National Technical University of Athens
School of Naval Architecture and Marine Engineering
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Diploma Thesis

Techno-economical feasibility study on the retrofit of double-ended Ro/Pax ferries into battery-powered ones

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Supervisor: J. Prousalidis

Associate Professor N.T.U.A. of Marine Electrical Engineering

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Abstract

Humanity by necessity is being forced to reduce its carbon footprint and invest in operations aimed at limiting emissions and improving resource efficiency in order to achieve sustainable growth. Air pollution and climate change are intertwined and they have also started occurring. Ports, coastal cities and their local communities are amongst the most vulnerable to extreme weather conditions resulting from them.

The concept of the all-electric-ship seems to be the optimal solution from shipping sector. The all-electric-ship design which aims at supporting and promoting energy efficiency, if powered from electricity generated from renewable sources may claim to be a 100% zero-emission transportation mean.

Purpose of this thesis, therefore, is the techno-economical feasibility investigation of the retrofit of existing small double-ended ferries into battery powered-ones, as it is stated in chapter one. It includes retrofit cost calculation, a comparison analysis of fuel and O&M savings on a year's operation, shore side's appropriate infrastructure and it's arrangement, and externalities costs because of the emissions saved.

In second chapter of the dissertation, an option analysis is offered under the target of a zero-emissions vessel. Moreover, a brief historical guide to all-electric ships, from their birth to nowadays is presented. Next chapter analyzes battery storage systems, their structure, their chemistry technologies and how to evaluate them for marine application use.

Existing vessels' under investigation main characteristics, machinery equipment and operational routine is described in the fourth chapter. Retrofit's overview concerning vessels' and shore's basic machinery installations and modifications is described. Moreover, the legal and regulatory framework for launching an all-electric ship and installing an onshore power supply system is outlined before proceeding into the technical design of the conversion.

Chapter five describes the conceptual electrical topologies that can be applied on vessel and on shore side. Depending from vessel's characteristics and power demands different configurations can be used for AC, DC distribution networks or LV, HV systems. Details for the interconnection system are reported, as well.

The design methodology concerning the estimation of battery capacity required on-board according to vessel's operational profile and safety criteria is presented in chapter 6. A plexus of scenarios depending to operational characteristics, vessel's currently installed power output, charging procedures and battery specifications is created in order to evaluate the significance of each parameter. Each scenario's outcomes are the total number of batteries needed, their price, their weight and volume, and life expectancy. General design guidelines from methodology's implementation are highlighted.

Chapter seven discusses about air pollution and its multivariate impacts on flora and fauna, and its contribution to climate change. Tools for estimating the amount of pollutants which will be saved due to vessel's retrofit are offered alongside. Moreover, externality cost values per tn of pollutant emitted are presented based on the impact pathway analysis.

The retrofit electrification methodology is applied into a typical small double-ended Ro/Pax ferry and the results are shown in chapter eight. In addition, according to the scenario selected system's total installation price and savings from fuel consumption are calculated. Financial and economical appraisal of the project is presented, including the externalities costs integration.

Key words: Battery-ship, all-electric ship, shipping emissions, shipping externalities, regulatory framework, sustainable shipping, history of electric ships, short-sea shipping, future vessel, investment analysis, health costs of air pollution, shore-side electricity, interconnection system, battery-powered, green ships

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Contents

1. Introduction

1.1 Background of study

The first ever actually useful rotary electrical motor was used to propel a boat generating energy from a battery storage system; the history of electric motors and the development of batteries as a mobile power source intertwine with that of water transportation and have left their mark in naval architecture and electrical engineering.

Since first attempts to propel a boat on batteries almost two centuries have elapsed. Though, in today's age it seems imperative to reconsider and redesign shipping sector in terms of sustainability and efficiency.

Maritime transport is the most environmentally friendly type of transport mode. However, air pollution and greenhouse gases from ship emissions are increasing because of the growing maritime traffic. These exhaust emissions cause global warming, acid rain and a reduction in air quality which has serious adverse effects on human health.

Air pollution and climate change are interlaced and they have also started occurring. Ports, coastal cities and their local communities are amongst the most vulnerable to extreme weather conditions resulting from them.

In harbor cities, ship emissions are a dominant source of urban pollution affecting the health of people living and working in these areas. Pollutant emissions from shipping have continued to rise, while emissions from land-based sources have gradually come down due to dedicated efforts to achieve green production. Port and the City have always co-existed with many ports having developed in very close proximity to urban areas and many urban areas being developed due to the existence of a thriving port entity.

Humanity by necessity is being forced to reduce its carbon footprint and invest in operations aimed at limiting emissions and improving resource efficiency in order to achieve sustainable growth. The concept of the all-electric-ship seems an ideal clean solution.

The all-electric-ship design aims at supporting and promoting energy efficient, zero greenhouse gas (GHG) emission and air pollution free waterborne transportation for island communities, coastal zones and inland waterways in Europe and beyond. Moreover, the overall objective of battery-ship design is to apply an extremely energy efficient design concept and demonstrate a 100% electric, emission free, ferry for passengers and cars, trucks and cargo.

Moreover, all-electric ships with energy storage in large batteries and optimized power control can give significant reductions in fuel costs, maintenance and emissions, in addition to improved ship responsiveness, regularity, operational performance, absence of vibrations, smaller starting times of the engines and safety in critical situations. During the last ten years, a variety of lithium-ion based batteries has been developed. Batteries have been optimized for energy density, power density, cycle life, cold weather performance, robustness, safety and cost.

In Greece, 98% of the population lives within 100 km from the coast and 33% in coastal cities or villages not more than 2 km from the coast, whereas in the wider damaging context it should be mentioned that no place in Greece is more than 150 km from the sea. Almost all of the twelve million tourists arriving in Greece every year visit the Greek coast, whether mainland or island. Greece has the 10th longest coastline in the world a coastline of 13 780 km which is about 5% and 30% of the entire European and Mediterranean coastline, respectively.

Along Greek coastlines there are over 150 vessels serving routes of short sea shipping connecting neighboring coastal communities. Most of them are of "open-type" and double ended shape. All of them, though are powered by fossil fuels.

We need to preserve our environment, and ferries running on electricity appear to be the only ready to be applied solution.

Battery-powered ships that are charged from the grid and the environmental savings depend on the emissions created by generating the electricity. For example, for the Norwegian electricity-generation mix, with close to 100% renewable electricity generation, the savings from all existing electric ferries are substantial.

Due to its climate conditions (the country enjoys more than 250 days of sunshine—or 3,000 sunny hours—a year, and has many areas of strong winds), Greece possesses significant untapped generation potential.

Greek shipping sector shall take the lead and hopefully in following years electricity consumed for propulsion and hoteling loads on board may be generated solely from renewable energy sources.

This study aims at investigating the retrofit of existing double-ended Ro/Pax ferries into battery powered ones and the benefits generated from their operation on batteries concerning energy efficiency, fuel and O&M savings, and externalities costs.

1.2 Problem statement and objectives

The purpose of this thesis is to describe the design choices made in order to make the vision of an E-ferry concept possible and to evaluate these design choices in a broader context as to the operational challenges of exploiting the new technology and possibilities for battery driven ferries. From a design perspective the following challenges need to be approached.

The required installed capacity on board in order to ensure safety for passengers and the vessel and redundancy according to the ferry's operational profile.

Compliance with national and international rules which state the prerequisites for having certified a battery ship.

Design of a drive train layout with a battery management system and battery packs sufficient to ensure a complete operational working day for the ferry and at the same time a viable life-span of batteries in terms of recycles and shelf life.

Design of a shore charging connection system and transformer stations to interconnect with public electricity grid capable of very high charging powers in order to minimize charging time during port calls.

Incorporate social benefit from the reduction of ships' emissions in the economical appraisal of the project.

All the above have to be in accordance with project's financial sustainability.

1.3 Structure of study

This study is structured as follows:

Chapter 2
Chapter presents the alternative choices of zero-emission vessels which can serve as well local communities and environment's protection. Though, battery storage systems in conjunction with electric motors is a rather old idea being tested since early 19^{th} century. Therefore, the most important electric vessels of the last two centuries will be presented in order to have a broader image of technological advancements in our field, its motives and integration in everyday life.

Chapter 3
The third chapter describes battery's functions and how to evaluate each battery's technology characteristics. In addition, the most important battery technologies alongside with their specifications and applications are presented in order to help us evaluate the appropriate battery chemistry for the all-electric ship.

Chapter 4
In the fourth chapter, the main characteristics of double Ro/Pax ferries operating in Greek waterways, last year, are presented and an outline of the retrofit procedure which will be followed. Before moving though to retrofit's technical design we present the rules and regulations with whom we need to comply in order to launch the all-electric ship.

Chapter 5
Conceptual design of electrical topologies on board, on shore and cost calculation method are described. Possible electrical diagrams and infrastructures either on shore or on the boat depending to different scenarios/energy demands (existing electrical grid, high voltage/low voltage etc.).

Chapter 6

Chapter 6 presents our retrofit design philosophy and the methodology developed for the estimation of the required battery capacity installed on board. It's inputs and equations are described and the most important guidelines generated from the methodology are outlined.

Chapter 7
Health externalities of ship air pollution and how can be translated in monetary units. External costs are estimated in an attempt to highlight the economic burden they impose upon the society and facilitate the cost–benefit analysis of the proposed emission abatement technologies. Moreover generation of electricity from shore side is compared to that on board.

Chapter 8
Results from the implementation of the methodology in case study of: Perama-Salamina are presented. Topology designs, number of batteries installed according to operational profile and financial sustainability of the project are investigated.

Chapter 9
Final conclusions on vessel's retrofit and recommendations for future investigation are presented.

2. Green shipping, history and alternatives

2.1 Option analysis

Undertaking a project entails the simultaneous decision of not undertaking any of the other feasible options. Therefore, in order to assess the technical, economic and environmental convenience of our project, an adequate range of options should be considered for comparison.

With our target being a zero-emissions water transport mean with high frequency of itineraries there are really few other possible choices.

Some alternative that could be considered concerning the storage of electrical energy besides battery systems are flywheels, ultracapacitors or hydrogen to be used in fuel cells.

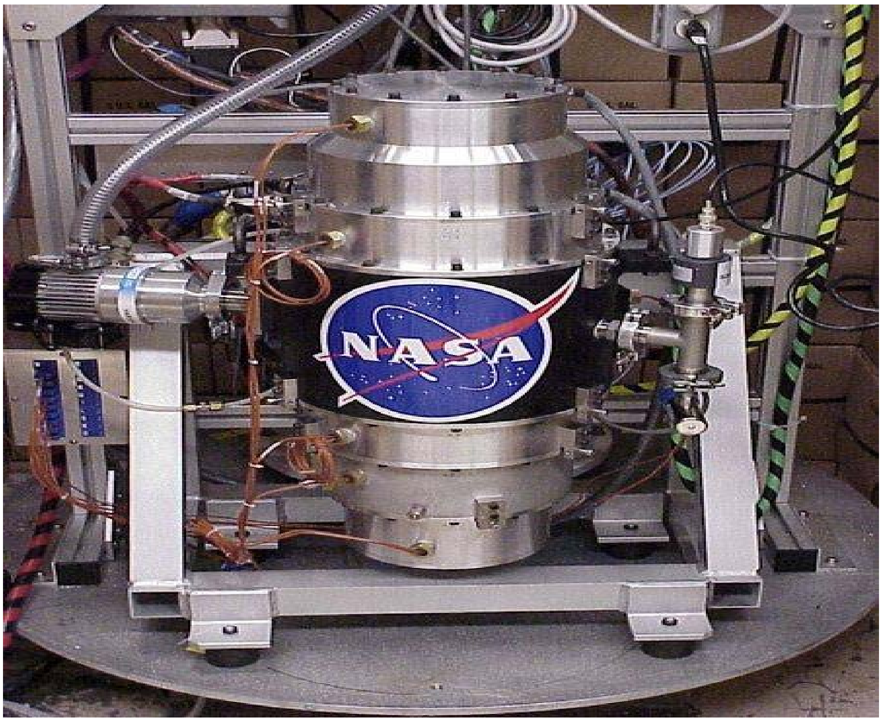


Figure 2-1:Flywheel made by NASA

The main advantages of flywheel storage systems are the high charge and discharge rates for many cycles. Indeed, the high cycling capability of flywheels is one of their key features and is not dependent on the charge or discharge rate. Full-cycle lifetimes range from 10^5 up to 10^7. In fact, the limiting factor in some applications is more likely to be the flywheel lifetime which is quoted as typically 20 years. Also, typical state-of-the-art composite rotors have high specific energies, up to 100 Wh/kg, with high specific power. Their energy efficiency is typically around 90% at rated power. (Hatzipaschalis, 2008). Also, the lifetime and maintenance of flywheel technologies are around 20 to 30 years and some can operate with no maintenance in that time. Batteries often need strict environmental conditions to operate correctly, such as operating temperatures below 40 degrees. Flywheels also do not suffer from the memory effect, which plagues some types of batteries. Flywheels can operate under higher temperatures and a wider range of environmental conditions.

However, use of flywheel accumulators is currently hampered by the danger of explosive shattering of the massive wheel due to overload. One of the primary limits to flywheel design is the tensile strength of the material used for the rotor. Generally speaking, the stronger the disc, the faster it may be spun and the more energy the system can store. When the tensile strength of a flywheel is exceeded the flywheel will shatter, releasing all of its stored energy at once; this is commonly referred to as "flywheel explosion. A growing use for flywheel technology involves frequency regulation on the electricity grid used as Uninterruptible Power Supply (UPS) systems to deliver power protection for critical operations

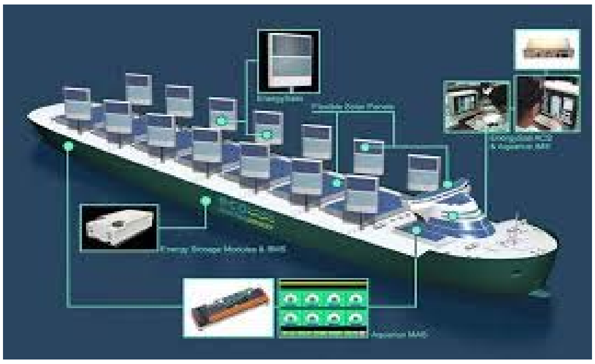
Due to their high specific power, flywheels, along with ultracapacitors, can charge and discharge much quicker than batteries. The most crucial performance drawback of high-speed flywheels is that they experience relatively high losses which cause them to self-discharge more rapidly compared to batteries and ultracapacitor.

When a supercapacitor is charged, the energy is stored as a charge or concentration of electrons on the surface of a material. This means a supercapacitor is capable of very fast charges and discharges which can achieve a very large number of cycles without degradation, even at 100% depth of discharge (DOD). Capacitors are made from various materials in many ways, from multilayer ceramics, ceramic disc, multilayer polyester film, tubular ceramic, axial and radial polystyrene, to carbon nanotubes. Supercapacitors found their first application in military projects such as starting the engines of battle tanks and submarines or replacing batteries in missiles. Common applications today include starting diesel trucks and railroad locomotives, actuators, and in electric/hybrid-electric vehicles for transient load levelling and regenerating the energy of braking. NASA has used 30 large supercapacitors in its turbo-electric city bus (EERE, 2006).

Even though, both systems present advantages, their high-prices, smaller capacity compared to battery systems make them unattractive choices as main storage systems on marine applications. Batteries are the dominant technology to be used when continuous energy supply is paramount, while technologies such as flywheel and supercapacitors are more suited to power storage applications and where very brief power supply is required such as in uninterrupted power supply requirements.

Another alternative to achieve zero-emissions from a vessel would be to produce the required energy on-board, from renewable sources. That can be achieved either by placing solar panels, big sails or an advanced combination of both. In the following figures, such modern ship configurations are presented.

Although these systems are attractive, they are too sophisticated compared to current technologies used on-board.



Flexible Solar Panels
Energy Storage Modules & BMS

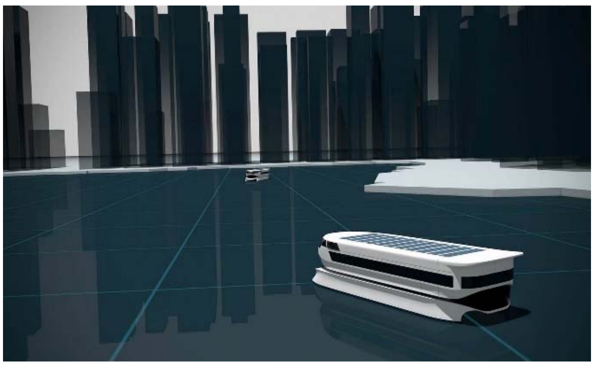


Figure 2-2: Green ships of the future

2.2 From the first all-electric ship to nowadays

Electric boating is currently enjoying a worldwide revival, yet as early as the turn of the 19th century there were 100 electric launches on the Thames river alone.

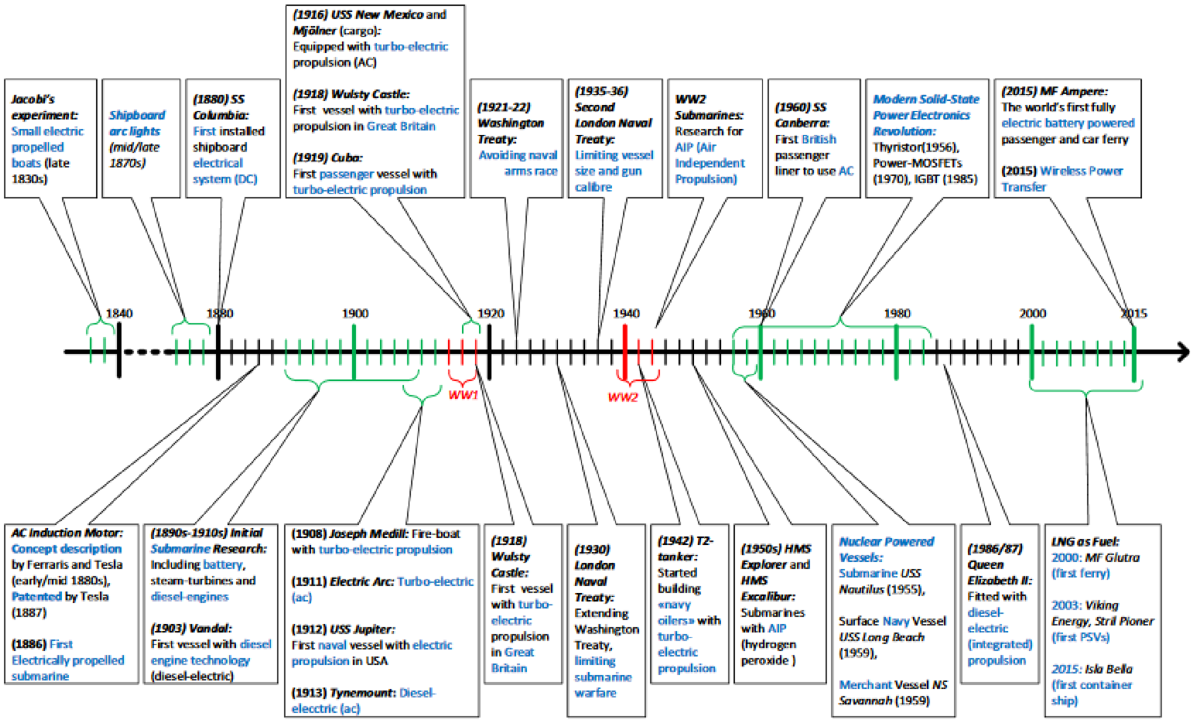


Figure 2-3: guides the reader through the milestones in the evolution of the marine vessel electrical power system from 1830 to 2015

As far as our case is concerned, the foundation for building electric motors was laid with the invention of the battery (Allessandro Volta, 1800), the generation of a magnetic field from electric current (Hans Christian Oersted, 1820), and the electromagnet (William Sturgeon, 1825).

These developments led Jacobi Moritz in 1834 to attempt the first ever application of electric motors; as a means to propel with electricity a boat. Physicist Moritz Hermann Jacobi was a Prussian inventor working in Königsberg towards the development of a simple battery-powered direct current (DC) motor.

Figure 2-4: Jacobi's first electric motor

Jacobi investigated the usage of electromagnetic forces for moving machines and the transfer of power from a battery to an electric motor. By determining the amount of zinc consumed by the battery and testing different motors' outputs, he eventually deduced the *maximum power theorem*.

In September 1838 the first documented launch of an electric boat took place; Jacobi constructed the requested 28-foot electric motor boat powered by battery cells. The engine Jacobi built comprised electromagnets to drive two paddlewheels. Using zinc batteries that had 320 pairs of plates and weighed more than 180 kg, the boat reached a speed of 2,5 km/h. The general arrangement proved successful and the electric paddle-boat began to voyage up the River Neva carrying 14 passengers, applauded by the Tsar and his Court. However, the motor gave out as much nitrous fumes as smoke from a steam train. The crew choked and asphyxiated by these sickening and suffocating fumes, and were subsequently obliged to stop their observations. The following year Jacobi worked on improving his boat-motor design, and carried out another experiment with the same boat. It was equipped with a battery a fifth the size of the previous one. Following the recent formula published by British physicist William Grove, it was charged with concentrated nitric and sulfuric acid. The vessel attained an average speed of 4.5km/h with some 12 or 13 passengers aboard.

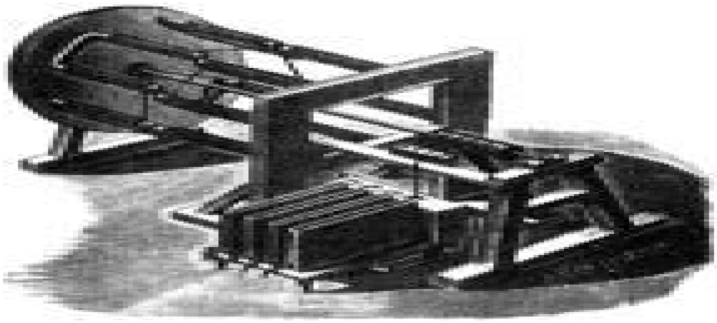


Figure 2-5: One more modification of Jacobi's electro-motor

The following years, many inventors tried their ideas on electric boats. Chemistry professor Sibrandus Stratingh of Groningen, Netherlands, who also worked on electric car designs, developed an electric boat that he launched in 1840. In August 1848 another electric boat was demonstrated on the private lake of Penllergaer near Swansea, Wales. It was propelled by a motor developed by Benjamin Hill, again deriving its energy from a Grove cell. Both suffered from numerous imperfections and as a result there was no immediate adoption of electric propulsion for ships. Commercial production of electric boats in 1850s was not yet practical. Batteries were too large, heavy, and difficult to recharge.

In 1859, French physicist Gaston Planté invented a lead-acid, wet cell storage battery, the first commercial rechargeable electric battery. Using two sheets of lead and sulfuric acid, Planté's battery was a precursor to rechargeable batteries used in modern automobile industry.

In 1866, George Lechlancé invented a dry cell battery using zinc, manganese, and ammonium chloride. These developments in efficient rechargeable batteries allowed for further motor improvements. Some years were to elapse before a certain Monsieur de Molins launched his electric paddleboat in the Bois de Boulogne lake. Despite her strong electric batteries (developed by Robert Bunsen and using carbon electrodes instead of platinum) the boat started slowly, disappeared behind the island which forms the centre of the lake and did not reappear.

Disinterest continued over this promising form of motive power until William Woodnut Griscom of Philadelphia in 1879 and a Parisian electrical precision instrument maker Gustave Trouvé, arrived on the scene, enabling the commercial production of electric boats.

In May 1880 Gustav Trouvé patented a small 11lb (5kg) electric motor and described its possible applications (Patent N°136,560). Trouvé suggested using two such motors, each driving a paddle wheel on either side of the hull. Later he progressed to a multi-bladed propeller. Modifications to this master patent date from August 1880, then March, July, November and December 1881. To quote*: "It is the rudder containing the propeller and its motor, the whole of which is removable and easily lifted off the boat…"*

With this invention, Trouvé could not only lay claim to the world's first marine outboard engine but, in taking the same motor and adapting it as the drive mechanism of a Coventry-Rotary pedal tricycle or velocipede, Trouvé also pioneered the world's first electric vehicle.

On 1 August 1881 Trouvé made his benchmark report to the French Academy of Sciences, stating: "I had the honour to submit to this Academy, in the session of 7th July 1880, a new electric motor based on the eccentricity of the Siemens coil flange. By suggestive studies, which have allowed me to reduce the weight of all the components of the motor, I have succeeded in obtaining an output which to me appears quite remarkable. A motor weighing 5kg [11lb], powered by 6el of Planté's batteries producing an effective work of 7kgm/sec, was placed, on the 8th April, on a tricycle whose weight, including the rider and the batteries rose to 160kg and recorded a speed of 12km/h. The same motor, placed on the 26 May in a boat of 5.5m long by 1.2m beam [18 x 4ft], carrying three people, gave it a speed of 9km/h in going down the Seine at Pont-Royal and 5.5km/h in going back up the river. The motor was driven by two bichromate of potassium batteries each producing 6el and with a three-bladed propeller. On the 26th June 1881, I repeated this experiment on the calm waters of the upper lake of the Bois de Boulogne, with a four-bladed propeller 28cm [11 ¼in] in diameter and 12el of Ruhmkorff-type Bunsen plates, charged with one part hydrochloric acid, one part nitric acid and two parts water in the porous vase so as to lessen the emission of nitrous fumes. The speed at the start, measured by an ordinary log, reached 150m [490ft] in 48 seconds, or a little more than 3m/sec ; but after three hours of functioning, this had fallen to 150m in 55 seconds and after five hours, this had further fallen to 150m in 65 sec .One bichromate battery, enclosed in a 50cm [20in] long case, will give a constant current of 7 to 8 hours. There is a great saving of fuel and cleanliness."

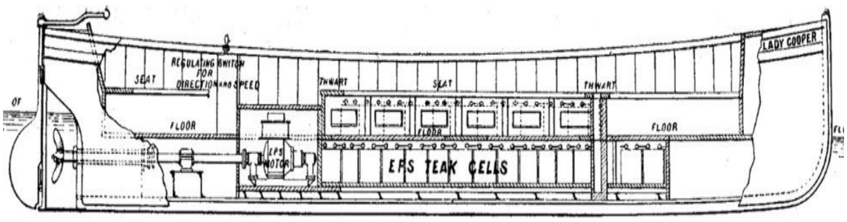


Figure 2-6: The arrangement of teak battery cells and motor in an early E.P.S. launch

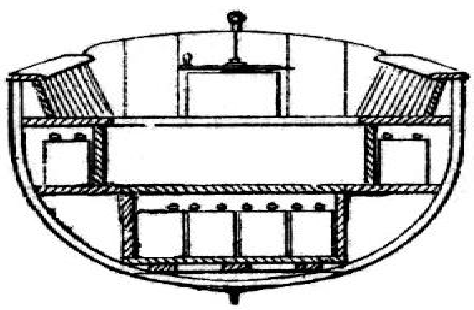


Figure 2-7: Cross-section showing the batteries below deck

The idea had caught on elsewhere, as well. By 1882, the Electrical Power Storage Company at Millwall, London had produced the first commercial river launches for electric boats on the Thames River in England. The first boat was called Electricity. The iron-hulled (7.6 m) Electricity, designed by the Austrian-born Anthony Reckenzaun, was built for the Electric Power Storage Company to accommodate 12 passengers. Power came from 45 Planté accumulators, modified by Messrs Sellon and Volchmar to total 96 volts and supply power for six hours at 4hp to two Siemens D3 dynamos with regulators and reverse gear, belt-driving a 20in screw propeller of 3ft pitch (500mm x 0.9m) at 350 rpm enabling her a speed of 13km/h . Either or both motors could be switched into circuit at will. On 28 September 1882 Electricity made a pioneering trip on the River Thames to London Bridge.

Another successful electrically powered vessel was the Elektra, a passenger ferry with a capacity of 30 persons, built by the German firm Siemens & Halske in 1885. Measuring 11 meters long by 2 meters wide, it was powered by a 4.5 kW motor supplied by batteries

Figure 2-8: Elektra, by Siemens & Halske in 1885

Some years were to elapse before the next significant step was made by Moritz Immisch and Viscount Bury who built a fleet of electric boats along the Thames and charging stations along the riversides. Moritz Immisch, German-born clockmaker turned electrical engineer and entrepreneur; having worked on battery-operated trams in London, in 1887 Immisch teamed up with Viscount Bury to pioneer the world's electric hireboat-fleet. Working with Magnus Volk, Immisch & Co.'s fleet of six boats was the first deployed along the Thames in 1889.

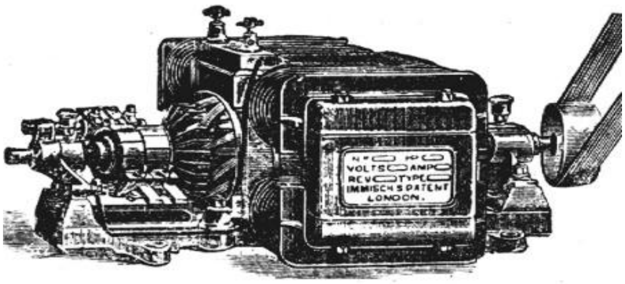


Figure 2-9: Immisch's motor

Floating charging stations designed by William Sargeant were introduced in 1888 as well. An 80ft (24m) Thames houseboat was converted to a charging station with semi-portable steam-engined dynamo. Four other stations were set up, the one on Platts Eyot Island near Hampton becoming the headquarters. From an initial six launches, by 1904 the Immisch operation had grown to some 23, all capable of carrying from 4 to 50 passengers.

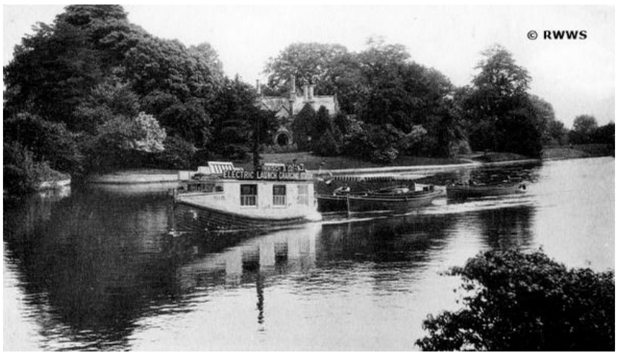


Figure 2-10: The Immisch floating recharging station at Runnymede

Electric Power Storage Company manufactured the accumulators for the Immisch motors from 1.5hp up to 12hp, at 65, 95 and 120 volts, and gave a run of 30 miles at 6mph, half upstream and half downstream, on one charge.

In 1888 there were half-a-dozen charging stations on the Thames, but by 1902 there were over 20 on land and two floating barges. At Maidenhead alone, seven electric hireboat operations jostled for business. During the same period, over 50 British boat builders are known to have built one or more electric launches. Most of these were Thame's riverside yards. Launches were also exported to Venice, Ceylon and South Africa, while Eastern princes and rajahs received sumptuously fitted-out vessels.

The Thames Valley Launch Company of Weybridge, Surrey, offered 29 launches for hire, many of which were fitted with feathering propellers. Messrs Andrews & Sons of Maidenhead had a fleet of 12 electric launches, each one named after a freshwater fish, with an additional flagship called the Angler. It was on the Angler that King Edward VII, Queen Alexandra and a royal party enjoyed the pleasures of the Thames.

Eventually electric powered boats, driven by large numbers of batteries, were very fashionable in the 1890s. Apart from these 100-odd launches on the 93 miles of the Thames between Teddington Lock and Oxford, a number of local corporations bought electric boats for used in their ornamental parks. The Bergen Elektriske Færgeselskap (BEF) company was founded in 1894 and a fleet of small electric passenger boats started to operate in Bergen harbor, Norway. In Leeds, moreover ,a 70ft (11m) launch called Mary Gordon (built in 1898) was capable of taking either 75 adults or 120 children for trips on Waterloo Lake, Roundhay Park. Mary Gordon was one of the largest electric launches built at the time and is believed to be the largest and oldest electrically powered boat still in existence. Again, a similar boat plied for hire at Southport. The English Lake District and Irish and Scottish lakes also had a number of launches for hire.

Figure 2-11: Mary Gordon, built in 1898

Elsewhere, British electrical boat pioneer Anthony Reckenzaun and his brother Frederick, emigrated to the USA and settled in Newark, New Jersey. Using experience gained with the cross-Channel Volta and other vessels, they built for their own use a 8 m launch which they named Magnet, with a 2.5hp, 191kg Reckenzaun's motor powered by two banks of accumulators made by the Electric Accumulator Company of Newark. The vessel was reviewed by Thomas Martin, Editor of The Electrical Engineer, who described a voyage of 50-60 miles without recharging, so supporting the Reckenzaun's claim of 60-70 miles over 10 hours

It was in 1891 that the fabulously wealthy WK Vanderbilt became the first American to order an electric boat. It was built at Charles L. Seabury's yard, measured 9m in length and was called Alva. In terms of length, US millionaire John Jacob Astor sported the largest privately-owned electric launch in the world: the 22m Utopia which had two motors, each developing around 25hp and was luxuriously fitted out like a miniature Titanic. The largest electric passenger boat in the world, however, was the 28.4m Victory, designed by William S. Sargeant in 1904 and licensed to carry 350 passengers above Westminster Bridge.

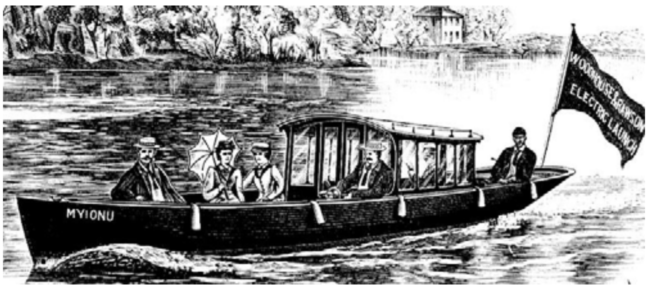


Figure 2-12: An early electric boat designed by William Sargeant, from Electricity In The Service Of Man, 1897

The availability of electric power for illumination, communication, and propulsion had fostered the concept of an all-electric naval ship. It was therefore logical to extend that concept to submarines for which a practical power source had remained an elusive goal. There had been much experimentation with the concept of underwater crafts during the 19th century; propulsion varied from manual to stored compressed air, even pressure from chemical reactants. In 1885, the French designer Claude Goubet had introduced electric propulsion with a pair of experimental submarines. Goubet started his demonstration of electric propelled submarines by building two small private venture vessels, Goubet I in 1885 and Goubet II in 1889. Both vessels showcased the benefits of electric propulsion, but were otherwise unsuccessful regarding maneuverability. In 1886 the submarine Nautilus was built in Tilbury with two electrical motored twin-screws. In 1888 the Gymnote (59 feet long, displacing 30 tons) was built with a 50hp motor resulting in a speed of about 7 knots.

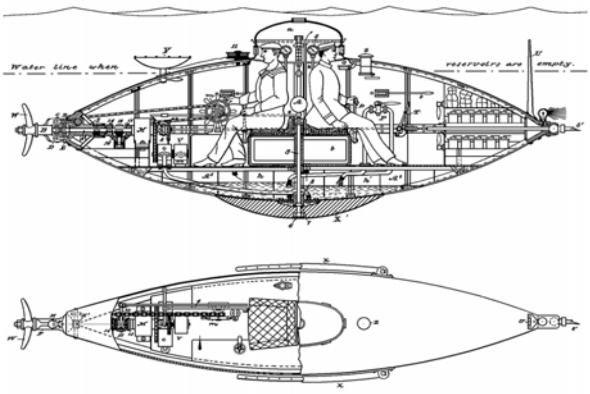


Figure 2-13: Goubet I submarine

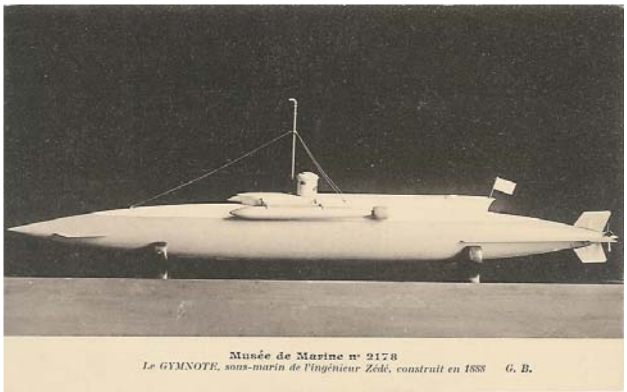


Figure 2-14: Gymnote submarine

From this point on, electric propulsion came to be the common factor between the different submarine designs, as solutions involving compressed air and compressed steam did not provide the necessary response to achieve the needed maneuverability when diving.

In the late 1890 and the early 1900s many nations were occupied by making their own naval submarines for warfare with a range of different weapon system designs, including torpedoes, air cannons, and large calibre guns. France, the United States, and Britain were exploring, in deep waters, the submarine concept

The French Navy was independently developing its own submarine, while the Royal Navy and the US expanded on the work of John Philip Holland. Irish engineer John Philip Holland, originally a school teacher, spent decades working on submarine designs and improvements, prior to his successful efforts with a privately built type, launched on 17 May 1897. This was the first submarine having an electric battery system to power the boat when submerged, and employed a diesel powered internal combustion to propel the boat when on the surface. The Electric Boat Company was founded in 1899 to produce Holland's work. The US Navy purchased the Holland VI on 11 April 1900, after rigorous tests and commissioning it as the USS Holland (SS-1) on 12 October 1900. While nuclear power eventually replaced this system for the larger submarines, electric motors were still used when crafts wanted to be silent and the combination of diesel and electric power remains a practical solution for smaller submarines. The use of combustion engines to charge the battery proved to be a valid option, as turbo-electric systems required the submarine to come to a stop before submerging, which made dive operations slow. Even after the steam-plants had been shut down, the power system retained a lot of heat, which made the climate within the submarine almost unbearable. In addition, when surfacing, starting the steam plant was a slow process, due to the fact that the boilers had to be reheated

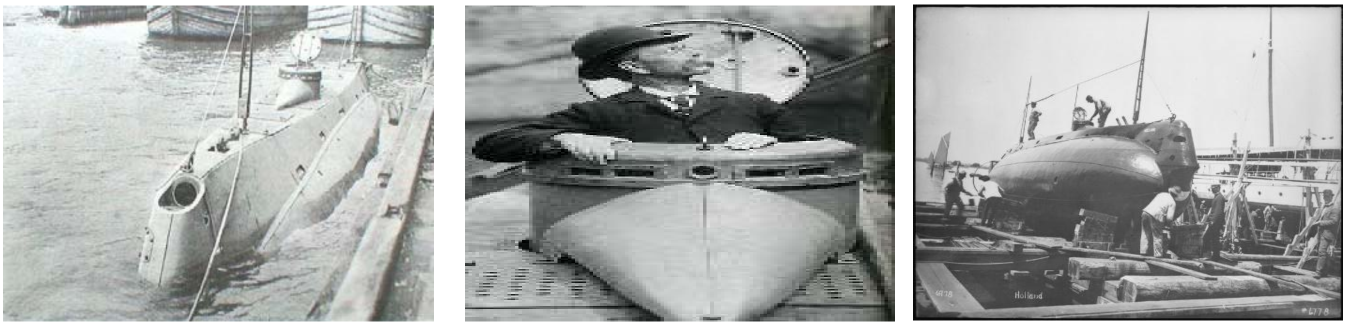


Figure 2-15: Phillip Holland standing in the hatch of USS Holland

The 20th century was dominated by a chain of events that heralded significant changes in world history as to redefine the era: World War I, World War II, space exploration, nationalism, decolonization, the Cold-War and Post-Cold War conflicts, intergovernmental organizations, and cultural homogenization.

The two world wars and their interconnected events played a major role in the way technology advanced and innovation was deployed in the dawn of post-war societies. The century saw a major shift in many people's lives, with changes in politics, ideology, economics, society, culture, science, technology, and medicine. The 20th century may have seen more technological and scientific progress than all the other centuries combined since the dawn of civilization.

When it comes to naval architecture, several advancements led step by step to today's all-electric ships. In the beginning with the usage of hybrid-systems to produce electricity from oil-powered engines and driving it to the rotating motor. As research progressed, storing the produced electric energy in battery packs for later consumption became central, as military submarines required underwater propulsion. Eventually, the focus was shifted to producing this energy from renewable energy resources, such as solar, and turning it in kinetic energy. The intermittent nature of renewables made energy storage crucial to their development. Consequently, when batteries became of the adequate size, the attempts to produce electricity outside the vessel and then transfer it in batteries reignited, combining renewable and storage technologies.

These steps are of vital importance in order to understand in depth the advantages of the versatile usage of electricity in marine vessels. Looking back to the driving forces of innovation in the early 20th century, as well as the effect technological breakthroughs had in almost every aspect of everyday lives, it is important to reflect on what kind of factors drive R&D today and to what kind of needs today's advancements respond to. If the 20th century was about survival of the fittest, what are the lessons learnt and technology industry's motivations for 21st century ?

Since the late 1970s, there has been a revival of interest in electric boats for few commercial ships but mostly on pleasure boating on the inland waterways around the world. Considering the energy crises of the period, interest in this quiet and potentially renewable marine energy source has been increasing steadily again, especially as solar cells appeared at the time, for the first time making possible motorboats with an infinite range like sailboats. Better underwater hull designs, lighter glass-fiber construction, improved motors and batteries, modern electronic control, faster recharge systems have given birth to a new generation which is already contributing more environmentally friendly pleasure boating for the 21st century. It wasn't until 1980 that the Electric Boat Association was formed, solar powered boats started to emerge and commercial electric boats experienced a revival in those latter decades of the 20th century. Lastly, we need to note down that in last decades of the century electric boats were set again for hiring in canal cities such as Venice, Italy or Amsterdam, Netherlands

Duffy Electric Boat Company of California was the first to begin mass producing small electric crafts powered from batteries in 1968, and has produced more than 10,000 boats to date.

Figure 2-16: uffy's Co has been producing electric boats from 1968 to date

Not only did passenger and cruise vessels stared to convert to diesel/battery-electric systems. Also offshore vessels such as Platform Supply Vessels (PSV), anchor handling and a range of special purpose vessels adopted a diesel-electric configuration in the 1980s. Due to an increase in electric equipment and systems used for different operational profiles - a transition towards All Electric Ships (AES) - the vessels needed reliable power generation which could supply the often rapidly varying load profiles. Also the introduction of Dynamic Positioning (DP) systems aboard, in which interest started to grow with the offshore drilling in the 1960s when drilling moved to deeper waters where jack-up barges could no longer be used, added requirements for more robust and reliable systems.

Previous century was the age of the internal combustion engine just as the 19th was the age of steam. Humanity went from horse and buggy, sail and balloons to the development of railway networks, automobiles, engine-driven ships, airplanes, rockets, computers and finally internet connection.

21^{ST} century is going to be the century of electricity, automations, mobile communication devices, wireless connections, autonomous self-driving transportation vehicles etc. More specifically, in our field, interest in electric and other alternatively fueled vehicles has increased due to growing concern over the problems associated with hydrocarbon-fueled vehicles' emissions and their damage to the environment which is by now a proven fact and let's hope reversible.

The great advances in battery technologies, which are discussed thoroughly on the following chapter, concerning lowering their weight while increasing their specific energy have provoked the outbreak of numerous applications of battery-powered transportation means, mobile devices etc. If combined with the augmenting use of renewable energy resources for power production the future looks bright for our target, the all-electric-ship.

The all-electric ships of today are altogether more complex than the ships of a century ago, which had relatively few electrical systems beyond propulsion and rudimentary communications and hotel requirements. The first generation of ships also did not need pulsing—the storing and releasing of high volumes of energy in short timespans. But as the history of electric drive suggests, sometimes good ideas take time to develop fully. In addition having as a target autonomous/drone self-aware e-ships the following years of the century seem prosperous, promising and full of technological advancements.

Reaching 2017, since the beginning of the century we can note down the launch of a serious number of both research, commercial and navy battery powered marine vessels. Starting from some experimental/research electric vessels we can note down the release of Turanor Planetsolar. The *Tûranor PlanetSolar* is currently the largest solar-powered boat in the world at 31 meters. Launched in Kiel, Germany, in 2010, it became the first solar-powered electric boat to circumnavigate the world in 2012. With 8.5 tons of lithium-ion batteries onboard, PlanetSolar is said to be "the largest civilian mobile battery" in the world. From empty it takes about two days to fully charge, and the batteries can drive the boat for 72 hours without any sunlight.

Fig. X, Turanor after achieving its target of circumnavigating the globe powered only by its 512 m^2 solar panels is now operated as a demonstration and scientific platform in the fight against plastic pollution in the oceans. Additionally while in Greece it had another mission as well, an archaeological mission involving the exploration and surveying of a prehistoric settlement in the sea area of Argolid Gulf.

The next big research vessel ,which will be launched on Feb 2017, is the Energy Observer or the water-borne answer to the Solar Impulse, the plane that completed its round-the-globe trip using only solar energy.

Fig. X, The Energy Observer, a 30m catamaran powered by solar and wind energy will sail around the globe as a floating exhibition and clean energy laboratory. Details about its batteries have not been yet announced.

September 2016 marks the 178th anniversary of Jacobi's launch on the Neva and after almost two centuries of development, electric boats continue to provide a clean and quiet method to traverse the planet's waterways.

Figure 2-17: Edorado's e-boat

Figure 2-18: Hydros HY-41

New marine companies have started appearing at the forefront by manufacturing small battery powered pleasure boats or bigger yachts for inland waterways around the world. Worth mentioning that Africa's and India's river transportation system is a huge bet for everyone in the sector. ex. Purewatercraft are building high-performance small electric boats with batts, Tesla of the sea, as they like to refer to themselves

Moreover, traditional players of the marine sector have used their r&d capabilities to push for the development of autonomous all-electric self-aware drone ships and below we can take a look at some of their concepts/projects published ex. DNV, Rolls-Royce either on small coastal ferry routes or on big ocean cargo vessels.

Figure 2-19: some of Rolls Royce's published projects:

Figure 2-20: DNV-GL's published thoughts on the future boats ,Powered by batteries, it takes sightseeing while going through the vulnerable Nærøyfjord or commuting between Scandinavian ports to a new – and more sustainable – level.

Finally, in more environmentally conscious and advanced countries the first all-electric battery powered ships have made their appearance.

In January 2015, world's first fully electric battery powered passenger and car ferry, MF Ampere, was set in operation (commissioned and delivered October 2014) in Norway. The vessel was a joint development between the Norwegian ferry company Norled AS , the shipyard Fjellstrand and Siemens AS . The vessel, certified by DNV-GL is powered by a lightweight Corvus Energy Storage System (ESS), weighting only 20 metric tons, and which supplies all the vessel's power demands while at sea . 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 (5,7 km), near Bergen, Norway, takes about 30 minutes. The ship's batteries, which are approximately 1MWh combined, are charged on each side of the route using the villages' electric grids, which distribute hydro-generated power. Due to the need of 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 has been designed suitably to host the battery installation and to be energy effective. Each port is equipped with a docking system which uses vacuum mounts to keep the ferry at rest without using the vessel's propulsion. It is reported that fuel savings reach up to 60% compared to traditionally powered ferries. Moreover since the energy consumed derives from hydro-electric power plants it is considered the first zero-emission vessel.

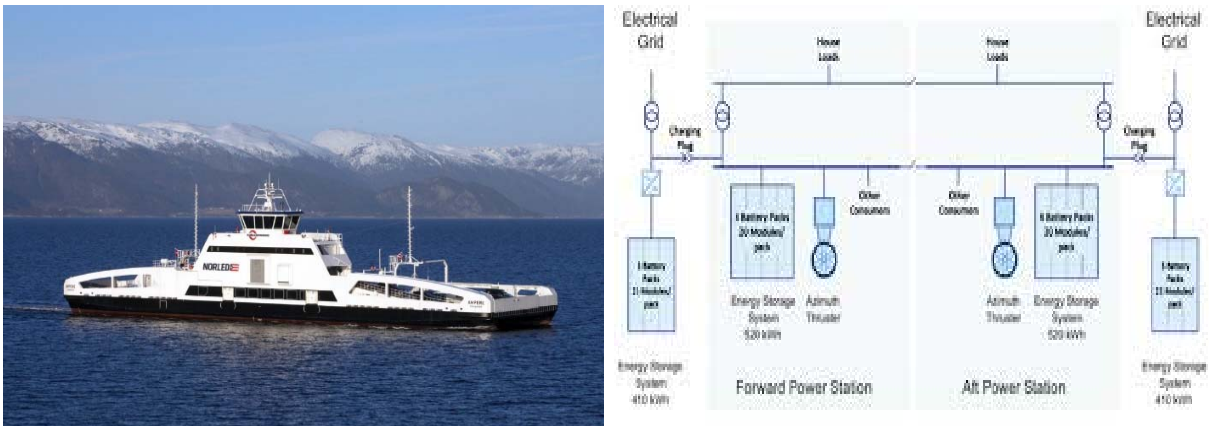


Figure 2-21: Mf Ampere and its electrical one-line simplified diagram

In addition, after 1,5 year of operation imitators have showed up. Five new double-ended battery powered vessels with very similar principal dimensions to Mf Ampere have been ordered by Norwegian companies Fjord1 and Basto-Fosten from Turkish shipyards in order to serve the routes along Norwegian coastline.

Furthermore in Sweden’s capital, Stockholm, another AES has been running lately. Movitz vessel operates in the center of Stockholm, on a route between Solna Strand and Gamla Stan, the heart of Stockholm's Old Town. Instead of a 250kW diesel engine using 50 m^3 of diesel per year, omitting 130 tons of CO2, 1,5 tons of NOX 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-Hydrid (NiMH) 180 kWh batteries from the Swedish company Nilar. NiMH batteries deliver high power instantly and can be charged very quickly. Boat need 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 NOx 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 2-22: Movitz in the service of Stockholm’s clean and quiet enviroment

Another ambitious project has been running as well, lately, at the ferry services across Scandinavia and the Nordic region; world’s pioneers in terms of progressive environmentally friendly solutions. Two double-ended Ro/PAX ferries, Tycho Brahe and Aurora, will be converted in order to operate completely/ solely on battery power between Helsingør (Denmark) and Helsingborg (Sweden), a distance of approximately 4 km carrying more than 7.4 Million passengers and 1.9 million vehicles annually. Each of the two electric ferries will have 4.16 MWh batteries to provide power for primary propulsion and auxiliary loads, making them world’s largest zero-emission ferries. Another great achievement will be charging those batteries. Automated shore-side charging stations will use an industrial robot to optimize connection and charging time; the plan is to recharge some 1,200 kWh every short visit at port (5.5 minutes or 9 minutes using a 10 kV, 10 MW robot connection. There is an also an on-board transformer (10 kV to 800 V). According to studies using battery power on these two ferries will help lower total emissions across the fleet by more than 50 percent from the current diesel operated vessels.

Figure 2-23: largest electric ferry on-order and its advanced robotic charging station

Finally its worth mentioning that relevant research has started in China, as well, and a 500 tn cargo vessel powered by batteries has been going on lately several tests in Huangpu river, Shanghai. Moreover other coastal cities such as Istanbul, Turkey; Bangkok, Thailand; and Lagos, Nigeria have begun experimenting with water-based transport systems. Each of these cities illustrates the benefits and challenges at different stages of developing urban water transport systems but in any case their future looks electric too.

3. Battery storage systems

3.1 An introduction to battery technology

Nature offers many ways to produce power. Most result through combustion, mechanical movement and photosynthesis, as in a solar cell. Electrical energy generation in the battery is developed from an electrochemical reaction between two metals of different affinities. When exposed to acids, a voltage develops between the metals as part of ion transfer; closing the circuit induces a current. In 1800, inventor Alessandro Volta discovered that the voltage potential became stronger the farther apart the affinity numbers moved.

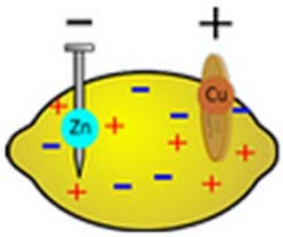


Figure 3-1:Lemon battery, The experiment is often used for educational purposes. The electrodes are zinc in the form of a galvanized nail and copper in a coin. The lemon juice acts as electrolyte to induce a chemical reaction.

A battery is an electrochemical storage device that stores electrical energy in the form of chemical potential between its positive and negative electrodes. The key components of an elementary battery cell are the anode and the cathode, which form the electrodes, the electrolyte and the separator, as shown in figure 3-2. Upon discharge, chemical reactions initiate a flow of electrons from the anode to the cathode, which produces an electric current in the external circuit. The separator allows for positive charges to migrate from the anode to the cathode in the electrolyte without the passage of other molecules.

Based on the desired output voltage and capacity a battery consists of one or more cells connected in series, parallel or both. Each cell consists of:

- The anode or negative electrode; the chemical reaction at the anode (oxidation) releases electrons that flow to the cathode through an external circuit. The anode material is selected based on its efficiency, high specific capacity, conductivity, stability, ease of fabrication and low cost.

- The cathode or positive electrode; the chemical reaction at the cathode (reduction) accepts electrons. The cathode is selected based on its voltage and chemical stability over time.

- The electrolyte complete the cell circuit by transporting the ions between the anode and the cathode. The electrolyte can be liquid, like water, acids, alkalis or solvents with dissolved salts. The electrolyte can be selected based on its high conductivity, non-reactivity with the electrode materials, and stability in properties in various temperatures, safety and cost.

Physically, the electrodes are electronically isolated preventing internal short-circuit situations, however , they are surrounded by the electrolyte. In a practical cell design separators which are permeable to the electrolyte are used to provide mechanical separation between the electrodes. The most beneficial combination of all these elements are those which result in a cell with light weight, high voltage and high capacity

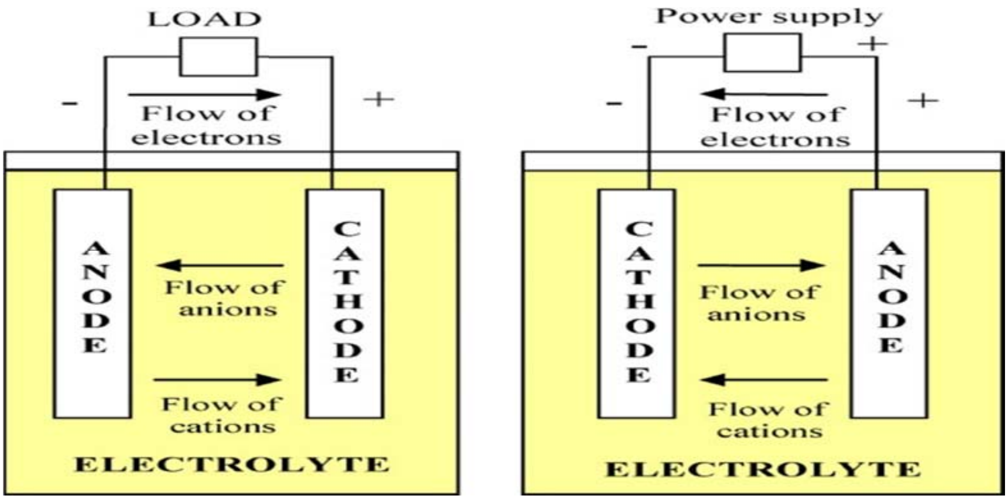


Figure 3-2: Chemical reactions taking place in a battery

When chemical reactions happen in a cell, chemical energy of the system decreases due to its transformation in electrical energy. The theoretical cell voltage is a function of the property of materials and is the sum of the anode and cathode potentials. The theoretical capacity is a function of the amount of active materials used in the cell.

Batteries are classified into two broad categories, primary batteries which host irreversible reactions and can thus be used only within a single cycle, and secondary batteries whose reactions are reversible and can be charged and discharged numerous times. Secondary batteries are charged by applying an external electric current. The current triggers the chemical reactions to operate in reverse, bringing the battery back to a state of high energy. Given the cyclical nature of marine applications, batteries used in marine industry are of course rechargeable.

The battery cells are made in different form factors, such as cylindrical, prismatic and pouch, and come in all sizes, from the small cells primarily made for consumer electronics to large sizes targeting heavy commercial applications. The maritime-focused systems have mainly been based on Li-ion cells with NMC (Nickel Manganese Cobalt Oxide) cathodes and graphite anodes. Systems based on iron-phosphate cathodes have also been used. Both the NMC and iron-phosphate chemistries represent a good compromise between the most important parameters of safety, energy, power density, cycle life and cost.

3.2 Evaluating battery technology

Batteries are described or evaluated using a set of parameters that reflect their performance. The key parameters generally used to evaluate battery technical specifications and condition for marine applications (thus rechargeable or secondary batteries) are:

C- and E- rates: In describing batteries, discharge current is often expressed as a C-rate in order to normalize against battery capacity, which if often very different between batteries. A C-rate is a measure of the rate which a battery is discharged relative to its maximum capacity. A 1C rate means that the discharge current will discharge the entire battery in 1 hour. For a battery with a capacity of 100 Amp-hrs, this equates to a discharge current of 100 Amps. A 5C rate for this battery would be 500 Amps and a C/2 rate would be 50 Amps. Similarly, an E-rate describes the discharge power. A 1E-rate is the discharge power to discharge the entire battery in 1 hour. (MIT-EVT, 2008)

Nominal Voltage (V): The reported or reference voltage of the battery.

Cut-off Voltage (V): The minimum allowable voltage. It is this voltage that generally defines the empty state of the battery.

Capacity or Nominal capacity (Ah for a specific C-rate) : The coulometric capacity, the total Amp-hours available when the battery is discharge at a certain current (specified as a C-rate) from 100 percent state-of-charge to the cut-off voltage.

Capacity Fade: Carbonaceous materials used in all Li-Ion batteries [30], are known to have dominant effects in the capacity loss at high discharge rates [31]. Among the various carbonaceous materials, natural graphite is the most attractive choice as it has a high theoretical capacity, abundance and low cost. During the cell operation, non-reversible chemical reactions on the surface of graphite happen among Lithium ions, solvents and electrons. The by-products of these reactions, accumulate and form a surface film on the carbon electrode known as Solid Electrolyte Interface (SEI). A Battery can stop performing when the Lithium ions can no longer pass the SEI layer due to its thickness. Therefore, lifetime and cyclab ility of a cell depends on its SEI layer [30]. Capacity fade of batteries depends on the various factors such as average discharge current and temperature of the cell. Capacity fade has two components (Moshirvaziri, 2013):

- Calendar fade: The reduction of capacity with the passage of time firstly due to the extension of direct interface between electrode and electrolyte and secondly because of the loss of active material.
- Cycling fade: The reduction of capacity due to successive charge/discharge cycles which result in the alternation of electrode's structure and mechanical fatigue.

Coulombic efficiency: The ratio of the output of charge by a battery to the input of charge. Coulombic efficiency is determined by the internal resistance of a cell.
The coulombic efficiency of a battery is defined as follows:

Where, η_C is the coulombic efficiency $\eta_c = \frac{Q_{out}}{Q_{in}}$

Q_{out} : is the amount of charge that exits the battery during the discharge cycle (C)

Q_{in} : is the amount of charge that enters the battery during the charging cycle (C)

Coulombic efficiency is not 100% because of losses in charge, largely because of secondary reactions, such as the electrolysis of water or other redox reactions in the battery. The coulombic efficiency of a typical lead-acid battery is >95%.

Energy or Nominal Energy (for a specific C-rate), (Wh): The "energy capacity" of the battery, the total Watt-hours available when the battery is discharged at a certain discharge current (specified as a C-rate) from 100 percent state-of-charge to the cut-off voltage.

Cycle Life (number for a specific DOD): The number of discharge-charge cycles the battery can experience before it fails to meet specific performance criteria. Cycle life is estimated for specific charge and discharge conditions. The actual operating life of the battery is affected by the rate and depth of depth of cycles and by other conditions such as temperature and humidity.

Specific energy (Wh/kg): The nominal battery energy per unit mass, sometimes referred to as the gravimetric energy density. Specific energy is a characteristic of the battery chemistry and packaging. It determines the battery weight required to achieve a given electric range.

Energy density (Wh/L): The nominal battery energy per unit volume, sometimes referred to as the volumetric energy density. Specific energy is a characteristic of the battery chemistry and packaging.

Specific power (W/kg): Specific power or gravimetric power density, indicates loading the maximum available power per unit mass. Specific power is a dynamically changing characteristic of the battery chemistry and packaging since it depends on the connected load. Therefore each battery is characterized by a maximum value of specific energy.

Power Density (W/L): The maximum available power per unit volume. Specific power is a characteristic of the battery chemistry and packaging. It determines the battery size required to achieve a given performance target.

Maximum Continuous Discharge Current (A): The maximum current at which the battery can be discharged continuously. This limit is usually defined by the battery manufacturer in order to prevent excessive discharge rates that would damage the battery or reduce its capacity. Along with the maximum continuous power of the motor, this defines the top sustainable speed and acceleration of the vessel.

Maximum 30-sec Discharge Pulse Current (A): The maximum current at which the battery can be discharged for pulses of up to 30 seconds. This limit is usually defined by the battery manufacturer in order to prevent excessive discharge rates that would damage the battery or reduce its capacity. Along with the peak power of the electric motor, this defines the acceleration performance.

Charge Voltage (V): The voltage that the battery is charged to when charged to full capacity. Charging schemes generally consist of a constant current charging until the battery voltage reaching the charge voltage, then constant voltage charging, allowing the charge current to taper until it is very small.

Float Voltage (V): The voltage at which the battery is maintained after being charge to 100 percent SoC to maintain that capacity by compensating for self-discharge of the battery.

(Recommended) Charge Current (A): The ideal current at which the battery is initially charged (to roughly 70 percent SoC) under constant charging scheme before transitioning into constant voltage charging.

(Maximum) Internal Resistance (Ohm): The resistance within the battery, generally different for charging and discharging.

State of Charge (SoC) (%): An expression of the present battery capacity as a percentage of maximum capacity. SoC is generally calculated using current integration to determine capacity over time.

Depth of Discharge (DoD) (%): The percentage of battery capacity that has been discharged expressed as a percentage of maximum capacity. A discharge of at least 80% DoD is referred as deep discharge.

Terminal Voltage (V): The voltage between the battery terminals with load applied. Terminal voltage varies with SoC and discharge/charge current.

Internal Resistance (Ohm): The resistance within the battery, generally different for charging and discharging, also dependent on the battery's state of charge. As internal resistance increases, the battery efficiency decreases and thermal stability is reduced as more of the charging energy is converted into heat.

Watts and Volt-Amps (VA): Watt is real power that is being metered; VA is the apparent power that is affected by a reactive load. On a purely resistive load, watt and VA readings are alike; a reactive load such as an inductive motor or fluorescent light causes a phase shift between voltage and current that lowers the power factor (pf) from the ideal one (1) to 0.7 or lower. The sizing of electrical wiring and the circuit breakers must be based on VA power.

Cold cranking amps (CCA): Starter batteries, also known as SLI (starter light ignition) are marked with CCA. The number indicates the current in ampere that the battery can deliver at –18°C (0°F).

Thermal Management: High power batteries for electric ships are prone to rapid heating, which could ultimately lead to an explosive discharge of energy. This thermal runaway occurs during uncontrolled charging or from electrical of physical abuse of cell. These risks are currently addressed by designing an enclosure that serves as a physical barrier.

Ragone Chart: A Ragone chart is a chart used for performance comparison of various energy-storing devices. On such a chart the values of specific energy (in W-h/kg) are plotted versus specific energy (in W/kg). Both axes are logarithmic, which allows comparing performance of very different devices (for example, extremely high and extremely low power). The Ragone chart was first used to compare performance of batteries, however, it is suitable to compare any energy-storing devices, FigX. Conceptually, the vertical axis describes how much energy is available, while the horizontal axis shows how quickly that energy can be delivered, otherwise known as power, per unit mass. A point in a Ragone chart thus represents the amount of time during which the energy (per mass) on the Y-axis can be delivered at the power (per mass) on the X-axis, and that time (in hours) is given as the ratio between the energy and the power densities. Consequently, the iso curves in a Ragone chart are straight lines with unity slope.

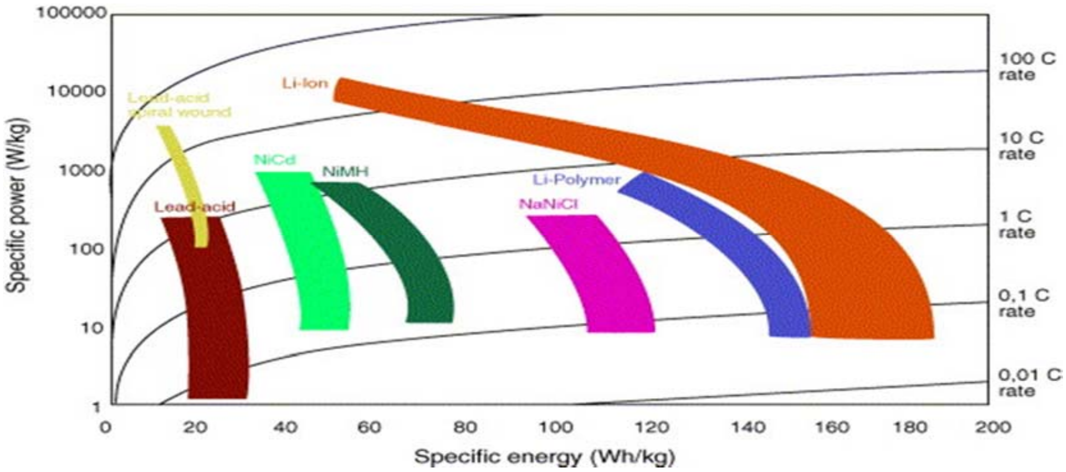


Figure 3-3: Ragone chart for different batteries

3.3 Battery chemistries

Lead Acid

Invented by the French physician Gaston Planté in 1859, lead acid was the first rechargeable battery for commercial use and continues to be in wide use today. There are good reasons for its popularity; lead acid is dependable and inexpensive on a cost-per-watt base. There are few other batteries that deliver bulk power as cheaply as lead acid, and this makes the battery cost-effective for automobiles, golf cars, forklifts, marine and uninterruptible power supplies (UPS).

The grid structure of the lead acid battery is made from a lead alloy. Pure lead is too soft and would not support itself, so small quantities of other metals are added to get the mechanical strength and improve electrical properties. The most common additives are antimony, calcium, tin and selenium. These batteries are often known as “lead-antimony” and “leadcalcium.”

Adding antimony and tin improves deep cycling but this increases water consumption and escalates the need to equalize. Calcium reduces self-discharge, but the positive lead-calcium plate has the side effect of growing due to grid oxidation when being over-charged. Modern lead acid batteries also make use of doping agents such as selenium, cadmium, tin and arsenic to lower the antimony and calcium content. Lead acid is heavy and is less durable than nickel- and lithium-based systems when deep cycled. A full discharge causes strain and each discharge/charge cycle permanently robs the battery of a small amount of capacity. This loss is small while the battery is in good operating condition, but the fading increases once the performance drops to half the nominal capacity.

Depending on the depth of discharge, lead acid for deep-cycle applications provides 200 to 300 discharge/charge cycles. The primary reasons for its relatively short cycle life are grid corrosion on the positive electrode, depletion of the active material and expansion of the positive plates. This aging phenomenon is accelerated at elevated operating temperatures and when drawing high discharge currents.

Charging a lead acid battery is simple, but the correct voltage limits must be observed.

Lead acid has a moderate life span, but it is not subject to memory as nickel-based systems are, and the charge retention is best among rechargeable batteries. While NiCd loses approximately 40 percent of their stored energy in three months, lead acid self-discharges the same amount in one year. The lead acid battery works well at cold temperatures and is superior to lithium-ion when operating in subzero conditions.

At classic lead acid batteries sulphate accumulation prevents the delivering of sustained performance; partial charge and aging are the main culprits because the negative lead plate is not sufficiently scrubbed. The advanced lead-carbon (ALC) solves this by adding carbon to the negative plate (cathode). This turns the battery into a *quasi-asymmetric supercapacitor* to improve charge and discharge performance, as shown.

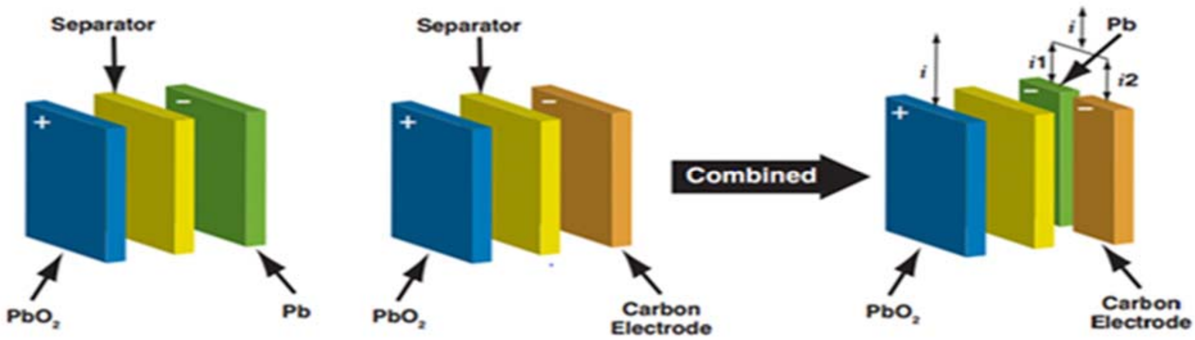


Figure 3-4: The classic lead acid develops into an advanced lead-carbon battery, the negative plate is replaced with a carbon electrode that shares the qualities of a supercapacitor

Nickel - Based Batteries

For 50 years, portable devices relied almost exclusively on nickel-cadmium (NiCd). This generated a large amount of data, but in the 1990s, nickel-metal-hydride (NiMH) took over the reign to solve the toxicity problem of the otherwise robust NiCd. Many of the characteristics of NiCd were transferred to the NiMH camp, offering a quasi-replacement as these two systems are similar. Because of environmental regulations, NiCd is limited to specialty applications today.

Nickel-cadmium (NiCd)

Invented by Waldemar Jungner in 1899, the nickel-cadmium battery offered several advantages over lead acid, then the only other rechargeable battery; however, the materials for NiCd were expensive. Developments were slow, but in 1932, advancements were made to deposit the active materials inside a porous nickel-plated electrode. Further improvements occurred in 1947 by absorbing the gases generated during charge, which led to the modern sealed NiCd battery. For many years, NiCd was the preferred battery choice for two-way radios, emergency medical equipment, professional video cameras and power tools. In the late 1980s, the ultra-high capacity NiCd rocked the world with capacities that were up to 60 percent higher than the standard NiCd. Packing more active material into the cell achieved this, but the gain was shadowed by higher internal resistance and reduced cycle count.

The standard NiCd remains one of the most rugged and forgiving batteries, and the airline industry stays true to this system, but it needs proper care to attain longevity. NiCd, and in part also NiMH, have memory effect that causes a loss of capacity if not given a periodic full discharge cycle. The battery appears to remember the previous energy delivered and once a routine has been established, it does not want to give more. Table X lists the advantages and limitations of the standard NiCd.

Nickel – Metal – Hybrid

Research on nickel-metal-hydride started in 1967; however, instabilities with the metal-hydride led to the development of the nickel-hydrogen (NiH) instead. New hydride alloys discovered in the 1980s eventually improved the stability issues and today NiMH provides 40 percent higher specific energy than the standard NiCd. Nickel-metal-hydride is not without drawbacks. The battery is more delicate and trickier to charge than NiCd. With 20 percent self-discharge in the first 24 hours after charge and 10 percent per month thereafter, NiMH ranks among the highest in the class. Modifying the hydride materials lowers the self-discharge and reduces corrosion of the alloy, but this decreases the specific energy. Batteries for the electric powertrain make use of this modification to achieve the needed robustness and long life span.

NiMH has become one of the most readily available rechargeable batteries for consumer use. Available in AA, AAA and other sizes, these cells can be used in portable devices designed for these norms. Even though the cell voltages may vary, the end-of-discharge voltages are common, which is typically 1V/cell. Portable devices have some flexibility in terms of voltage range.

Nickel-iron (NiFe)

The nickel-iron battery (NiFe) uses an oxide-hydroxide cathode and an iron anode with potassium hydroxide electrolyte. They do not use constant voltage charge as with lead acid and lithium-ion batteries, but allow the voltage to float freely.. NiFe is resilient to overcharge and over-discharge and can last for more than 20 years in standby applications. Resistance to vibrations and high temperatures made NiFe the preferred battery for mining in Europe; during World War II the battery powered German V-1 flying bombs and the V-2 rockets. Other uses are railroad signaling, forklifts and stationary applications.

NiFe has a low specific energy of about 50Wh/kg, has poor low-temperature performance and exhibits high self-discharge of 20–40 percent a month. This, together with high manufacturing cost, prompted the industry to stay faithful to lead acid. Though, improvements are being made, and NiFe is becoming a viable alternative to lead acid in off-grid power systems. Pocket plate technology lowered the self-discharge; the battery is virtually immune to over- and under-charging and should last for over 50 years. This compares to less than 12 years with deep cycle lead acids in cycling mode. NiFe costs about four times as much as lead acid and is comparable with Li-ion in purchase price.

Nickel-zinc (NiZn)

Nickel-zinc is similar to nickel-cadmium in that it uses an alkaline electrolyte and a nickel electrode, but it differs in voltage; NiZn provides 1.65V/cell rather than 1.20V, which NiCd and NiMH deliver. NiZn charges at a constant current to 1.9V/cell and cannot take trickle charge, also known as maintenance charge. The specific energy is 100Wh/kg and can be cycled 200–300 times. NiZn has no heavy toxic materials and can easily be recycled. Some packaging is available in the AA cell format.

In 1901, Thomas Edison was awarded the U.S. patent for a rechargeable nickel–zinc battery system that was installed in rail cars between 1932 and 1948. NiZn suffered from high self-discharge and short cycle life caused by dendrite growth, which often led to an electrical short. Improvements in the electrolyte have reduced this problem, and NiZn is being considered again for commercial uses. Low cost, high power output and good temperature operating range make this chemistry attractive.

Lithium Based Batteries

Pioneering work of the lithium battery began in 1912, but it was not until the early 1970s that the first non-rechargeable lithium batteries became commercially available. Attempts to develop rechargeable lithium batteries followed in the 1980s but failed because of instabilities in the metallic lithium used as anode material.

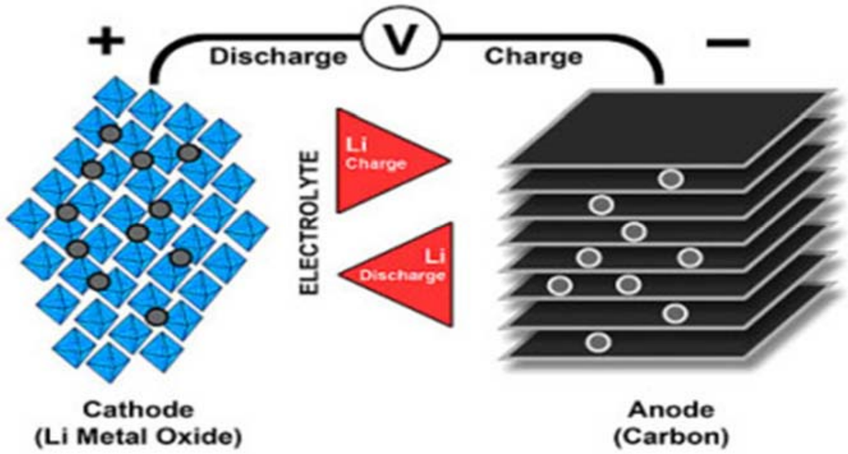


Figure 3-5: Lithium-ion uses a cathode (positive electrode), an anode (negative electrode) and electrolyte as conductor. The cathode is metal oxide and the anode consists of porous carbon. During discharge, the ions flow from the anode to the cathode through the electrolyte and separator; charge reverses the direction and the ions flow from the cathode to the anode. Figure 1 illustrates the process.

Lithium is the lightest of all metals, has the greatest electrochemical potential and provides the largest specific energy per weight. Rechargeable batteries with lithium metal on the anode can provide extraordinarily high energy densities; however, it was discovered in the mid-1980s that cycling produced unwanted dendrites on the anode. These growth particles penetrate the separator and cause an electrical short. The cell temperature would rise quickly and approach the melting point of lithium, causing thermal runaway, also known as “venting with flame.”

The inherent instability of lithium metal, especially during charging, shifted research to a non-metallic solution using lithium ions. Nowadays, this chemistry has become the most promising and fastest growing battery on the market.

Lithium Cobalt Oxide ($LiCoO_2$)

Its high specific energy makes Li-cobalt the popular choice for mobile phones, laptops and digital cameras. The battery consists of a cobalt oxide cathode and a graphite carbon anode. The cathode has a layered structure and during discharge, lithium ions move from the anode to the cathode. The flow reverses on charge. The drawback of Li-cobalt is a relatively short life span, low thermal stability and limited load capabilities (specific power). Figure 1 illustrates the structure. Li-cobalt cannot be charged and discharged at a current higher than its C-rating.

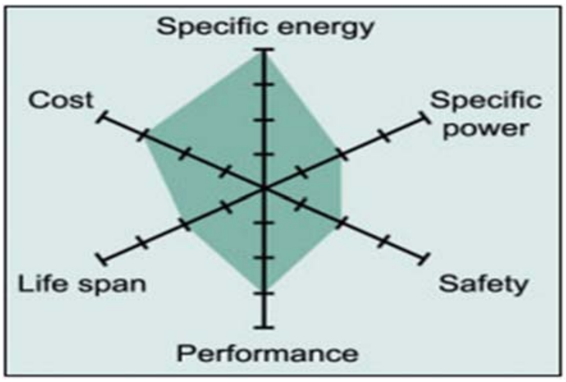


Figure 3-6: Li-cobalt structure.

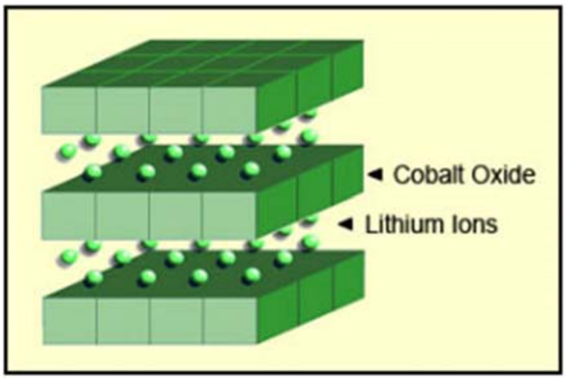


Figure 3-7: Snapshot of an average Li-cobalt battery. Li-cobalt excels on high specific energy but offers only moderate performance specific power, safety and lifespan.

Lithium Manganese Oxide (LiMn2O4)

In 1996, a Li-ion cell with lithium manganese oxide as cathode material was commercialized. The architecture forms a three-dimensional spinel structure that improves ion flow on the electrode, which results in lower internal resistance and improved current handling. A further advantage of spinel is high thermal stability and enhanced safety, but the cycle and calendar life are limited. Low internal cell resistance enables fast charging and high-current discharging.

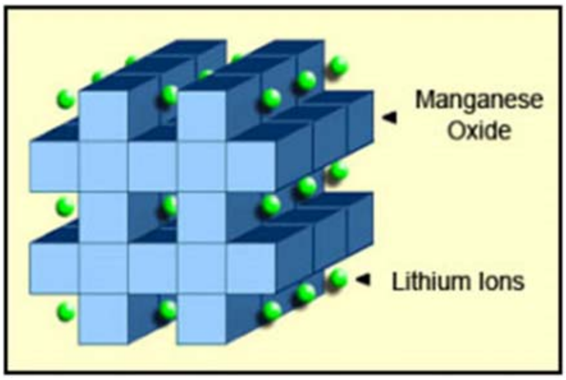


Figure 3-8: Li-manganese structure. The cathode crystalline formation of lithium manganese oxide has a three-dimensional framework structure that appears after initial formation. Spinel provides low resistance but has a moderate specific energy than cobalt

Li-manganese has a capacity that is roughly one-third lower than Li-cobalt. Design flexibility allows engineers to maximize the battery for either optimal longevity (life span), maximum load current (specific power) or high capacity (specific energy). For example, the long-life version in the 18650 cell has a moderate capacity of only 1,100mAh; the high-capacity version is 1,500mAh.

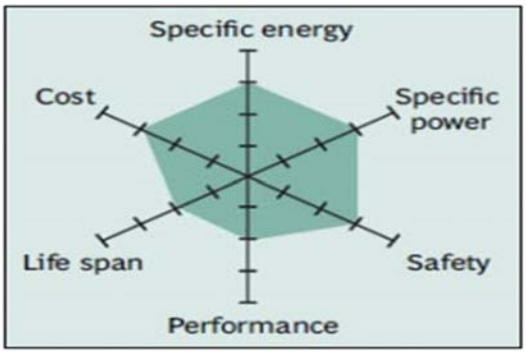


Figure 3-9: Spider web of a pure Li-manganese battery. Alhough moderate in overall performance new designs of Li-manganese offer improvements in specific power, safety and life-span.

Most Li-manganese batteries blend with lithium nickel manganese cobalt oxide (NMC) to improve the specific energy and prolong the life span. This combination brings out the best in each system, and the LMO (NMC) is chosen for most electric vehicles. The LMO part of the battery, which can be about 30 percent, provides high current boost on acceleration; the NMC part gives the long driving range.

Li-ion research gravitates heavily towards combining Li-manganese with cobalt, nickel, manganese and/or aluminum as active cathode material. In some architecture, a measured amount of silicon is added to the anode. This provides a 25 percent capacity boost; however, the gain is commonly connected with a shorter cycle life as silicon grows and shrinks with charge and discharge, causing mechanical stress.

These three active metals, as well as the silicon enhancement can conveniently be chosen to enhance the specific energy (capacity), specific power (load capability) or longevity. While consumer batteries go for high capacity, industrial applications require battery systems that have good loading capabilities, deliver a long life and provide safe and dependable service.

Lithium Nickel Manganese Cobalt Oxide (LiNiMnCoO2 or NMC)

One of the most successful Li-ion systems is a cathode combination of nickel-manganese-cobalt (NMC). Similar to Li-manganese, these systems can be tailored to serve as Energy Cells or Power Cells. NMC is the battery of choice for power tools, e-bikes and other electric powertrains. The cathode combination is typically one-third nickel, one-third manganese and one-third cobalt, also known as 1-1-1. This offers a unique blend that also lowers the raw material cost due to reduced cobalt content. Another successful combination is NCM with 5 parts nickel, 3 parts cobalt and 2 parts manganese. Further combinations using various amounts of cathode materials are possible. New electrolytes and additives enable charging to 4.4V/cell and higher to boost capacity.

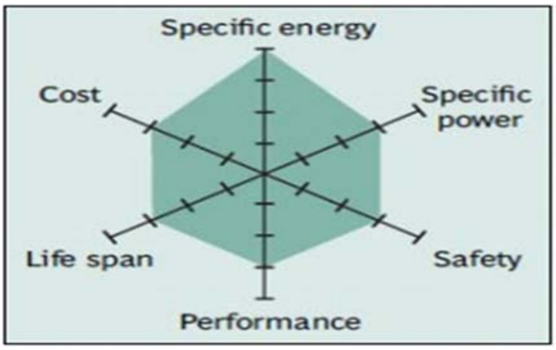


Figure 3-10: Snapshot of NMC characteristics, NMC has good overall performance and excels on specific energy. This battery is preferred for the electric vehicles cause of the low self-heat rate.

There is a move towards NMC-blended Li-ion as the system can be built economically and it achieves a good performance. The three active materials of nickel, manganese and cobalt can easily be blended to suit a wide range of applications for automotive and energy storage systems (EES) that need frequent cycling. The NMC family is growing in its diversity.

Lithium Iron Phosphate (LiFePO4)

In 1996, the University of Texas (and other contributors) discovered phosphate as cathode material for rechargeable lithium batteries. Li-phosphate offers good electrochemical performance with low resistance. This is made possible with nano-scale phosphate cathode material. The key benefits are high current rating and long cycle life, besides good thermal stability, enhanced safety and tolerance if abused.

Li-phosphate is more tolerant to full charge conditions and is less stressed than other lithium-ion systems if kept at high voltage for a prolonged time. As a trade-off, the lower voltage of 3.2V/cell reduces the specific energy to less than that of Li-manganese. With most batteries, cold temperature reduces performance and elevated storage temperature shortens the service life, and Li-phosphate is no exception. Li-phosphate has a higher self-discharge than other Li-ion batteries, which can cause balancing issues with aging.

Li-phosphate is often used to replace the lead acid starter battery. Four cells in series produce 12.80V, a similar voltage to six 2V lead acid cells in series. Vehicles charge lead acid to 14.40V (2.40V/cell) and maintain a topping charge. With four Li-phosphate cells in series, each cell tops at 3.60V, which is the correct full-charge voltage. At this point, the charge should be disconnected but the topping charge continues while driving. Li-phosphate is tolerant to some overcharge; however, keeping the voltage at 14.40V for a prolonged time, as most vehicles do on a long drive, could stress Li-phosphate. Cold temperature operation starting could also be an issue with Li-phosphate as a starter battery.

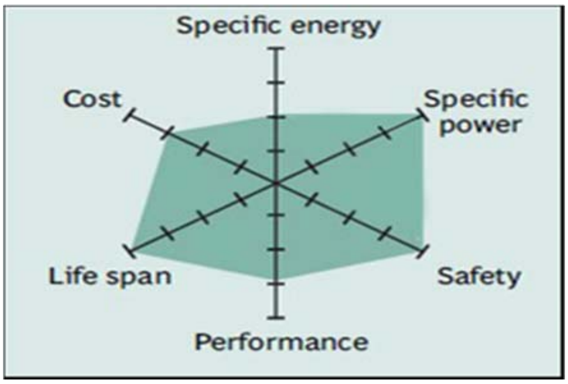


Figure 3-11: Snapshot of a typical Li-phosphate battery. Li-phosphate has excellent safety and long life span but moderate specific energy and elevated self-discharge.

Lithium Nickel Cobalt Aluminum Oxide (LiNiCoAlO2)

Lithium nickel cobalt aluminum oxide battery, or NCA, has been around since 1999 for special applications. It shares similarities with NMC by offering high specific energy, reasonably good specific power and a long life span. Less flattering are safety and cost. NCA is a further development of lithium nickel oxide; the adding of aluminum gives the chemistry greater stability.

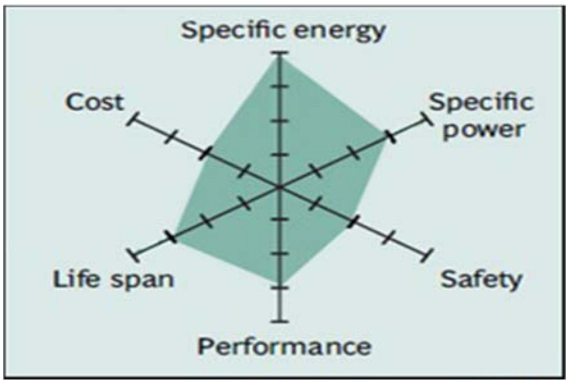


Figure 3-12: Snaphot of NCA batteries characteristics. High energy and power densities, as well as good life span, make NCA a candidate for EV powertrains. High cost and marginal safety are negatives.

Lithium Titanate (Li4Ti5O12)

Batteries with lithium titanate anodes have been known since the 1980s. Li-titanate replaces the graphite in the anode of a typical lithium-ion battery and the material forms into a spinel structure. The cathode is graphite and resembles the architecture of a typical lithium-metal battery. Li-titanate has a nominal cell voltage of 2.40V, can be fast charged and delivers a high discharge current of 10C, or 10 times the rated capacity. The cycle count is said to be higher than that of a regular Li-ion. Li-titanate is safe, has excellent low-temperature discharge characteristics and obtains a capacity of 80 percent at –30°C (–22°F). However, the battery is expensive and at 65Wh/kg the specific energy is low, rivalling that of NiCd. Li-titanate charges to 2.80V/cell, and the end of discharge is 1.80V/cell. Figure 13 illustrates the characteristics of the Li-titanate battery. Typical uses are electric powertrains, UPS and solar-powered street lighting.

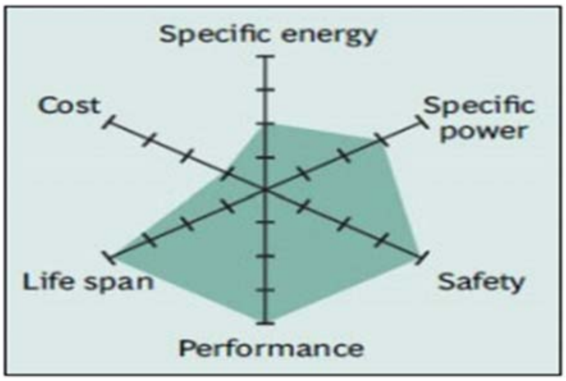


Figure 3-13: snapshot of Li-titanate.Li-titanate excels in safety, low-temperature performance and life span. Efforts are being made to improve the specific energy and lower cost.

Li-Polymer

Lithium-polymer differs from other battery systems in the type of electrolyte used. The original polymer design dating back to the 1970s used a solid (dry) polymer electrolyte that resembles a plastic-like film. This insulator allows the exchange of ions (electrically charged atoms) and replaces the traditional porous separator that is soaked with electrolyte.

A solid polymer has poor conductivity at room temperature, and the battery must be heated to 60°C (140°F) and higher to enable current flow. Large polymer batteries for stationary applications were installed that needed heating, but these have since disappeared. To make the modern Li-polymer battery conductive at room temperature, gelled electrolyte has been added. Most Li-ion polymer cells today incorporate a micro porous separator with some moisture. Li-polymer can be built on many systems, the likes of Li-cobalt, NMC, Li-phosphate and Li-manganese, and is not considered a unique battery chemistry. The majority of Li-polymer packs are cobalt based; other active material may also be added.

As far as the user is concerned, lithium polymer is essentially the same as lithium-ion. Both systems use identical cathode and anode material and contain a similar amount of electrolyte. Li-polymer is unique in that a micro porous electrolyte replaces the traditional porous separator. Li-polymer offers slightly higher specific energy and can be made thinner than conventional Li-ion, but the manufacturing cost is said to be higher than cylindrical design.

While a standard Li-ion needs a rigid case to press the electrodes together, Li-polymer uses laminated sheets that do not need compression. A foil-type enclosure reduces the weight by more than 20 percent over the classic hard shell. Thin film technology liberates the design as the battery can be made into any shape Li-polymer can also be made very slim to resemble a credit card. Light weight and high specific power make Li-polymer the preferred choice for hobbyists.

Charge and discharge characteristics of Li-polymer are identical to other Li-ion systems and do not require a dedicated charger. Safety issues are also similar in that protection circuits are needed. Gas buildup during charge can cause some prismatic and pouch cells to swell, and equipment manufacturers must make allowances for expansion. Li-polymer in a foil package may be less durable than Li-ion in the cylindrical package.

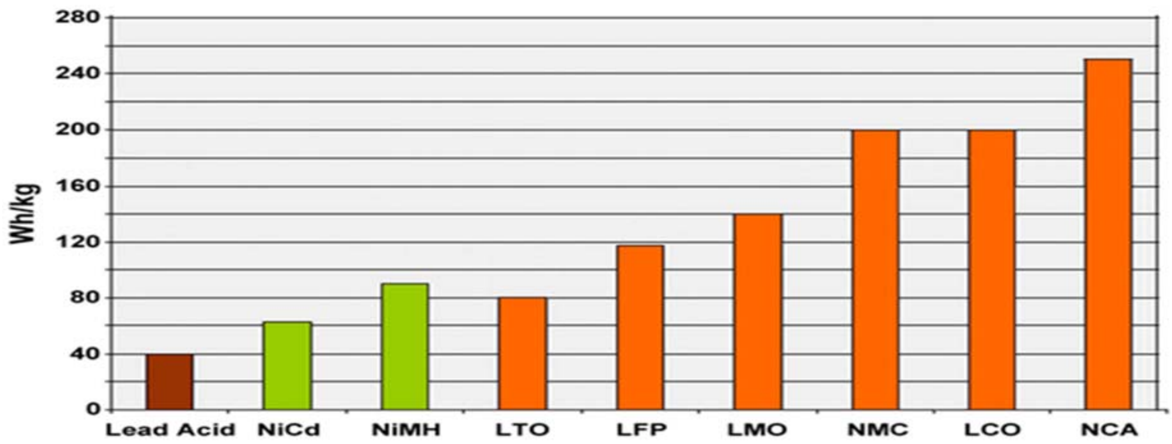


Figure 3-14: Comparison of specific energy of lead-, nickel- and lithium based systems

Li-aluminum (NCA) is the clear winner by storing more capacity than other systems, this only applies to specific energy. In terms of specific power and thermal stability, Li-manganese (LMO) and Li-phosphate (LFP) are superior. Li-titanate (LTO) may have low capacity but this chemistry outlives most other batteries in terms of life span and also has the best cold temperature performance.

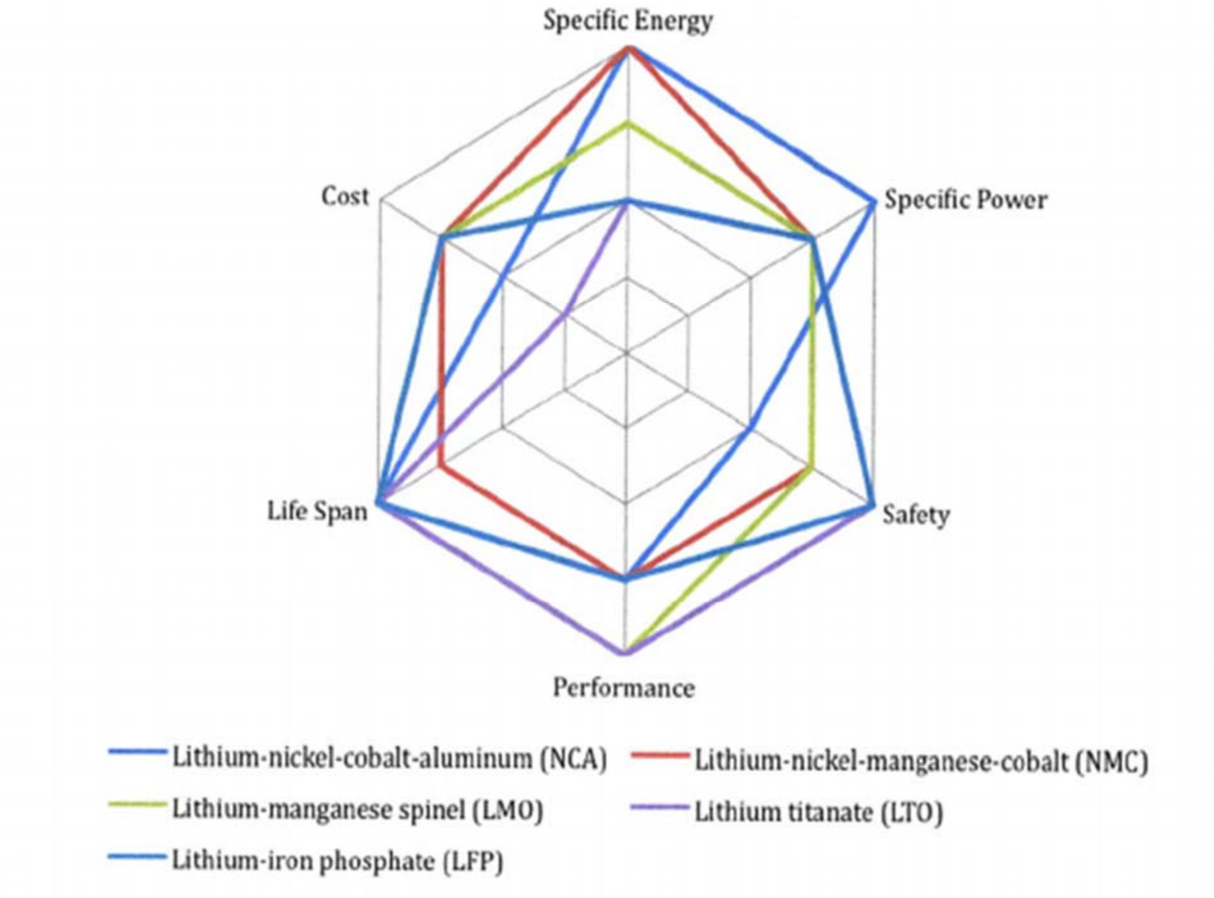


Figure 3-15

It is the huge development in lithium-ion batteries over the past few years and, in particular, the adoption of high-quality batteries for electric and hybrid vehicles and large-scale grid systems that have now made battery systems a viable option for maritime applications. The maritime-focused systems have mainly been based on Li-ion cells with NMC (Nickel Manganese Cobalt Oxide) cathodes and graphite anodes. Systems based on iron-phosphate cathodes have also been used. Both the NMC and iron-phosphate chemistries represent a good compromise between the most important parameters of safety, energy, power density, cycle life and cost. (Lu, 2012)

Table 3-1: Overview of battery technologies characteristics

				Cobalt	Manganese	Phosphate
Specific energy (Wh/kg)	30–50	45–80	60–120	150–250	100–150	90–120
Internal resistance	Very Low	Very low	Low	Moderate	Low	Very low
Cycle life[2] (80% DoD)	200–300	1,000[3]	300–500[3]	500–1,000	500–1,000	1,000–2,000
Charge time[4]	8–16h	1–2h	2–4h	2–4h	1–2h	1–2h
Overcharge tolerance	High	Moderate	Low	Low. No trickle charge		
Self-discharge/ month (room temp)	5%	20%[5]	30%[5]	<5% Protection circuit consumes 3%/month		
Cell voltage (nominal)	2V	1.2V[6]	1.2V[6]	3.6V[7]	3.7V[7]	3.2–3.3V
Charge cutoff voltage (V/cell)	2.40 Float 2.25	Full charge detection by voltage signature		4.20 typical Some go to higher V		3.60
Discharge cutoff voltage (V/cell, 1C)	1.75V	1.00V		2.50–3.00V		2.50V
Peak load current Best result	5C[8] 0.2C	20C 1C	5C 0.5C	2C <1C	>30C <10C	>30C <10C
Charge temperature	–20 to 50°C (–4 to 122°F)	0 to 45°C (32 to 113°F)		0 to 45°C[9] (32 to 113°F)		
Discharge temperature	–20 to 50°C (–4 to °F)	–20 to 65°C (–4 to 49°F)		–20 to 60°C (–4 to 140°F)		
Maintenance requirement	3–6 months[10] (toping chg.)	Full discharge every 90 days when in full use		Maintenance-free		
Safety requirements	Thermally stable	Thermally stable, fuse protection		Protection circuit mandatory[11]		
In use since	Late 1800s	1950	1990	1991	1996	1999
Toxicity	Very high	Very high	Low	Low		
Coulombic efficiency[12]	~90%	~70% slow charge ~90% fast charge		99%		
Cost	Low	Moderate		High[13]		

Batteries are the most economical for larger power applications where weight is of little concern.

Nickel Cadmium (NiCd) batteries are mature and well understood but relatively low in energy density. They are used where long life, high discharge rate and economical price are important. The NiCd batteries contain toxic metals and are environmentally unfriendly.

Nickel - Metal Hydride (NiMH) batteries have a higher energy density compared to the NiCd at the expense of reduced cycle life. However, this type of batteries does not contain any toxic metals.

Lithium Ion (Li-ion) batteries are the fastest growing battery system. Li-ion are used where high-energy density and lightweight is of prime importance. This type of batteries do not require maintenance. Nevertheless, the technology is fragile and a protection circuit is required to assure safety.

Lithium Ion Polymer (Li-ion polymer) batteries offer the attributes of the Li-ion in ultra-slim geometry and simplified packaging.

Lithium Iron Phosphate (Lithium-Phosphate) batteries have lower energy density than common lithium-ion batteries, but offer longer lifetimes, better power density and are naturally safer.

Experimenting with cathode and anode material allows manufacturers to strengthen intrinsic qualities, but one enhancement may compromise another. As above figures shows, there is no ultimate chemistry that supersedes others along all parameters yet at least. A chemistry that optimizes safety, for example, compromises other dimensions such as specific energy and power-as in the case of lithium-ion phosphate (LFP). The best performing chemistries are either less safe (LMO) or too expensive (LTO). While it is generally accepted that lithium-ion batteries are the highest performing commercial batteries the still exhibit some limitations that need to overcome. (TRONCOSO, 2013)

Maritime battery systems are mostly based on the same or very similar large-format cells as those used for EVs and hybrid cars. However, the maritime battery system design is more related to the MWh systems designed for grid installations. The size, voltage and power requirements of such systems are quite similar to those for hybrid installations in ships whereas safety related requirements may differ. The cost level for energy-optimized maritime battery systems is expected to reach the 500 USD/kWh level, where the grid systems are today, within a few years. (DNV-GL, 2014)

All characteristics stated above makes Li-ion and Li-polymer suitable for marine applications

Finally, all prediction from prominent people of the battery industry foresee an expansion of battery use in every sector of our lives.

"I do think that cost per kWh at the cell level will decline below $200, in the not-too-distant future." *Elon Musk, CEO Tesla Motors.*

"Today there are prototypes out there with 400 Wh/kg, the industry is in a period of rapid transformation*." Gary Smyth, GM Director of Global Research and Development.*

"In the next 3-4 years there will be more progress in battery development than the previous 100 years*." Ian Robertson, BMW Board Member.*

"Through mass production, we will soon lower production costs to a quarter of what they were in 2009." *President Makoto Yoda, GS Yuasa Corp (Mitsubishi Motors Corp battery supplier).*

As clearly stated in these quotes, there are on-going and potentially transformative developments in the battery sector. On short and medium sight, significant increase in cycle life, energy density and lower cost are expected. Predictions given by McKinsey&Co, indicate that complete battery packs of automotive quality (which in quality is comparable to what is required for a marine battery pack), will drop in price from current 500 US$/kWh to 200 US$/kWh in 2020 and 160 US$/kWh in 2025.

The cost decrease will partly be due to increased manufacturing volumes, cost decreases in the supply chain and improved yield. On the technology aspects, significant improvements in energy density, which will also lead to lower cost per kWh, are expected. Additional cost reductions may accompany the entry of battery technologies into new markets. There will be significant improvements in C-rates, power density, safety and life-expectancy.

On longer term, future technologies like Li-Air, Li-Sulfur and other similar chemistries will be available. Improvements in electrode materials will boost power capabilities which are important for hybrid applications. Together with improved cycle life, power batteries can be made much smaller and thus cheaper than today's solutions. Such development will expand the market for marine battery systems significantly. The trend is supposed to go towards more specialized solutions.

4. Methodology’s delimitation

Purpose of this study, as aforementioned, is the creation of a generic model investigating the technical design of the retrofit of double-ended Ro/Pax ferries into battery-powered ones. Both a technical and a financial point of view are offered including necessary shore’s adaptation. An electrification design methodology has been developed in order to assess the retrofit options. Eco-benefit has also been taken into account.

As we understand the electrification of these so widely used vessels may be cost-demanding but can offer a great advantage for local societies, contributing significantly towards a cleaner environment and a more sustainable shipping. Battery system will be vessel’s unique source of power. Ship’s propulsion and hoteling loads are to be served from it, so much attention should be given at their calculation.

4.1 Project overview

In their current state the vast majority of Ro/Pax ferries serving routes under investigation is of ”open-type” and has been constructed with two bows, a certainly practical design solution. Their double ended shape offers elimination of maneuvering time; they connect the neighboring coastal cities, coming back and forth as if on a track.

Figure 4-4-1: Photos of typical double-ended Ro/Pax ferry serving Greek waterways

As implied from their hull’s form, their propulsion system is based on 2 or 4 azipod thrusters installed in both ends of vessels, coupled to corresponding number of diesel engines of equivalent power output. This characteristic, also, means at least 2 different engine rooms and their adjacent fuel tanks at both ends of ships.

Currently operating double-ended Ro/Pax ferries’ main machinery consists of:

- two or four medium-speed diesel engines for powering (corresponding) number of azipod thrusters for propulsion, located at both ends of ships. Thrusters and diesel engines have the same nominal power output
- two or three diesel electric generators for the power of hoteling loads
- an emergency generator located above the weather-deck

Vessels are designed to use all thrusters to achieve $V_{SERVICE}$. In some routes, though, with high frequency of itineraries and where ports are in very close proximity it is acceptable to cruise at a lower speed using almost half of their propulsion power. Due to the very short duration of voyage, 7-9 min, a small delay of 1-2 min is unnoticeable for passengers but may be a huge economic benefit for ship owners. Of course, in case of an emergency all azipod thrusters can be utilized and rotated. Therefore, much attention should be given into battery system sizing in order to keep it redundant and economical. On Table 4.1, average main characteristics of these vessels are presented.

Table 4-1:Main characteristics of double-ended Ro/Pax vessels serving Greek waterways on 2016, (ΥΝΝΠ, 2016)

Average Main Dimensions	Main Machinery
L (Length) : 60 – 100 m	2 or 4 Azipod Thrusters of 300-660 kW each
B (Beam) : 14 – 20 m	2 or 4 Medium Speed D.E. of 300-660 kW each
T (Draft) : 1.7 – 2.7 m	2 or 3 Electric Generator of 200-400 kVA total
$V_{SERVICE}$: 6.5 – 8.5 knots	1 Emergency Generator of 50-80 kVA
Passengers : 300 – 600 prs	
Cars : 100 – 200 vehicles	
Trucks : 20 – 50 vehicles	Year Built : 2000-2016

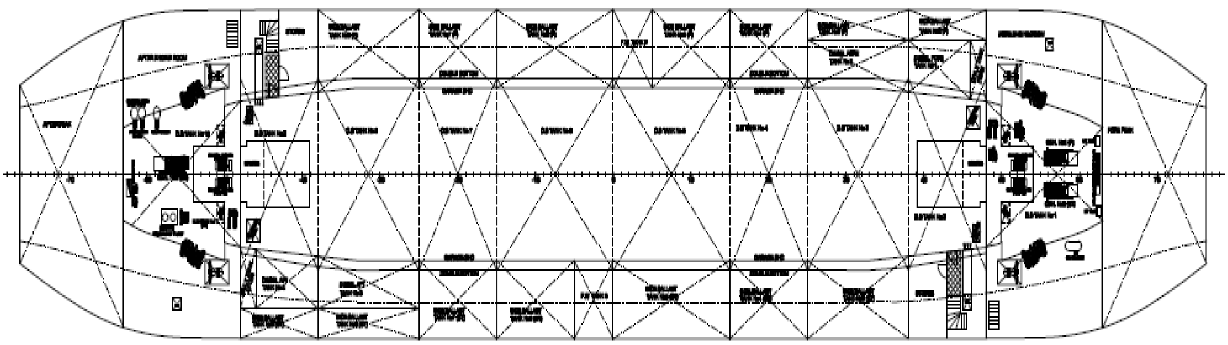


Figure 4-2:, Tank top view from a General Arrangement plan of a typical double-ended vessel, illustrating the two different engine rooms at both-ends of the ship and the four azipod thrusters.

Their electrical distribution network is AC 60 Hz,

For the investigated electrification of vessels, appropriate number of batteries will be installed on board, and will provide the demanded electrical energy for ships' propulsion and hoteling loads. Batteries will be recharged via shore connection while berthed from the utility grid. Modifications will be needed not only on board but on shore side, as well.

Specifically, the retrofit or electrification of vessels should consist of:

- Installation of appropriate number of battery modules forming battery packs in the place of existing fuel tanks

- Suitable arrangement of battery packs into arrays in order to ensure the required voltage and capacity(Ah) based on the desired operational profile and regulatory framework
- Location of the battery system shall be according national and international legislation
- Installation of Battery Management System
- Replacement of existing internal combustion diesel engines with electrical motors of the same power output responsible for driving thrusters
- Modifications on shaft and propeller for coupling new electric motors with existing thrusters
- Suitable transformation of ship's electrical distribution network
- Uninstallation of electric generators, thus/since the required electrical power will be provided directly from the battery system
- Installation of a connection point with shore-side for recharging

Appropriate modifications and installations will be needed on shore side, as well, which will consist of:

- Underground Cables
- At least one substation including :
  - Frequency converters and/or rectifiers
  - Power transformers
  - All the necessary protection equipment
- Interconnection equipment including
  - Plugs and sockets
  - Cables and cable reels
  - Cranks
  - Mooring system

The task of finding the optimal layout, sizing and setup of modifications both on shore and on board is a multivariate problem. Many parameters need to be taken into consideration both from the technical side/design, operational requirements of the route in question and safety criteria, for the optimization of this task. Main priorities of a battery system for maritime applications are safety and reliability of the passengers and the vessel, and sufficient life for the system to be economically feasible.

4.2 Legal & Regulatory framework

In order to proceed to the technical design of ship's retrofit with batteries and shore side's charging system, we need firstly to have an overview and make sure to comply with current legislations which state the prerequisites for launching certified a battery powered ship published from flag-state authorities, International Maritime Organization (I.M.O.), I.E.C. and different international registries either as mandatory rules or guidelines

According to I.M.O.'s rules (EUROSOLAS-directive 98/18/EC),to which Greece as a member state and as flag-state authority complies, state the following for double-ended Ro/Pax vessels under retrofit:

- Belong to class D, for passenger ships engaged only on domestic voyages in sea areas where the probability of significant wave heights exceeding 1.5 meters is less than 10% over a one year period for all year round operation.
- Serve routes of categories: VI. Regional routes (≤ 6 nm)

VII. Protected zones

- Vessels serving routes VI and VII are allowed to be of “open-type”

Ensuing, legislation either from I.M.O. or Greek-state concerning vessels having batteries as unique source of power is absent and currently under development. Vessel after retrofit must ensure the same safety and integrity level as before, when powered from conventional internal combustion engines. SOLAS chapters for electrical installation and fire protection are the most suitable for our retrofit.

For the emergency cases related with the emergency generator and its fire-fighting capabilities we will not interfere. Our decision is to maintain the emergency generator as it placed, since it has already been dimensioned and approved.

It is important to note that the range of available cell chemistries makes it unfeasible to have a prescriptive set of rules for all available batteries in the market.

Next step is the selection of an international registry for the classification of the battery-powered vessel in order to have it certified “battery-ready”. Since this choice is a delicate matter it was preferred to look at more than one registries and present the most important points risen and related to our design.

In the following chapters the technical design of the battery system and its arrangement in the vessel is described, based on the following publications:

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

Figure 4-3: New fuel tanks (CORVUS, 2016)

4.3 Battery system

Battery System is the heart of our vessel; its' role is to provide energy for every function of the ship. The main components of the generic battery system are the cells, the hardware needed for making battery modules, sub packs, packs, the required components for thermal management, safety features as contactors and fuses, bus-bars and high voltage cabling, electronics, voltage and temperature sensors and low voltage cabling and connectors.

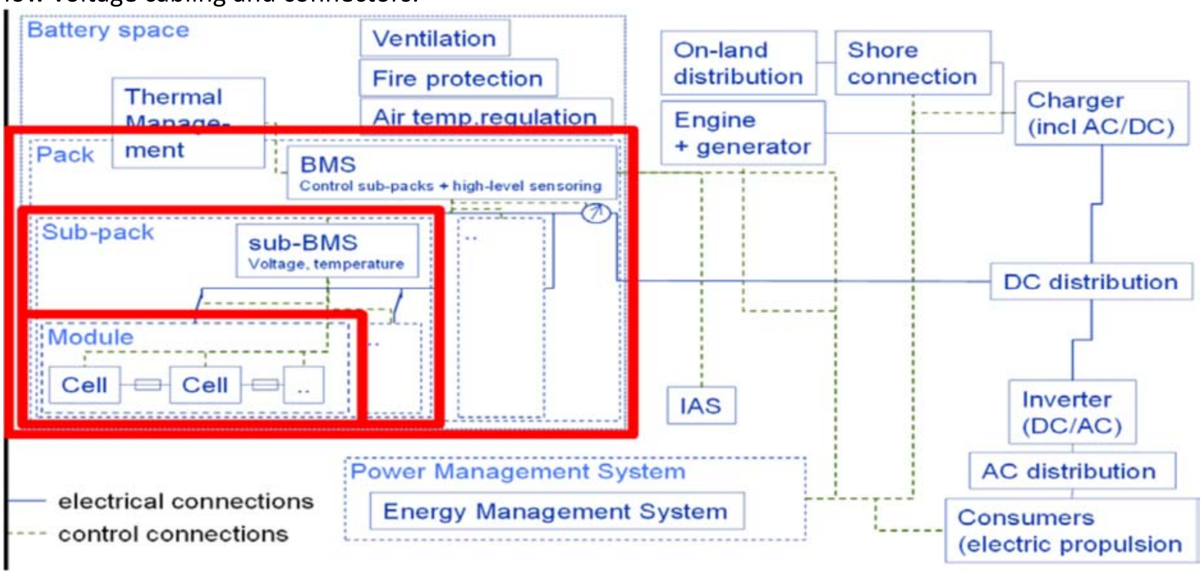


Figure 4-4:Battery system and related sub-systems (DNV, 2014)

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

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

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

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

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

CELL'S DANGERS:
- High Impedance
- Internal short circuit
- Insulation fault
- Electrolyte leakage

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

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

PACKS' DANGERS:

- High level sensor failure
- Voltage and temperature imbalance
- Battery life too short

- Contactor does not open/close when required
- Reverse polarity protection
- Emergency shutdown

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

Low contact impedance for the electrical connections is crucial to avoid over-heating and control the fire risk, as well as maximum efficiency. Several parallel strings will decrease the risk of overheating from increased contact impedance. It can also ease the detection of elevated levels of contact impedance in the electrical connections resulting in increased safety of the system.

The battery casing, covering modules and cells, shall be made of a flame-retardant material.

The requirements for Ingress Protection (IP) rating of the batteries depends on the location. As a minimum, IP 44 is required. IP 44 is required as a minimum based on the use of water-based fire extinguishing system in the battery space. If other extinguish system is used then the minimum IP rate can be reduce but not lower than IP2X for low voltage (< 1500 VDC) installations or IP32 for high voltage (> 1500 VDC) installations.

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

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

4.4 Battery system capacity

The required installed capacity (Ah) depends from vessel's operational profile and the following safety rules.

Battery sizing must ensure redundancy. Reliability and safety of the complete system must be at least as good as conventional vessels with internal combustion engines.

At least two completely independent battery packs/systems shall be installed. The useable energy of the battery system must be such that safe return to port is possible with one battery array not working.

Capacity of the battery system shall be sufficient for the intended operation of the vessel. Charging will be possible during port stay to keep acceptable state of charge and it must be verified sufficient for the planned voyage before leaving the port.

Battery capacity installed shall be designed for a safety margin of at least 10 % or higher for weather adjustments to propulsion energy consumption. Battery capacity installed is not designed to cope with extreme operational situations encountered only one or two times per year, for example the relocation to ship yard for maintenance. Instead mobile power packs should be an option for such planned deviations.

Emergency generator can be omitted if national flag authorities agree.

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

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

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

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

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

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

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

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

Battery lifetime shall be such that the business case is economically reasonable.

4.5 Battery system

Battery space is the physical installation room or space including walls, floor, ceiling, and all functions and components which contribute to keep the battery system in the defined space at a specified set of environmental conditions (e.g. temperature or moisture level). In our effort to ensure its optimum performance, appropriate controls and alarms ought to be installed.

It is obligatory to assess hazards from the design phase that may arise from batteries’ operation, and develop ways to eliminate these risks, with our goal being passengers’ and vessel’s safety. The biggest threat is, of course, overheating which may cause fire or gas leakage. Therefore, the guidelines presented here forth concerning battery space’s arrangement and operational environment’s controls and alarms should be carefully followed.

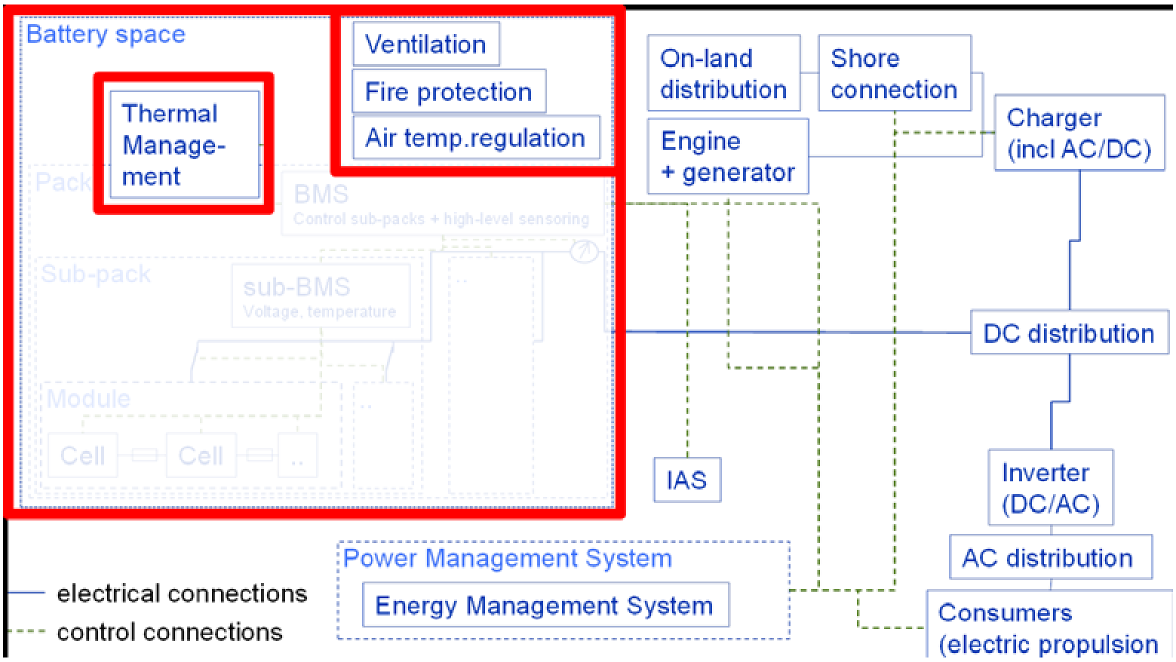


Figure 4-5: Illustration of battery system(DNV, 2014)

4.5.1 Arrangement

Arrangement of the battery spaces must be such that the safety of passengers, crew and vessel is ensured. In order to do so, the following points need to be applied:

Battery spaces shall be positioned aft of collision bulkhead. Boundaries of battery spaces shall be part of vessels structure or enclosures with equivalent structural integrity.

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

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

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

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

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

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

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

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

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

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

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

4.5.2 Operational Environment

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

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

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

- Air temperature regulation
- Ventilation
- Fire protection
- Thermal Management

The following shall be monitored and presented at a manned control station:

- ambient temperature of battery space
- indication of ventilation running.

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

- high ambient temperature in battery space
- failure of ventilation.

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

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

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

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

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

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

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

It is necessary to ensure proper detection of gases that may be emitted from the battery system. In the event of a serious fault conditioning, relief and ventilation of battery space to prevent the formation of explosive atmospheres is obligatory. The air at the exhaust outlet shall be monitored and give an alarm at 30 % LEL and interlocked to ensure automatic disconnection of the batteries. It shall de-energise any electrical circuit within the space upon detection exceeding lower explosion limit. These LEL conditions shall give alarm at bridge. A failure in the gas detection system should not lead to disconnection or de-energising of the batteries.

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

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

As a general fire extinguishing medium (heavy) foam could be, also, be considered. It's advantages are:
1. 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).
2. Potential off-gas which is warmer than air can be ventilated from a high position in the battery space while foam can be injected from the top and spreading slowly downwards.
3. 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, Controls and Alarms

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

More specifically,

The Battery Management System (BMS) shall:

- provide limits for charging and discharging to the charger (NA BALW K AFTA BILIES)
- protect against overcurrent, over-voltage and under-voltage)
- protect against over-temperature
- control cell balancing.
- protect against over-pressure (NiMH batteries)

The following parameters shall be measured:

- cell voltage
- cell temperature
- battery string current.

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

- system voltage
- max, min and average cell voltage
- max, min and average cell temperature
- battery string current
- ambient temperature
- electrical insulation resistance.

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

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

Finally, important battery parameters shall be logged and stored in a non-volatile memory.

4.7 Connection System

In principal there are two possible interconnection systems

- AC interconnection system
- DC 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.

4.7.1 Shore Side

These standards aim to establish the requirements to ensure compatibility between ship and high-voltage shore connection equipment, compatibility between ship and shore connection equipment, appropriate operating procedures; and encourage compliance with the standard so that a maximum number of ships can use shore connection equipment at as many ports as possible.

The standard guarantees simple, straightforward connection—eliminating the need for ships to make adaptations to their equipment at different ports. Ships that do not comply with the standard may find it impossible to connect to compliant shore supplies.

The standards cover: quality of the power supply, electrical requirements; environmental and mechanical requirements, safety, electrical equipment requirements, ship requirements, compatibility between shore connection and ship equipment, ship-to-shore connection and interface, plugs and sockets, verification and testing.

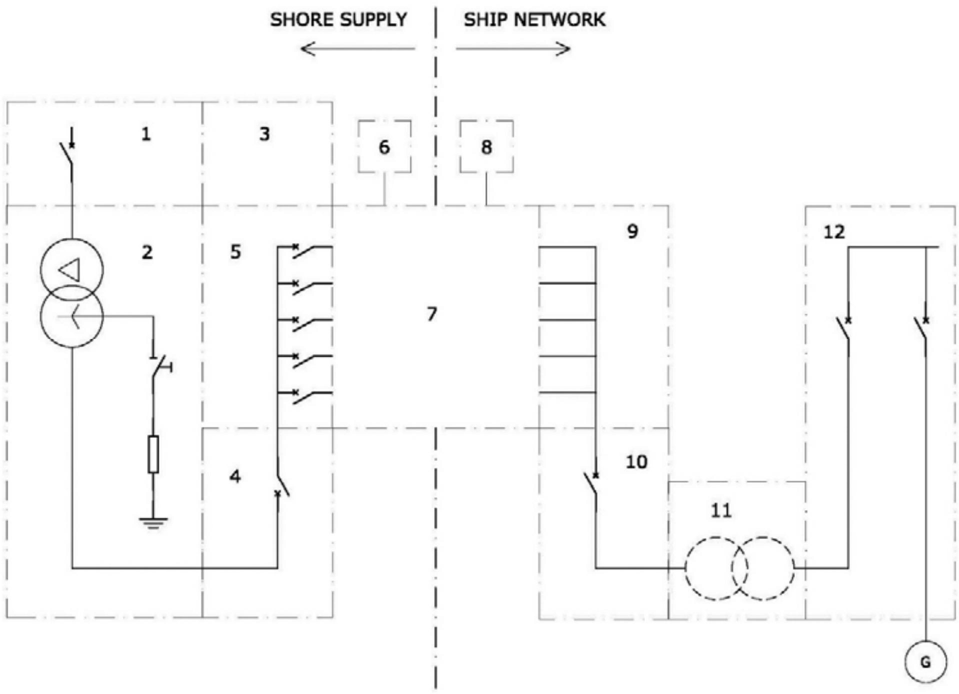


Figure 4-6: port side configuration for a LVSC system presented in IEC/ISO/IEEE 80005-3

The standards propose similar configurations for both the HVSC and the LVSC systems. The main difference between the two configurations consists of the earthing equipement and its relevant interlocks used in the High Voltage systems to avoid residual charges. Above figure illustrates the port side configuration for a LVSC system presented in IEC/ISO/IEEE 80005-3. The main components of this configuration are:

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.

One thing that both the HVSC and the LVSC systems have in common is the use of a dedicated isolated transformer as the last power component before the interconnection between the ship and the port. The term dedicated transformer means only one ship connection to one transformer to satisfy the galvanic isolation requirements, in order to protect the ship power system from abnormalities in the shore power system.

Many power system grounding problems and stray currents associated with other port facilities can affect the ship power-supply ground fault protection, unless the shore power system has its own grounding zone provided by a dedicated transformer with a neutral grounding resistor. The isolation transformer should be of Dyn configuration, with the star winding connected to the ship-side.

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 the neutral earthing resistor shall be continuously monitored. In the event of loss of continuity the shore-side circuit-breaker shall be tripped.

Equipment earthing conductors terminated at the shore power outlet box receptacles shall be connected to the ship and continued to the ship to create an equipotential bond between the 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.

Table 4-2: Number of feeding cables as a function of the maximum power demand and the voltage of the connection.

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

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 4-3: maximum corresponding current per cable

4.7.2 Ship Side

For an AC connection with shore side the vessel's system shall have its own battery charger(S) system.

The charger shall communicate with and operate within the limits given by the battery management system.

The charger shall be designed with the needed capacity specified by the battery application.

The charging system and shore connection shall include temperature sensors in order to detect high impedance and heating in an early stage.

The mating process of the shore connection shall be preferably automatic. If not, a risk assessment for involved personnel shall be done.

The charger should be designed in such a way that too high charge currents and voltages are *avoided.*

The charger shall be designed to prevent exceedance of the specified current level (C-rates) and voltage level.

Charging failure shall give alarm at a manned control station.

The charging system and other relevant systems shall detect the connection to shore power and activation of propulsion shall be inhibited in this case. Note that some applications will need propulsion power even when connected to shore power, in those cases safety measures must be taken to avoid unintended un-plugging of the charging interface.

Moreover the vessel's system shall comply with the following requirements:

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

An onboard shore connection switchboard shall be provided at a suitable location, as close as possible to the receiving point.

The distance between supply point and receiving point shall be as short as possible. The shore connection switchboard shall be in accordance with IEC 61439.

The switchboard shall include a circuit-breaker 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.

The circuit-breaker shall be in conformity with IEC 60947-2.

The rated making capacity of the circuit-breaker shall not be less than the prospective peak value of the short-circuit current (*I*P) 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 (*I*AC(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:

a) voltmeter: all three phases;

b) short-circuit devices: tripping and alarm; c) overcurrent devices: tripping and alarm; d) earth-fault indicator: alarm; and
e) 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.

Tripping and alarm criteria for the circuit-breaker shall be:

a) short-circuit: tripping with alarm,
b) overcurrent in two steps:
    1) alarm, and
    2) tripping with alarm,
c) earth fault:
    1) alarm,
    2) tripping if required by the type of isolation system used
d) over-/under-voltage in two steps:
    1) alarm, and
    2) tripping with alarm

e) over-/under-frequency in two steps:

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

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 propagation from connector to environment and vessel.

5. Conceptual design of electrical topologies

Most of modern double ended Ro/Pax vessels are equipped with two or four azipod propulsion motors located in independent machinery rooms. For the power supply of the electrical loads (lighting, air condition etc.) two diesel generators are usually installed in separated machinery rooms.

Sufficient and reliable power supply is a critical success factor for plug-in all-electric ships. Ship systems require an electricity supply with a stable voltage and at certain frequencies. The shore side needs to provide the required infrastructure in order for batteries in ships to be a success.

The electricity is supplied by the utility grid and distributed to the connection point or seaside terminal. One of the biggest advantages of the all-electric ship is that the amount of energy needed for the charging of batteries may have produced from renewable sources close to the port such as wind or solar power plants, leading to zero emission transportation means.

The mechanism of shore side electricity from ship to shore is not a simple cable but a complex system equipped with automations and alarms in order to achieve the safety requirements. All equipment designed to control, monitor and handle the LV or HV flexible power and control cables and their connection devices is called Cable Management System (CMS).

The following sections present the conceptual design of vessels' electrical topologies of and the shore-side's infrastructure. A short reference in the different types of CMS is presented in the last part of the chapter.

5.1 Vessel topologies

This chapter presents the one line diagrams of the power network configurations for the retrofit of a double ended RO/PAX ferry. The design philosophy was based on a vessel with four engine room and four individual battery packs, installed in every engine room for redundancy.

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.

For the grounding of the batteries an isolated system-isolated positive and negative terminal-is recommended by DNV-GL

Figure *5-1* bellow presents the one line diagram of the power network with a DC distribution system. The DC distribution system offers some advantages compared to the AC one, such as the amaller number of cables. Considering all the excising ferries have an AC distribution system, this configuration would be considered as an alternative for a new building and not for the retrofit of an existing vessel because it would significantly increase the cost of the investment as it would demand extensive modifications in the distribution network.

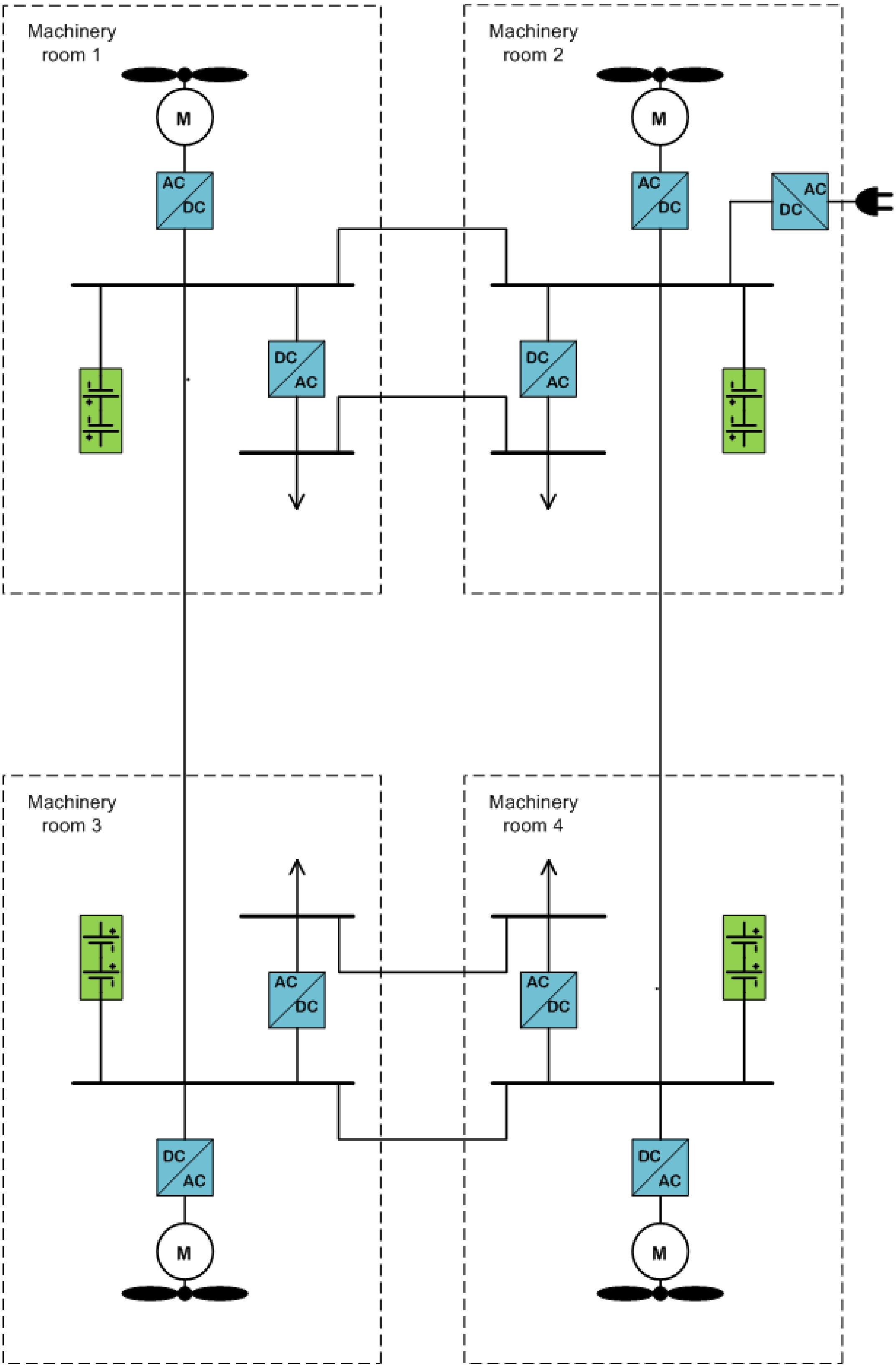


Figure 5-1 All-electric ship OLD with a DC distribution network

The main components of this configuration are:

- Four inverter (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
- 4 DC cables (2 conductors) for the interconnection of the machinery rooms.
- 4 DC buses

If a DC shore connection was utilized the on board rectifier could be omitted. Although this would lower the overall cost of the investment (port and vessel costs), as the same onshore frequency converter could be used to charge more than one ferries, there is no current standard or recommendation covering the DC shore connections and has never been adopted globally.

Figure *5-2* presents the one line diagram of the power network for a double ended RO/PAX ferry with a AC distribution system. This configuration is more suitable for a retrofit of an existing vessel.

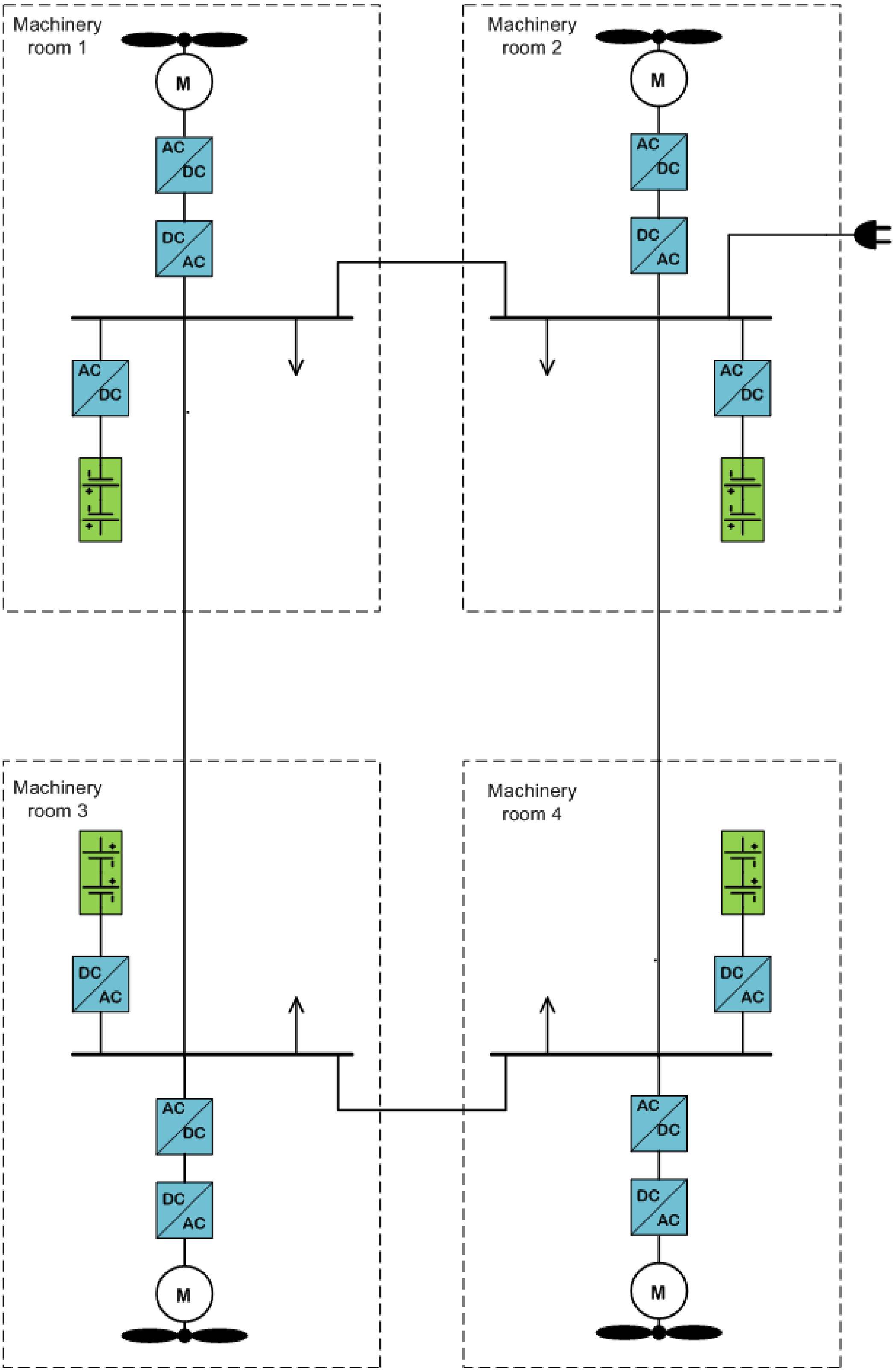


Figure 5-2 All-electric ship OLD with a AC distribution network

The main components of this configuration are:

- Four inverters (AC/ DC), one after every battery array, for the conversion of the DC voltage of the batteries to AC.
- Four back-to-back converters (AC/DC/AC) for for the control of the induction propulsion motors of nominal power equal or greater to the nominal power of the motor.
- 4 three-phase AC cables for the interconnection of the machinery rooms.

If the maximum charging power of the system is more than 1 MW, an HV shore connection must be adopted according to IEC/IEEE/ISO 80005. In this case a step down transformer must be installed onboard for adapting the connection voltage (3.3/6.6/11 kV) to the vessels voltage (380/400/440 V).

Figure *5-3* below presents an alternative configuration utilizing a double busbar system that could be used in the case of the retrofit of an existing vessel when the vessel distribution system operates at 60 Hz and the shore utility network at 50 Hz, or vice versa. It offers the advantage of eliminating the necessary frequency converter (onshore or offshore) for supplying the hoteling load while charging in the port. Three battery packs could be charged interchangeably while the fourth one will supply the hoteling and auxiliary loads.

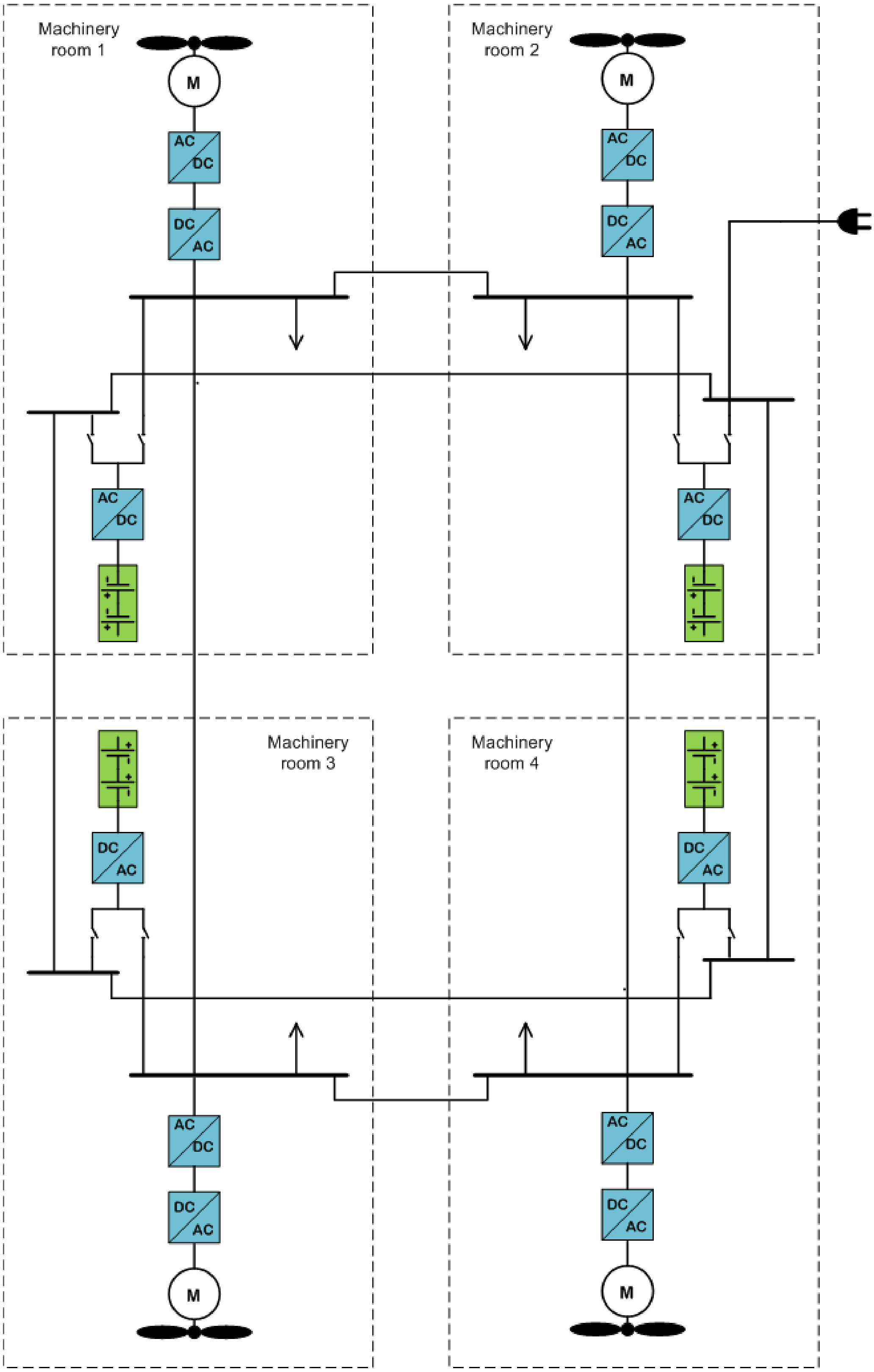


Figure 5-3 All-electric ship OLD with a AC distribution network and double busbar system

5.2 Shore side topologies

This chapter presents the shore side power network configurations utilized for charging the batteries while the vessel is at berth.

Figure 5-*4* below depicts the shore side configuration for an AC shore connection. It includes:

- A main substation equipped with a MV switchboard supplying the shore side substations
- Shore side substations supplying the connection points between the vessels and the port, equipped with:
    - An isolation transformer of Dyn configuration for adapting the utility grid MV to the connection voltage, with the neutral point grounded (possibly through a grounding resistance)
    - The outgoing switchboard supplying the plugs of the point of connection between the port and the vessel

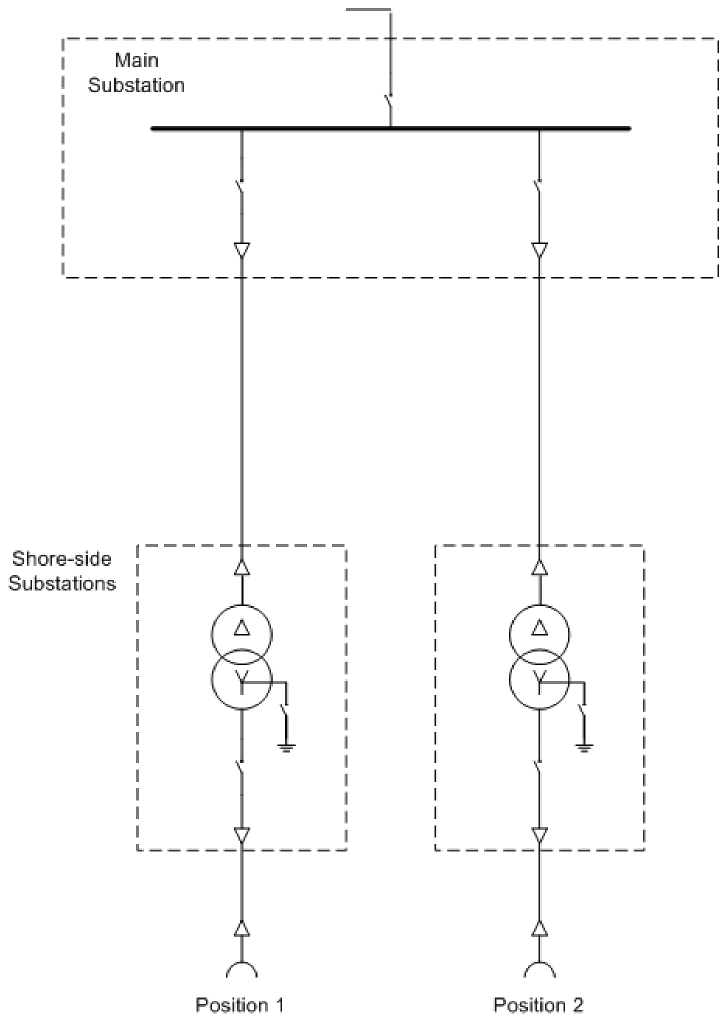


Figure 5-4 shore side configuration for a AC LV shore connection

In case the maximum charging power of the system is more than 1 MW an HV shore connection must be adopted. An earthing switch must be added after the outgoing circuit breaker, for earthing trapped charges in the HV connection cable, as depicted in figure *1-5* below.

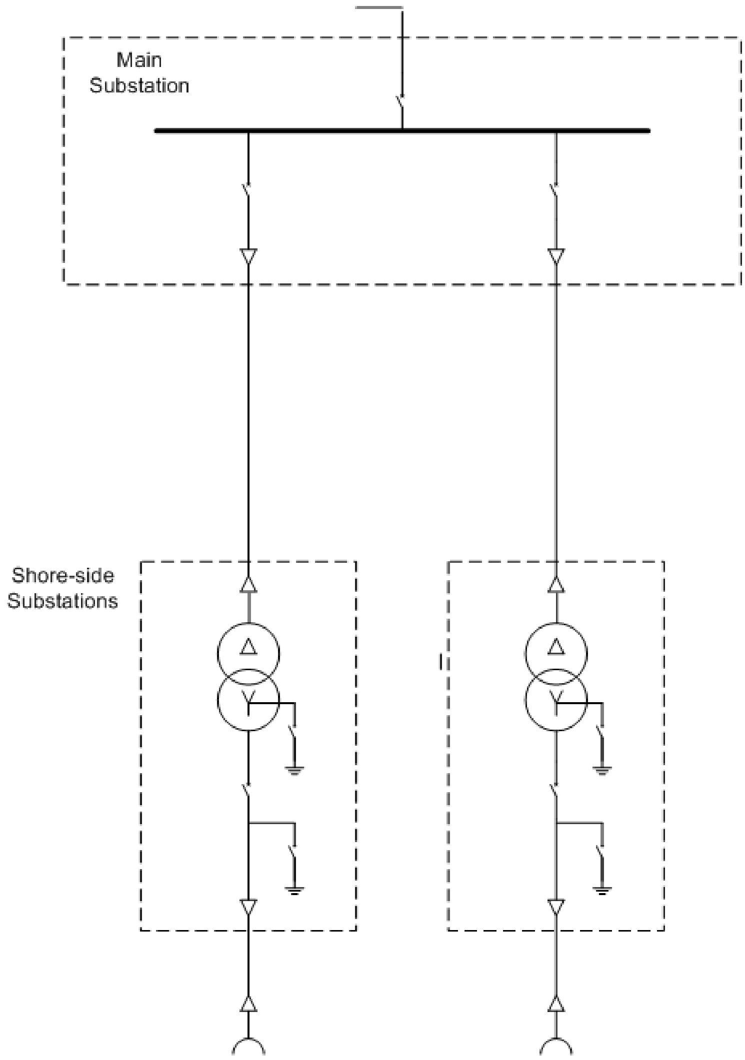


Figure 5-5 shore side configuration for a AC HV shore connection

Finally, figure *1-6* presents the shore side configuration for a DC shore connection. A rectifirer is installed downstream the step down transformer for converting the AC voltage to DC.

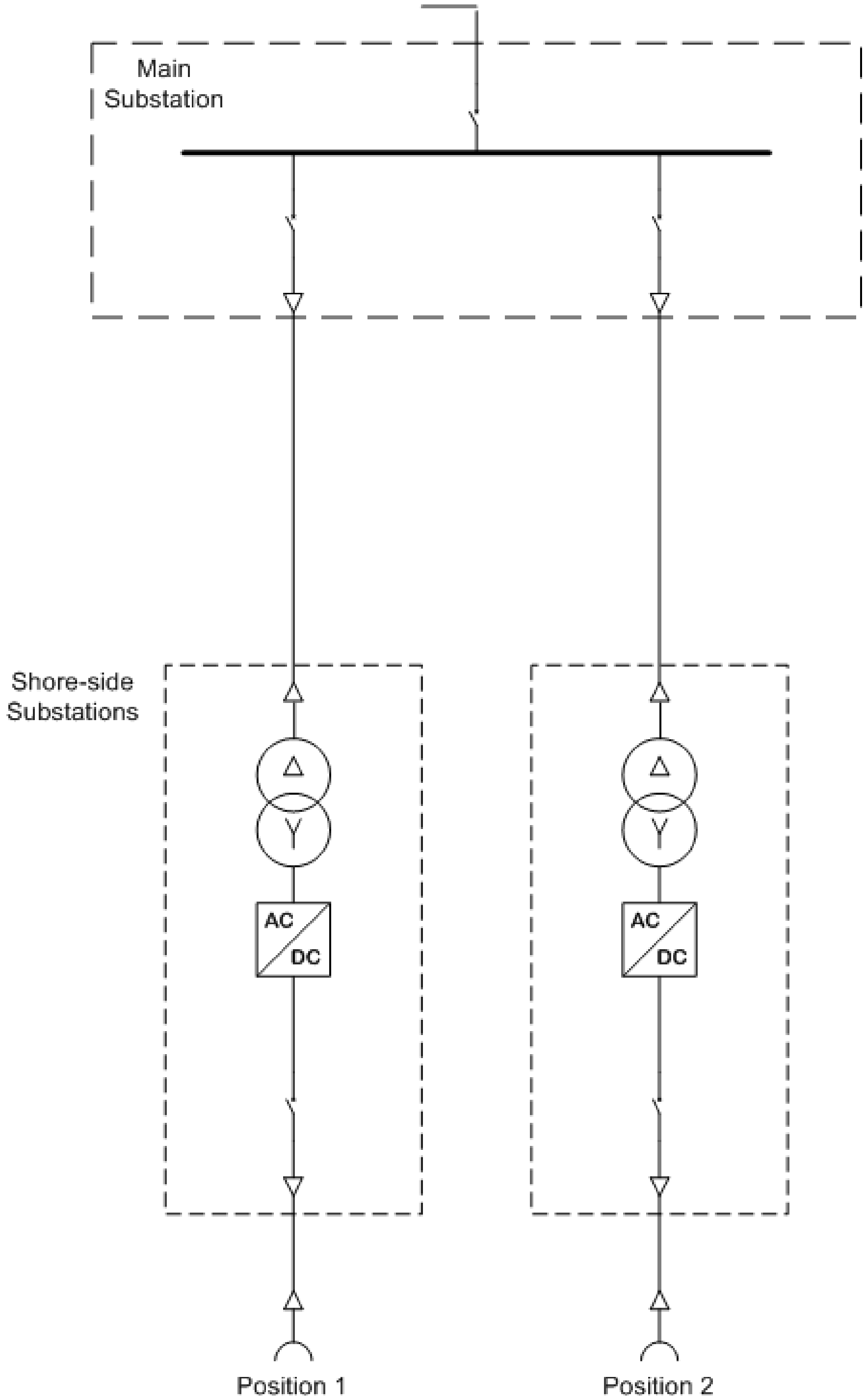


Figure 5-6 shore side configuration for a DC shore connection

5.3 Ship-to-shore connection and interface equipment

Ship-to-shore connection and interface equipment includes standardized LVSC or HVSC systems, cables, earthing and communications between ship and shore.

A ship-to-shore connection cable installation should be arranged to provide adequate movement compensation, cable guidance and anchoring/positioning of the cable during normal planned ship-to-shore connection and operating conditions.

Emergency disconnection shall be arranged as hardwired circuit and separated from cables used for control, monitoring and alarm functions.

There are, mainly, two alternative CMS solutions on the market:

- the shore-based system and
- the ship-based system

The shore based systems can be fixed, mobile or mounted to a special barge. The fixed shore-based CMS becomes an integrated part of the quay and cannot be moved after installation, whereas, the mobile systems usually adopt an electrically driven unit to bring the power supply right up close to the moored ship without restricting other port traffic.

After operation the unit can be driven back to holing bay, ready for the next ship to be berthed. Finally, the third alternative to the shore-based systems uses a barge equipped with specially designed cable drums to supply ships moored at a distance from the actual quayside.

Figure 5-3 – Fixed shore-based cable management system

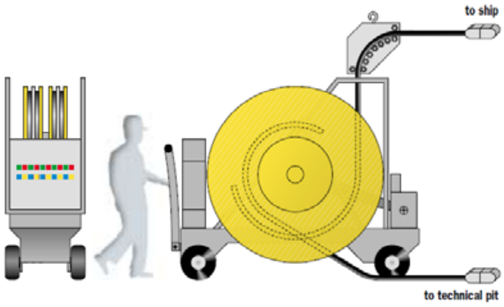


Figure 5-4 – Mobile shore-based cable management system

The ship-based cable management systems, which are ideal when the quay is completely occupied by crane installations and auxiliary loading and unloading vehicles, can be also fixed or mobile. The fixed based systems consist of a number of flexible cables wrapped around a cable drum which is mounted on the deck of the ship.

On the other hand, in the case of mobile ship-based systems the power supply system together with the cable drums and all the auxiliary equipment is installed into either one 40ft container or two 20ft containers. The customer has the possibility to change the position of the container or to move the system from one ship to the other depending on the shipping routes. In both cases, the cables are lowered and plugged in electrical connectors usually installed in a hatch close to the edge of the dock.

Figures 8 and 9 illustrate a typical shore-based cable management systems, while figures 10 to 11 below present the ship-based systems.

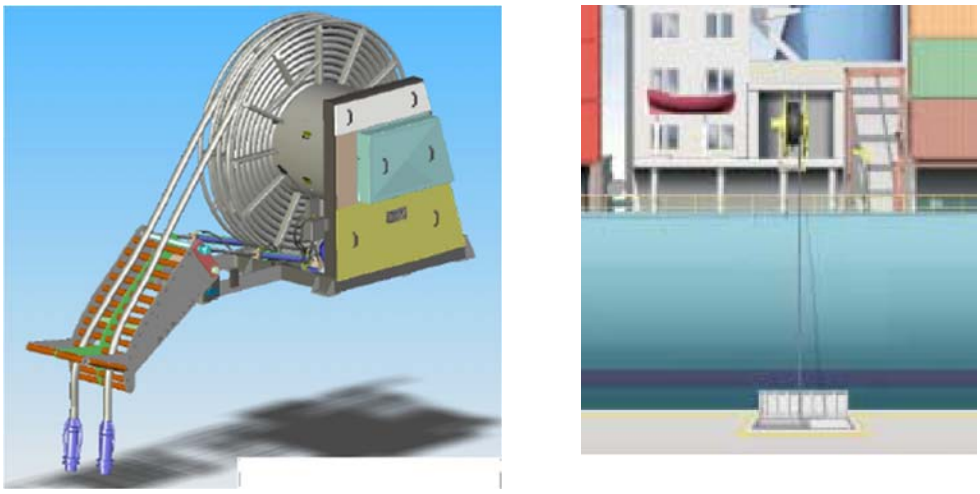


Figure 5-5 - Fixed ship-based cable management system


Figure 5-6 - Mobile ship-based cable management system

6. Design methodology

6.1 Retrofit philosophy

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

Once the batteries are installed and operated the most meaningful advantage of this retrofit will have been achieved, No air pollution and minimized noise pollution will be caused on the nearby, impaired regions and inductively for global environment.

Table 6-1: Past, present and future of small double ended ferries lead/show the way/ to a more sustainable water transportation way.

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

The number of battery modules needed and their arrangement in the vessel depends, as well, from market available battery solutions. When battery system is installed, it will power directly all hoteling loads and electric motors driving the azipod thrusters. While at berth, it will be recharged either between trips and/or after the end of the shift from the utility grid.

The replacement or uninstallation of emergency generator will not be investigated. It may be possible from a technical point of view but lack of advanced legislation concerning modern system emergency topologies, its position above the weather deck and the fact it has already been certified for the specific category from authorities held us off.

Required installed energy, is primarily based on vessel's propulsion requirements for $V_{SERVICE}$ at specific loading conditions (DWT) and correlated draft, T. In Ro/PAX vessels, cargo (DWT) is considered the number of passengers and vehicles on board. There are several different ways to address this problem depending on the outcome's accuracy and available data.

The most precise way to calculate hulls and its' appendages resistance for V_{DESIGN} at different drafts (T) is through CFD modelling. Lack of enough data, though, concerning vessels' lines plan or of a systematic series used for these vessels, were the two constraints that dissuaded us. Moreover the above shortage of information, the apparent rise of retrofit total cost and the surpassing of this thesis target kept us off from trying to redesign ships propulsion system having in mind changes purposed by new "fuel" volume and weight of the battery system.

Another approach to determine required power output, would be to calculate ship's main machineries' consumptions and translate these measurements into required installed energy (kWh). Imprecise and sloppy data of fuel consumptions kept on board, at some of our inspections on vessels, prohibited this choice in fear of over/under estimating ship's power demands. Moreover, this tactic would alienate us from the aim to create a more generic model addressing to a variety of vessel types.

As explained above, it was preferred for our calculation methodology to build an energy balance sheet based on ship's operational profile in accordance with the existing diesel engines' nominal output and electrical load balance.

In that way a reasonable cost for the retrofit can be kept. Few changes will be caused in ship's thrusters and electrical AC distribution network. Our target is the retrofit of existing low cost vessels, therefore, we need to keep in mind that battery storage systems are, even today, quite expensive choice for these categories of routes.

Vessel's main dimensions are variables that will not affect final outcome. As explained above, vessel's resistance won't be possible to be calculated. Current machinery has been designed to be adequate for ship's operational profile and V_{DESIGN}. With that in mind, new electric motors will be of the same power output as their diesel burning ancestors.

Time maneuvering, also, is not a parameter of this problem due to vessels' double-ended shape.

The most possible, initially, scenario is that vessels will charge only in one port. Scenarios, though, for charging in either port will be presented.

Concerning vessel's shift itinerary, it will be divided into trips and voyages as defined below:

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

Number of trips within a shift and available charging time will be two of the most critical variables of the problem forming different alternative scenarios. As we understand, more trips during shift mean more required batteries on board, less available charging time, the same as well. Charging procedure and routine will affect decisively, as well, the outcome. Choices upon the available charging frequency, charging currents applied and time needed to plug-in/off and start charging from grid are translated into alternations of provided quantity of energy to the system, therefore suggesting smaller or larger battery system, more or less lifecycles. All the above are, of course, interrelated with available battery solutions in the market, their chemistry and technical characteristics, and finally offered prices.

Depending on the input data from ship owner, route in question, battery market models, port facilities, different scenarios will be created. For each scenario life expectancy and retrofit's total price will be from owner's side the most important criterions.

A plexus of different scenarios will be created in order to understand the significance of each of the parameters examined in order to optimize and facilitate this green electrification retrofit.

The integration of restrictions and guidelines highlighted on Chapter 4 will be presented in each step of the methodology separately.

System's efficiency and safety at a minimized cost are the targets under optimization. But local societies' welfare and health by decreasing environment's further pollution are the most aspiring reasons for this retrofit. We will establish a battery system safe, redundant, attractable for investment and with zero emissions locally, though; helping to a more sustainable shipping.

6.2 Model inputs and equations

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

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

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

Concerning route characteristics, following data inputs are required:

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

Concerning battery modules characteristics:

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

- Nominal D.O.D.

The energy demand for propulsion per voyage, $E_{PR/VOYAGE}$, is calculated by the formula:

$$E_{PR/VOYAGE} = \left[P_{THRUST} \times N_{THRUST} \times Lf \times {}^{T_{CRUISING}}/_{60} \times {}^{1}/_{\eta_{EL.MOTOR}}\right].(kWh) \quad (Eq.\ 6\text{-}1)$$

where, P_{THRUST} :Thrusters nominal power output (kW)
N_{THRUST} : No of thrusters operating while cruising
Lf : Main engine load factor(%)
$T_{CRUISING}$: Time cruising (min)
$\eta_{EL.MOTOR}$: New electric motors efficiency index

The energy demand for hoteling/electrical loads, $E_{HOT/VOYAGE}$, for one voyage is:

$$E_{HOT/VOYAGE} = \left[P_{HOT/SEA} \times Df \times \frac{T_{CRUISING}}{60}\right] + \left[P_{HOT/PORT} \times Df \times \frac{T_{PORT}}{60}\right], (kWh) \quad (Eq.\ 6\text{-}2)$$

where, $P_{HOT/SEA}$ = Electric Load Balance at Sea (kW)
$P_{HOT/PORT}$ = Electric Load Balance at Birth (kW)
Df = Diversity factor (%)
$T_{CRUISING}$ = Time cruising (min)
T_{PORT}= Time at birth (min)

*Note that If electrical balance sheet is not available, energy for hoteling loads can be calculated in the same way as propulsion energy.

The total energy required for one trip, E_{TRIP}, is calculated:

$$E_{TRIP} = 2\ x\ (E_{PR/VOYAGE} + E_{HOT/\ VOYAGE}), (kWh) \quad (Eq.\ 6\text{-}3)$$

The total demanded energy of the vessel per day or shift, according to selected number of trips is:

$$E_{TOTAL/DAY} = N_{TRIPS} \times E_{TRIP}, (kWh) \quad (Eq.\ 6\text{-}4)$$

where, N_{TRIPS}: Number of trip per day/shift

The minimum installed energy on board, $E_{MIN.INSTALLED}$, for fulfilling the number of trips per shift/day while operating at nominal DOD for maximum lifecycles, may be calculated in two ways according to vessel's operational profile:

a) According to requested number of trips without interval charging:

$$E_{MIN.INSTALLED} = {(E_{TOTAL/DAY}/N_x)}/{DOD}\ , (kWh) \qquad \textit{(Eq. 6-5a)}$$

b) According to time available for charging each time at port:

$$E_{MIN.INSTALLED} = {E_{TOTAL/DAY}}/{((N_{TRIPS}-1)\times f + DOD)}\ , (\text{kWh}) \qquad \textit{(Eq. 6-5b)}$$

where, DOD = Depth of Discharge of Battery system for maximum life-cycles (%)

N_X = Number of trips without interval charging

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

$$f = \left(\frac{C1}{C2}\right) x \frac{(T_{PORT} - T_{PLUG})}{T_{100}} \qquad \textit{(Eq. 6-6)}$$

$C1$ = Charging current

$C2$ = Nominal charging current

T_{100}= total time needed to charge completely (0-100%) battery system at nominal charging current

T_{PLUG}= total time needed to plug-in/off vessel to the grid

The number of modules connected in series $N_{Bt.SERIES}$ is :

$$N_{Bt.SERIES} = {V_{SYST}}/{V_{Bt}} \qquad \textit{(Eq. 6-7)}$$

where, V_{SYST} = System's main bus bar's voltage (V)

V_{Bt} = Battery module's nominal voltage (V)

The number of parallel battery strings is calculated by the formula:

$$N_{Bt.PARAL} = {E_{MIN.INSTALLED}}/{(N_{Bt.SERIES} \times V_{Bt} \times Ah_{Bt})} \qquad \textit{(Eq. 6-8)}$$

where, Ah_{Bt}= Battery module's nominal capacity (Ah)

Next according to rules of *Section 4.2* and current vessel's general arrangement our system will be separated in 2 or 4 battery packs to ensure redundancy. For that, $N_{Bt.PARAL}$,must be corrected so that an integer number of battery modules is installed in each pack..

The total number of batteries, $N_{Bt.TOTAL}$, and of the energy installed on board, $E_{INSTALLED}$, are:

$$N_{Bt.TOTAL} = N_{PACKS}\ x\ N_{Bt.PACK}\ x\ N_{Bt.SERIES} \qquad \textit{(Eq. 6-9)}$$

$$E_{INSTALLED} = N_{Bt.TOTAL} \times V_{Bt} \times Ah_{Bt}, (kWh) \qquad \textit{(Eq. 6-10)}$$

In order to ensure safe return to the port after failure to one battery pack/array (see section 4.2.1) the remaining energy calculated, E_{REMAIN}, , by Eq. 1-10, must be greater than E_{VOYAGE} .

$$E_{REMAIN} = {}^{(1-DOD)\times E_{INSTALLED}}/_{N_{PACKS}}, (kWh) \qquad \textit{(Eq. 6-11)}$$

$$E_{VOYAGE} = {}^{E_{TRIP}}/_{2}$$

The total weight, W_{TOTAL}, and volume, ∇_{TOTAL} of the installed battery system are:

$$W_{TOTAL} = N_{Bt.TOTAL} \times W_{Bt}, (tn) \qquad \textit{(Eq. 6-12)}$$

$$\nabla_{TOTAL} = N_{Bt.TOTAL} \times \nabla_{Bt}, (m^3) \qquad \textit{(Eq. 6-13)}$$

where, W_{Bt}: Battery module's weight (tn)
∇_{Bt}: Battery module's volume (m^3)

Daily cycles considered for the estimation of battery system's life expectancy are:

a) Equal to the number of charges per day if the $E_{MIN>INSTALLED}$ according to *Eq. 1-5a*
b) Calculated by the following formula, if the $E_{MIN>INSTALLED}$ according to *Eq. 1-5b*

$$Cycles_{Daily} = \frac{T_{CHARGING}\times(N_{TRIPS}-1)}{DOD\times T_{CHARG(0-100)}} + 1 \qquad \textit{(Eq. 6-14)}$$

$$LifeExpectancy = {}^{Cycles_{NOMINAL}}/_{Cycles_{DAILY}} \qquad \textit{(Eq. 6-15)}$$

where, $Cycles_{DAILY}$ = battery cycles per day
$Cycles_{NOMINAL}$ = nominal number or cycles if system is operated at nominal values
$T_{CHaRGING} = T_{PORT} - T_{PLUG}$
$T_{CHARG0-100}$ = time needed to recharge from 0-100% at nominal charging current

6.3 General design guidelines

The following graphs and recommendation related to normal operation of a typical double-ended ferry have derived from the implementation of the above described methodology.

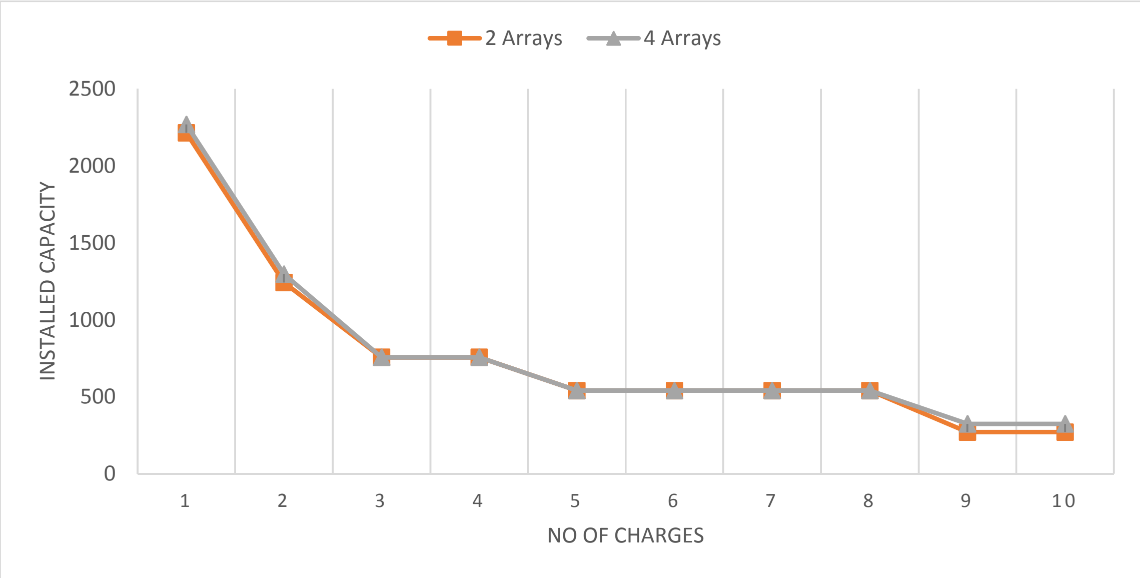


Figure 6-1 – Installed capacity as a function of the number of charges per shift

Figure 6-1 presents the total required capacity installed as a function of the number of charges, for 2 or 4 independent packs/systems.

As illustrated, if the system is divided into 2 packs the required number of battery modules installed is smaller.

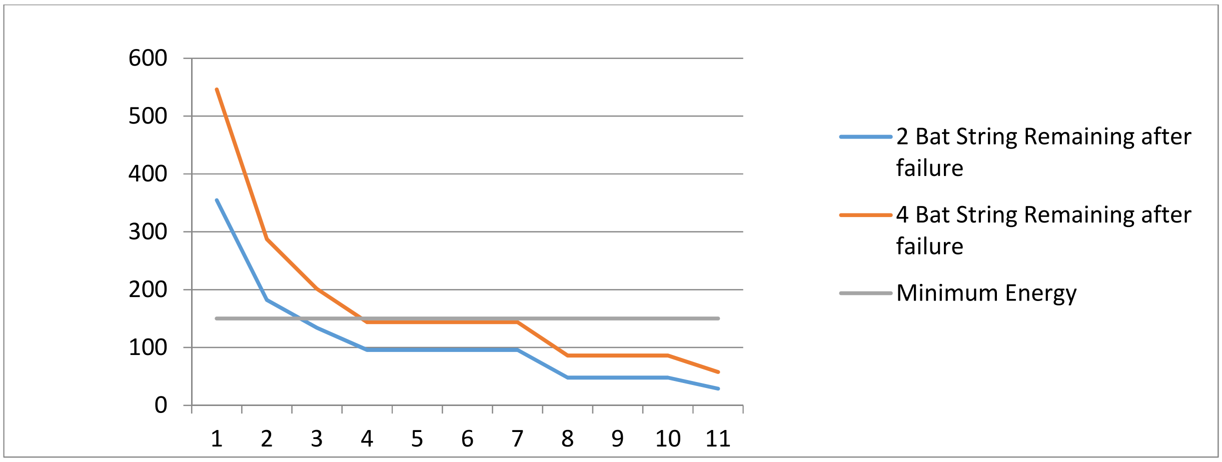


Figure 6-2 remaining energy after failure in one pack at lower operating DOD

Figure 6-2 presents the available remaining capacity after failure in one battery pack at 80% DOD as a function of the number of charges per day. The straight line shows the minimum required energy for safe return to the port after failure in one pack at the end of the shift.

As we can see in *Figure 6-3*, the total installed capacity decreases as the number of charges during 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.

Moreover, besides the safety problems arised from a very low capacity system, the total required charging time makes them time consuming. A very small system would require to be charged from lower operating DOD to 100% DOD after every trip. But charging fully every time will result to extend shift duration. Since we know frequent charging means less batts, we need to reduce the total charging time. This thing can be done by installing batteries that can be charged with high currents (at bigger C rate). If the system is charged with higher currents than those proposed by the manufacturer, the total life expectancy of the system also decreases.

Figure 6-3 bellow present a typical charging profile of a battery system, charging at C/2 (nominal) rate. The blue line corresponds to the state of charge (SOC) as a function of time, while the green line corresponds to the external voltage at the corresponding SOC.

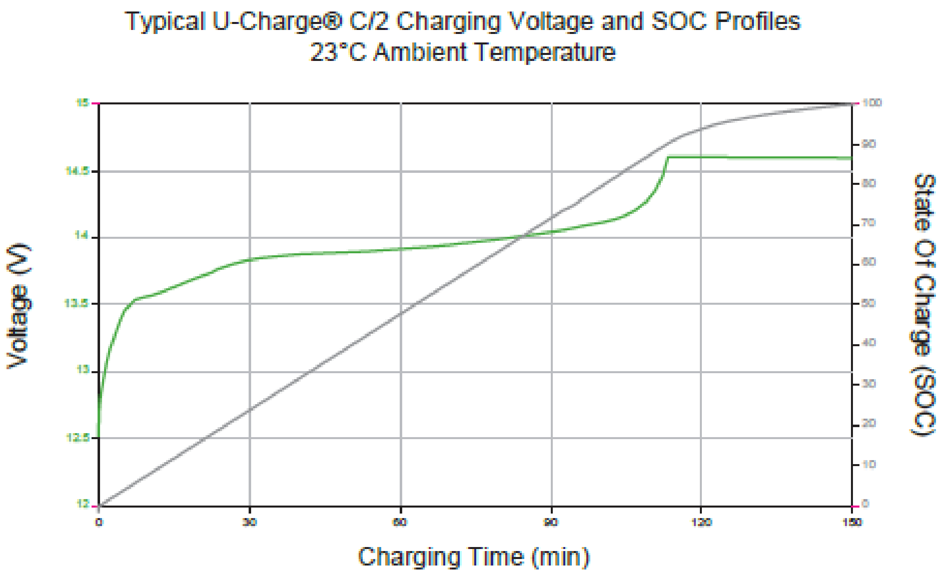


Figure 6-3

On the other hand, even if the total charging time is acceptable, charging the batteries from lower operating DOD to 100% DOD each time results in more full cycles per day, lowering the total life expectancy of the system.

Figure 6-4 bellow depicts the total capacity of the batteries at 100% DOD in percentage of the initial capacity as a function of the cycles that the battery system has served.

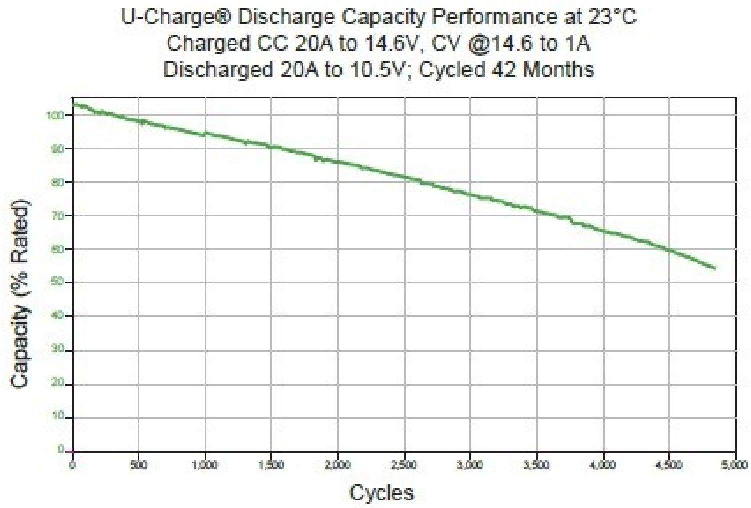


Figure 6-4

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. The most reliable configuration, though, is the 4 pack one.

7. Environmental Impact Analysis

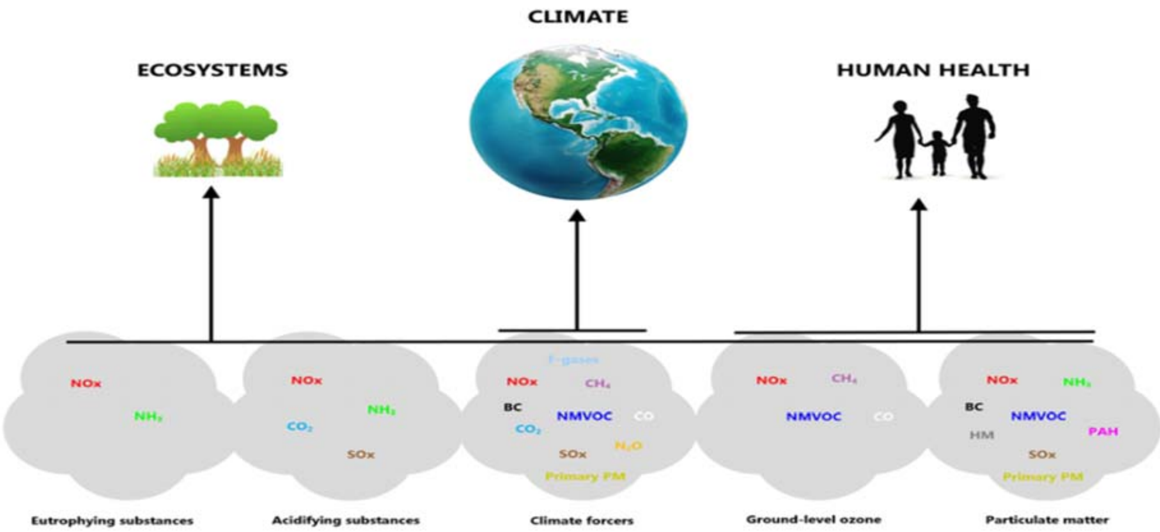


Figure 7-1: Impacts of air pollution

7.1 Hazards of air pollution

Air pollution is an effect of human activity, and ship activity has been correlated with human progress. Moreover, environment conditions as we know them, are prerequisites for human or nature existence. Since the Industrial Revolution humans have been emitting increasing amounts of greenhouse gases, predominantly carbon dioxide, which are building up in the atmosphere. These human-produced greenhouse gases are enhancing the natural greenhouse effect, causing the planet to warm. The more carbon dioxide we release, the warmer the planet will become. Increase in global temperatures will almost certainly result in a series of catastrophic changes across the globe, including worse droughts, stronger storms, flooding of low-lying areas by rising sea levels, extinction of many species and a major disruption in the global production of food.

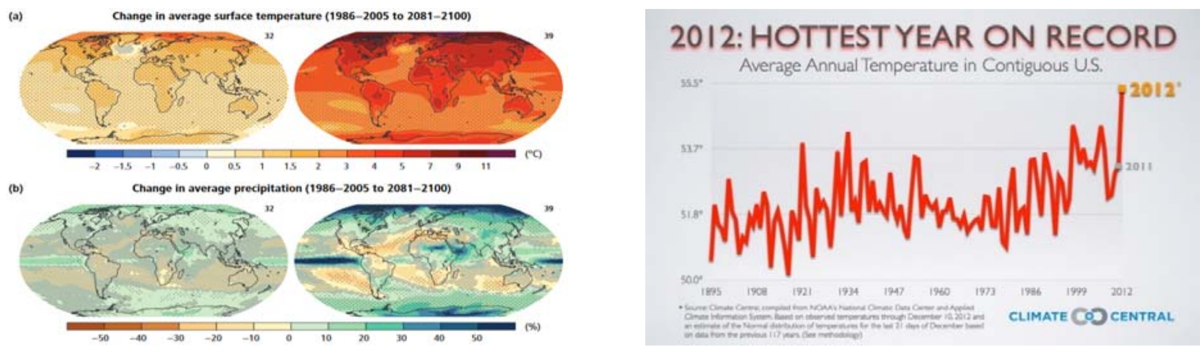


Figure 7-2: Illustrate the rise in global temperate in years

What does this all mean for biodiversity, and what does biodiversity mean for us? In short, everything. All of our food comes directly or indirectly from higher plants, of which there are an estimated 425,000 species. Tens of thousands of these have been cultivated for food at some time by some people, but at present, 103 of them produce about 90% of our food worldwide, while three kinds of grain, maize, rice, and wheat, produce about 60% of the total. We have detailed knowledge of perhaps only a fifth of the species of plants in the world, and a majority could be gone in nature by the end of the century we entered recently. The same can be said for other groups of organisms, on which we depend for many of our medicines, ecosystem services, atmospheric purification, carbon storage, and everything that really makes our lives possible.

Maritime transport is the most environmentally friendly type of transport mode. However, air pollution and greenhouse gases from ship emissions are increasing because of the growing maritime traffic. Shipping sector can/may pollute in various ways environment as shown in (Fig.7.1)

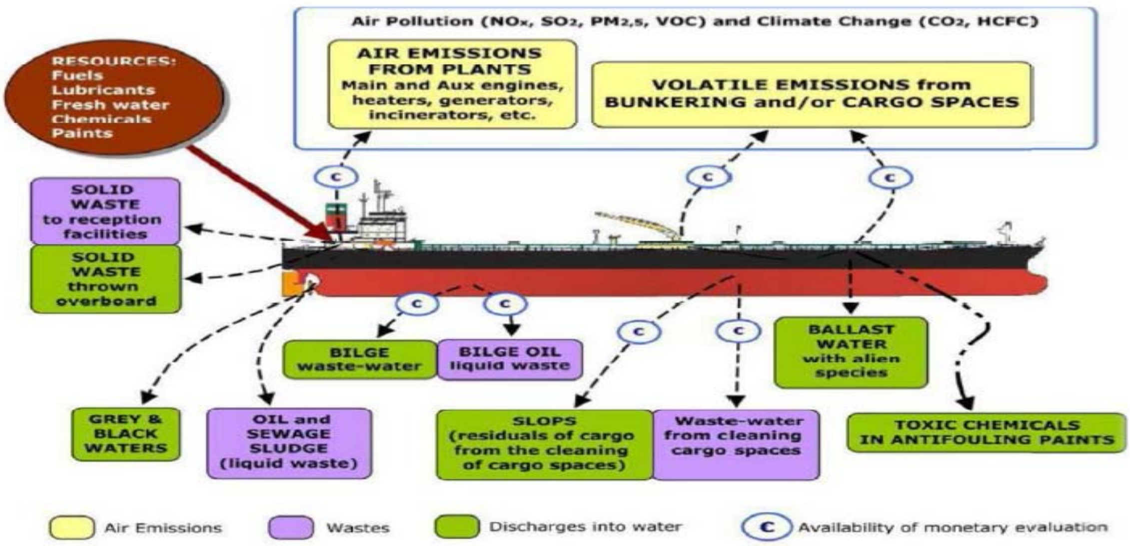


Figure 7.1 : Ship's Resources Consumption and Pollution (source: Maffii et al.,2007)

Air pollution and climate change are intertwined and they have also started occurring. Ports, coastal cities and their local communities are amongst the most vulnerable to extreme weather conditions resulting from them. Air pollution has become a major threat to human health and the environment. Moreover, The World Health Organisation (WHO) considers the exposure to air pollution as the world's largest single environmental health risk, causing 1 in 8 of total global deaths, or 7 million deaths in year 2012 (WHO, 2014).

Under the Paris Agreement all countries and all sectors of the economy need to take immediate action and to contribute keeping the increase of the global temperature well below 2°C. The EU and national climate measures that are currently being developed to implement the Paris Agreement, will oblige ports to reduce the carbon footprint of their land-based activities. These efforts should be accompanied by measures covering emissions generated at sea. The environmental reputation of the maritime and port sector is at stake.

On global thinking but on scale with local environment, ferries under investigation from their part have contributed to the environment's degradation affecting local flora and fauna. Actually, for almost a century vessels with internal combustion engines of various sizes and purposes, have been travelling ceaselessly up and down these waterways connecting the neighboring coastal communities and hurting area's ecosystem. Port and sea exhaust pollution in such close proximity have the same environmental impact.

With these in mind, zero-emission vessels under retrofit will serve local communities in a sustainable way and will be ready to use electricity generated from inland's renewable sources of energy. And sadly have to remind that according to European Environmental Agency's recent published report, Greece is 5th from last in Eu-28 for annual premature deaths caused by air pollution (PM) (E.E.A. , 2016)

Moreover, the World Economic Forum (WEF) in its 12th edition of published annual risks report for 2017 cities the environment as the number one risk to humanity. (WEF, 2016)

Figure 7-3: Top-10 environment priorities of European ports for 2016

7.2 Ship emissions and their impacts

Like all engines which are combusting fuel oil to produce mechanical or electrical energy, current ship engines also cause exhaust gases and release them into air while burning oil. Air emissions of shipping may be grouped, subject to their general impact, to:

A) Emissions causing air pollution
B) Emissions contributing to the climate change phenomenon.

The first category includes emissions of Sulphur Oxide (SO_X), Nitrogen Oxides (NO_x), Particular Matters (PM), Carbon Monoxide (CO) and Volatile Organic Compounds (VOC) whereas the second one includes Carbon Dioxide(CO_2), HCFC, and Methane (CH_4). Ship emissions having human health impacts may be further categorized in primary and secondary pollutants. The primary pollutants are emissions that have immediate effects in the proximity of the emission source (local effects). Secondary pollutants derive when emissions are transformed during their distribution in the atmosphere to produce other pollutants. This transformation is subject to chemical reactions and may take place far away (some hundreds of kilometers) from the emission source. The secondary pollutants in shipping are Ozone (O_3), sulfates and nitrates.

SO_X: are outcome of the combustion process in diesel engines. Marine fuel's quality depends from its content of sulphur. The combustion of sulphur-containing fuel leads to SO_2 emissions.

NO_X: are produced from ship engines because of the combustion in conditions of high temperature and pressure inside the engine's cylinders.

PM: are also a dangerous kind of pollutant. PM's are usually consisted of soot, metal oxides and sulfates, all of them produced during the incomplete combustion of fuel or the dirt inside the fuels and lubricating oil being used in ships. PM's are of great range in terms of size, shape and chemical composition. Based on their diameter, PM's are separated in PM_{10} (inhalable PM's with less than 20 μm diameter) and in $PM_{2.5}$.

VOC: are organic chemicals that have a high vapor pressure at ordinary room temperature. Their high vapor pressure results from a low boiling point, which causes large numbers of molecules to evaporate or sublimate from the liquid or solid form of the compound and enter the surrounding air, a trait known as volatility. The most important VOC linked with ship activity is benzene which is a natural constituent of crude oil and one of the most elementary petrochemicals.

CO: is a gas emitted from incomplete combustion of fossil fuels and therefore it is emitted directly from ship's funnel. In the atmosphere CO has a lifetime span of 3 months or so because it oxidizes into CO_2 forming O_3 during the process. (EEA, 2013).

CO_2: is naturally part of the atmosphere but It can also be produced from incomplete combustion of fossil fuel and like CO is emitted from ship's funnel. Carbon dioxide is a greenhouse gas and is found naturally in the Earth's atmosphere, where it plays a role in regulating the Earth's temperature.

O_3: Ground-level tropospheric O_3 unlike primary air-pollutants is not emitted directly into the atmosphere; instead it is formed from complex chemical reactions following emissions of precursor gases such as NOx and non-methane VOC (EEA, 2013).

Ships emissions do affect:

- Climate Change Phenomenon
- Ecosystem
- Human Health

and these impacts can be monetized in order to have a better understanding of their impacts.

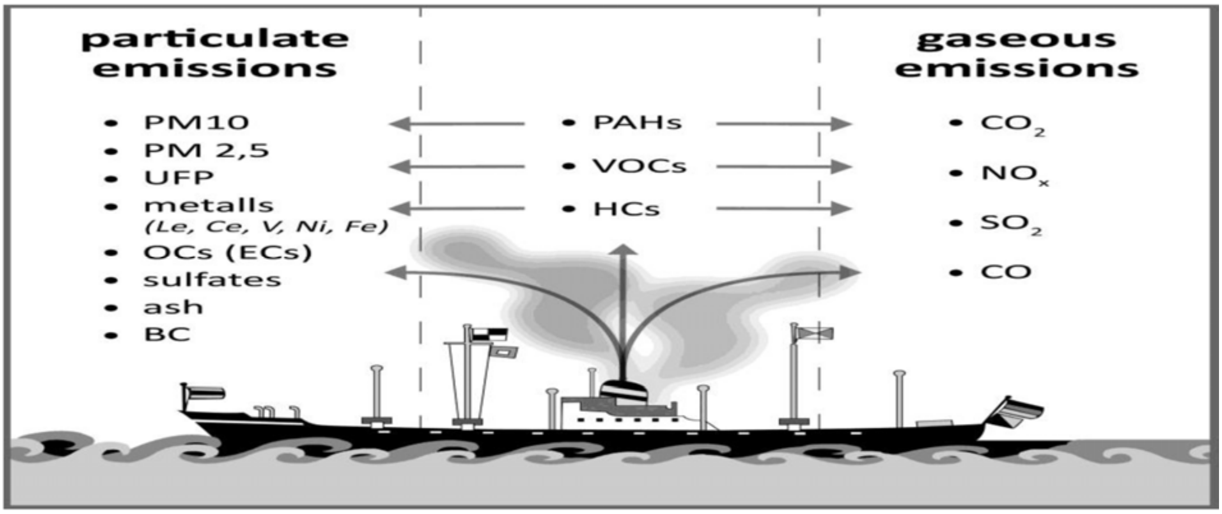


Figure 7-4:Overview of the ship exhaust emissions (Mueller, 2011)

7.2.1 Their impacts on climate change

Global warming is the phenomenon where increasing concentrations of greenhouse gases cause a continuing rise in the average temperature of Earth's climate system (Stocker at al. 2013). CO_2 is a greenhouse gas. Several air pollutants are also climate forcers, which have a potential impact on climate and global warming in the short term (i.e. decades). GHG emissions from the burning of fossil fuels are contributing to the amount and rate of climate change. In addition, they damage the ozone layer and affect the environment negatively. GHG emissions also increase the greenhouse effect and raise the Earth's surface temperature. GHGs, thus, cause the following disasters (EPA, 2013):

- Rainfall patterns
- Polar icecap retreat
- Sea level rise
- Changes in ecosystems supporting human, animal and plant life
- Human health impacts
- Ocean acidification

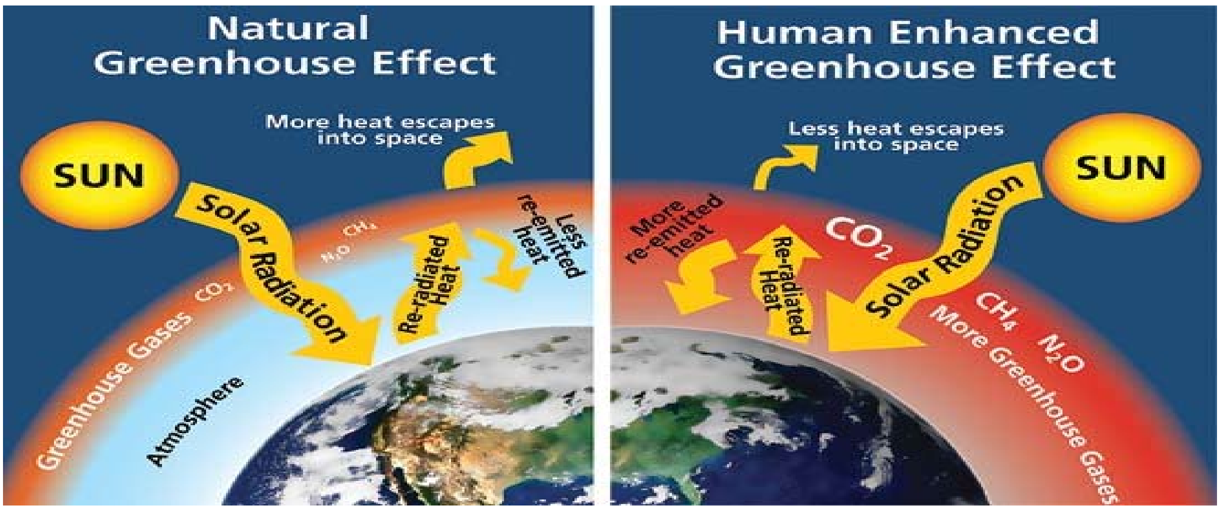


Figure 7-5: Greenhouse effect

Air pollution and climate change are interlaced. Tropospheric O_3 and black carbon (BC), a constituent of PM, are examples of air pollutants that are short-lived climate forcers and that contribute directly to global warming. Other PM components, such as organic carbon (OC), ammonium (NH_{4+}), sulphate (SO_4) and nitrate (NO_3), have a cooling effect. In addition, changes in weather patterns due to climate change may change the transport, dispersion, deposition and formation of air pollutants in the atmosphere. For example, a warmer climate leads to an increase in ground-level O_3 production, and increased O_3 levels then contribute to more warming. Measures to cut BC emissions, along with those of other pollutants that cause tropospheric O_3 formation, such as methane (CH_4) (itself a greenhouse gas), will help to reduce health and ecosystem impacts and the extent of global climate warming. Air quality and climate change should therefore be tackled together by policies and measures that have been developed through an integrated approach. (EEA, 2016)

7.2.2 Their impacts on eco-system

Air pollution also harms the environment and vegetation. The atmospheric deposition of sulphur and nitrogen compounds has acidifying effects on soils and freshwaters. Acidification may lead to increased mobilisation of toxic metals, which increases the risk of uptake in the food chain. The deposition of nitrogen compounds can also lead to eutrophication, an oversupply of nutrients that may lead to changes in species diversity and to invasions of new species. It is estimated that 63 % of the total sensitive ecosystem area and even 73 % of the EU Natura 2000 (45) area was exposed to eutrophication in 2010 (EEA, 2014). Ground-level O_3 can damage crops and other vegetation, impairing their growth. In addition, toxic metals and persistent organic pollutants may have severe impacts on ecosystems. This is mainly because of their environmental toxicity, and in some cases also their tendency to bio-accumulate, a process whereby the toxin cannot be digested and excreted by an animal and, therefore, slowly accumulates in the animal's system, causing chronic health problems. Bio-magnification within the food chain may also occur, i.e. increasing concentration of a pollutant in the tissues of organisms at successively higher levels in the food chain.

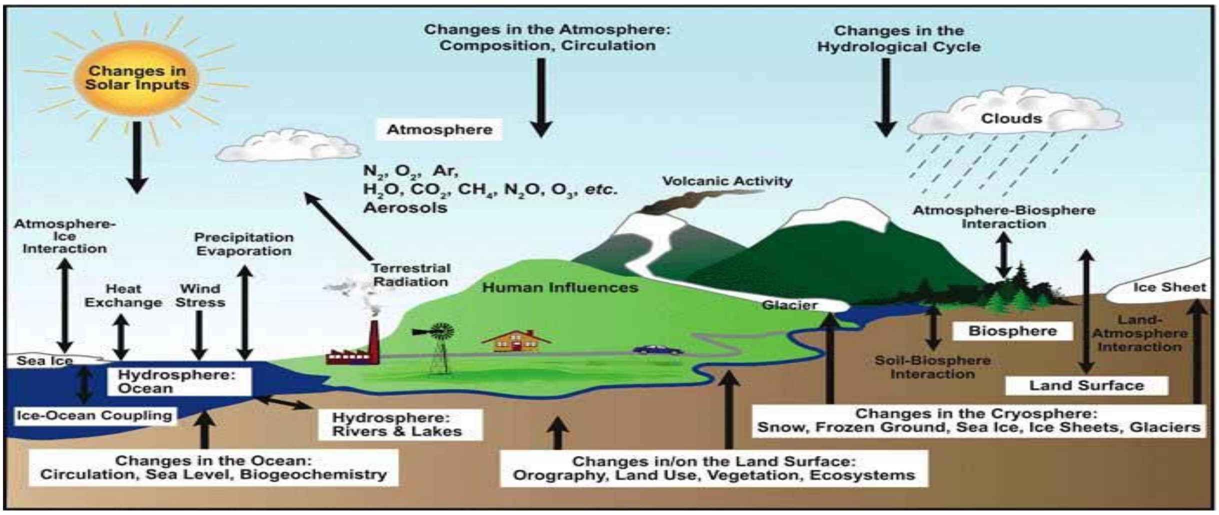


Figure 7-6: Air pollution impacts on eco-system

The impacts of air pollution on the environment depend not only on the air pollutant emission rates but also on the location, potency, lifetime and reaction products of the emissions. Factors such as meteorology, physiography and topography are also important, as these determine the transport, chemical transformation and deposition of air pollutants. Furthermore, the environmental impacts of air pollution also depend on the sensitivity of ecosystems to toxins (e.g. O3 and metals), acidification and eutrophication.

Determining the extent to which air pollutants affect biodiversity is complicated. Different pollutants affect species in a variety of ways. The mixture of air pollutants and their products to which organisms are exposed varies in composition, and each combination has a slightly different effect. Different pollutants in combination can sometimes have a greater effect (also called a cocktail effect) than the sum of the effects each one of them would have separately, while in other combinations they can cancel each other out (EEA. 2016).

Deposition on the Earth's surface is one of the principal mechanisms for removing O_3 from the atmosphere, in particular through absorption by plants. This absorption damages plant cells, impairing their ability to grow. In some sensitive plants, O_3 can cause leaves to exhibit what appear to be burn marks. By impairing plants' reproduction and growth, high levels of O_3 can thus lead to reduced agricultural crop yields, decreased forest growth and reduced biodiversity.

Eutrophication refers to an excess of nutrients in the soil or water. It threatens biodiversity through the excessive growth of a few species that thrive in the presence of the added nutrients, to the detriment of a larger number of species that have long been part of the ecosystem but are accustomed to a lower-nutrient environment. The two major causes of eutrophication are excess nutrient nitrogen (mainly nitrates and ammonium) and excess phosphates in ecosystems. Air pollution contributes to the excess of nutrient nitrogen, as the nitrogen emitted to the air, namely NO_X (mainly from combustion of fuels) and NH_3 (mostly from livestock breeding and mineral fertilizer application), deposits on soils, vegetation surfaces and waters. Atmospheric nitrogen deposition contributes to eutrophication in freshwater and in the sea.

The emission of nitrogen and sulphur into the atmosphere creates nitric acid and sulphuric acid, respectively. The fate of much of these airborne acids is to fall to the earth and its waters as acid deposition, reducing the pH level of the soil and water and leading to acidification. Acidification damages plant and animal life, both on land and in water. Owing to the considerable SO_X emission reductions over the past three decades, nitrogen compounds emitted as NO_X and NH_e have become the principal acidifying components in both terrestrial and aquatic ecosystems, in addition to their role causing eutrophication. However, emissions of SO_X, which have a higher acidifying potential than NOX and NH_3, still contribute to acidification.

Although the atmospheric concentrations of As, Cd, Pb, Hg and Ni may be low, they still contribute to the deposition and build-up of toxic metal contents in soils, sediments and organisms. These toxic metals do not break down in the environment, and some bio-accumulate and bio-magnify. This means that plants and animals can be poisoned over a long time through long-term exposure to even small amounts of toxic metals. If a toxic metal has bio-accumulated in a particular place in the food chain — for example in a fish — then human consumption of that fish may present a serious risk to health. Some ecosystem areas are at risk owing to the atmospheric deposition of Cd, Pb and Hg. The proportion of national ecosystem areas in Europe exceeding critical loads for Cd is < 1 % in most countries, except countries that have set lower critical loads than other countries (Slootweg, 2010).

7.2.3 Their impacts on human health

Air pollution is the single largest environmental health risk in Europe; recent estimates suggest that disease burden resulting from air pollution is substantial (Lim et al., 2012; WHO, 2014a). Heart disease and stroke are the most common reasons for premature death attributable to air pollution and are responsible for 80 % of cases of premature death; lung diseases and lung cancer follow (WHO, 2014). In addition to causing premature death, air pollution increases the incidence of a wide range of diseases (e.g. respiratory and cardiovascular diseases and cancer), with both long- and short-term health effects. The International Agency for Research on Cancer has classified air pollution in general, as well as particulate matter (PM) as a separate component of air pollution mixtures, as carcinogenic (IARC, 2013).

Emerging literature (WHO, 2005, 2013a) shows that air pollution has been associated with health impacts on fertility, pregnancy, infants and children. These include negative effects on neural development and cognitive capacities, which in turn can affect performance at school and later in life, leading to lower productivity and quality of life. There is also emerging evidence that exposure to air pollution is associated with new-onset type 2 diabetes in adults, and may be linked to obesity and dementia.

While air pollution is harmful to all populations, some people suffer more because they live in polluted areas and are exposed to higher levels of air pollution, or they are more vulnerable to the health problems caused by air pollution. The proportion of the population affected by less severe health impacts is much larger than the proportion of the population affected by more serious health impacts (e.g. those leading to premature deaths). In spite of this, it is the severe outcomes (such as increased risk of mortality and reduced life expectancy) that are most often considered in epidemiological studies and health-risk analyses, because there are usually better data available for the severe effects (EEA, 2013a).

The health impacts of air pollution can be quantified and expressed as premature mortality and morbidity. Mortality reflects reduction in life expectancy owing to premature death as a result of air pollution exposure, whereas morbidity relates to occurrence of illness and years lived with a disease or disability, ranging from subclinical effects to chronic conditions that may require hospitalization. Even less severe effects might have strong public health implications, because air pollution affects the whole population on a daily basis, especially in major cities where concentrations tend to be higher than in rural areas (with the exception of ozone).

PM: Can cause or aggravate cardiovascular and lung diseases, heart attacks and arrhythmias, affect the central nervous system, the reproductive and may cause cancer. Their outcome can be premature death.

SO_X: aggravate asthma and can reduce lung function, cause irritant effects by stimulating nerves in the respiratory system. This leads to cough, irritation and a feeling of chest tightness and generally headache, discomfort and anxiety.

NO_X: can affect the liver, lung, spleen and blood, can aggravate lung and heart diseases leading to respiratory symptoms and increased susceptibility to respiratory infection, and cause cancer.

O_3: Can decrease lung function, aggravate asthma and other lung diseases and can lead to premature mortality.

CO: can lead to heart disease and damage to the nervous system; can also cause headache, dizziness and fatigue.

Benzene (C_6H_6): a human carcinogen which can cause leukemia and birth defects. Can affect the central nervous system, blood production and harm the immune system.

P-A-Hs, in particular Benzo-a-Pyrene (**BaP**): are carcinogenic, may cause irritation of the eyes, nose, throat and bronchial tubes.

More information on air pollution impacts can be found in Appendix A.

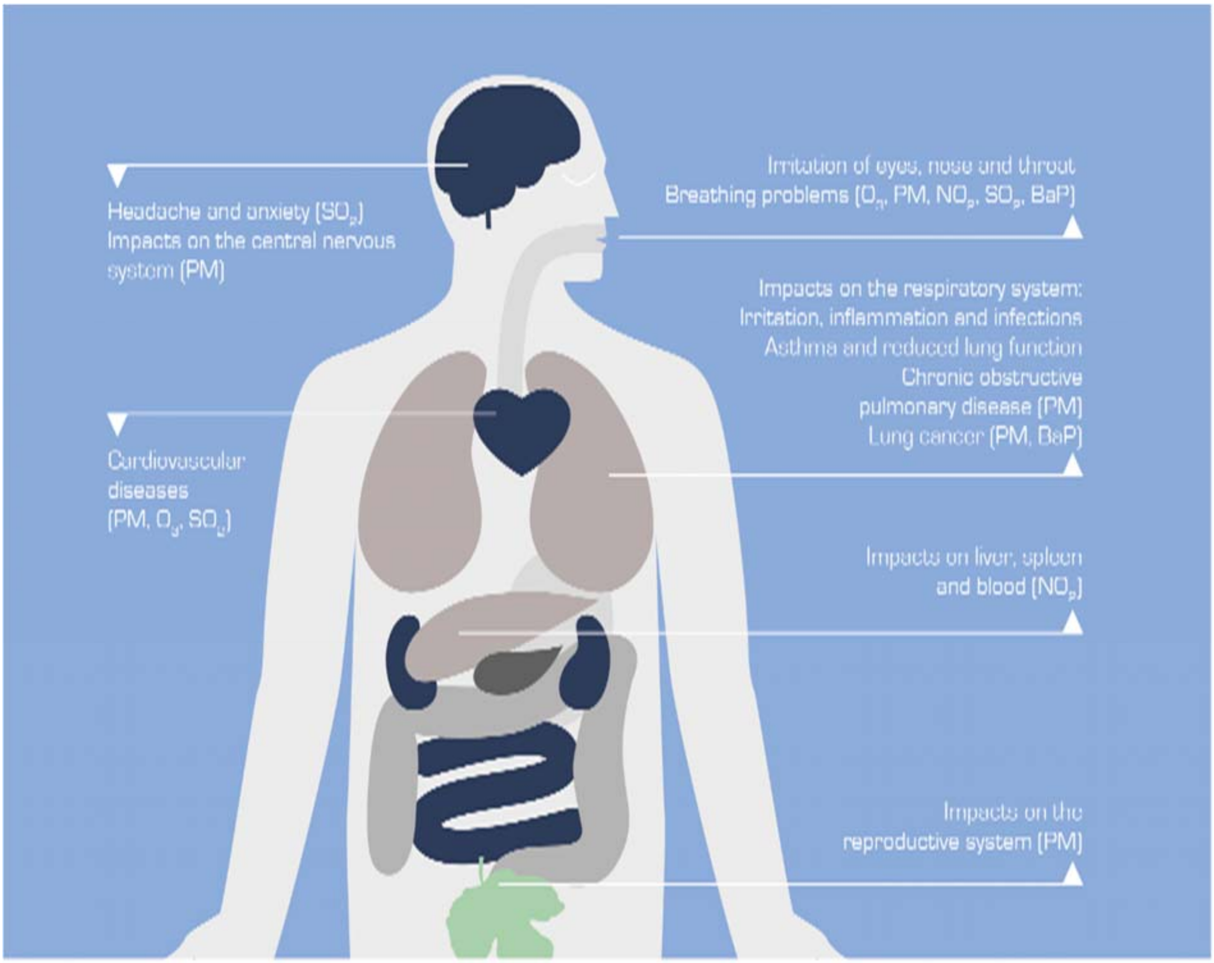


Figure 7-7: Impacts of air pollution on human health

7.2.4 Their impacts on economy

The effects of air pollution on health, crops and forests yields, ecosystems, the climate and the built environmental also entail considerable market and non-market costs. The market costs of air pollution include reduced labor productivity, additional health expenditure, and crop and forest yield losses. The organization for Economic Co-operation and Development (OECD) projects these costs to reach about 2 % of European gross domestic product (GDP) in 2060 (OECD, 2016), leading to a reduction in capital accumulation and a slowdown in economic growth. Non-market costs (also referred to as welfare costs) are those associated with increased mortality and morbidity (illness causing, for example, pain and suffering), degradation of air and water quality and consequently ecosystems health, as well as climate change.

The European Commission estimated that total health‑related external costs in 2010 were in the range of EUR 330–940 billion, including direct economic damages of EUR 15 billion from lost work days, EUR 4 billion from healthcare costs, EUR 3 billion from crop yield loss and EUR 1 billion from damage to buildings (European Commission, 2013a). The potential total economic consequences of both market and non-market impacts of ambient air pollution are very significant and underscore the need for strong policy action.

These costs, usually referred as externalities' cost, will be examined on the next paragraph.

7.3 Externalities costs

Purpose of this paragraph is the presentation of methodology to be followed for the estimation of the external costs resulting from emissions of existing vessels' power consumption within a period of a year, according to the design operational profile.

An externality, in economics, is the cost or benefit that spills over from the project towards a party who did not choose to incur that cost of benefit (Buchanan, James, Wm, Craig. Stubbledine, 1692).

External cost occurs when the activities of one group of persons have an impact (which is not fully accounted or compensated for) on another group (ExternE, 2005).

According to definitions, externalities can have either a negative or positive impact. External costs of shipping may derive from all the above described acts e.g. discharges into the sea (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 i.e. the averted damages. Valuing, those externalities, can sometimes be difficult even though they may be easily identified. It is really tough to have an accurate cost that can depict the damage caused because of its intercomplexity with local geography, population density, fuel emission factors, meteorological date.

In our study, as CBA.2014 suggests for EU projects contributing to reduction of air pollution, we will monetize external costs originated from:

- climate change phenomenon
- air pollution

The emissions will be calculated based on detailed literature of air pollutant emissions for inland transport sector as published in "EMEP/European Environmental Agency air pollutant emission inventory guidebook (Carlo Trozzi, 2016)".

Ensuing the estimated quantity of emissions will be multiplied by unit costs per pollutant (by region type and taking into account population density), as available from international sources.

FIRST STEP

The quantification of the volume of emissions saved in the atmosphere because of vessel's retrofit is based on guidelines of TIER-III protocol which requires as input the individual consumptions of main and auxiliary engines and estimates their emissions during each phase of the trip. For our case, cause of the routes in question standard schedule, no AIS data are needed, and vessel's consumptions while at sea and at port have been estimated, see Chapter 6.

For a single trip the emissions can be expressed as:

$$EM_{TRIP} = EM_{AT\ SEA} + EM_{AT\ PORT}, (tn) \qquad (Eq.\ 7\text{-}1)$$

For each phase known the emissions of pollutant *I* can be computed for a complete trip by:

$$EM_{TRIP,i,j,m} = \sum_{P}\left(FC_{j,m,p} \times EF_{i,j,m,p}\right), (tn), \qquad (Eq.\ 7\text{-}2)$$

where:
EM_{TRIP} = emission over a complete trip (tn)
FC = fuel consumption (tn)
EF = emission factor (kg/tn) from Table 7-1
i = pollutant (NOx, NMVOC, $PM_{2,5}$, PM_{10}, CO, SO_X)
m = fuel type (HFO, MDO/MGO, LNG)
j = engine type (slow-, medium-, gas-turbine etc.)
``

Table 7-2: Emission factors for inland navigation according to (EEA,2016) guidelines

Engine	**Phase**	**Engine Type**	**Fuel Type**	**NO_X EF (g/kWh)**	**NMVOC EF (g/kWh)**	**TSP PM_{10} $PM_{2.5}$ EF (g/kWh)**	**CO* (kg/tn)**	**SO_X* (kg/tn)**
Main/ Aux	Cruise	Medium Speed Diesel	MDO/MGO	12.3	0.5	0.3	7.4	20 x s**
	Stand-By			9.9	1.5	0.9		
	Cruising/			13	0.4	0.3		
	Hotelling			13	0.4	0.3		

*CO, SO_X emission factors taken from TIER-1 for ships using MDO/MGO
***s*: sulphur content of fuel (%)

For the quantification of greenhouse gases pollutants according to IPCC 2006:

Table 7-3: IPCC default emission factors for European ships for inland waterways

Engine	**Phase**	**Engine Type**	**Fuel Type**	**CO_2 EF (kg/tn)**	**CH_4*EF (kg/tn)**	**N_2O* EF (kg/tn)**
Main/ Aux	At Sea/At port	Medium Speed Diesel	MDO/ MGO	3.19	0.18	1.3

*GHG other than CO_2 are converted into CO_2 e by multiplying the amount of emissions of the specific GHG with a factor equivalent to its Global Warming Potential (GWP). If CO_2's GWP is set equal to unity (=1), the GWP for CH_4 and N_2O are 25 and 298 respectively, (IPCC, 2007)

SECOND STEP

To calculate the external costs caused by air pollution, the bottom-up approach is regarded as the most elaborated and best practice methodology, above all for calculating site-specific external environmental costs. This approach is based on impact-pathway method.

Air pollution health costs are estimated with the so-called Willingness to Pay (WTP) approach, reflecting the society's willingness to pay in order to protect the valued items of Life and Health. The damage cost is calculated at local and regional level.

For the internalization of external costs, costs of air pollutants with specific reference to Greece and water transports will be taken from:

A. Handbook on estimation of external costs in the transport sector (CE DELFT, 2008).

B. Estimation of annual External Health Cost of air pollution in the port of Piraeus using the impact pathway analysis (Oikonomou, 2014).

C. Air emissions and their impacts, Piraeus port case study (Tzanatos, 2010).

*Table 7-4: Price per tn of pollutant in €$_{2017}$**

	$PM_{2.5}$(€$_{2017}$/tn)	PM_{10} (€$_{2017}$/tn)	NO_x (€$_{2017}$/tn)	SO_X (€$_{2017}$/tn)	NMVOC (€$_{2017}$/tn)
(A)	34303.5	93109.5	784.08	1372.14	294.03
(B)	85389.1		15248.4	18934.4	-
©	96515	57844.52	3635.2	4510.4	-
Mean Value	85389.1	75477	3635.2	4510.4	294.03

* The inter-temporal elasticity of environmental externalities to GDP per capita growth has been taken into account and the unit prices are expressed in €$_{2017}$, according to Greek CPI.

Due to the global effect of global warming, there is no difference between how and where in Europe GHG emissions take place. For this reason, the same unit cost factor applies to all countries. However, the cost factor is time-dependent in the sense that emissions in future years will have greater impacts than emissions today, (CBA, 2013).

Table 7-5: Unit Cost of GHG emissions (Source EIB, 2013)

	Value 2010 (€/tn-CO_s)	Annual adders 2011 to 2030
High	40	2
Central	25	1
Low	10	0.5

7.4 Comparison of emissions between onboard and shore electricity generation, and battery production

Battery-powered ships that are charged from the grid and the environmental savings depend on the emissions created by generating the electricity on shore. Therefore, in this chapter, we will compare the amount of pollutants emitted from on board energy production compared to shore–side energy production (national utility grid).

Electricity in Greece is produced with various methods. An important fraction of the total production (30%) comes from the lignite power plants which are rather pollutant but are still in use because of the great lignite availability in Greek soil. Almost 20% of the electricity is produced in natural gas power plants and another 20% comes from power exchange from Italy, Bulgaria, FYROM and Albania. Renewable energy from solar power, wind power and hydroelectric power accounts for 20% of the total electricity generation.

Table 7-6: Electricity generation in Greece by type (Jan-Mar 2016)

January – March 2016		
Type	Gwh	Usage %
Natural Gas	2458	19.22
Lignite	3862	30.20
Hydroelectric	1224	9.57
Renewable Sources	1460	11.42
Exchange	2722	21.29
Other	1061	8.30
Total	12787	

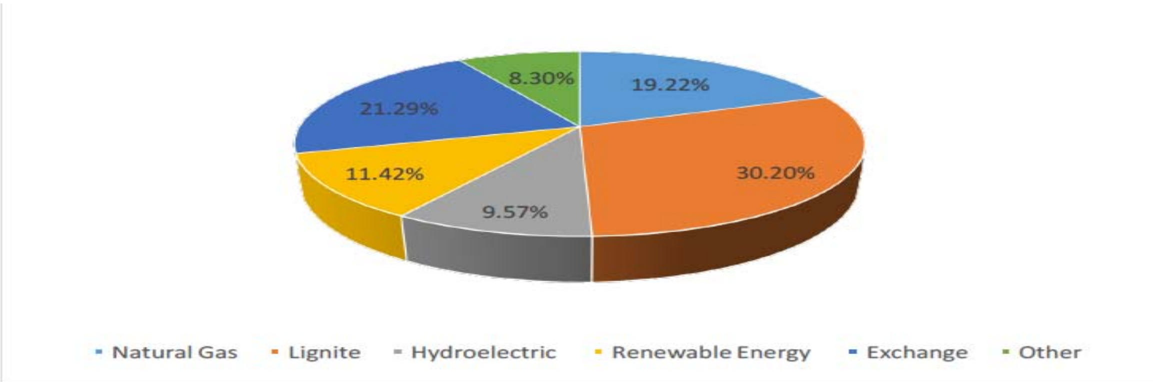


Figure 7-8: Electricity generation in Greece by type (Jan-Mar 2016)

Based on information which is available in the annual reports of the Public Power Corporation (ΑΔΜΗΕ, 2016), the methods of electricity generation can be categorized based on their 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.

Table 7-7: Comparison of Emissions from energy generation in Greece and on-board energy production

Type	Usage	CO_2	SO_X	NO_X	PM
	%	g/kWh			
Natural Gas	19.22	584.844	0.020	0.300	0.030
Lignite	30.20	984.29	2.800	2.300	1.020
Hydroelectric	9.57	0	0	0	0
Renewable Sources	11.42	0	0	0	0
Exchange	21.29	0	0	0	0
Other	8.30	0	0	0	0
Total	100	402.783	0.85	0.752	0.314
On-board (MDO/MGO)		638	0.2	12.05	0.45

Comparing emission factors of shore power generation compared to those of on-board power production, conclusion is that shore power generation is a greener option. Under the fact, also, that use of renewable sources of energy for power generation will grow up in next years in Greece, ships under retrofit will be ready to be the first vessels with 100% zero-emissions.

Finally, for the questions raised about how environmentally friendly battery-powered solutions are in a life-cycle perspective, the energy and emissions related to producing the batteries, are small amounts compared to the savings due to the many hours of operation according to DNV-GL. In contrast to lead-acid batteries which contain poisonous lead, nickel cadmium batteries that contain even more poisonous cadmium and NiMh batteries that contain rare earth materials, the lithium-ion batteries contain no poisonous heavy materials and very little rare earth materials. Their main environmental footprint comes from the energy used in the production process, but as illustrated from a recent research on CO_2 emissions for a hybrid ship using 300kWh battery system carried by DNV-GL the environmental benefits of maritime battery systems by far exceed the negative impact from the battery production itself as.

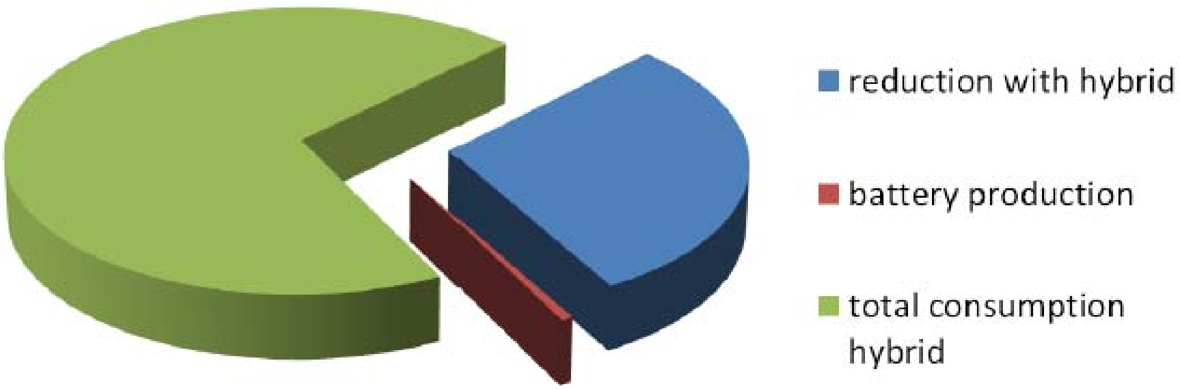


Figure 7-9:, Illustration of the distribution of CO2 emissions for a hybrid ship using 300kWh battery system.

8. Case Study: Perama - Salamina

8.1 Study area

Purpose of this dissertation is the investigation of feasibly running an existing double-ended vessel on batteries and its benefits compared to current way of operation. Herewith, the route of Perama – Salamina has been selected in the context of the study area in all aspects, geographical, traffic and legal. In addition, the ship selected for retrofit is quite young, built in 2016 allowing us to have an up to date understanding of their operations, functions and emissions.

From geographical aspect, port of Perama is located in the Saronic gulf next to the port of Piraeus, the third most populated municipality in Greece ,with a population of 175 697 people (in 2001). It is only 14.7 km far from Athens, Greece's capital. Island of Salamina, during summer period may reach a population of almost 300000 inhabitants. People and goods are transferred only via these double-ended ships on this waterway of 1.6 nm.

The case of Perama - Salamina route is of particular interest mainly because it presents a most dense ship traffic within the Greek seas. Working, 24/7 these ships do not stop serving local community. Despite their benefits, their exhaust emissions (NO_X, SO_X, CO_2, PM, VOC) have caused a great damage at local natural environment and ecosystem in both ports. Perama's position next to Piraeus' port and to shipbuilding factories, multiplies impacts from air pollution upon the highly populated, sensitive and culturally precious Greek coastline.

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

8.2 Data analysis

Vessel's characteristics

Table 8-1: Double-ended vessel's characteristics

L_{OA}	105.56 m
L_{WL}	89.77 m
B	18.08 m
T_{DESIGN}	2.7 m
Year built	2016

Main diesel engines	4 x Caterpillar C18 Acert 600 HP@1800RPM
Azipod thrusters	4 x Veth Z-drive (VZ-400) 600 HP
Power generators	1 x CAT power set 88 kVA
	2 x Cummins power set 110 kVa

Operational characteristics

Table 8-2: Operational characteristics

Electrical Load Balance At Port (kW)	71.87
Electrical Load Balance At Sea (kW)	90.69
Diversity Factor	0.9
No of Operating Main Engines At Sea	2
Main Engine Load Factor	0.9
Electric Motors Efficiency	0.98
Propulsion Load (kW)	791.3988
Electric Propulsion Load (kW)	807.5497959
Load at port (kWh)	16.17075
Load at sea (kWh)	133.3756194
Energy/trip (kWh)	299.0927388
Max trips/day	9
DOD (nominal for max lifecycles)	0.7
System dc voltage (V)	1000
Time to plug-in/off (min)	4

Perama – Salamina route's characteristics

Table 8-2: Route's under investigation characteristics

Distance	1.6 nm
$T_{CRUISING}$	9 min
$T_{AT\ BERTh}$	20-30 min

Battery modules specifications (LiFeMgPO4)

Table 8-3: battery modules specifications

Nominal Module Voltage		38.4 V
Nominal Capacity (C/5, 23°)		46.2 Ah
Dimension (LxWxH)		306 x 172 x 255 mm
Weight		19.6 kg
Volume		0.11 m^3
Specific energy		91 Wh/kg
Energy density		148 Wh/lt
Standard Discharging @25°C	Max Cont. Current	90 A
	Peak Load Current (30sec)	135 A
	Cut-off Voltage	30 V
Standard Charging	Max charge voltage	43.8 V
	Float Voltage	41.4 V
	Rec. current C/2	23 A
Charging time for max l.f. (DOD: 100% -> 0%) (h)		2.5

8.3 System's calculation

Topologies

According to *chapter 5* the next two topology designs have been selected for vessel's distribution network and shore side's interconnection system.

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, it is not required to transform the connection voltage to the exact vessel's system's voltage in terms of V, Hz, i.e. 440V, 60Hz in our case.

The average vessel's load for hoteling load and nominal charging current is around 70 kVA. The nominal power of the shore side substation shall be 1 MVA allowing the system to be charged with higher currents.

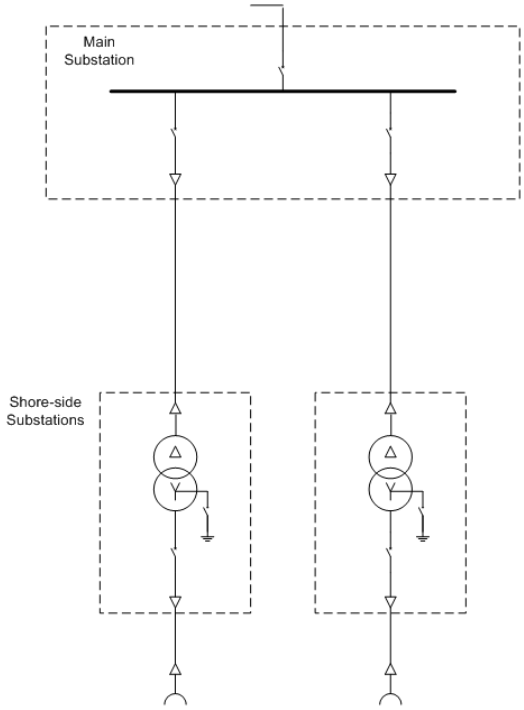


Figure 8-1 – Shore side topology

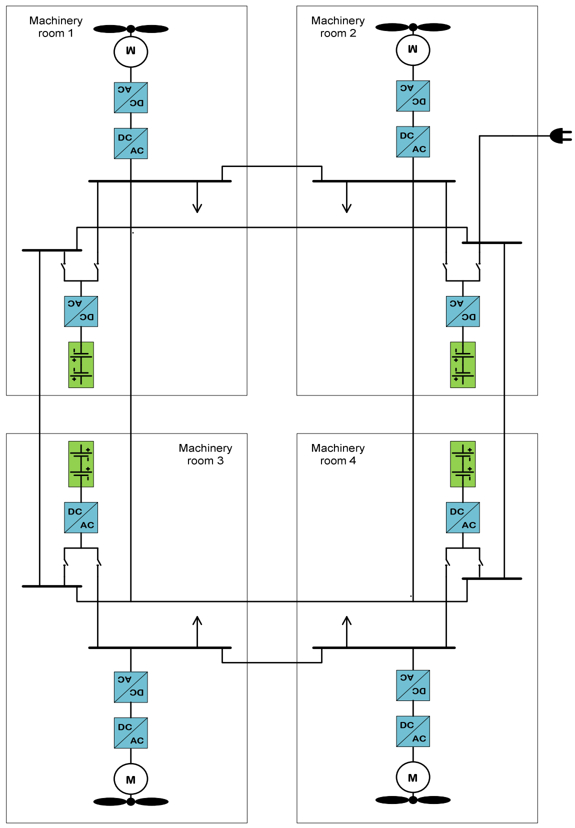


Figure 8-2 – vessel's network

Vessel's calculations

Concerning the number of batteries installed on board, the most feasible scenarios are presented in next table.
Scenario 3 was selected for the following reasons:

Table 8-4

Scenario	Time at Port (min)	$E_{MIN.INSTALLED}$ (kWh)	$N_{Bt.SERIES}$	$N_{Bt.PARAL}$		$N_{Bt.TOTAL}$	
				2 packs	4 packs	2 packs	4 packs
1	20	1,732.9	27	38	40	1026	1080
2	25	1,479.0	27	32	32	864	864
3	30	1,290.0	27	28	28	756	756
4	35	1,143.8	27	24	24	648	648

Table 8-5

Scenario	$E_{INSTALLED}$ (kWh)		E_{REMAIN} (kWh)		W_{TOTAL} (tn)		∇_{TOTAL} (m^3)	
	2 packs	4 packs	2 packs	4 packs	2 packs	4 packs	2 packs	4 packs
1	1,820.2	1,916.0	273.0	431.1	20007	21060	12,150	12,790
2	1,532.8	1,532.8	229.9	344.9	16848	16848	10,232	10,232
3	1,341.2	1,341.2	201.2	301.8	14742	14742	8,953	8,953
4	1,149.6	1,149.6	172.4	258.7	12636	12636	7,674	7,674

Table 8-6

Scenario	Cycles/ Day	Optimal Life Expectancy (years)
1	2	13.8
2	2	13.8
3	3	9.2
4	3	9.2

Scenario 3 divided into 4 packs was considered optimal as:

- it serves the safety requirements imposed, $\boldsymbol{E_{REMAIN.\ 4\ PACKS}} = 301.8$ kW > E_{VOYAGE} ≅145 kWh
- time needed ≅ $10\ hr$(for charging is within acceptable limits concerning vessel's shift duration.
- $\boldsymbol{W_{TOTAL}} = 14.74$ tn. Ship examined has fuel tanks of 50 tn capacity for current diesel engines. That means that vessel after retrofit can cruise at lower draft, leading to smaller energy consumptions. consider also the weight reduction from the uninstallation of auxiliary engines
- $\boldsymbol{\nabla_{TOTAL}} = 8.95$ m^3 .This volume can be fitted easily either in or adjacent the engine room according to vessel's GA (see Appendix B).
- The above life expectancy is estimated for optimal operation but battery manufacturer suggests a 7-year period.

VESSEL RETROFIT COST

Table 0-4: Vessel's retrofit total costs

VESSEL RETROFIT COST	
Number of batteries	756

INSTALLATION COST	
Battery cost (€)	871,896.2
BMS – 50% of batteries' cost (€)	435,947.9
Battery Inverter (200€/kW)	
4 x Inverter of 300kW**	240,000.0
Motor Driver (250€/kW)	250.0
4 x Motor drives of 440kW**	440,000.0
Electric Motor (60€/kW)	60.0
4 x Electric motors of 440kW**	105,600.0
Contigencies 10%	
SUM (1 € = 1.08)	2,302,788

SALES OF EXISTING MACHINERY	
Used Medium Speed Diesel Engines (40€/kW)	
4 x Main Engines 440kW x4	70,400.0
Used Electric Generators (35€/kW)	
Existing Electric Generator-1 88 kW	3,080.0
Existing Electric Generator-2 88 kW	3,080.0
Existing Electric Generator-3 70 kW	2,450.0
SUM (€)	79,010.0
FINAL COST OF RETROFIT (€)	2,223,778

OPERATION AND FUEL SAVINGS COMPARISON

Table 0-5

FUEL COST COMPARISON FOR 1 YEAR OPERATION	
Days Working	360
Trips Per Day	8
WITH BATTERIES	
Required Energy Per Trip (kWh)	337.2
Total Required Energy for 1 Year Operation (kWh)	971,229.0
Price of kWh from Utility Grid (€/kWh) - B1B Pricelist	0.05
Total Cost (€)	48,561.4
WITH EXISTING MACHINERY	
Main Engine Efficiency	0.55
Electric Generators Efficiency	0.9
Main engines Annual Cruising kWh	1,381,350
Main engines Annual Stand-by kWh	461,704
Auxiliary engine Annual Stand-by kWh	114,992
Auxiliary engines Annual cruising kWh	87,062
SFOC according to TIER –II protocol (g/kWh)	203
Price of Marine Diesel Oil per tn (incl VAT**)	550
Total Cost (€)	228,365
Benefit from Fuel Saving in 1 Year of operation (€)	179,775.1

Table 0-6

OPERATION AND MAINTENANCE COST COMPARISON FOR 1 YEAR	
WITH BATTERIES	
Fixed Operation & Maintenance is 2% of the PCS cost (€) per year	17437.924
Variable O&M is ($/Wh)	1
variable O&M expenses for installed energy (€)	1241.856
TOTAL O&M COST PER YEAR	18679.78
WITH EXISTING MACHINERY	
Maintenance cost: 12.6€/HP	
Total Installed Power = 4 x 599HP	32585.6
Total O&M Cost Per Year (€)	30,171.9
TOTAL BENEFIT FROM O&M EXPENSES (€)	11,492.1

8.4 Investment appraisal

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% $Ah_{NOMINAL}$.

Financial and socio-economic analysis will be in accordance with cost-benefit analysis guide for investment projects (CBA, 2014) published from European commission for green projects.

Benefit from fuel and O%M costs may be considered as the only revenues in the analysis (in order to have a clear comparison of running the vessel on batteries).

The residual value of equipment bought is estimated 65% of their initial price:

- 30% of batteries' initial cost
- 70% for the rest of equipment
- Oil growing price 3.5%
- Electricity growing price 1%

Residual value is not considered as cash inflow.

Contingencies costs are estimated 10% of project value.

NPV rate is estimated 6%.

FRR C

Table 8-7:FRR before EU grant

FRR©									
Calculation of Return of Investment	NPV 6%	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7
		Construction	**Operation**						
Investing Cost (€)	-2.223.779	-2.223.779							
BENEFIT FROM FUEL AND O&M Cost (€)	1.190.730	-	191.267	198.773	206.554	214.620	222.980	231.646	240.627
Revenue (€)	-	-	-	-	-	-	-	-	0
Residual Value of investments (€)	742.638	0	0	0	0	0	0	0	1.116.653
FNPV©-Nefore EU Grant / Net Cash Flow (€)	-1,033,049	-2.223.779	191.267	198.773	206.554	214.620	222.980	231.646	240,627
FRR© - Before EU Grant	-0.086								

Since FNPV < 0 , the project is eligible for EU grant according to EC guidelines and that can amount 85% of total investment cost.

The markedly negative financial net present value of the investment (FNPV(C) = -EUR 1,033,048 million) shows that the project requires EU assistance to make it viable.

The project is a net revenue generating operation in the meaning of Article 61 of Regulation (EU) 1303/2013. In this case, the contribution from the EU Cohesion Fund to the project has been determined using the method based on the calculation of the discounted net revenue. The resulting pro-rata application of discounted net revenue is 93.4 %. This, multiplied with the eligible cost shown in section IV above (EUR 2,223,778 million) and with the co-financing rate of the relevant priority axis of the OP (85 %), gives a EU grant for the project of EUR 790,282 million.

The remainder of the investment is provided by the promoter entirely from equity, without the need to contract loans. The equity contribution will be financed through additional paid-in capital from the State, for which a formal commitment exists.

Table 8-8: Calculation of EU grant

EU GRANT									
Calculation of Discounted Investment Cost (DIC)	**NPV 6%**	**Year 0**	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Year 7**
		Construction	**Operation**						
Investing Cost (€)	2223779	2223779	0	0	0	0	0	0	0
DIC / Investment Cost Cash-Flow (€)	2223779	2223779	0	0	0	0	0	0	0
Calculation of Discounted Net Revenues (DNR)									
Revenue (€)	-	-	-	-	-	-	-	-	-
O&M Costs --> OUR BENEFIT (€)	1190730	-	191267	198773	206554	214620	222980	231646	240627
Residual Value of Investment (€)	742638	0	0	0	0	0	0	0	1116653
DNR / Net Revenue Cash Flow (€)	1190730	-	191267	198773	206554	214620	222980	231646	240627
ELIGIBLE COST - EC (€)	2,001,400								
Pro-Rata application of DNR=(DIC-DNR)/DIC (€)	0.46								
CO-FINANCING RATE OF PRIORITY AXIS (CF)	0.85								
EU GRANT (= EC x PRO-RATA x CF)	790282								

Table 8-9: FNPV, FRR of promoter's capital

FRR (K)									
Private Capital % of Total Investment	15%	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7
	NPV 6%	**Construction**	**Operation**						
Promoter's Contribution		-1433496	0	0	0	0	0	0	0
Calculation of the Return on Private Capital									
Promoter's Contribution (€)	-1433496	-1433496	0	0	0	0	0	0	0
BENEFIT FROM FUEL AND O&M Cost (€)	1190730	0	191267	198773	206554	214620	222980	231646	240627
Revenue (€)	-	-	-	-	-	-	-	-	-
Residual Value of investments (€)	742638	0	0	0	0	0	0	0	1116653
FNPV(K) - After EU Grant /Net Cash Flow (€)	-242,656	-1433496	191267	198773	206554	214620	222980	231646	240627
FRR© - Before EU Grant	0.01								

Table 8-10: Financial sustainability of the project

FINANCIAL SUSTAINABILITY	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7
	Construction	**Operation**						
EU Grant	790,282	0	0	0	0	0	0	0
Promoter's Contribution	-1,433,496	0	0	0	0	0	0	0
Revenue	-	-	-	-	-	-	-	-
Total Cash Inflows	2223779	0	0	0	0	0	0	0
Investing Cost (including contigencies)	-2223779	0	0	0	0	0	0	0
BENEFIT FROM FUEL AND O&M Cost	0	191267	198773	206554	214620	222980	231646	240627
Total Cash Outflows	0	191267	198773	206554	214620	222980	231646	240627
Net Cash Flow	0	191267	198773	206554	214620	222980	231646	240627
Cumulated Net Cash Flow	0	191267	390040	596595	811215	1034195	1265841	1506468

Note that the FNPV(K) on national capital remains negative because the EU grant is covering only 85 % of the gap, while the remainder is covered by a national public grant.

The project appears to be financially sustainable, as the investment cost during implementation is covered by an equal amount in financing sources and its cumulated net cash flow during operations is positive during the entire evaluation period.

Externalities costs

According to *Ch.7.3* the externalities costs from the emission savings are calculated:

Table 8-11

EXTERNALITIES COST IN 1 YEAR OPERATION										
Pollutant		$PM_{2.5}$	PM_{10}	NO_X	CO	SO_X	NMVOC	CO_2	CH_4	N_20
SUM (tn)		0.89	0.89	24.19	3.07	0.08	1.46	1487		
Values (€)		85,389.1	75477.01	3635.19		4510.4	294.03	52704		
SUM (€)		76,043.8	67,216.5	87,928.7		374.5	430.5	78,373.59		
BENEFIT (€)	310,367									

<u>Socio/Economic Analysis</u>

Table 8-12: Project's economic analysis

ERR									
Calculation of the Economic Rate of Return	**NPV 6%**	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7
		Construction	**Operation**						
Project Investment Cost	-2223779	-2223779	0	0	0	0	0	0	0
Proect O&M Costs - BENEFIT FOR US	1,190,730	0	191267	198773	206554	214620	222980	231646	240627
Residual Value of investments	742,638	0	0	0	0	0	0	0	1116653
Total Economic Costs	-290,411	-2223779	191267	198773	206554	214620	222980	231646	1357280
B1. AIR POLLUTION	1,295,079	0	231994	231994	231994	231994	231994	231994	231994
B2. CO2 GHG	437,511	0	78374	78374	78374	78374	78374	78374	78374
Total Economic Benefits (B1+B2)	1,732,590	0	310368	310368	310368	310368	310368	310368	310368
ENPV / Net Benefits	1,568,053	-	-1722144	509141	516922	524987	533348	542013	1667647
ERR	0.27								
B/C RATIO	5,14								

9. Conclusions and recommendations

9.1 Conclusions

- The retrofit of an existing vessel is not feasible without external financial aid.
- Fuel cost savings are considerably high but cannot outbalance battery system's expenses taking into account system's life expectancy.
- Batteries' price is the biggest expenditure but cost of the rest of equipment needed is not negligible, as well.
- Even though batteries' specific energy is lower than that that of fuel oil, batteries as an on-board power source can be considered lighter according to operational profile.
- The required charging power for a double ended ferry for route examined (Perama - Salamina) is less than 1 MVA, thus eliminating the necessity for a high-voltage shore connection system.
- The double bus-bar system on board combined with a smart charging management system eliminates the need for a frequency converter for supplying the hoteling loads while charging, and it is rather an expensive piece of equipment.
- Passengers' and vessel's safety are the priority for a vessel therefore system's division in at least two packs, as DNV-GL suggests, is important and has a great influence in system's design.
- The configuration with an AC distribution network is more suitable for the retrofit of an existing vessels while the configuration with a DC distribution would be more appropriate for a new building especially if combined with a DC shore connection.
- 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. The most reliable configuration, though, is the 4 pack one.
- 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.
- A very small system would require to be charged from lower operating DOD to 100% DOD after every trip. But charging fully every time will result to extend shift duration. Since we know frequent charging means less batteries, we need to reduce the total charging time

The introduction of any alternative energy source will take place at a very slow pace initially, as technologies mature and the necessary infrastructure becomes available. The retrofit of existing vessel into all-electric ships is still an expensive choice despite the fact that fuel cost savings are significant; however, battery system's cost compared to its life expectancy is difficult be compensated for.

The good news is that we seem to be on the verge of a power revolution. All future predictions are estimating a great decline in battery prices justified by the volume of production and their integration in our everyday lives. Moreover, development on battery chemistries is expected to be massive from every aspect i.e. specific energy, shape, charging time.

Use of composite materials in shipping sector has, also, started growing significantly during last years.

Batteries as a fuel on-board can be considered lighter than diesel oil. On a broader context they are a steady weight comparable to the average fuel weight. In addition, to that, volume required for the battery system, from a practical point of view, is smaller compared to that of fuel-oil tanks.

Electric motors efficiency undeniably surpasses that of internal combustion engines.

Under the above terms, all-electric ship seems to be the future in shipping sector. Judging, though, from the economical results of current thesis ship owners will be hard to be convinced to retrofit an existing vessel into all- electric one.

But, if a new ship was to be ordered for routes examined, it should be an all-electric one. Close proximity and frequent stops at port ease often recharging intervals. Batteries' weight if considered from vessel's design phase can be distributed evenly on the ship, having the advantage of being a steady weight.

A lighter vessel leads to a smaller draft and subsequently to smaller power consumption and fuel savings. If lighter composite materials are used, financial gain can be even bigger.

9.2 Recommended next steps

This study focuses on small double-ended ferries of "open-type" since for the routes examined their shape is the most practical design solution. But, methodology developed can be adapted and applied for bigger vessels, as well. In that case, though, time maneuvering has to be considered. In addition to that, for bigger vessels attention must be given for ship's energy demands since these ships cruise mainly in open-seas and engines' load cannot be considered stable, as in our case.

Concerning national grid and national port policy

Ports in accordance with national policy should give an incentive of low tax to 'green' ships to encourage them to use 'green' energy. Hence, there is a need for the port to cooperate with municipality and encourage government approval of this program, like in Norway's '"green coastal program".

Moreover national electrical corporation may facilitate use of electricity on-board by applying a special port pricelist.

Greece should augment the proportion of power generation from renewable resources. In that way, the first 100% zero-emission Greek vessels can be launched.

Concerning electrical topologies

The DC shore connection needs to be studied and standardized.

Detailed study of vessel's electric networks is recommended.

Advanced legislation concerning emergency topologies should be investigated even though the criterion of emergency generator's place above the weather-deck is difficult to be overcomen.

Besides IMO rules and ISO standards, development of appropriate rules and recommended practices is necessary for the safe implementation of any of these technologies in the future. To achieve this, the role of Class societies will be crucial. Adopting new technologies is likely to be an uncomfortable position for ship-owners. To ensure confidence that technologies will work as intended, technology qualification from neutral third parties, such as classification societies, is also likely to be more widely used.

Consideration must be taken for batteries' recyclement. The augmenting use of them will be another environmental project. All batteries independent of chemistry shall be recycled and in most countries importers of batteries have to sign up to a battery recycling scheme. Facilities for recycling of lithium-ion batteries are existing and the value of the recycled materials more or less pays for the cost of the recycling.

The battery hasn't really advanced in decades. But we're on the verge of a power revolution. Big technology companies, and now car companies that are making electric vehicles, are all too aware of the limitations of lithium-ion batteries and that for, are pumping investing into battery developments.

Batteries storage system's technological development is expected to be radical.

Shipping sector must follow and be kept up to date for battery breakthroughs. Battery chemistry such as lithium-air means using oxygen as the oxidiser, rather than a material. The result is batteries that can be a fifth of the price and a fifth as light as lithium-ion. In addition, battery researchers are very optimist about the development of Li-air batteries because they use a fundamentally different technique to store energy. The battery cell uses metallic lithium in its negative side and reacts with atmospheric oxygen on its positive side. Because one of the reactants in the battery is air, in theory you need half as much battery materials to store the same amount of energy, and the weight of the battery can be reduced by half.

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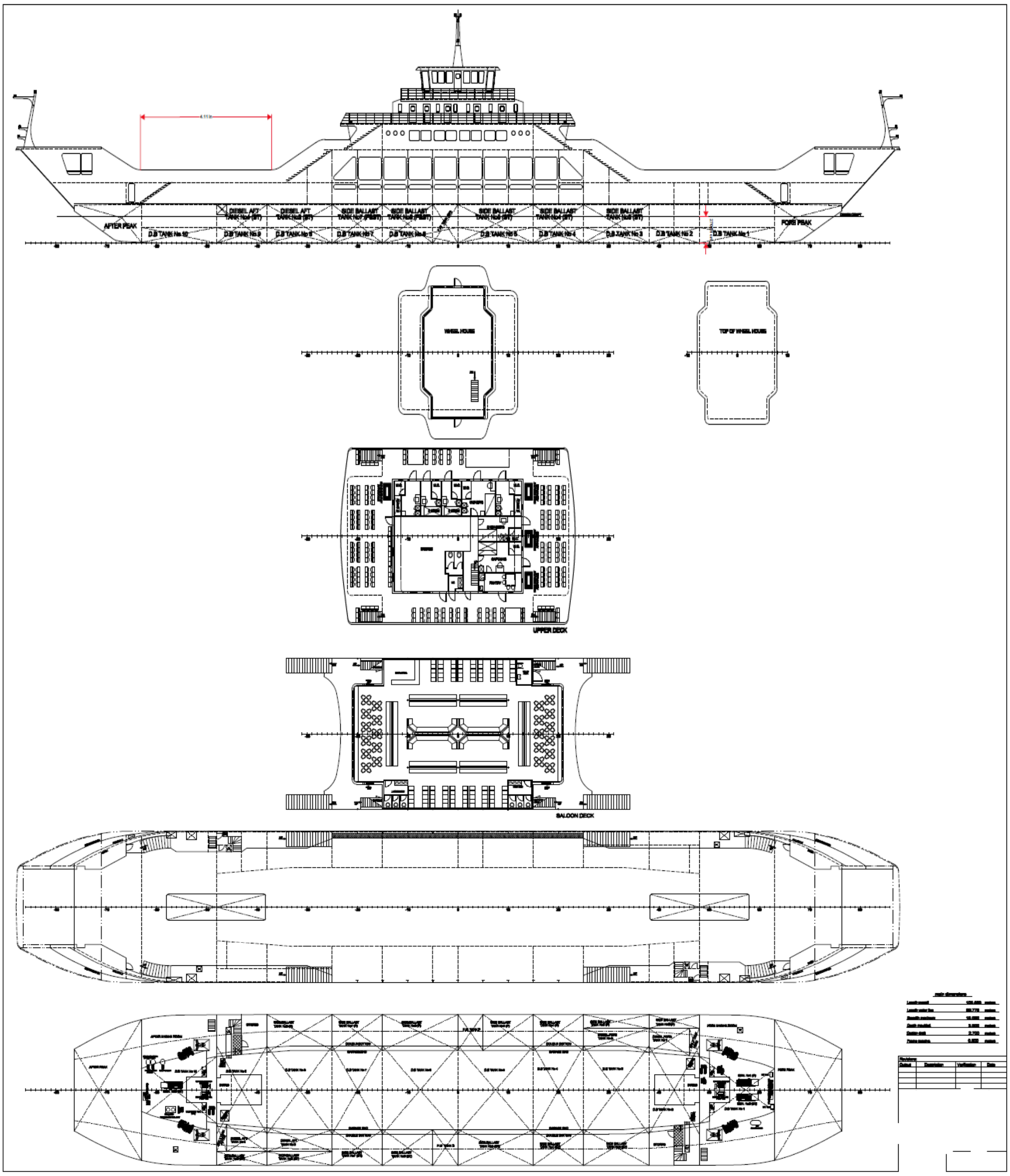
Appendix A

Table 1.1 Effects of air pollutants on human health, the environment and the climate

Pollutant	Health effects	Environmental effects	Climate effects
Particulate matter (PM)	Cancause or aggravate cardiovascular and lung diseases, heart attacks and arrhythmias, affect the central nervous system, the reproductive system and cause cancer. The outcome can be premature death.	Can affect animals in the same way as humans. Affects plant growth and ecosystem processes. Can cause damage and soiling of buildings. Reduced visibility.	Climate effect varies depending on particle size and composition: some lead to net cooling, while others lead to warming. Can lead to changed rainfall patterns. Deposition can lead to changes in surface albedo (the ability of the earth to reflect radiation from sunlight).
Ozone (O_3)	Can decrease lung function; aggravate asthma and other lung diseases. Can lead to premature mortality.	Damages vegetation, impairing plant reproduction and growth, and decreasing crop yields. Can alter ecosystem structure, reduce biodiversity and decrease plant uptake of CO_2.	Ozone is a greenhouse gas contributing to warming of the atmosphere.
Nitrogen oxides (NO_x)	NO_2 can affect the liver, lung, spleen and blood. Can aggravate lung diseases leading to respiratory symptoms and increased susceptibility to respiratory infection.	Contributes to the acidification and eutrophication of soil and water, leading to changes in species diversity. Acts as a precursor of ozone and particulate matter, with associated environmental effects. Can lead to damage to buildings.	Contributes to the formation of ozone andparticulate matter, with associated climate effects.
Sulphur oxides (SO_x)	Aggravates asthma and can reduce lung function and inflame the respiratory tract. Can cause headache, general discomfort and anxiety.	Contributes to the acidification of soil and surface water. Causes injury to vegetation and local species losses in aquatic and terrestrial systems. Contributes to the formation of particulate matter with associated environmental effects. Damages buildings.	Contributes to the formation of sulphate particles, cooling the atmosphere.
Carbon monoxide (CO)	Can lead to heart disease and damage to the nervous system; can also cause headache, dizziness and fatigue.	May affect animals in the same way as humans. Acts as a precursor of ozone.	Contributes to the formation of greenhouse gases such as CO_2 and ozone.
Arsenic (As)	Inorganic arsenic is a human carcinogen. It can lead to damage in the blood, heart, liver and kidney. May also damage the peripheral nervous system.	Highly toxic to aquatic life, birds and land animals. Soil with high arsenic content, reduces plant growth and crop yields. Organic arsenic compounds are persistent in the environment and subject to bioaccumulation.	No specific effects.
Cadmium (Cd)	Cadmium, especially cadmium oxide, is likely to be a carcinogen. It may cause damage to the reproductive and respiratory systems.	Toxic to aquatic life. Cadmium is highly persistent in the environment and bioaccumulates.	No specific effects.
Lead (Pb)	Can affect almost every organ and system, especially the nervous system. Can cause premature birth, impaired mental development and reduced growth.	Bioaccumulates and adversely impacts both terrestrial and aquatic systems. Effects on animal life include reproductive problems and changes in appearance or behaviour.	No specific effects.
Mercury (Hg)	Can damage the liver, the kidneys and the digestive and respiratory systems. It can also cause brain and neurological damage and impair growth.	Bioaccumulates and adversely impacts both terrestrial and aquatic systems. Can affect animals in the same way as humans. Very toxic to aquatic life.	No specific effects.
Nickel (Ni)	Several nickel compounds are classified as human carcinogens. It may cause allergic skin reactions, as well as affecting the respiratory, immune and defence systems.	Nickel and its compounds can have highly acute and chronic toxic effects on aquatic life. Can affect animals in the same way as humans.	No specific effects.
Benzene (C_6H_6)	A human carcinogen, which can cause leukaemia and birth defects. Can affect the central nervous system and normal blood production, and can harm the immune system.	Has an acute toxic effect on aquatic life. It bioaccumulates, especially in invertebrates. Leads to reproductive problems and changes in appearance or behaviour. It can damage leaves of agricultural crops and cause death in plants.	Benzene is a greenhouse gas contributing to the warming of the atmosphere as it contributes to the formation of ozone and secondary organic aerosols, which can act as climate forcers.
PAHs, in particular Benzo-a-pyrene (BaP)	Carcinogenic. Other effects may be irritation of the eyes, nose, throat and bronchial tubes.	Is toxic to aquatic life and birds. Bioaccumulates, especially in invertebrates.	No specific effects.

Appendix B



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