

A vessel based system could be also fixed or mobile and it is ideal when the dock is occupied. The fixed based system consists of flexible cables wrapped around a cable drum which is mounted on the deck of the ship. A mobile vessel based system is installed into one or two containers (40ft or 20ft vice versa). The containers can be moved in different places on the ship or even moved from one ship to another. The system operates by lowering the cable and plugging the connectors in a socket usually close to the edge of the quay.


*Figure 10: Fixed ship-based CMS [28]*


*Figure 11: Mobile ship-based CMS [28]*

# 6 Environmental Study

## 6.1 General information

In the atmosphere gasses that transmit and absorb radiation within the thermal infrared range are called Greenhouse Gasses (or GHG). Those are carbon dioxide ($CO_2$), methane ($CH_4$), water vapor, ozone ($O_3$), nitrogen oxide ($N_2O$) and Chlorofluorocarbons (CFCs). GHG affect directly the temperature of earth. Calculations on atmospheric concentrations of $CO_2$ show an increase about 40% since 1750, when biomechanical revolution occurred. In north hemisphere it has reached the enormous number of 400pm (parts per million), mainly due to the increase of the temperature in the human atmosphere. Atmosphere, forests, ground and oceans save carbon, which moves between them in an endless cycle. $CO_2$ is mainly emitted from the combustion of fuels that have as a basis carbon and that is oil, natural gas, coil and wood.

The main emissions of ships are ozone particles, $NO_x$, sulfur dioxide, $SO_2$, and $CO_2$. These emissions are all oil combustion products which can be classified as primary or secondary pollutants. The primary pollutants are pollutants formed directly during the combustion process (sulfur oxide, oxide of carbon, nitrogen oxide) while secondary pollutants are formed results of chemical reactions in the atmosphere (nitrogen dioxide, ozone, secondary particles).

Greenhouse gas emissions related to ships are important and rapidly growing. Without action, these emissions will be more than double by 2050, due to the expected growth of the global economy and the associated transport demand as shown in Figure 1 [35]. This is why stringent international regulations have been established or are in project, concerning limitation of ship emissions.

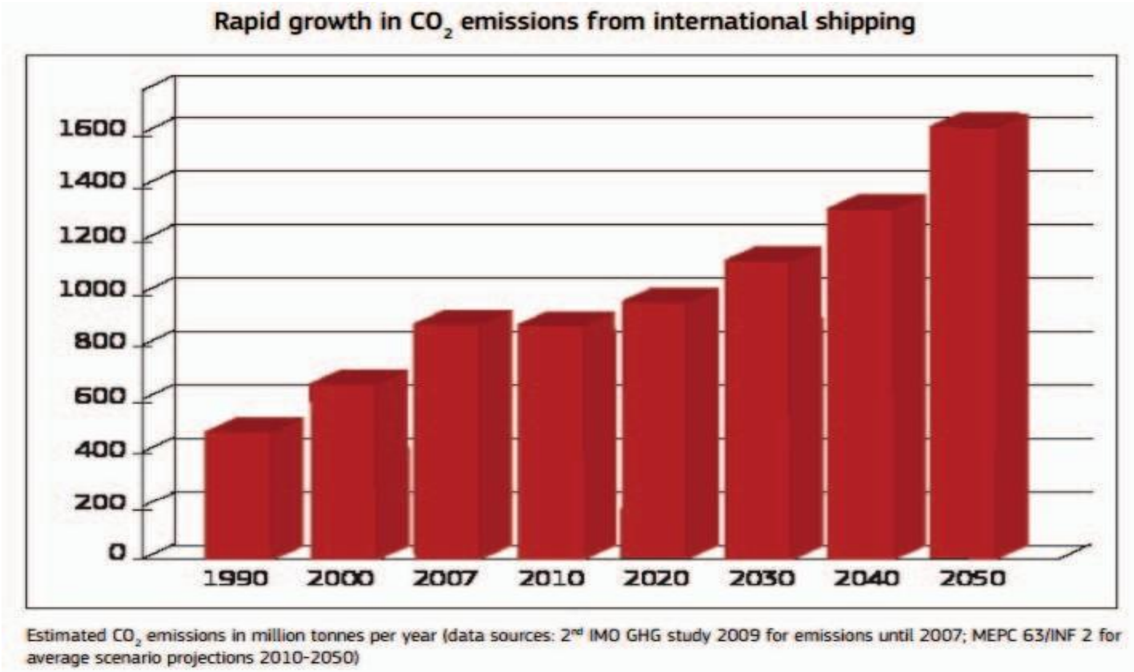



*Figure 1: The evolution of $CO_2$ emissions in shipping [35]*

## 6.2 Consequences

GHG emissions are constantly increasing and affect with a growing rate the ecosystems of earth, but also the living conditions of humans, causing bio-chemical changes in the oceans and marine systems. The most important consequences in human health and the environment are the following:

- Heat strokes, injuries and deaths from changes of the weather and increase of the temperature.
- Numerous diseases from atmospheric pollution.
- Food and water alternations and increase of transmitted illnesses.
- Global warming, that will lead to the melting of ice and snow mainly in Antarctica, and thus the level of the sea will increase and cover whole seaside regions.
- Waves of embers and thunderstorms.
- Difficulties in adaption and diseases in wild fauna and distinction of many species, with the creation of desert and barren land. Many species of animals and plants are already distinct, while their population migrates in order to find food and water, due to the drought.

From an economic perspective, the Organization for Economic Co-operation and Development (OECD) calculates the cost from the consequences of atmospheric pollution in the health of humans, in crops and forests, in the ecosystem and climate and estimates it will reach 2% of European GDP (Gross Domestic Product) in 2060. The cost that relates to the degradation of air and water, the climate change, the health of ecosystems, increased morbidity and mortality correlates also to the previous percentage of expenditure. Political action is necessary to be taken.

Externalities costs are also important. An external cost occurs when producing or consuming a good or service imposes a cost upon a third party. Externalities can have either a negative or positive impact. If there are external costs in consuming a good (negative externalities), the social cost will be greater than the private cost. The existence of external costs can lead to market failure. External costs of shipping may derive from all marine pollution, solid and liquid waste, resources consumption, noise pollution, ship recycling, air emissions etc. The evaluation of externalities is important towards a cost internalization policy and in a cost–benefit analysis where the costs to establish measures to reduce a certain environmental burden are compared with the benefits.

## 6.3 Troubleshooting measures

In this chapter the measures for reduction of GHG are examined from a technological view. Ships are an important source of atmospheric pollution and emission of GHG. By the enforcement of regulation the desirable reduction of the ships emissions can be achieved. The basic categories of solutions for this reduction are presented below:

- Use of electrical power for propulsion, loading and unloading, hoteling and other loads of the ship, with the use of batteries and electric engines.
- Use of renewable sources of energy like solar and wind.
- Design and function of ships with developed energy efficiency. That means to be more productive with the same energy consumption.
- Use of biofuel and natural gas, which have lower total emissions in the cycle of fuel per work unit.

- Special technologies able to keep and convert chemically various hazardous substances.

Concerning the first category, the moderate technologies of batteries and electric motors provide a satisfactory energy efficiency that ensures the propulsion and safety of the ship. The grand majority of ships use internal combustion engines and concerning the fact that the average life of a vessel is 25 years, the electrification of ships is seriously examined from the ship-owners. A techno economical study on every case can show if it's profitable for a vessel to stay as it is until its withdrawal and the provision afterwards with a new battery-powered one or it's better to retrofit an existing vessel.

Concerning the second and fourth category, renewable sources of energy can be either directly used on ships or produced on shore and be provided at the ships. The directly used sources of energy in ships can exploit sun (photovoltaic), wind (traditional cloths, rotor sails) or wave (gyro-based systems, wave soils, trimarans). The sources produced on shore can be fuels with small fuel cycle (biofuels, natural gas) or renewable energy (solar and wind energy, hydropower, geothermal plants).

Concerning the third category, MEPC (Marine Environment Protection Committee) has developed an index named EEDI (Energy Efficiency Design Index) in order to increase efficiency. It concerns mainly the new building of ships which means that the results will be achieved with new designs of ships that will be delayed due to the existing serving routes ships. The design concerns mainly the interaction between energy and propulsion systems, hull and superstructures, design speed and transport capability. Concerning function, the basic sections of saving energy comes to energy management, optimization of trip, logistics, motivation and management of fleet.

Concerning the fifth category, technologies has been grown that reduce the emissions by creating chemical processes on exhaust fumes and thus cleaning them from the toxic substances. For the reduction of $SO_x$ the use of fuels of low sulphur and a system of cleaning the fumes can be used, like scrubbers. For the reduction of $NO_x$ solutions are SCR (Selective Catalytic Reaction), EGR (Exhaust Gas Recirculation), water emulsification and Miller cycle. $CH_4$ and NMVOC (Non Methane Volatile Organic Compound) can be reduced with the optimization of combustion procedure, use of scrubbers, careful design to avoid cracks and use of gas engines. PM (Particulate Matter) can be reduced with changes on the basis of lube oil and reduction of quantity of soot.

## 6.4 International Law

The need for maintenance of a minimum required power for maneuvering of the vessels lead to the development of guidelines in order to be adopted from the MSC (Mediterranean Shipping Company) in 2012. This minimum power depended on the DWT of the ship. In order to ensure the buoyancy of the ship in case of lower power than needed in intense conditions a detailed evaluation has been developed.

Vessels of 400GT (Gross Tones) and above are obliged to have the certificate IAPP (International Air Pollution Prevention), since the IMO introduced Annex VI as a protocol in 1997, thus vessels that belong to sections of MARPOL 73/78 has to edit certificate IAPP. Flag must ensure that the vessel complies with the regulations in the annex and an annual intermediate check in order to renew the certificate is necessary. According to annex VI the preparation for the compliance is related to the following regulations:

**Regulation 12- ODS (Ozone Depleting Substances)**

This regulation does not apply for permanently sealed equipment. Every deliberate emission of ODS is strictly restricted. Same applies for infrastructures that include ODS (including HCPC (Chlorodifluoromethane) from this year. Records and recordings of the following have to be kept:

- Every ship that has a rechargeable system that includes ODS has to keep a book of ODS recordings that has been approved from the administration.
- A list of appliances that include ODS.
- The indications in the ODS book must be recorded in relation to the mass (kg) of the substance related with: recharge of equipment, repair or maintenance, release of ODS into the

atmosphere, whether intentional or unintentional, release of ODS into onshore facilities, supply of ODS to the ship.

**Regulation 13- Control of $NO_x$ emissions**

This regulation applies for all ships with engines of 130kW and more. Depending on RPM engines are distinguished in 3 categories, each of which has a different restraint of $NO_x$ emissions. The recordings and checks that have to be made in the different methods of checking emissions are:

First one is the parametric method of engine that includes:

- The EIAPP (Engine-IAPP) certificate is issued to all engines classified in the above categories. This certificate is issued after proof of compliance with $NO_x$ emission limits.
- All certified engines shall be supplied with an individual technical file containing the engine's $NO_x$ compliance specifications. The $NO_x$ technical file must be on board.
- This method required IMO identification markings for the effect of $NO_x$ components. All parts listed must be IMO-labeled according to the technical documentation. In the case of fittings, if renewed with spare parts, the IMO marking for new spare parts must be in accordance with the technical documentation and must be kept in a register.

Second one is the simplified method of measurement, including:

- EIAPP certificate
- Technical documentation
- All recommendations by the engine manufacturer that have been approved from the management
- Test result

Third one is Instant Monitoring and Measurement method, which includes:

- EIAPP certificate
- A technical file including the vessel's monitoring manual
- Approval of installed measuring equipment
- Recorded measurement results

**Regulation 14- Control of SOx emissions**

$SO_x$ emissions are strictly limited, and the limit is up to where the ship is, if it is inside the ECA (Emission Control Area) or not. Documents and recordings that have to be kept are the following:

- Vessels using different fuels on ECA must be fitted with the recording procedure, indicating how it is intended to switch fuel and this plan has to be approved.
- Date, time, location of the ship, when fuel transfer process has been completed, should be recorded in the logbook as required.

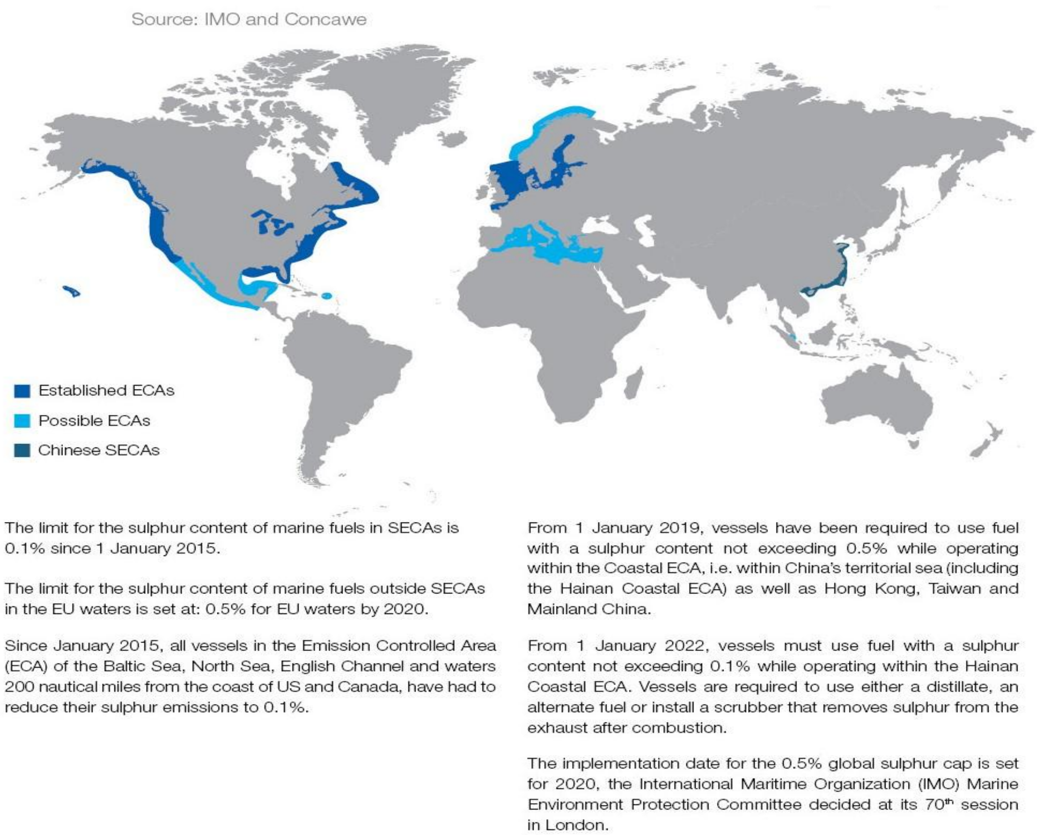



*Figure 2: Emission control areas [33]*

### Regulation 15- VOC (Volatile Organic Compounds)

This regulation refers to mandatory VOC Management Plan which a tanker vessel carrying crude oil shall implement and have onboard. Ship specific VOC Management Plan shall provide written procedures for minimizing VOC emissions during the loading, sea passage, and discharge of cargo.

### Regulation 16-Incineration on board

According to the IMO regulations the following solid and liquid waste can be burned in an IMO certified shipboard incinerator: Plastic, cardboard, wood, rubber, cloth, oily rags, lube oil filters. The quantity that has been incinerated has to be recorded on the logbook together with time and location of the ship. A warning of the material that is going to be incinerated has to be put on the incinerator.

### Regulation 18- Availability and quality of the fuel

It is a requirement that any process of delivery and use of liquid fuel on board intended for combustion should be recorded in the BDN (Bunker Delivery Note), which should be kept on board for at least 3 years. Each BDN must be accompanied by a representative sample of the fuel delivered. The sample must be sealed and signed by both the supplier's representative and the responsible service officer. The sample must be kept on board for at least 12 months. Thus, keeping all of the above documents ready, the IAPP overview can be easily processed and the IAPP certificate can be renewed.

## 6.5 Production of electricity in Greece

The way that electricity is produced is the most important issue for the pollution of environment. If electricity is produced with renewable means of energy and ships use this electricity for those batteries then zero emission is possible.

According to the last data from the energy exchange, ‘Green’ by one-third was the blend of electricity that covered the needs of Greece. Significant, but perfectly interpretable, due to the increased cost of $CO_2$, was the reduction of lignite participation in favor of natural gas production.

More specifically, 22.08% of electricity production was based on renewable means of energy, mainly windy and solar. By adding the 10.06% of hydroelectric production a total 32.14% of ‘green’ production results, which cover one third of total electricity production for covering all needs. The production from natural gas marginally surpassed for the first time lignite with 33.96% against 33.90%. It is remarkable that in 2018 for 23 hours the System Marginal Price (SMP) was zero, which means that the total needs of electricity were covered from renewable sources. The total value of electricity price that has been transferred during the year comes to 3.4 billion €.

The last decade from the rapid growth of the installed power of wind and solar power and the reduction of total supply of electricity, renewable sources of energy have constantly high prices with a growing rate (22.08% in 2018, 20.1% in 2017). Wind energy from the zero levels of twenty century increased to 5.5TWh in 2017, while solar energy achieved an even bigger development, 25 times bigger, from 0.16TWh in 2010 to 3.5TWh in 2017. Hydroelectric energy consists the bigger percentage of renewable sources every year with annual fluctuations. Greece has also a small percentage of electric production from biofuels, which comes to lower than 1% of the total production. In the figure below we see the percentages of each renewable energy source (left axis) and the percentage of renewable energy sources to the total electricity generation.

Another potential that Greece has is the development of geothermal power generation, another renewable source of energy. It is based on the availability of natural resources in areas of Greece that is geothermal fields with high or medium enthalpy fluid, as well as the level of research already implemented.

Greece along with Italy and Portugal is the only country in European Union in which there are fields of high enthalpy (areas in which fluids can be produced with temperatures greater than 150°C, which are used for the production of electric power. The geological conditions in Greece generally favored the creation of a very important geothermal low enthalpy potential. According to IGME (Institute of Geological and Mining Research), today's known geothermal energy reserves of low temperature amount to 200.000 tons of oil equivalent per year.

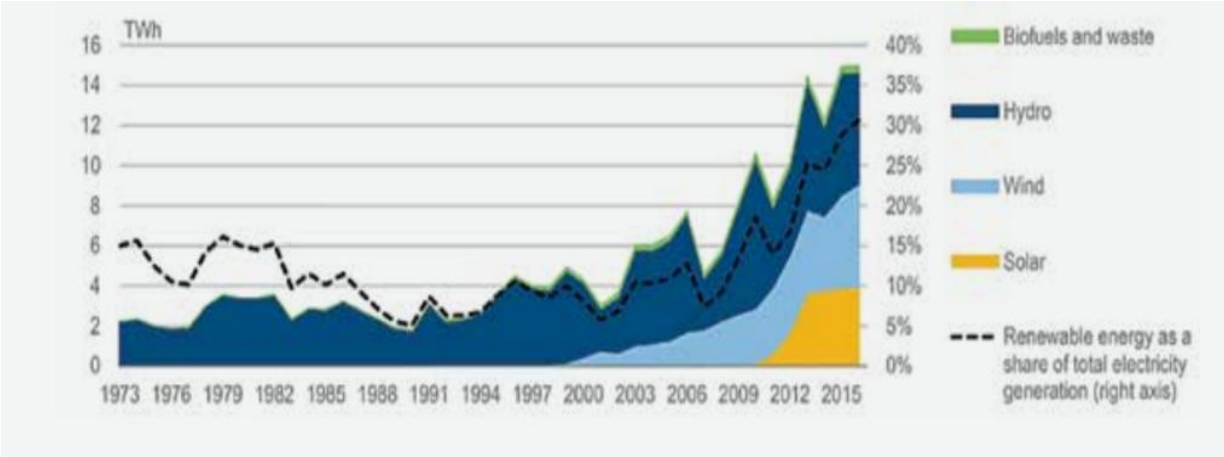



*Figure 3: Share of renewable sources to the total production in Greece [34]*

Based on information which is available in the annual reports of the Public Power Corporation (ADMIE), the methods of electricity generation can be categorized based on its emissions of $CO_2$, $SO_x$, $NO_x$ and PM in g/kWh. Lignite power plants are the most polluting with almost 1000 grams of $CO_2$ and 2.8 grams of $SO_x$ per generated kWh of electricity. In general, lignite and natural gas power plants in Greece are located far from populated cities and therefore there is a small percentage of the population that is directly affected by their emissions. What's more, there is a national plan in Greece for reduction of the share of the lignite in the production of electricity to 17% until 2030.

From the last data of production of electricity the following table results, where a comparison of emissions of energy generation and on board is made.

| Comparison of emissions between electricity generation and on board fuels | | | | | |
|---|---|---|---|---|---|
| **Type** | **Use** | **$CO_2$** | **$SO_x$** | **$NO_x$** | **PM** |
| | **(%)** | **gr/kWh** | | | |
| **Natural gas** | 33.96 | 584.8 | 0.02 | 0.3 | 0.03 |
| **Lignite** | 33.90 | 984.3 | 2.8 | 2.3 | 1.02 |
| **Hydro** | 10.06 | 0 | 0 | 0 | 0 |
| **Renewable sources** | 22.08 | 0 | 0 | 0 | 0 |
| **Total** | 100 | 532.3 | 0.96 | 0.88 | 0.36 |
| | | | | | |
| **On board (MGO/MDO)** | | 638 | 0.20 | 12.05 | 0.45 |

*Table 1: Hazardous substances comparison*

It is obvious that the current production of electricity is a greener option than on board combustion engines. If we take into consideration the rapid growth of the share of renewable sources, the plan for the radical reduction of the share of lignite and the last trends for electricity production, it is obvious that the future of electricity generation belongs to greener options with a tendency to zero emissions. This future is globally favorable for the retrofit of vessels into all-electric with zero emissions.

We finally have to examine the battery's life cycle and the energy consumption for its production. Lead acid batteries contain lead; NiCd batteries contain cadmium and NiMh batteries contain rare earth materials. All these substances are toxic and dangerous for the human and the environment. However, lithium batteries do not contain any poisonous heavy metals and very little rare earth materials. Their main environmental footprint derives from the energy used during their production process, but according to recent research on $CO_2$ emissions for a hybrid ship using 300kWh battery system, the system's operation benefits exceed the negative impacts from its production.

# 7 Methodology of ferries electrification

The philosophy of the retrofit is presented in this chapter as well as an analysis of the program Retrocalc that Mr. Michail made, which has been used in chapter 9 as a tool for the techno-economic analysis of the retrofit of different ferries covering small distances in Greek seas and a comparison between them.

## 7.1 Retrofit Philosophy

The most important part of the electrification process, after the topology design 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, its position above the weather deck as well as the fact that is already certified.

Different routes will be examined, depending on the operational data from the ship owner, the battery market, the port infrastructure, in order to understand the magnitude of each variable and calculation of the total cost will be estimated from the operator's side.

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. In this thesis, Retrocalc will be used.

## 7.2 Retrocalc presentation

Retrocalc is a computation program written in Visual Basic.NET and it was developed to satisfy the need for a powerful way to calculate the cost of retrofit conversion for a current vessel, using conventional propulsion systems. In addition, a report form is designed, through which the user can visualize the results of each analysis and compare different ships and scenarios. Its accuracy is proven as it was crosschecked with the results of Mr. Bakirtzoglou thesis.

### 7.2.1 Input Data

According to their nature, data is divided to the following sections:

The data related with the existing main engines and electrical generators are:

Main Engine:

- M/E Maker
- M/E Power and units
- M/E Number (total number, number of used engines)
- M/E Load Factor
- M/E Specific Fuel Oil Consumption and units
- M/E Efficiency

Generator Engine:

- G/E Maker
- G/E Power and units
- G/E Number (total number)
- System’s Voltage Magnitude
- G/E Specific Fuel Oil Consumption and units
- G/E Efficiency
- Generated Current’s Frequency

- El. Motor's Efficiency

The data used to describe the route of the vessel and its time variables are the following:

- Total Days of Operation in one year of operation
- Total Trips completed in one day of operation
- Load required during sailing
- Load required during birth
- Time spent in birth
- Sailing Time
- Diversity Factor

It should be noted, that the available time at birth is the main factor, which affects the results of the analysis.

As far as the batteries are concerned, the essential data for the calculations are:

- Maker of the Batteries
- Nominal Voltage of the Batteries
- Capacity of the Batteries, expressed in Ampere Hours
- Cost of the Batteries (can be entered by unit or by kWh)
- Battery's Dimensions and Weight
- Charging Current of the Batteries (recommended value)
- Number of Arrays, in which the batteries will be divided
- Years of Life for the batteries
- Charging Current, recommended for Maximum life
- Charging Time, nominal for full charge
- Depth of Discharge Allowed

Finally, data regarding the cost of installed equipment and other costs need to be inserted. These data are:

- Batteries initial cost
- Batteries Inverter
- Motor Drivers
- Electric Motors
- Used Price for the Main Engines
- Used Price for the Electric Generators
- Electricity Price and Growing Rate
- Fuel Price and Growing Rate

### 7.2.2 Calculation Procedure

After, the above data have been gathered the required calculations can be done, divided in the following sections:

- Battery number calculations

In this section, the number of batteries needed to replace the existing engines and cover the energy needs of the vessel is calculated. The program assumes the capability of the vessels to charge their batteries between each trip. As shown in the flowchart below, first of all the energy demand of the vessel for one trip is calculated.

One trip includes a two-way voyage between the starting port and the destination port according to the equations:

- 1 trip = 2 x voyages + 2 x Port stand-by
- Time per trip = $2 \times T_{CRUISING} + 2 \times T_{PORT}$.

After, the minimum installed energy is calculated, according to the available time for charging in each port. Then, the number of modules connected in series is calculated, so that the voltage will be the same with the desired one. The number of battery strings is calculated with respect to the systems desired amperage. The total number of batteries is calculated with a simple multiplication giving the desired result.

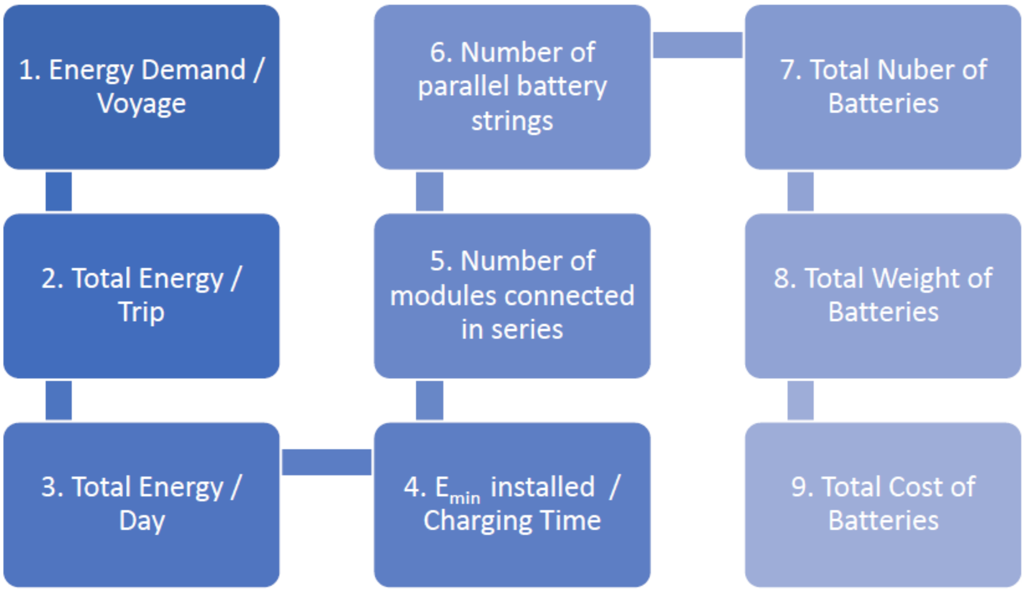



*Figure 1: Battery calculations of the program [29]*

- Operational and Maintenance costs calculations

The total cost for the installation of a complete battery system, including the electric motors, ac to dc converters etc. is calculated. Also, a cost benefit analysis takes place, concerning the years of investment.

First, the installation cost is calculated, which includes the cost of the batteries and the electrical components needed for propulsion, charging etc. Afterwards, a comparison is made between fuel and electricity cost for one year operation, as well as the cost for their maintenance. Finally, a comparison is made between the two systems in the period of one year and for multiple years, according to the flowchart.

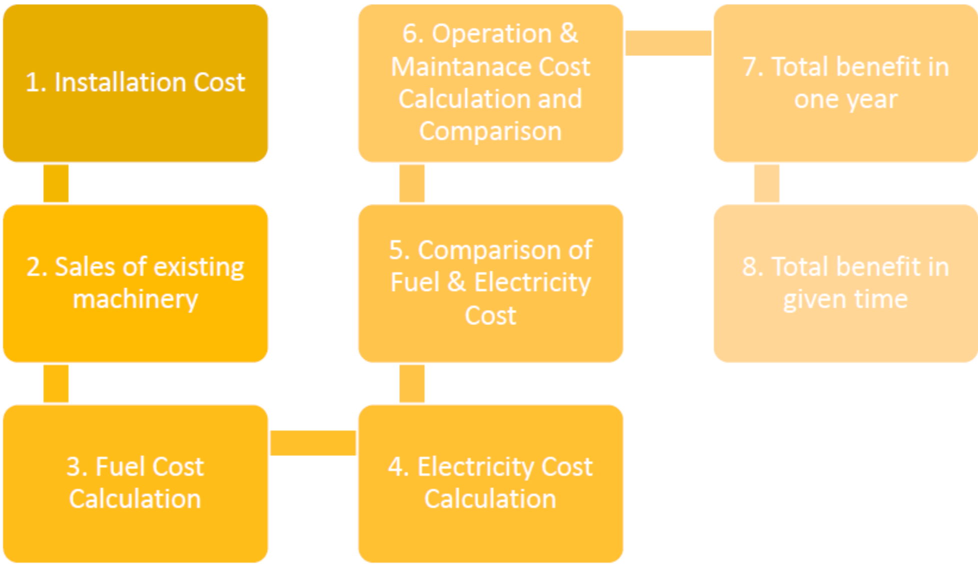



*Figure 2: Operational and maintenance calculations of the program*

- Emissions produced calculations

Finally, the total mass of emissions produced from the existing machinery is calculated and an approximate cost analysis is made. The quantification of the volume of emissions saved in the atmosphere because of vessel's retrofit is based on guidelines found on TIER III protocol which requires as input the individual consumption of main and auxiliary engines and estimates their emissions during each phase of the trip.

The amount of emissions produced by current machinery systems is great, and as described in the environmental study it is obligatory to reduce this amount for the sake of social health and environmental prosperity.

Firstly, the total fuel mass that is used in a period of one year is calculated. Secondly, the total mass of emissions is computed using the stoichiometry of marine diesel fuel, according to TIER III instructions. Given the above calculations and an emission-cost method it is possible to reach a result for the total cost benefit from the reduction of the emissions produced with the conventional propulsion systems.


*Figure 3: Emissions produced calculations of the program*

### 7.2.3 Output Data

Output data consists of the following report form (output comes from a comparison on the next chapter between 2 different types of ships):


*Figure 4: Output of the program*

Concerning the graphics section it consists of two graphs. In the first diagram the number of batteries according to time of charging available in port is presented (green curve). The total cost of batteries related with the charging time (white curve) is also presented. The time available in port is expressed in minutes and the cost of batteries in Euro (€) currency. The graph shows the effect of the charging time, to the total batteries needed, hence the initial cost of the installation.

The second graph shows the remaining energy (kWh) after failure of one array according to the available time for charging in the port (green curve). In addition, the minimum energy required in case of failure for the ship to safely return to a port is presented (red line). The graph shows the energy requirements of the vessel and the effect of the choice of arrays, thus the minimum required number of arrays and total energy in order to ensure safe return and an operational day.

Different scenarios-routes (vessels) can be displayed by switching the menu tool in the top part of the form.

In the comparison graph section, two graphs are presented. The first one (column graph) displays the total benefits next to the fuel benefits for each route. In the Y-axis the amount of money is displayed in Euro (€) currency and in the X-axis the name of each route.

The second graph displays the total benefits from each scenario, with respect to the charging time available in port. From these diagrams the user is able to compare the benefits of the calculated routes and the effect of available charging time on them. In fact, this chart combines all the individual charts displayed in the bottom left area.

At the bottom side of the form, the calculated values are displayed. These values correspond to each calculated route and are refreshed every time the user selects another route from the drop-down menu.
The Values Section is divided into 4 Sub-Sections:

- **Batteries related section**

These values of batteries are calculated:

- Total Number of Batteries
- Total Weight of Batteries

- Total Volume of Batteries
- Total Cost for the Batteries

- **Trip related section**

In this part, the charging time available in each port is displayed. As previously mentioned, the value of time is the most crucial value in this analysis, due to the methodology used. The amount of time can be changed manually so the other prices are changed vice versa.

- **Emissions related section**

The related values displayed are:

- Emissions Total Mass ( expressed in Metric Tons)
- Emissions Total Cost (€).

- **Benefits related section**

Here the main benefits, created by the use of batteries, are presented. These are:

- Benefits from not using fossil fuel
- Total benefit related to operational and maintenance costs
- Both of the Above Benefits Combined

The above benefits are calculated for the lifespan of the project. The total benefits until the last year of the study are shown.

# 8 Case Study of vessels covering small distances

In this chapter, an investigation of the vessels covering small distances in Greek seas will be made. A classification of the different vessels will be also made according to their technical characteristics and the routes that cover. For the routes that have been chosen our criterion is the distance, which has to be small, less than 2 hours the distance between the ports. For the vessels our only limitation is to have the typical design of a vessel and use conventional means of propulsion, which means 1 or 2 diesel engines merged with their propellers.

After the collection of all required data and the classification of routes and vessels, the program Retrocalc will be used and the output data will be examined in order to reach a conclusion if the retrofit of a vessel is possible and which is the most preferable of the examined routes to apply the retrofit. Eleven different routes will be studied. For each route one vessel is chosen for retrofit, and the program will be run for 11 different vessels.

For each ferry studied different input data was gathered by various sites, mainly from www.marinetraffic.com and www.maritime.ihs.com.

## 8.1 Classification of routes and vessels

An effort has been made to collect as many as possible routes in which electrification of the vessels could be possible. In chapter 4, a brief presentation of the range of technical characteristics in Greek coastline was made. In this chapter, specific routes and vessels will be chosen and examined.

The following tables present the routes that will be examined, their distance measured in nautical miles, an average time in which the existing vessels cover the distance and service speeds of the vessels covering these routes. In addition, a classification is made, in ascending order, of the distance and of the frequency of these routes.

| **Route** | **Distance in nautical miles (nm)** | **Cruising Time (min)** | **Time at berth (min)** |
|---|---|---|---|
| Rio-Antirrio | 1.5 | 15 | 10 |
| Spetses-Kosta | 1.5 | 20 | 15 |
| Perama- Salamina | 1.6 | 10 | 15 |
| Argostoli-Liksouri | 2.5 | 20 | 15 |
| Glyfa-Agiokampos | 3.5 | 35 | 25 |
| Thasos-Keramoti | 6 | 55 | 20 |
| Aidipsos-Arkitsa | 7 | 50 | 15 |
| Agia Marina-Stira | 7.2 | 45 | 20 |
| Kavala-Thasos | 12 | 100 | 20 |
| Kerkira-Igoumenitsa | 17 | 95 | 30 |
| Killini-Kefalonia | 18 | 90 | 30 |
| Zakinthos-Killini | 18 | 90 | 30 |

*Table 1: Classification according to distance in ascending order of routes*

| Route | Max trips per day | Number of ships | Number of passengers 2018 | Number of vehicles 2018 (1) |
|---|---|---|---|---|
| Rio-Antirio | 10 | 12 | 1,300,205 | 548,436 |
| Perama-Salamina | 9 | 19 | 6,745,727 | 3,440,330 |
| Aidipsos-Arkitsa | 8 | 2 | 364,045 | 111,240 |
| Agia Marina-Stira | 7 | 2 | 347,540 | 135,811 |
| Argostoli-Liksouri | 7 | 3 | 483,885 | 229,798 |
| Glifa-Agiokampos | 6 | 2 | 320,287 | 107,512 |
| Zakinthos-Kilini | 6 | 2 | 1,094,006 | 318,405 |
| Kilini-Kefalonia | 5 | 2 | 480,926 | 166,783 |
| Spetses-Kosta | 4 | 1 | 147,522 | 38,181 |
| Thasos-Keramoti | 4 | 5 | 1,785,401 | 526,189 |
| Kavala-Thasos | 3 | 2 | 177,565 | 37,061 |
| Kerkira-Igoumenitsa | 3 | 4 | 1,457,356 | 420,547 |

(1)Trucks, passenger cars and two-wheelers - tricycles

*Table 2: Classification of route frequency [30]*

Cruising time and time at port was found from marine traffic that has very precise times, for service speeds that correspond to the vessels studied. In many of these routes there are Ro-Ro ferries with 2 sterns and 4 engine rooms merged with propellers that need a smaller amount of time to cover the distance. In our case we will study ferries with traditional design that may require more time (E.g. for maneuvering time).

An additional time needs to be mentioned, connection time, which is the time required to connect and disconnect the batteries and it is estimated to be 4 minutes per voyage, same for all routes. If we remove the connection time from time at berth, all the remaining time can be used by the all-electric ferry in order to charge its batteries.

In order to calculate the max trips/day we added up the daily itineraries of the routes and divided with the number of vessels covering that distances. Routes that are covered by more than one ship but not too many at the same time, are the most preferable because alternate ships can share the itineraries while a satisfactory number of trips is made and thus a satisfactory deadening over time. The number of trips is the biggest possible as it is calculated on a demanding summer basis.

One assumption that has been made is that specific ships cover specific routes, which is not completely accurate because in some routes the same joint venture owns the ships and alternates the ships between different routes (e.g.  Killini-Kefalonia and Killini-Zakinthos). Load at sea and at port of Fior di levante, a sister ship of Mare di levante covering the above routes was calculated in Dimitrios Giahountis thesis [31] while others were calculated approximately.

The number of passengers and trucks are taken from the Hellenic Statistical Authority (ELSTAT) [30] and is an indicator for the retrofit procedure. Routes with a great number of passengers and ports with a significant amount of marine traffic are preferred.

For each route one ship is chosen with a regular design. The characteristics of each ship are presented in the following tables (service speed, principal dimensions, year built, power of machinery and generators, loads at sea and at port).

Power of main machinery and power generators was found from sea web (www.maritime.ihs.com). However, for some ships' generators no information was available so the power of generators was calculated according to the equation: $P_{G=} 1.2*(100 + 0.55*SHP^{0.7})$ [9], where SHP is the total shaft horsepower. By crosschecking this equation for the vessels, whose generators power is already known we ascertain that the equation gives satisfactory results for the ferries studied.

| **Route** | **Ship's name** | **$V_{SERVICE}$ (kn)** | **Principal dimensions (LxBxT)** | **Year Built** |
|---|---|---|---|---|
| Rio-Antirrio | Theologos Eleni | 9.8 | 71x15x2.5 | 2002 |
| Spetses-Kosta | Katerina Star | 6.5 | 44x12x1.8 | 2001 |
| Argostoli-Liksouri | Vasos k | 9.9 | 57x15x2.6 | 1997 |
| Glyfa-Agiokampos | Aggeorgios | 8.8 | 75x15x2.6 | 1977 |
| Thasos-Keramoti | Agios Athanasios | 8.9 | 51x12x2 | 1979 |
| Aidipsos-Arkitsa | Georgios K | 9.0 | 72X16X1.9 | 2018 |
| Agia Marina-Stira | Apostolis T | 10.3 | 76x17x2.4 | 2009 |
| Kavala-Thasos | Agios Panteleimon | 10.3 | 57x14x2.3 | 1999 |
| Kerkira-Igoumenitsa | Kerkyra Expess | 15.4 | 77x15x3.8 | 1991 |
| Killini-Kefalonia | Kefalonia | 19.5 | 121x17x5.5 | 1975 |
| Zakinthos-Killini | Mare di levante | 14.7 | 120x21x4.5 | 1984 |

*Table 3: Choice of vessels studied with their basic characteristics*

| Ship's name | Machinery (hp) | Generators (kW) (1) | Load at sea (kW) | Load at port (kW) |
|---|---|---|---|---|
| Theologos Eleni | 1x 1800 | 3x220 | 121 | 107 |
| Katerina Star | 2x 340 | 3x170 | 48 | 43 |
| Vasos k | 1x 820 | 3x180 | 55 | 49 |
| Aggeorgios | 2x208 | 3x160 | 28 | 25 |
| Agios Athanasios | 2x420 | 3x180 | 56 | 50 |
| Georgios K | 2x600 | 3x200 | 81 | 71 |
| Apostolis T | 2x1521 | 3x270 | 204 | 181 |
| Agios Panteleimon | 2x305 | 3x170 | 41 | 36 |
| Kerkyra Expess | 2x2000 | 3x300 | 268 | 237 |
| Kefalonia | 2x6890 | 3x540 | 925 | 818 |
| Mare di levante | 2x4500 | 3x510 | 604 | 534 |

(1) $P_G = 1.2*(100 + 0.55*SHP^{0.7})$ [9]

*Table 4: Mechanical characteristics of the vessels studied*

## 8.2 Input variants analysis

Most of the data gathered above is used as input in the program. The other input data of the program is considered to have small or no differences between them and is presented below:

- **Machinery**

| | |
|---|---|
| **Main engine's variables** | |
| Load factor | 0.9 |
| Efficiency | 0.55 |
| SFOC according to TIER –II protocol (g/kWh) | 203 |
| **Electric generator's variables** | |
| Efficiency | 0.9 |
| Electric motors efficiency | 0.98 |
| System's voltage (V) | 1000 |

*Table 5: Common machinery variables*

The 20 kV, 50 Hz utility grid is transformed into suitable low voltage for the shore connection up to 1kV. Because of the double bus-bar system's installation on-board, explained on chapter 5, it is not required to transform the connection voltage to the exact vessel's system's voltage in terms of V, Hz, e.g. 440V, 60Hz in our case.

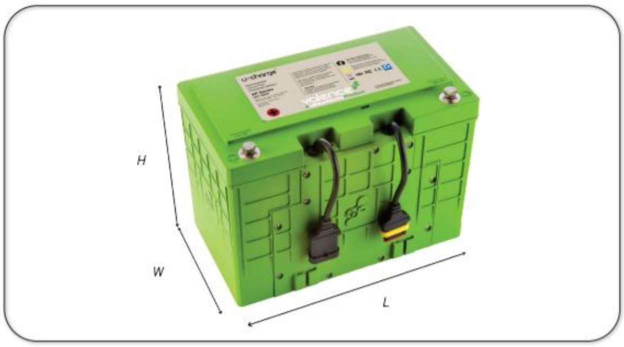
- **Batteries Specs**

The system with the 2 packs generally leads to slightly less required capacity for the same number of charges (or charging intervals) and consequently to lower volume, weight and price. However, in some cases the remaining energy is lower than the minimum required energy that's why a most reliable configuration will be chosen, that with 4 arrays.

In our study we will electrify the vessels using 2 different types of batteries, which are included in Retrocalc, the characteristics of whom are presented below:

- U27-36XP (Group 27, 36 Volt 50 Ah Lithium Ion Battery Module)

The U27-36XP is a high-performance, 36 volt battery, built on a lithium iron phosphate chemistry platform providing a safe, reliable and mobile energy solution. Its cost is 1153.3 €/battery approximately.




**Electrical Specifications**

| | |
|---|---|
| Voltage (nominal) | 38.4 V |
| Capacity @ C/5, 25 °C (typical) | 50 Ah |
| Energy | 1.92 kWh |
| Discharge Cont./Peak (30 sec) | 100 A / 150 A |
| Discharge Cutoff Voltage | 30 V |
| Recommended Charge Voltage | 43.8 V |
| Charge Float Voltage Range | 41.4 - 43.8 V |
| Recommended Charge CCCV | ≤ 25 A to 43.8 V |

| | |
|---|---|
| Discharge Temperature | -10 °C to 50 °C |
| Charge Temperature | 0 °C to 45 °C |
| Self Discharge @ 25 °C | < 2% per month |
| Specific Energy | 102 Wh/kg |
| Energy Density | 162 Wh/l |

**Mechanical Specifications**

| | | |
|---|---|---|
| Height (excluding bolts) | 225 mm | 8.86" |
| Width | 172 mm | 6.77" |
| Length | 306 mm | 12.0" |
| Weight | 18.7 ± 0.1 kg | 41.1 lbs |
| Cell Configuration | 12IFpR19/66-33 | |

| | | |
|---|---|---|
| Terminal Hardware | M8 x 1.25 | |
| Terminal Torque | 16 Nm | 142 in-lbs |
| Plastic Case | Flame Retardant | |
| IP Rating | IP56 | |

*Figure 1: Mechanical and Electrical specifications of U27-36XP battery (www.lithiumwerks.com)*

- U27-12XP

| | Product | Voltage | Capacity | Weight | Dimensions L x W x H | BCI Group Number | Max. Cont. Current | Charge Voltage | Energy |
|---|---|---|---|---|---|---|---|---|---|
|  | U1-12XP | 12 V | 45 Ah | 6.4 kg/ 14.1 lbs | 7.76" x 5.12" x 7.17" 197mm x 131mm x 182mm | U1R | 90 A | 14.6 V | 576 Wh |
|  | U24-12XP | 12 V | 118 Ah | 16.3 kg/ 35.8 lbs | 10.2" x 6.77" x 8.86" 260mm x 172mm x 225 mm | Group 24 | 150 A | 14.6 V | 1510 Wh |
|  | U27-12XP | 12 V | 144 Ah | 19.2 kg/ 42.2 lbs | 12.0" x 6.77" x 8.86" 306mm x 172mm x 225 mm | Group 27 | 150 A | 14.6 V | 1843 Wh |

*Figure 2: Characteristics of U27-12XP battery (www.lithiumwerks.com)*

- **Trip info**

Route and time variables of the trip are different for every vessel. The only assumption that will be the same for every ferry is that they operate 360 days per year with a diversity factor of 0.9 (90% diversity means that the device operates at its nominal or maximum load level 90% of the time that it is connected and turned on). Connection time (time to plug in-off) is 4 minutes for every voyage.

- **Costs**

Assuming the sale of the existing machinery and installing all the required equipment, an estimation of the prices in euro currency per kilowatt is shown on the following table.

| **Profit from selling existing machinery** | **Price (€/kW)** |
|---|---|
| Main engine after sale price | 40 |
| Generators after sale price | 35 |
| **Installation cost** | |
| Inverter price | 200 |
| Motor driver price | 250 |
| Electric motor price | 60 |

*Table 6: Vessel's retrofit costs*

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

Growing rates of fuel and electricity are taken 3.5 and 1% respectively. Price of electricity is taken as the average of the day and night-weekend charges of PPC (Greek Public Power Corporation) for industrial purposes and this is 0.0576 €/kW. As fuel cost we will take the average of the price of marine diesel oil (MDO) in Piraeus the last months, that is 585 €/ton. However, this price can be significant bigger as the routes studied are more or less distant from Piraeus.

## 8.3 Results and evaluation of each case

### 8.3.1 Case study Rio-Antirio

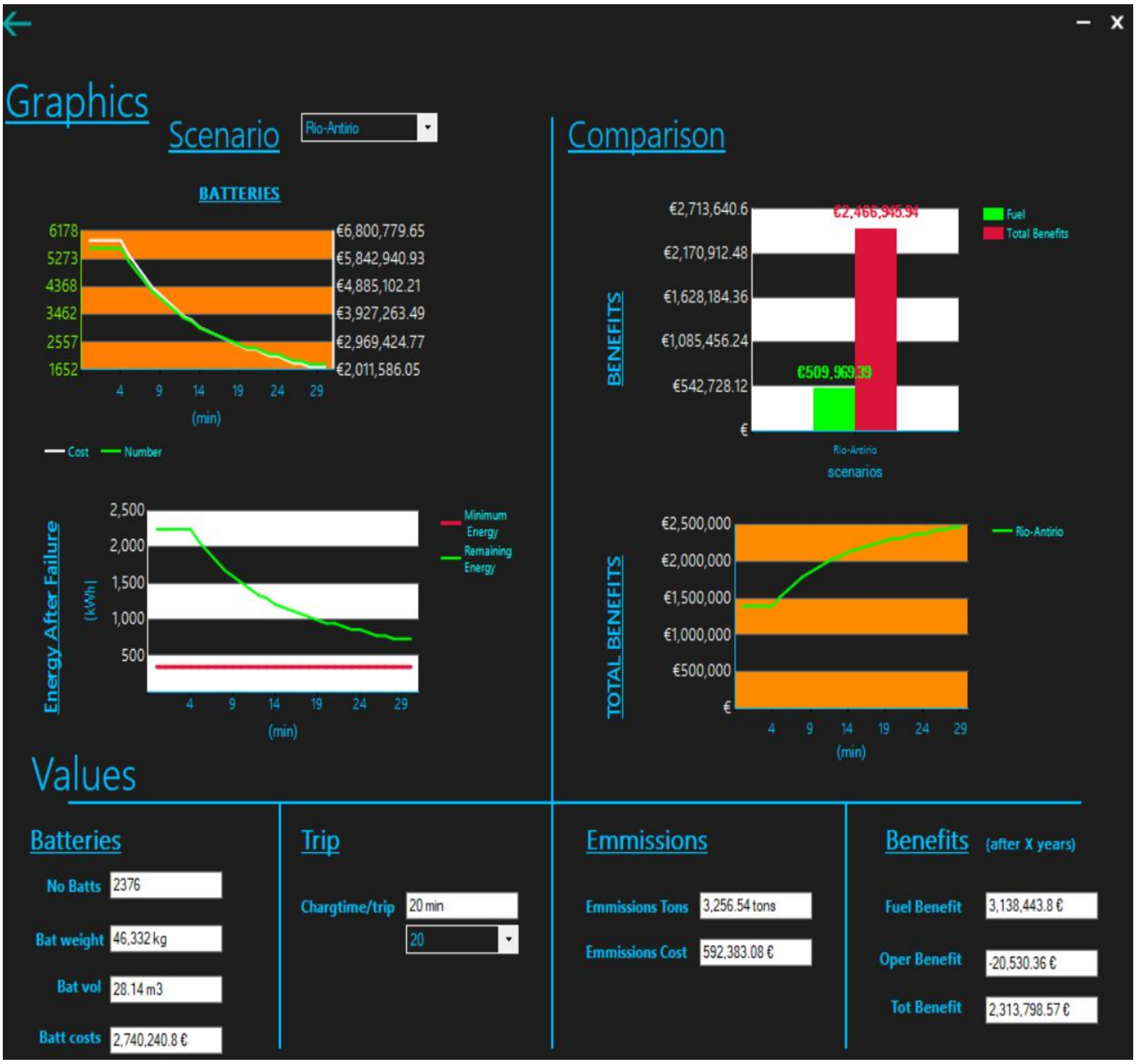



*Figure 3: Rio-Antirio scenario results*

In this case the small available time in port (10 minutes) in combination with the big engine that the selected ferry has, makes the necessity of a large number of batteries (2376). If the ferry had more time in port then a smaller number of batteries could be needed (1652) and the cost would be much smaller, as the total benefits would be. Another Ro-Ro ferry with 4 smaller engines-propellers could be a better investment for retrofit in comparison with the traditional ferry with one high power engine.

## 8.3.2 Case study Spetses-Kosta


*Figure 4: Spetses-Kosta scenario results*

In this case if the ferry had the opportunity to charge some more minutes in its 2-way voyage (32 minutes) then the number of batteries and the initial cost would be remarkably reduced. In small routes, like this one, a configuration with 2 arrays could be also examined for even less batteries. A factor that affects the total benefit is the small number of trips per day due to small movement of passengers and vehicles (In Spetses vehicles are forbidden).

### 8.3.3 Case Study Argostoli-Liksouri

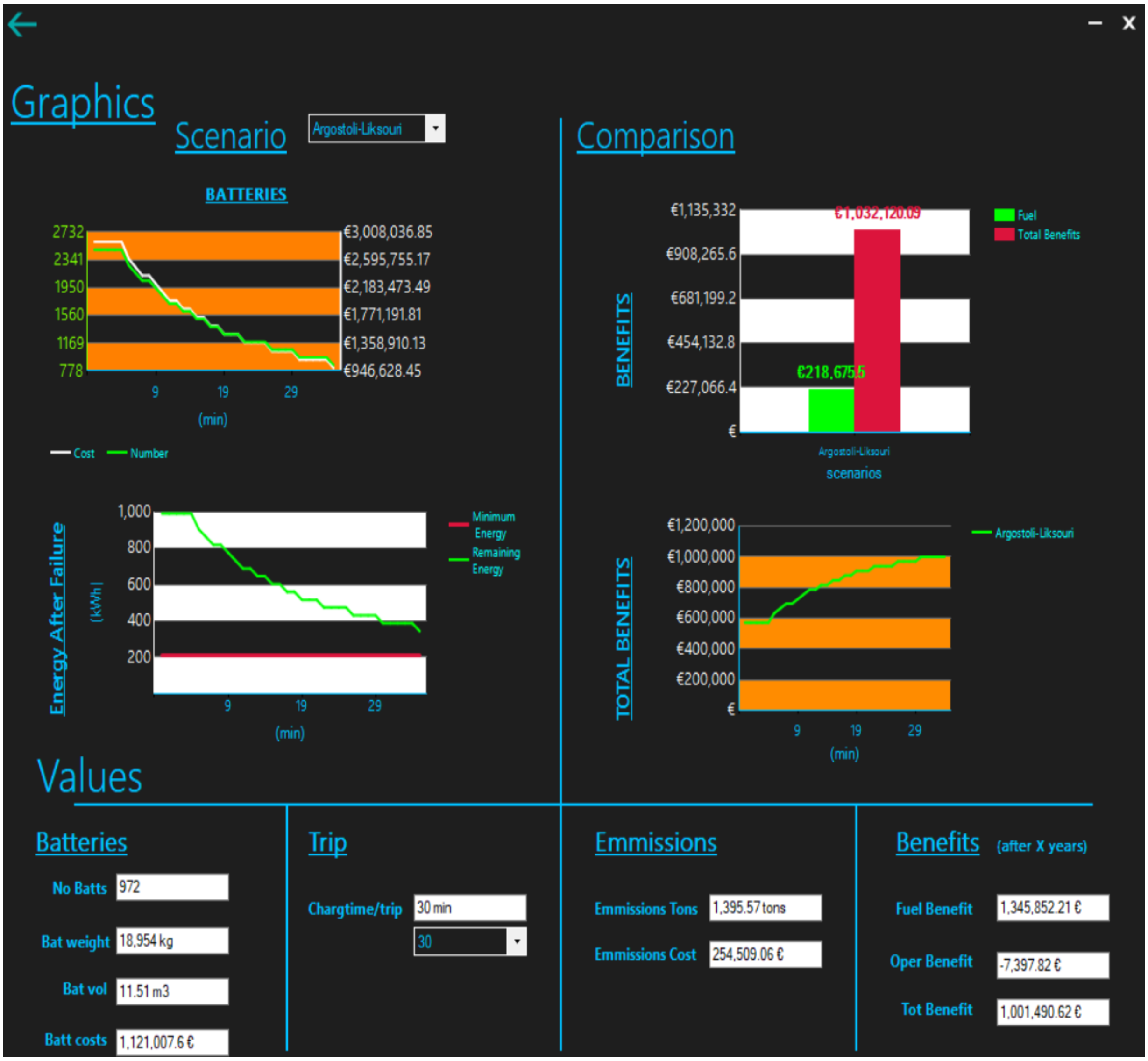



*Figure 5: Argostoli-Lixouri scenario results*

A small route that is more economically beneficial than the previous ones. Again some more minutes of available time at port could reduce batteries and thus cost, but in a smaller scale.

## 8.3.4 Case study Glyfa-Agiokampos


*Figure 6: Glyfa-Agiokampos scenario results*

In this case the luxury of greater available time of the vessel in port does not make the need of a large number of batteries. With the small engines the fuel benefits are not so important; however from an economical view the retrofit investment could be more feasible. Especially, if the ship could do more trips per day then the benefits would be bigger.

### 8.3.5 Case study Thasos-Keramoti


*Figure 7: Thasos-Keramoti scenario results*

Large cruising time and low service speed makes the need of a great number of batteries. In addition, there are a lot of vessels in this route and the small number of trips per day (4) makes the investment impractical. The retrofit of a double-ended ferry could be also examined.

## 8.3.6 Case study Aidipsos-Arkitsa


*Figure 8: Aidipsos-Arkitsa scenario results*

In this case there are a lot of trips per day and engines of higher power, so the fuel benefits are significant. As a drawback is the lack of available time in port for charging, as generally speaking, routes of high marine traffic have less available time for charging.

## 8.3.7 Case study Agia Marina-Stira


*Figure : Agia Marina-Stira scenario results*

The retrofit of that route's ferry is economical feasible with these data, however a drawback is the high power engines, that makes the need of a great number of batteries in order to replace them with total coverage. A vessel with smaller engines could cover the same distance and could be examined.

## 8.3.8 Case study Kavala-Thasos


*Figure 10: Kavala-Thasos scenario results*

This route has not high marine traffic and as a consequence no more than 3 trips per day can be made. This fact, in combination with the large cruising time makes the retrofit of the existing vessel impractical.

## 8.3.9 Case study Kerkira-Igoumenitsa


*Figure 11: Kerkira-Igoumenitsa scenario results*

The great number of ships covering this route doesn’t allow the ship to make more than 3 trips per day and the large cruising time makes the retrofit impractical.

## 8.3.10 Case study Zakinthos-Kilini


*Figure 12: Zakinthos-Kilini scenario results*

Big vessel chosen with medium power engines and great time available at port makes the circumstances ideal from the economic view of retrofit concerning the total benefits. An array with 6 or 8 batteries could be examined for greater safety.

However, the large numbers of batteries needed, creates a doubt if the space in the vessel's machinery room is big enough to be equipped with such a great number of batteries. After examination of Mr. Mertikas thesis, who has studied a ferry of similar technical characteristics, we conclude that the battery space needed is not prohibitive, as from the battery rooms' energy and dimensional information [32] a total space of 2 x 273.6 = 547.2m$^3$ is available (273.6 m$^3$ each battery room) and covers sufficiently the space needed (321.02m$^3$). A satisfactory space stays void, allowing the crew to complete the maintenance and supervision tasks.

**BATTERY ROOMS ENERGY AND DIMENSIONAL INFORMATION**

| Battery Room tag | Abbreviations | Embedded estim. energy | Preliminary Dimensions (LxBxH) |
|---|---|---|---|
| Battery Room No.1 serving Port side | BR1 | 4,000 kWh | 22,500 mmx3,200mmx3,800mm |
| Battery Room No.2 serving Starboard Side | BR2 | 4,000 kWh | 22,500 mmx3,200mmx3,800mm |

*Table 7: Battery rooms energy and dimensional information [32]*

### 8.3.11 Case study Kilini-Kefalonia


*Figure 12: Kilini-Kefalonia scenario results*

In this case, an even bigger vessel than the previous one is examined, with very high service speed and horsepower engines. The great number of batteries needed and the high initial cost make the retrofit impractical; however the battery space needed is not prohibitive. Surely, between the 2 ships of Kilini the first one would be more preferable, despite the higher total benefits of the second one.

## 8.4 Techno-economic comparison of the different routes

Concerning batteries cost and total benefits the vessels of each route that has been studied are classified in the following table in ascending order (related to batteries number and cost). The meaning of minus in difference means that the investment is unprofitable.

| **Route** | **Number of batteries** | **Batteries volume ($m^3$)** | **Cost of retrofit (€)** | **Total benefit after 7 years (€)** | **Difference (€)** |
|---|---|---|---|---|---|
| Glyfa-Agiokampos | 648 | 7.67 | 747.338 | 802.117 | 54.779 |
| Spetses-Kosta | 756 | 8.95 | 871.894 | 368.757 | -503.137 |
| Argostoli-Liksouri | 972 | 11.51 | 1.121.007 | 1.001.490 | -119.517 |
| Thasos-Keramoti | 1944 | 23.02 | 2.242.015 | 1.459.178 | -782.837 |
| Kavala-Thasos | 2268 | 26.86 | 2.615.684 | 1.331.285 | -1.284.399 |
| Rio-Antirio | 2376 | 28.14 | 2.740.240 | 2.313.798 | -426.442 |
| Aidipsos-Arkitsa | 3564 | 42.21 | 4.110.361 | 4.259.768 | 149.407 |
| Agia Marina-Stira | 6480 | 76.74 | 7.473.384 | 8.791.865 | 1.318.481 |
| Kerkira-Igoumenitsa | 11340 | 134.29 | 13.078.422 | 9.364.958 | -3.713.464 |
| Zakinthos-Kilini | 27108 | 321.02 | 31.263.656 | 46.761.644 | 15.497.988 |
| Kilini-Kefalonia | 40392 | 478.33 | 46.584.093 | 57.827.104 | 11.243.011 |

*Table 8: Number of batteries and cost of retrofit in ascending order*

From the economic results of the above table the deadening of a possible retrofit of vessels serving these routes is presented on a table. Surely, it is an indicator for the best choice of vessel for retrofit (from the bottom of the table to the top). Economic help from external factors and financial help from organizations are needed in most of cases. However in each case there are difficulties, some of which have been presented above, and make the investment impractical. Further analysis is provided below, where a comparison between the routes and an identification of the factors that have economic impacts on the procedure of retrofit are presented.

| **Deadening of routes in ascending order** |
|---|
| Kerkira-Igoumenitsa |
| Kavala-Thasos |
| Thasos-Keramoti |
| Spetses-Kosta |
| Rio-Antirio |
| Argostoli-Liksouri |
| Glyfa-Agiokampos |
| Aidipsos-Arkitsa |
| Agia Marina-Stira |
| Kilini-Kefalonia |
| Zakinthos- Kilini |

*Table 9: Deadening of routes in ascending order*

The comparison of routes with similar characteristics is presented on the following figures. The first figure shows the comparison of 4 ferries with similar available time for recharge at port (10-15 minutes per voyage), the second the comparison of 3 ferries with similar horsepower (400-600-800hp), the third 2 ferries of similar total benefit and the fourth two ships of bigger horsepower and scale of benefits and initial cost of a greater scale in comparison with the others.

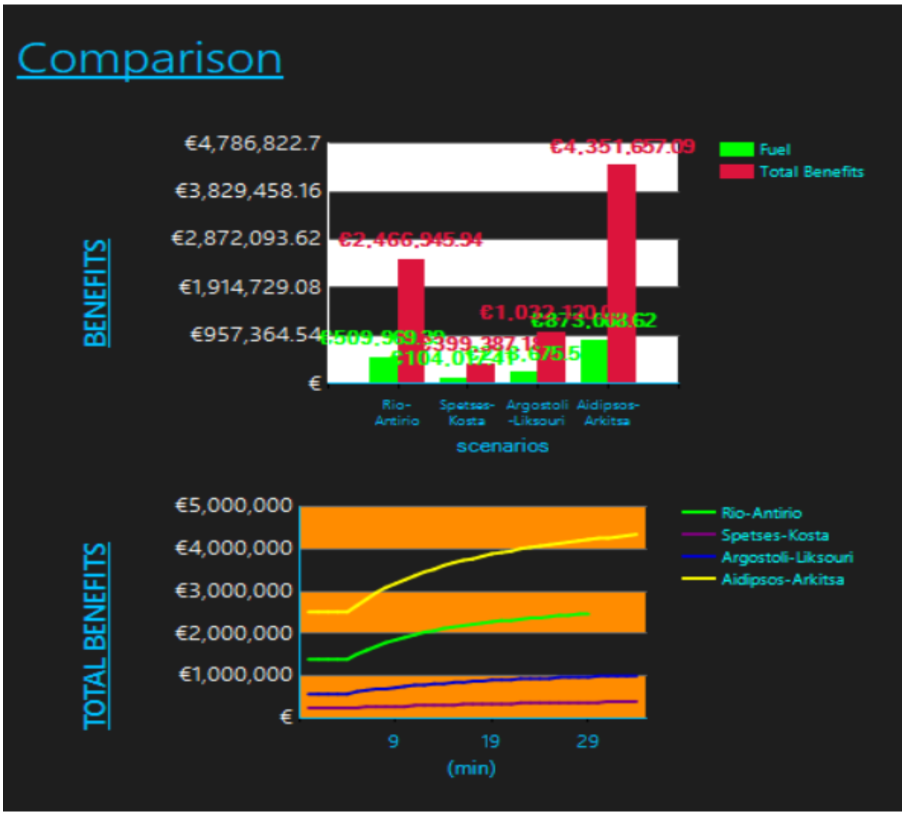



*Figure 13: Quality comparison of vessels of similar available time at port*


*Figure 14: Comparison of vessels of similar horsepower*


*Figure 15: Comparison of vessels of similar total benefit*

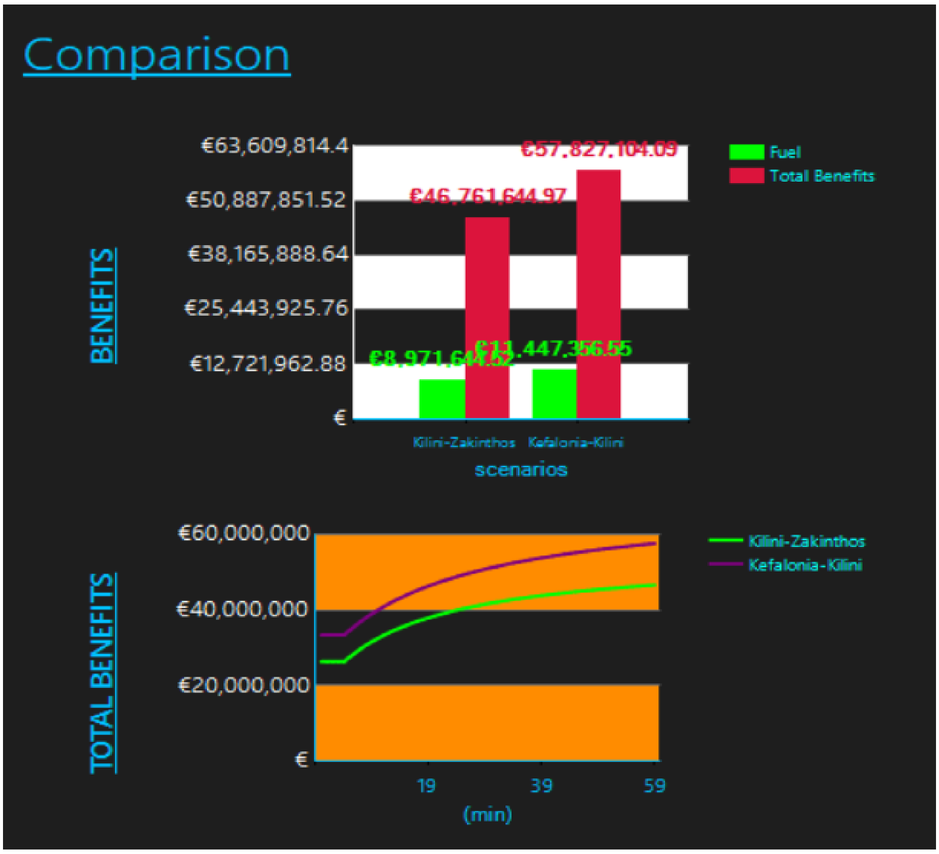



*Figure 16: Comparison of vessels of high initial cost and benefit*

From this comparison and these diagrams of vessels with different technical and economical characteristics we reach the following conclusions:

For the same time of charging and higher power installed engines:

- The benefits from fuel saving are Higher
- The operational benefits are higher
- The total benefits are higher
- On the other hand, more batteries are needed and a higher initial cost is created.

The number of trips per day plays an important role as we can see from the third diagram. Ships that make more trips per day, like the route Agia Marina-Stira, have more total benefits than the ones that make less trips, like route Kerkira-Igoumenitsa, even if there are higher power installed engines and thus fuel profits and more available time for recharge at the second route.

More available time at port means more total benefits, a fact that applies for every vessel, while more cruising time means higher energy requirements and greater prices of minimum required energy after failure and as a consequence  more batteries. For example, in the case of Kavala-Thasos, where a vessel with lower total power is examined in comparison with that of Thasos-Keramoti, more batteries are required as the crusing time is much bigger.

Big passenger ships with high loads at seas and at ports, like the ones at Kilini, may have great total benefits, however the initial cost of batteries is huge and the number of batteries required great. For that reason, the space that is needed for so many batteries for the vessel in Kefalonia makes impractical such an investment, while the one at Zakinthos with lower power engines and loads could be feasible.

Concerning arrays of batteries the configuration of 4 arrays is ideal, as in most cases with 2 arrays the remaining energy after failure is not sufficient. On the bigger trips and bigger ships, a configuration with 6 or even 8 arrays may be preferable for security reasons. It has to be mentioned also that in every case the remaining energy is bigger than the minimum required for the ship to return to the port in case of damage, as shown on the figures of each case.

Total installed capacity decreases as the number of charges per shift increases. Though, there is a lower limit of total installed energy as imposed by the safety criteria which limits the minimum amount of batteries that should be installed.

Small trips, medium engines and loads and a satisfactory available time at port and number of trips are the most appropriate combination for such an investment.

All these facts are ascertained by the following comparisons.

## 8.5 Optimization of economical results

From the evaluation of each route above we understand that there are a lot of factors that affect the retrofit procedure. In order to optimize the economical results a comparison between some of the previous ships with some others that cover the same routes and may have more favorably characteristics or some different scenarios for the same ships will be made in order to conclude which scenario is preferable.

### 8.5.1 Comparison in Rio-Antirio

In this route we will choose a Ro-Ro ferry with 4 main engines merged with 4 propellers to compare it with the 1 engine ferry, which has been studied before. The ferry Panagiotis D has been chosen, the characteristics of which are presented in the following table in comparison with the previous selected ferry:

| **Name** | **No. of engines (used)** | **Power (hp)** | **LxBxT (m)** | **$V_{service}$ (kn)** | **Generators (kW)** | **Load at sea/ at port (kW)** |
|---|---|---|---|---|---|---|
| Panagiotis D | 4 (2) | 4x600 | 92x18x2.5 | 11.1 | 2x500 | 90/70 |
| Theologos Eleni | 1 (1) | 1x1800 | 71x15x2.5 | 9.8 | 3x220 | 121/107 |

*Table 10: The two different types of ferries serving Rio-Antirio*


*Figure 17: Double-ended ferry Panagiotis D [38]*

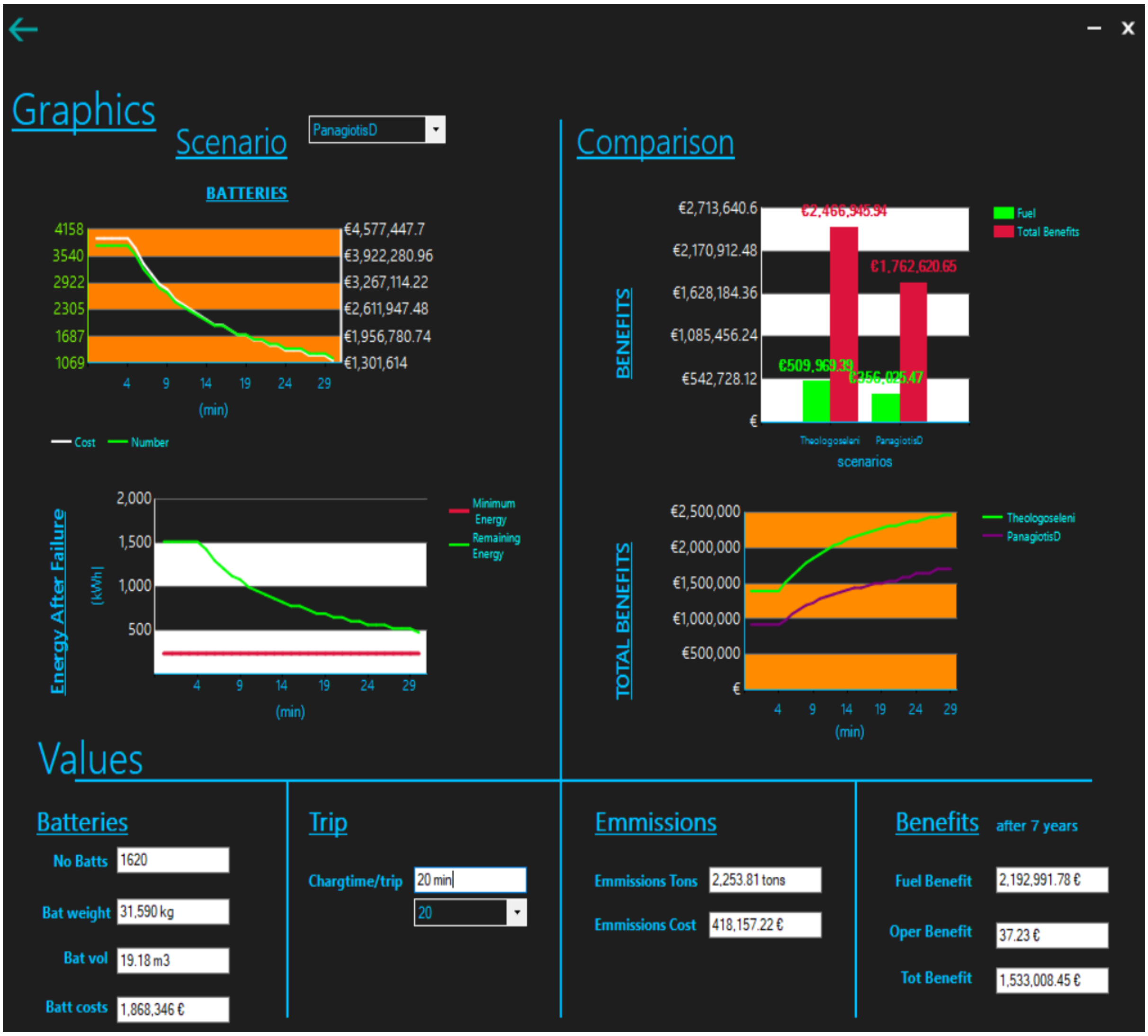



*Figure 18: Comparison between the traditional and the double-ended ferry*

From the comparison above we see that the retrofit of such a vessel has lower initial cost, as the batteries needed are less (1620 to 2376) and so is the space and the weight. However, fuel and total benefits are less as the traditional ferry uses higher power engines. As we understand, the small time in the port is an obstacle we cannot avoid. From an economic view, though, we would choose the double-ended ferry Panagiotis D as the lower initial cost surpasses the less favorable benefits from fuel consumption.

### 8.5.2 Comparison in Thasos-Keramoti

With the same philosophy as before, we will pick one suitable double-ended Ro-Ro ferry with 4 engines-propellers and compare it with the existing one. In the next table the characteristics of the 2 ferries are presented. An advantage of the ferry chosen is that in a distance of 6nm of Thasos-Keramoti the difference in service speed and the lack of need of maneuvers between the ships, could lead the double-ended one to reach its destination in 10 minutes less.

| **Name** | **No. of engines (used)** | **Power (hp)** | **LxBxT (m)** | **$V_{service}$ (kn)** | **Generators (kW)** | **Load at sea/ at port (kW)** |
|---|---|---|---|---|---|---|
| Anax | 4 (2) | 4x760 | 100x20x2.2 | 10.1 | 2x500 | 90/70 |
| Agios Athanasios | 2 (2) | 2x420 | 51x12x2 | 8.5 | 3x180 | 56/50 |

*Table 11: Two different types of ferries serving Thasos-Keramoti*


*Figure 19: Double-ended ferry Anax [38]*

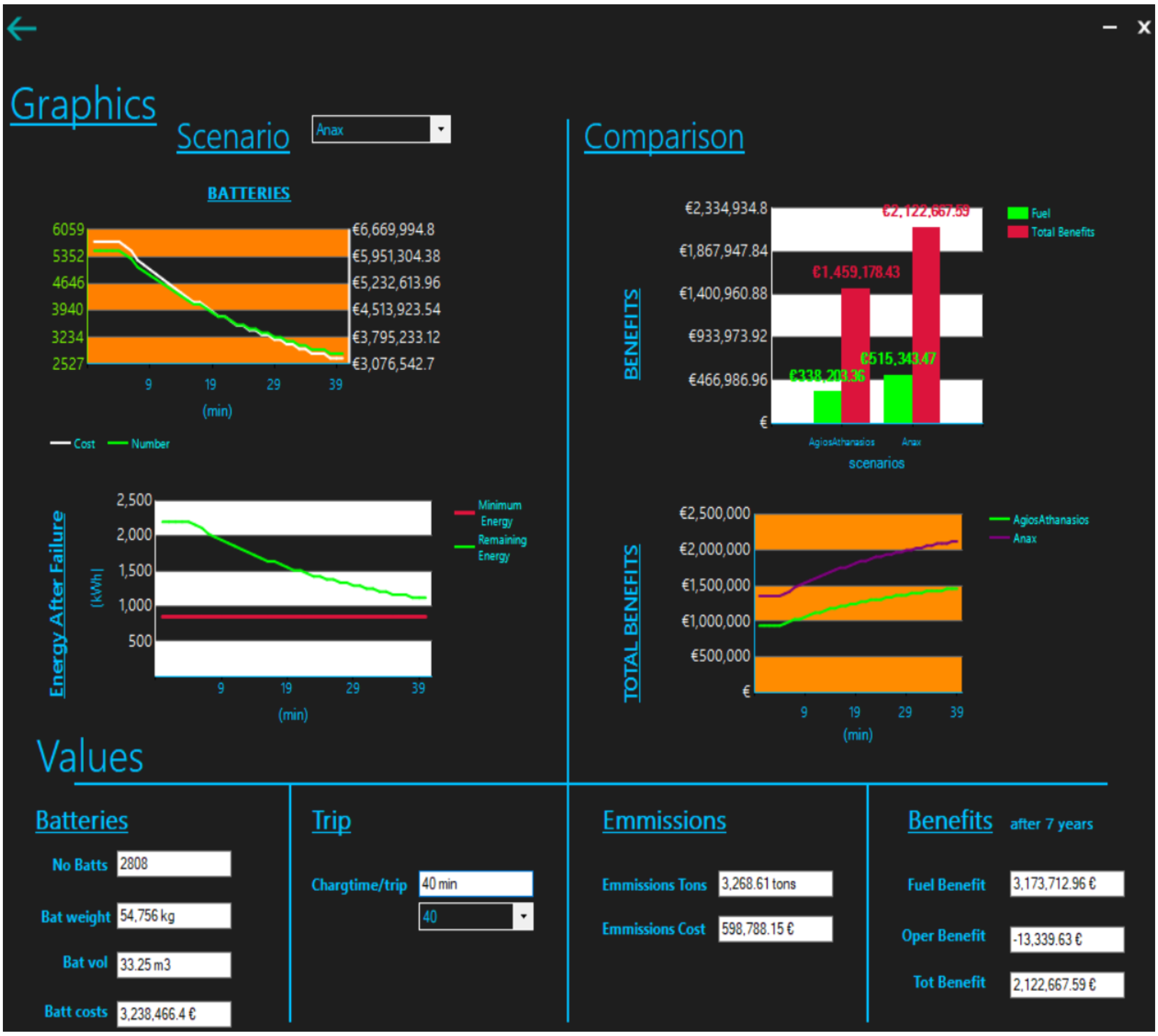



*Figure 20: Comparison between the traditional and double-ended ferry*

As we see there is a greater need of batteries (2808 to 1944) in the double-ended ferry, and not a remarkable total benefit difference, so we conclude that the double-ended ferry is not a solution and the traditional one would be more preferable to be retrofitted in this case.

### 8.5.3 Comparison in Spetses-Kosta

A comparison of the same ship with 2 and 4 arrays is made.


*Figure 21: Comparison between 2 and 4 arrays of batteries*

From the comparison above we understand that with 2 arrays the batteries needed are less (702 to 756), however for half an hour charge the remaining energy does not reach the required levels of minimum energy and that is the first reason why such a configuration cannot be applied. From the view of profits, there is a small difference translated in € with the configuration of 4 arrays as we see on the total benefits diagram.

## 8.5.4 Comparison in Agia Marina-Stira

As the distance is not so big, we will examine a ship of similar characteristics but with smaller engines (2 of 741HP each) named Michalakis3. The results are presented below.


*Figure 22: Comparison between 2 ferries serving the same route*

As the total power reduces the batteries (from 6480 to 3132) and thus the initial cost is reduced. However, the total benefits are less in comparison with the ferry examined before Apostolis T. In the period of 7 years it is more preferable to retrofit Apostolis T, the ferry with higher power engine. However, the high initial cost of batteries in the case of ships with higher power engines could make us choose vessels with lower energy requirements, like Michalakis3. The deadening is not the same as to vessels of higher energy requirements, but still has a significant price.

## 8.5.5 Comparison in Zakinthos-Kilini

This comparison will be made mainly for security reasons, as in routes of large distances, like this one, arrays of 6 or 8 batteries may be preferable.


*Figure 23: Comparison between 4 and 8 arrays of batteries*

As we see the difference between 4 and 8 arrays is 108 batteries and 1.28m$^3$ volume of batteries, while the benefits are slightly less (30.000 € in 7 years). In a retrofit of such a big vessel and this scale of investment this difference has no impact on the investor on money, but it has on the ship as it increases its safety.

# 9 Conclusion and recommendations

All-electric ships are a project that has been tested in some countries, like Norway, and showed that can be profitable. Greece should converge to the electric propulsion and should use the power generation from renewable resources of energy.

Electrification of vessels is a well known procedure with sufficient know-how that is adopted by more ship-owners, as it showed from the experience that it can be cost-beneficial. This was also confirmed in this thesis for some ferries serving specific routes. Variables that affect the economic results are many, but there are also many cases where a satisfactory deadening over time and a profitable investment are possible.

Concerning economic sector, globally there are a lot of programs that support financially and encourage electrification projects. Such a program is in Norway called 'green coastal program', where Norway has committed itself to reducing greenhouse gas emissions by 40 percent by 2030. Taxes should be reduced for these ships and governments should approve such projects and motivate municipalities for the ports infrastructure.

Besides the economic sector electrification of vessels has massive advantages in the environmental sector, where the emissions are minimum or even zero, in case electricity is produced with renewable sources, like wind, sun and water. In some years the strict enforcements in combination with the lack and high prices of fossil fuels will make the need of finding alternate solutions and an all-electric ferry is a good start. The emissions avoided will have a massive improvement on social health and environment preservation, which day by day is getting worse with fossil fuels. This improvement is translated also in money with externality costs.

Concerning legislation there are classification societies and authorities that have issued regulations and guidelines, however the legislation framework can and will be improved, as more electric-ships are retrofitted and build.

Being at the beginning of a power revolution makes it capable to reduce rapidly the cost of batteries. The batteries cost has already declined to one third of the price they had before 2 years. Other technologies of batteries besides the one studied in this thesis could be also examined, as in future sophisticated batteries chemistries are about to appear.

From this thesis, it was ascertained that the retrofit under circumstances is a profitable investment. Whether the conversion project is economic feasible or not, depends on many variants, as shown in the last chapter of this thesis. More specifically, the most important parameter is time available for charging at port. Routes like Rio-Antirio with small available time for charging must be avoided for retrofit as the cost of required batteries is high compared to total benefits. In routes like this the small available time at port is an obstacle that cannot make the retrofit feasible, even for small double-ended ferries.

As available time increases, then the total installed capacity decreases and so does the batteries and in that way the initial cost is minimized. However, there is a lower limit of total installed capacity that is imposed from safety criteria.

Concerning total benefits, those are maximized for higher power engines as the fuel profit plays an important role, as shown in the analysis of the results. However, higher power engines lead to higher energy requirements and thus to higher initial cost and that is why a good start could be the retrofit of routes covered by vessels of small power, where marine traffic allows a satisfactory available time for recharging. That route could be Glyfa-Agiokampos. For a larger scale investment of high initial cost but with the perspective of high total benefits and quick deadening in the future, the ideal route for the conversion project is Zakinthos-Kilini.

Concerning batteries, in this thesis it was proven that 2 arrays of batteries must be avoided as the energy requirements are not covered in most cases. On the other hand, it was proven that arrays with 4 batteries are the ideal for smaller ferries and for bigger ones, like Mare di Levante, 6 or 8 independent arrays could be also examined.

More cruising time means higher energy requirements and thus more batteries and this could be prohibitive for our project e.g. route of Kavala-Thasos. On the contrary, it is desirable for the ferry to make enough trips per day so the retrofit could be feasible. That is why routes of high marine traffic served by less ferries e.g. route of Zakinthos-Kilini are more preferable to those of low marine traffic e.g. route of Spetses-Kosta served from many ships e.g. route of Kerkira-Igoumenitsa.

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