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 mid-range ferries into battery-powered ones”

Rafina-Marmari (Greece) case study

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Abstract

The aim of this thesis is the techno-economical feasibility study for the retrofit of a diesel-powered ferry into an all-electric one. The study focuses on the definition of the battery's capacity, the design of the battery rooms and the propulsion system. Other technical characteristics came into account such as the proposed charging method, which includes shore connection power supply and onboard Charging Room including all critical engineering design criteria, regulatory framework compliance and individual operation profile of ferry. Presentation of propulsion motors, side thrusters, auxiliary engines, power conversion equipment, circuit breakers and DC distribution system is included. The ferry is designed to sufficiently serve all the power needs for the propulsion and other loads required for an one way crossing trip for the case study's root: Rafina-Marmari. The economical study includes retrofit cost calculation, a comparison analysis of fuel and O&M savings on a year's operation and externalities costs because of the emissions saved.

Introduction

Shipping has to find ways to reduce its carbon footprint and invest in operations aimed at limiting emissions and improving resource efficiency because of the IMO's (International Maritime Organization) new and stricter legislations. The increasing demand for the promising greener ships, power plants and eco-friendly naval applications so as to restrain the adverse effects from maritime externalities has become an ultimate aspiration in modern times. Under these circumstances electrification is gaining momentum as a zero emission option. The trend towards electrification will, without doubt, transform coastal and inland water-borne transportation. While limits to energy density mean that ocean-going ships will never rely purely on batteries - hydrogen, ammonia, methanol and other energy carriers are being discussed instead –even they will switch progressively to hybrid-electric propulsion systems. Short-distance vessels of all sorts, however, will be dominated by battery-based solutions, for both cost and performance reasons.

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. The installation of the Battery Energy Storage System (BESS) based on the individual operating profile of the naval application requires much consideration to be taken with respect to load sharing, design arrangements, individual integrated equipment technical specifications, ageing issues, operation and maintenance cost requirements.

Electric ferries can already offer improved economics vis-à-vis conventional diesel ferries on short and medium-distance routes: their up-front cost and that of shoreside charging infrastructure may be higher, but their running costs are lower. It is not just that electricity is cheaper than marine diesel; crew and maintenance costs are also lower. The main propulsion diesel engine is replaced with simpler electric motors and batteries; gearboxes, vibration isolators, fuel tanks, fuel lines, engine ventilation, cooling, and exhaust systems are all eliminated, as is the need for an onboard generator to meet ancillary electrical loads; and propeller shafts and their bearings can be replaced with electrical connections. In many ways, electric ferries are simply better vessels than their diesel equivalents: cheaper to run, and eliminating the exposure of crew and passengers to vibration and noxious exhaust gases. They also offer significant potential environmental benefits in terms of reduced CO2 emissions, improved air quality and reduced fuel spill risk. This feasibility study focuses on the installation of the B.E.S.S on a 85 m twin hull Ro Pax, boosting the all-electric ferry design concept and transforming it in a profitable solution capable to serve coastal needs.

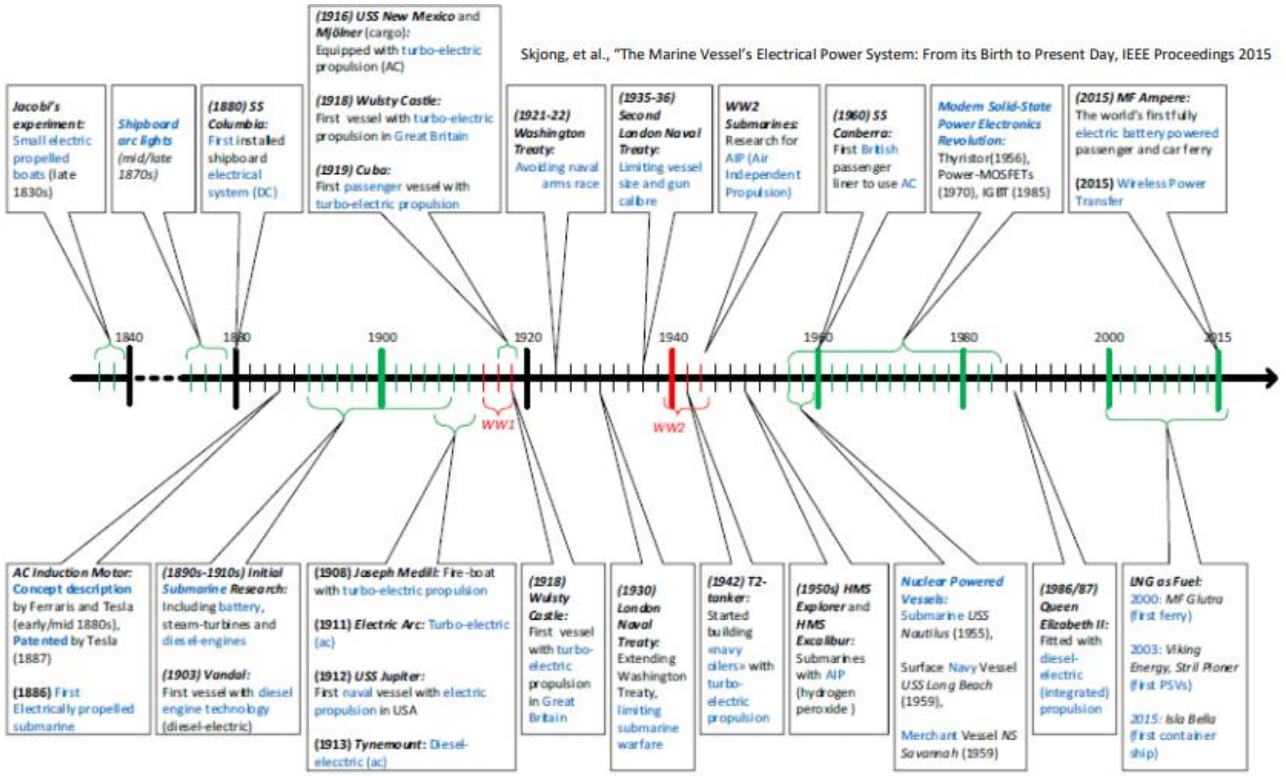
Electric ships, history and alternatives

Introduction of Electricity at sea

In the name of unobstructed marine transportation of goods, the increase of merchant navy and globalized trade bonds introduce inevitable financial incentives. The environmental betting for greener alternatives to minimize vessel's harmful footprint enables more demanding approaches in ship design and port infrastructure. In order to achieve such a demanding challenge, between marine development and environmental harm, the Engineering Society should respond with high-efficiency, greener and reliable solutions, where incorporation of the electricity at sea should be considered as well as other eco-friendly alternatives. Electrification on the maritime sector will prohibit the noxious vessel's operation while berthing and simultaneously mitigate the increased noise and vibration levels in comparison with conventional diesel generator engines. Existing regulatory framework, from the powerful initiative of International Maritime Organization to involve marine exhaust gas limitations, to the establishment of Emission Control Areas will play a key role in more efficient management of the harmful maritime action. Naval electrical applications will permit robust, flexible and cost-effective technological solutions to satisfy adequately both owner's requests and natural protection. Financial incentives, long-term benefits and deserving pay-back times are attracting investments in electrification at sea of a wide range of operators of innovative zero-emission marine applications in co-operation with designers and up-to-date equipment suppliers.

From the first all electric ship to nowadays

Historically, both electric cars and ships date back to the invention of batteries and motors in the mid 19th Century. In those days, water transport – on rivers, canals, lakes and oceans – carried most of the world's passengers and cargoes. Muscle power, sails, and later coal/steam power, were the main energy sources, and all three had significant disadvantages, being highly labour intensive. The commercial development of electric boats included small and medium-sized passenger boats, small ferries, and even canal barges like streetcars that used overhead power lines. But, just as with early electric cars, poor range, lack of charging facilities, and slow speeds were key disadvantages. The high energy storage density of oil, and the internal combustion engine put an end to most EB development by the early 20th century. Nevertheless, throughout the last 100 years, the need to power silent hybrid submarines and undetectable torpedoes ensured that battery and motor development continued, culminating in nuclear-electric submarines capable of travelling under the frozen ice of the Arctic to meet the threats of the cold-war era. Meanwhile, using manned and unmanned electric submersibles, exploration continues of the mysterious depths of the oceans.



Skjong, et al., "The Marine Vessel's Electrical Power System: From its Birth to Present Day, IEEE Proceedings 2015

Figure 1: *Evolution of the marine vessel electrical power system from 1830 to 2015*

The first steps were made as early as the 1830s when a series of inventions led to the development of the first electric motor. Namely, the battery by A. Volta (1800), the generation of a magnetic field from electric current by H. C. Oersted (1820), and the electromagnet by W. Sturgeon (1825).

Prussian physicist Moritz Jacobi was the first who attempted to use electricity in order to propel a boat by using a simple DC powered motor, in September 1838. 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 4 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. Due to the early motor design, which carried many imperfections, the invention was not adopted and used in any practical applications and was soon forgotten

The 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.

An Austrian émigré to Britain, Anthony Reckenzaun, was instrumental in the development of the first practical electric boats. While working as an engineer for the Electrical Power Storage Company, he undertook much original and pioneering work on various forms of electric traction. In 1882 he designed the first significant electric launch driven by storage batteries, and named the boat *Electricity*. The boat had a steel hull and was over seven meters long. The batteries and electric equipment were hidden from view beneath the seating area, increasing the space available for the accommodation of passengers. The boats were used for leisure excursions up and down the River Thames and provided a very smooth, clean and quiet trip. The boat could run for six hours and operate at an average speed of 8 miles per hour.

Moritz Immisch established his company in 1882 in partnership with William Keppel, 7th Earl of Albemarle, specializing in the application of electric motors to transportation. The company employed Magnus Volk as a manager in the development of their electric launch department. After 12 months of experimental work starting in 1888 with a randan skiff, the firm commissioned the construction of hulls which they equipped with electrical apparatus. The world's first fleet of electric launches for hire, with a chain of electrical charging stations, was established along the River Thames in the 1880s. An 1893 pleasure map of the Thames shows eight "charging stations for electric launches" between Kew (Strand-on-the-Green)and Reading. The company built its headquarters on the island called Platt's Eyot.

From 1889 until just before the First World War the boating season and regattas saw the silent electric boats plying their way up and downstream.

In the 1893nChicago World Fair 55 launches developed from Anthony Reckenzaun's work carried more than a million passengers. Electric boats had an early period of popularity between around 1890 and 1920, before the emergence of the internal combustion engine drove them out of most applications.

Most of the electric boats of this era were small passenger boats on non-tidal waters at a time when the only power alternative was steam.

The first electrically powered submarines were built in the 1890s, such as the Spanish Peral submarine, launched in 1888. Since then, electric power has been used almost exclusively for the powering of submarines underwater (traditionally by batteries), although diesel was used for directly powering the propeller while on the surface until the development of diesel-electric transmission by the US Navy in 1928, in which the propeller was always powered by an electric motor, energy coming from batteries while submerged or diesel generator while surfaced.

The following decades combustion engines dominated in all the means of transportation including shipping. Fossil fuels' energy density and availability is the main reasons that the overwhelming majority of ships run with combustion engines until nowadays. Electric propulsion was limited only in special cases such as inland passenger boats, scientific or military boats and submarines and other pilot projects. For example 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.

Previous century was the age of the internal combustion engine just as the 19th was the age of steam. Although 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.

21ST 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. If combined with the augmenting use of renewable energy resources for power production the future looks bright for our target, the all-electric-ship .

Three remarkable all-electric projects that already operate successfully in northern Europe are presented bellow.

Modern all-electric ferries projects

MV Ampere

MV Ampere is the world's first battery electric car ferry, operating between Lavik and Oppedal in Norway. It is owned and operated by Norled, and crosses the Sognefjord, the longest and deepest fjord in Norway. In 2015 MV Ampere made its maiden voyage. The vessel is a twin-hulled catamaran, capable of carrying 120 cars and 360 passengers. The route's distance is 5.9km and the ferry makes 17round trips per day with 10 knots service speed

Figure 2: *Ampere,* world's first all-electric ferry-*silent and robust as a white crocodile*-making huge impression with its reliable and sustainable power and propulsion technology

Ellen

Ellen is one of the most powerful e-ferries in the world. Built as a prototype, aiming to prove that electric ferries can be economically viable for medium distances, it operates on a 20km route between Danish islands of Als and Ærø. The ship, sailing at 13.5 knots per hour covers the 2-hour return trip, requiring only 40 mins of charging. To reduce costs, infrastructure was installed only in Ærø, meaning the ship makes a full return trip of 40km between charges. Ellen has been in operation since August 2019 and has achieved positive results both in terms of reliability and passenger satisfaction, with around 20% of passengers indicating that they would consider using the service more often due to its environmentally friendly features and reduced noise levels.

The project was supported by the EU Horizon 2020 technology programme, which provided €15 million out of the total cost of €21 million (including charging infrastructure). The developer claims that the cost of a 'third of a kind' project would be significantly lower, at €16.3 million (also including charging infrastructure). For comparison, a newly built diesel ferry with similar specifications would cost around €14.1 million, while a used boat would be slightly cheaper at €12.9 million.[4]

Figure 3: Ellen, one of the most powerful e-ferries

MF Tycho Brahe/MF Aurora

In 2017 two ships, which were both built in 1991, serving the route between Helsingør, Denmark and Helsingborg, Sweden, underwent a full retrofit including electrification. The vessels are capable of carrying 1,250 passengers and 240 cars, with a sailing speed of 14 knots. The operator, ForSea, decided that the diesel engines would be retained as a backup, but they are not used in daily operations. 4.1 MWh of batteries were installed on each vessel, allowing for three full crossings of the 5km strait without charging. However, to extend battery life and avoid going below 30% state of charge, the vessel is charged in both ports while passengers are boarding. As the route is extremely busy (more than 40 return trips per day), high voltage lines were installed, and charging takes place at around 10 MW.

The cost of converting the two vessels was 300 million Swedish crowns (€28 million), with the EU providing 120 million SEK (€11 million). Expected payback period is 8 years, while useful life of the vessels after the retrofit is estimated to be at least 15 years. [4]

Figure 4: The ferry MF Aurora

Battery storage systems

A battery is an electrochemical storage device that stores electrical energy in the form of chemical energy. The basic components of a battery are shown in Figure 1.1. In general, a battery is comprised of two different poles – a positive electrode called the cathode and a negative electrode called the anode. Then some material is used inside the battery, called electrolyte, that enables ions, or charge carriers, to be transferred back and forth between these poles by electrochemical reactions. A separator can be placed between the cathode and anode, preventing them from touching each other. Hence, when the poles are connected by an electrical conducting material, electrons will flow through the external electrical circuit, and ions to flow through the electrolyte. This process allows energy to be stored or produced in the battery. The chosen energy carrier material, electrode and electrolyte composition, and the shape of the electrodes determine the properties of the batteries.

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.

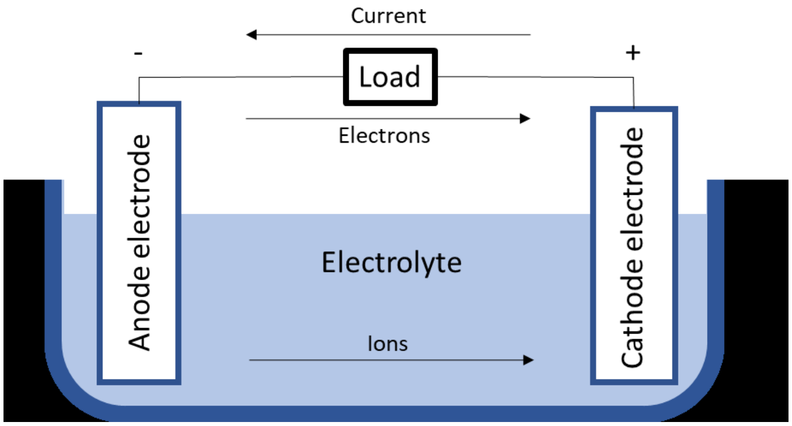


Figure 5: Components of a battery [7]

The most familiar energy carrier is lithium – positively charged, so it is then referred to as a lithium-ion. 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. Today the most common types of lithium-ion batteries are:

- **Lithium cobalt oxide, LiCoO2 (LCO) -** The main advantage of LiCoO2 is its relatively high energy density. However it typically displays lower power (rate) capabilities and shorter cycle life. Impedance increase over time is also a significant concern with LiCoO2 based cells. Cobalt oxide suffers from safety concerns due to the exothermic release of oxygen at elevated temperatures – producing a self-heating fire resulting in thermal runaway concerns. LCO type cells are very common in consumer electronics rechargeable batteries where a three year life span of a few hundred cycles to 80% of its original capacity often is sufficient.

- **Lithium manganese oxide spinel, LiMn2O4 (LMO) -** LMO is a somewhat unique cathode chemistry, being a spinel structure, which provides significant benefit in terms of power capabilities. The compound has additional safety benefits due to high thermal stability. However it has significantly lower energy capacity compared to cobalt based compounds, and is known to have a shorter cycle life characteristics especially at higher temperatures. Several material modification possibilities exist in order to improve the cycle life of LMO compounds.

- **Nickel manganese cobalt oxide, LiNi1-x-yMnxCoyO2 (NCM or NMC) -** NCM is one of the most recent cathode developments and is the present market leader for large format applications and are starting to replace LCO as the dominant chemistry for consumer electronics. It’s strength is the combination of attributes of the constituents of nickel (with a high specific energy), cobalt (high specific energy) and manganese (doped in the layered structure to stabilize it). The relative composition can be tweaked to produce different properties with regard to power density, energy density cost and safety, as well as customize the cells to certain applications or groups of applications. NCM can also be mechanically mixed with LCO or LMO in the cathode in order to produce yet another customization of properties.

- **Lithium iron phosphate. LiFePO4 (LFP) -** Like LMO, LFP differs significantly from most other cathode chemistries in terms of its structure, which is phosphorous-olivine rather than a layered metal oxide. A dominant benefit of this is the lack of an oxygen source at the cathode, thus posing a potentially reduced risk magnitude during thermal runaway. These cells are additionally more resilient to temperature fluctuations. The specific energy of LiFePO4 is relatively low, and the electrochemical potential (voltage) is lower, reducing the cell’s driving force. Power capabilities of a LiFePO4 based battery cell are inherently low; however, doping the LiFePO4 material with small amounts of other materials, conductive coatings and nanostructured active material particles have enabled typically high power battery cells using LiFePO4.

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 stateof- charge to the cut-off voltage.

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 $\eta c = \frac{Qout}{Qin}$

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.

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 anddischarging, 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.

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. 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.

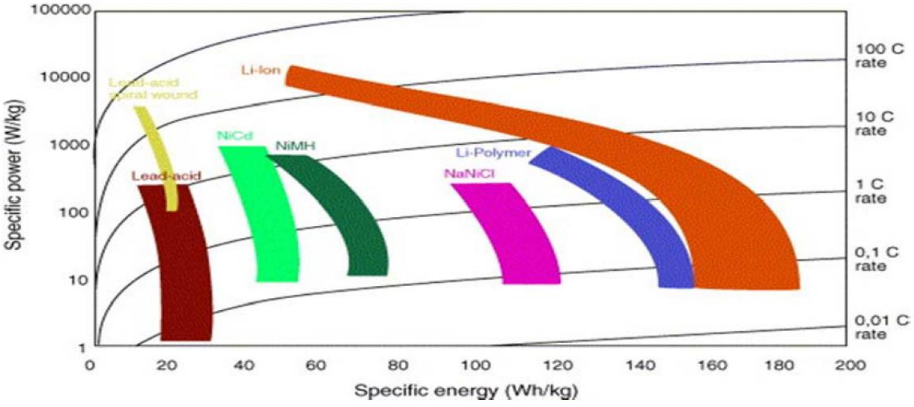


Figure 6: Ragone Chart

Purpose

Purpose of this study, as mentioned before, is the investigation of the potentials and technicalities of routing a battery powered ferry in a mid range route. Both a technical and a financial point of view are offered including necessary shore's adaptation. All-electric ferries have additional benefits which even they don't get into account on this study, although they have strong impact on the general attractiveness of the project.

- ✓ Evident improved environmental impact due to zero-emission by design;
- ✓ Improved impact due to noise and vibration;
- ✓ Amelioration of quality life onboard and around the ports;
- ✓ Increased overall efficiency;
- ✓ Reduced maintenance costs;
- ✓ Flexibility in machinery arrangements;
- ✓ Potential leverage of renewable energy in shipping;
- ✓ Facilitating sustainable growth;

Some of them satisfying the particular of coastal and passenger's needs.

Overview

The subject focuses on the retrofit of an eco-friendly twin hull ferry that can support a leading and flexible propulsion system which incorporates a cutting-edge Power Management System able to manipulate low-cost but robust propulsion, battery, manoeuvring and monitoring system. Its electric propulsion system is expected to be cost effective due to its lesser maintenance cost, minimized exhaust gas footprint, vibration, smell and noise in comparison with conventional diesel engines.

Intelligent electric propulsion combined with an innovative monitoring and automation system offers remarkable fuel saving operation, power resource conservation and reduced maintenance costs. An optimally performing system should allow proper integration of all involved integrated *custom-made Sub-Systems*: Propulsion System, Maneuvering equipment, batteries, power conversion, Bus-Bar Arrangement and consumers, as well as a safe, reliable and efficient communication and co-operation of all the above.

The on-board Battery plant will be capable of regenerate all of its energy while at berth through a convenient and automatic system on shore, while, also, quick redundancy could be achieved by battery swapping from available battery racks from the land.

The ship's electric system design is mainly addressed by the size of its propulsion requirements. In general, an effective propulsion system should be characterized by durability, flexibility, space optimization and should comply with the distinctiveness and operational purpose of its installed battery-powered machinery.

This thesis focuses on the establishment of a Battery Energy Storage System and the design of its individual Propulsion and Shafting System on an innovative 85m Ro-Pax Catamaran vessel which details are presented below.[1]

The vessel is designed to be operating for up to 15 Nautical Miles with a maximum speed of 15.5 knots. The nominal cruising speed of the vessel is selected at 14.8 knots.

Table 1: Main Particulas

VESSEL MAIN PARTICULARS AND DETAILS	
Vessel Type	Ro-Pax
Specific Hull Design	Twin-Hull (Catamaran)
Length Overall (m)	84.43
Length B.P.(m)	74.10
Beam Mld. (m)	26.00
Height to Deck 6 (m)	13.425
Draft Design Mld. (m)	3.83
Draft Scant. Mld. (tons)	4.500
Deadweight at Scantling Draft(tons)	925
Service Speed at Scantling Draft (knots)	15
Passengers(summer)	1175
Crew (persons)	41

Case Study Rafina Marmari

The route of Rafina - Marmari has been selected for the purpose of this study in all aspects. It’s a 15 nm route in the South Evian Gulf in Greece. Rafina port is one of the biggest passenger ports in Greece located on the eastern Attica, 40 minutes by car from Athens. Marmari is on the south side of the Evia island, a region with increased traffic during summer.

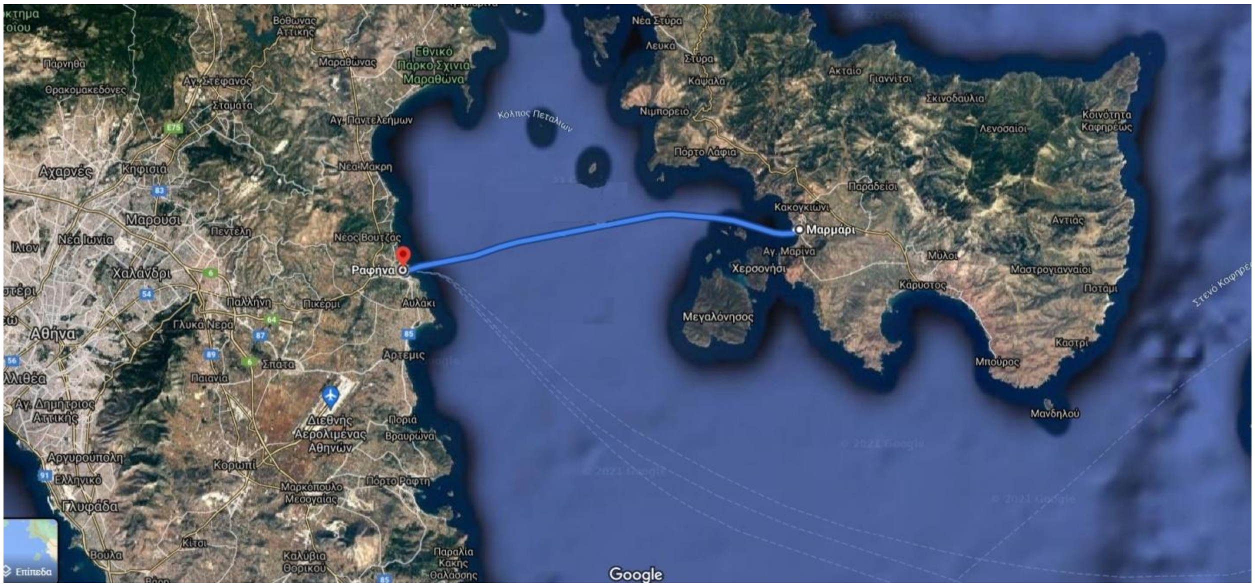


Figure 7: The route Rafina-Marmari

This thesis will compare the battery powered ferry with the current way of operation. The one way trip lasts about 1 hour with 14.8kn cruise speed. In both ports must be serious investment for the charging infrastructure.

Figure 8:Port of Rafina

Figure 9: Port of Marmari

Propulsion, Electric Motors & Hotel Load Power estimation

The intriguing benefits of electric propulsion boost the concept of the all-electric vessel to exceptionally distinguish, in terms of promotion of renewable energy on sea and increased efficiency in comparison with conventional propulsion and energy supply systems.

Sizing the naval electric power plant, will be accomplished by satisfying the prerequisite of reliability and availability. The Standard Handbook of Electrical Engineers defines the reliability of a power system as a measure of its *"ability to serve all power demands made by customers without failure over long periods of time"*. Availability is defined as the *"percent of time that a unit is available to produce power whether needed by the system or not*". Meanwhile, the required adequacy and security of the onboard power plant will sufficiently cover all possible needs of the electric loads of the vessel.

Reliable estimations on the design process require thorough attention in order to not only avoid energy supply inadequacy issues, but also, over sizing an onboard power plant ejecting the cost of the whole project. Only a detailed electric load analysis, in a more mature phase of the design, assuming the required consumers proposed to be installed and their utility factors to be in hand, is expected to indicate the exact power requirements of vessel's operational modes.

In this phase of the preliminary design, an estimation of the main propulsion and hotel load power requirements will be fulfilled. It is fundamental to adequately size the MCR and rotational speed of the two (2) electric Motors which will be the main means of Propulsion of the ferry. With respect to the propulsion power estimation, a power margin, rough sea and fouled hull as well as, shaft and gear box power losses are assumed to be taken into consideration. Side Thrusters are assumed to be operating only while maneuvering for a short duration in case of side berthing.

With respect to hotel load power estimation, the approach is based on details concentrated from similar *Ro Pax* vessels. In addition, in case of ferries and cruise ships following a well-known route, the hotel load power requirements are expected to behave in a typical manner, highly depended on water and air temperature. General time-dependencies during the day of trip are also to be taken into consideration.

Corresponding margins are expected to be taken into account with respect to "acquisition" design superstition and design margin in terms of "service life". Estimation for an additional load for three (3)-phase consumers would also be essential for our approach and has also been conducted. It is known that onboard loads on operating vessels are expected to be fluctuating with respect to the daily and seasonally power demand operational profile and temperature variations. The maximum continuous load is expected to be handled adequately by the onboard

B.E.S.S and it is to be calculated by simply summing all possible electric loads on a more mature phase of this design. [1], [16]

Power Loss Estimation for the B.E.S.S was estimated, as well as, proper sizing of the Side Thruster Motor(s) was carried out. Results on power estimations are summarized in the following table.

Table 2: Pre-estimation of Propulsion, Hotel load, Side Thrusters, Additional Load for three(3)-Phase Consumers power requirements

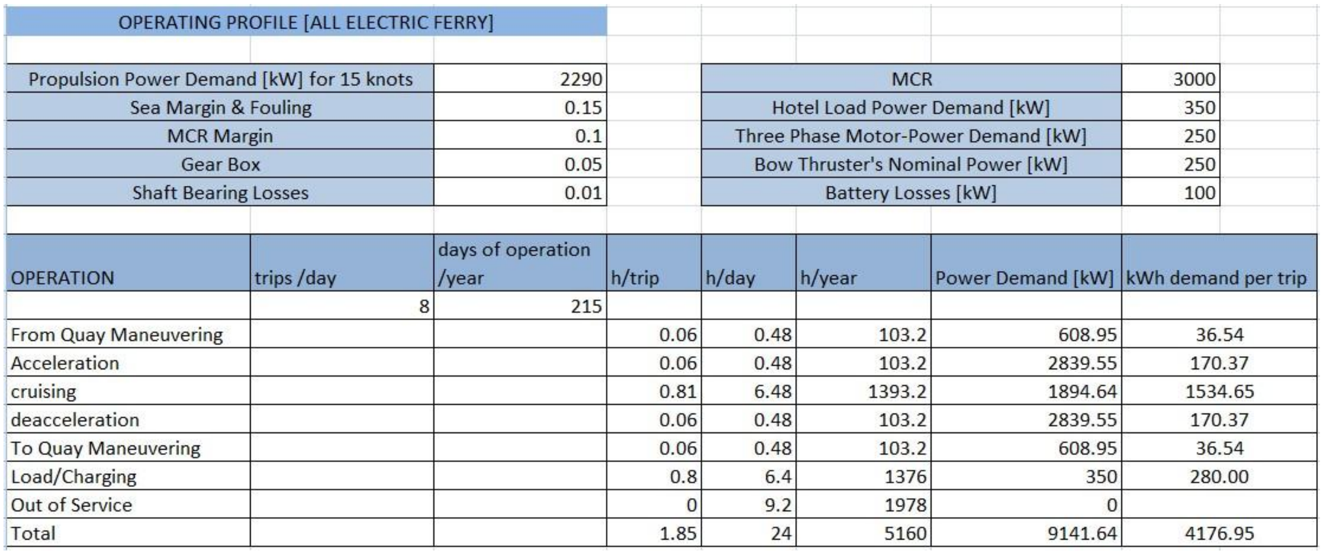
POWER ESTIMATION OF FERRY	
Main Engine Power (for 14.8 knots cruising)	2 x 3,000 kW
Hotel Load Demand	350 kW
Side Thruster Motors	2x125 kW
Additional Load for three (3)-phase consumers	250 kW

Ferry’s Design operation profile

With respect to this innovative onboard Battery System, it is expected to support all required loads of vessel during operation providing reliability, adequate flexibility and ensuring safety of passengers, crew and craft at all costs. The Battery Bank should be sized accordingly by the greater load demand or generation input to efficiently support the trip and ensures safety at all costs. [1]

The selected operational profile of vessel is designed to cover up to 15 Nautical Miles.

The main operation Design profile in terms of power consumption, as wells as, the average and design values of ferry’s Battery System are summarized on Table below.



OPERATING PROFILE [ALL ELECTRIC FERRY]

Propulsion Power Demand [kW] for 15 knots	2290
Sea Margin & Fouling	0.15
MCR Margin	0.1
Gear Box	0.05
Shaft Bearing Losses	0.01

MCR	3000
Hotel Load Power Demand [kW]	350
Three Phase Motor-Power Demand [kW]	250
Bow Thruster's Nominal Power [kW]	250
Battery Losses [kW]	100

OPERATION	trips /day	days of operation /year	h/trip	h/day	h/year	Power Demand [kW]	kWh demand per trip
	8	215					
From Quay Maneuvering			0.06	0.48	103.2	608.95	36.54
Acceleration			0.06	0.48	103.2	2839.55	170.37
cruising			0.81	6.48	1393.2	1894.64	1534.65
deacceleration			0.06	0.48	103.2	2839.55	170.37
To Quay Maneuvering			0.06	0.48	103.2	608.95	36.54
Load/Charging			0.8	6.4	1376	350	280.00
Out of Service			0	9.2	1978	0	
Total			1.85	24	5160	9141.64	4176.95

Figure 10: Operation Profile

More specifically, the main operating profile of the innovative ferry is described below:

- The vessel is expected to make eight one-way trips daily, operating for a total **215 days annually.**
- During each one-way trip, the vessel consumes abt. **4189 kWh** energy from the battery system (it is assumed all annual cycles follow the described profile).
- During loading/unloading, the vessel is connected to an automatic land-based **charging** station and charges **for 48 minutes** (0.8 hours). The battery will recover all energy consumed from the previous one-way crossing during that time period. Battery swapping at port should also be considered in a later phase of the design.
- While a **careful maintenance plan** is expected to be followed, the Battery System is designed for **at least seven (7) years of continuous operation**, resulting in 1283 cycles/year.

- **The B.E.S.S is expected to adequately serve the total required Design Power requirements of the ferry that are abt. 7297.5 kWh (i.e. 2x 3.0 MW for Design Propulsion, 350 kW for hotel load requirements, 250 kW for additional Load for three (3)-phase consumers, 2x125 kW for Side Thrusters, 100kW for Battery Loss and total single-trip period of 1hour).**
- The Nominal Voltage of the installed Battery System is estimated at 768 VDC.

Battery Energy Storage System Selection

Sizing adequately the Battery System of the ferry ensures profitable life-cycle operation, low maintenance and extended Battery Life which is mainly depended from the ambient temperature, Battery chemistry, cycling and maintenance plan. The stored capacity of the Batteries is to be such so as to conform with the safety of rules and regulations within the state of operation. Classification guidelines with stricter obligations ensure safety and reliability efficient and consistent battery installations.

The incorporation of a Battery Energy Storage System on a ferry introduces a wide range of significant benefits such as high availability, reduced maintenance load, radiated noise and vibrations as wells as zero-emission operation and increased survivability.

In a DC power distribution system, the proposed B.E.S.S is expected to increase system's reliability and flexibility in weight, space and energy reservation. Even when incorporated in DC hybrid Systems, is expected also, to improve transient performance and enable optimal load sharing among resources.

Depending on the system requirements for a B.E.S.S in a marine application stated by power profile, footprint and safety measures Li-on batteries, based on Nickel Manganese cobalt oxide (NMC), lithium nickel cobalt aluminum oxide (NCA) or Li-phosphate (LFP) cathodes and carbon) or Li-titanite (LTO) may be chosen. Most battery storage systems have to be designed with a sufficient initial over-sizing in order to cope with the fade in energy capacity and power capability over lifetime. Strings of batteries are paralleled to meet energy capacity and power capability requirements. Lithium-ion Battery technology distinguishes in terms of shot-trip coastal routes. Its' enhanced incomparable power density and its capability to allow a short-term regenerate of high amount of energy while loading/unloading operations are exceptionally promising in the all-electric ferry design.

The chemistry that selected for this project is LFP. This type of batteries have lower energy density than NMC but they have higher safety characteristics and they are resilient to temperature fluctuations.

The proposed B.E.S.S to be installed onboard is designed to sufficiently serve all power load requirements while ensuring reliability, efficient operation and convenient vessel's trips. The following battery system is proposed based on the estimated operation profile with remarkable energy density (Wh/L) and high degree of safety.

As a reference module will be considered a module with 128V output voltage and 7.8kWh capacity. To reach the required energy, 720 modules need to be installed. Six modules in row will form a pack with 768V Voltage. The pack's dimensions estimated as Height: 2060 mm | Width: 654 mm | Depth 500 mm. It's energy density is 8kg/kWh, so the total weight of the battery will be about 45 tons.[6]

Table 3: Battery Energy Storage System estimated technical characteristics

ESTIMATED TECHNICAL CHARACTERISTCS BATTERY SOLUTION		
Total Embedded Energy	2 x 2.8 MWh	*Each Battery System is to be accommodated inside a Battery Room, serving power requirements on each side of craft with enhanced redundancy*
Battery Voltage	Estim. 768V DC	
Cooling Method	Air/ Water	
Assumed Design Life	At least 5 years	*A careful maintenance plan expected to be followed*
Battery weight	*Estim. 45 tons*	

Power and Battery Management System

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
- protect against overcurrent, over-voltage and under-voltage)
- protect against over-temperature
- control cell balancing.
- protect against over-pressure

The following parameters shall be measured:

- cell voltage
- cell temperature
- battery string current.

Proposed B.E.S.S Charging Method

Enhancing the idea of utilization of the electricity at sea, forces port authorities to promote power charging shore-based systems that will allow vessels to fully-recharge their installed B.E.S.S while moored through an automatic, convenient and quick connection at berth. Sizing the proper Charging System is essential in terms of cost-saving operation, low maintenance and time conservation, as well as, profitable life-cycles. An Automatic Charging Plug-In System is expected to efficiently recharge the power system of the vessel at quay.

Connection to vessel's reception socket of the charging Cable is ensured by an automatic charging shore based system. The connection socket funnel can be located either to the side part or to the stern side of the vessel. It has also been noted that connecting the charging equipment while loading/unloading at port in cutting-edge automatic New Building Designs could also be achieved even with wirelessly technology in modern applications ensuring reliable, safe and easy operation.

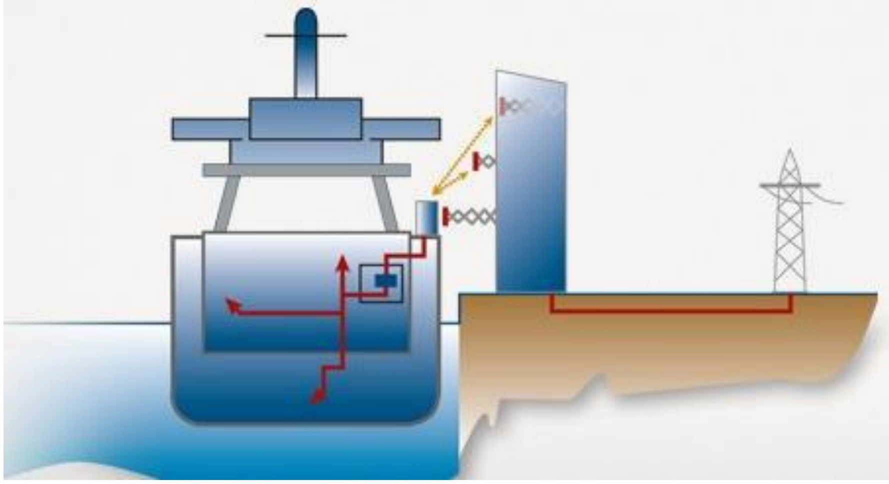


Figure 11: Schematic of a typical side charging system

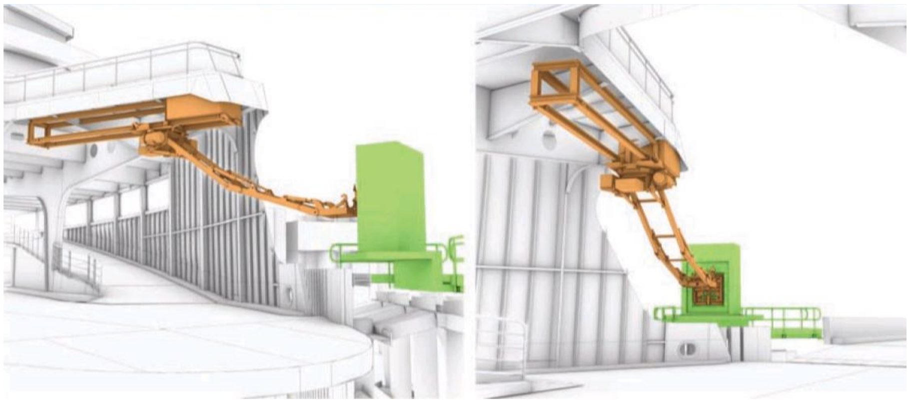


Figure 12: Proposed Stern Side System

Figure 13: Excample of an wirless charging system (wartsilla)

Shore side infrastructure

A wide array of electrical works is required to enable seamless operations for an electric ferry: laying kilometres of high voltage lines, building local substations, installing charge-points and – in some cases –buffer batteries to smooth the demand for power from the local grid and avoid excessive peak charges. The standards aim to establish the requirements to ensure compatibility between ship and highvoltage 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. For the case of this thesis, an AC interconnection system is chosen. IEC 80005-1 standard covers AC high-voltage shore connection systems.[2] Especially covers:

- quality of the power supply
- electrical requirements
- environmental and mechanical requirements
- safety
- electrical equipment requirements
- ship requirements
- compatibility matter between shore connection and ship equipment
- ship to shore connection and interface
- plugs and sockets
- verification and testing.

The standards propose similar configurations. The main components of this configuration are:

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

Ship side

A reliable and flexible onboard power system should be consisted of all required power electronic equipment, voltage switching gear and integrated circuit breakers for the protection of individual equipment. An automatic computerized alarm and monitoring system will ensure proper synchronization of involved equipment and efficient power transfer. A specially designed dock-side gantry/crane handling cable management should ensure reliable or even multiple power transmittal for vessel while at berth. Automatic, powerful and reliable mooring systems should be considered to draw the vessel against the quay and ensure convenient and secure charging in a more mature phase of the design.

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. Exceedance of the specified current level (C-rates) and voltages should be avoided. The protection settings in effect shall be clearly indicated at the control station.

Automatic Charging Land Based System

For the case study an onboard socket located at ferry's side will be protected with a hatch for mating, inspection and maintenance. The distribution of power from the grid to the shore power system will be through an Automatic Shore Substation installed System via an appropriate cabling to ensure transfer and adaptation of power supply on vessel's side cable system.[1]

Table 4: Shore based charging system technical data

SHORE BASED CHARGING SYSTEM TECHNICAL CHARACTERISTICS	
Nominal Voltage	7200V AC
Estimated Capacity:	6563 kVA
Nominal frequency:	50-60 Hz

Plug-In System on Vessel

On the side part of the vessel, caution has been made to design an onboard plug-in receipt socket system that will permit easy handling, sufficient space for acceptable maintenance and uninterruptible power transmittal when adjustment is ensured.

Subject design is to be made at an appropriate height to allow a convenient charging process and ensure safety at all costs.

The Shore side power voltage is expected to be matched with the vessel's power system, appropriate electronic devices, wiring and plugs and also, synchronization should be ensured to avoid any kind of disruption.

The onboard plug-in system's hatch proposed technical data are the following.[1]

Table 5: Receipt Design of Plug-in System on ferry technical data

PLUG-IN SYSTEM ON VESSEL TECHNICAL DATA	
Nominal Voltage	7200V AC
Nominal frequency	Estim. 50-60 Hz
Max current capacity	630 A

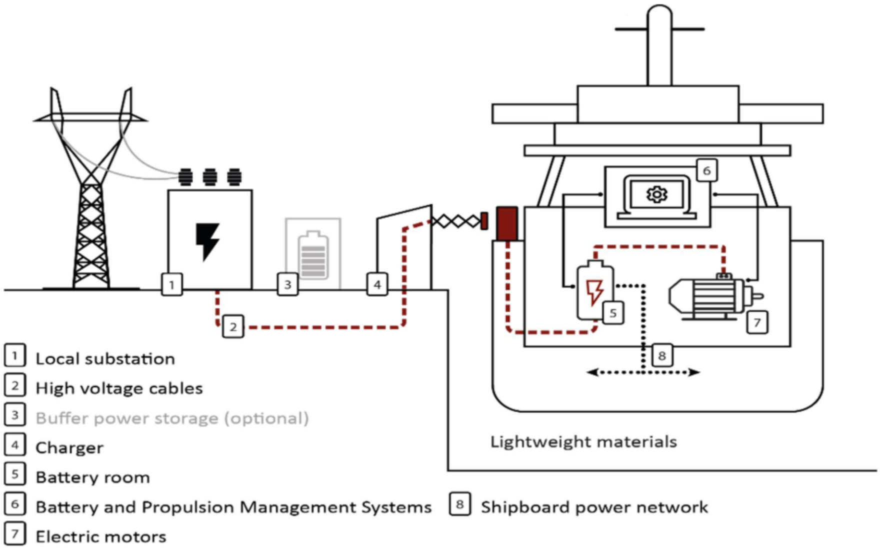


Figure 14: Schematic of an electric ferry and associated onshore infrastructure

Source: Liebreich Associates

Shore Connection to three (3) Winding Transformer

In order to obtain the required nominal voltage level for the charging process, a pre-magnetized three (3) winding transformer of dry type, will be provided reducing the voltage level of the grid from 7.2kV to 690 V and allowing the process of charging to be safely fulfilled. The required technical description is presented below. Subject transformer will be located at the Charging Room with proximity to the Charging plug-in receipt socket. All necessary fire protective equipment and gear is to be taken into consideration.[1]

Table 6: Shore Connection three (3) winding Transformer technical characteristics

THREE (3) WINDING TRANSFORMER	
Design Rating	7670 kVA
Power Factor	0.8
Primary/Secondary voltage level	7200 V/690 V
Frequency	50 Hz
Type	Dry type
Efficiency	98.00 %

Power Switchboards

DC Main Switchboard

The overall power distribution from the onboard Battery System will be through an active front end (AFE) technology converting produced DC to AC with the relevant frequency. An overall control system will be integrated in the power electronics to control the distribution from the energy source. Those are to be located with proximity to the Main Hotel Switchboards. Cable routing are to be arranged such so as to minimize voltage drop and interconnection with leakage or moisture sources as far as practical and operational. Interconnection between the two (2) Switchboards will be ensured. Design margins due to redundancy are to be taken into account[1]. Technical characteristics are presented in the following table.

DC MAIN SWITCH BOARD MAIN TECHNICAL DATA	
Bus-bar voltage	Estim. 768 VDV
Output voltage	0 – 660 VAC
Cooling method	Fresh Water

Hotel Load Switchboards

Two Main Hotel Switchboards are expected to be installed in order to serve the required Hotel Loads on each side of vessel. Interconnection between the two (2) Switchboards will be ensured. Technical characteristics are presented in the following table.

HOTEL SWITHCBOARD TECHNICAL DATA	
Nominal voltage	230V AC
Nominal frequency	50 Hz

The subject Switchboard could have sufficient space in all circumferential areas for easy inspection. All cables are expected to follow ascending cable routes from below.

Three (3)-Phase Consumers Switchboards

Estimation for additional loads for three (3)-phase consumers, representing mainly dedication to cooling requirements, was also taken into consideration. Basic technical characteristics are presented below.

THREE (3)–PHASE COSNUMERS SWITCHBOARDS	
Nominal voltage	440V AC
Nominal Power Requirement for feeders	2x125 kW
Rated Breakers to Power	420 A

Switchboard	
Rated Interconnection Breakers	210 A

Power Distribution Transformer of Hotel and three (3)-phase Switchboards

In order to serve all required hotel loads and three (3)-phase consumers' requirements, power distribution transformers will be required for each switchboard to ensure reliable operation of installed consumers.[1] Technical data is presented as follows

HOTEL POWER DISTRIBUTION TRANSFORMER	
Design Output	350 kW
Primary voltage level	660 V
Secondary voltage level	230 V
Frequency	50 Hz
Type	Dry type

THREE (3)-PHASE CONSUMERS POWER TRANSFORMER	
Design Output	250 kW
Primary voltage level	660 V
Secondary voltage level	440 V
Frequency	50 Hz
Efficiency	98.00 %
Type	Dry Type

Power electronic equipment expected to be utilized on the power plant is presented below

POWER ELECTRONICS OF FERRY	
DC/DC chopper for battery connection	2x 3500kW
Design Output of inverter for propulsion motor	2x 3000kW
Design Output of inverter for thruster motor	2x 125 kW
Design Output of inverter for Hotel Load requirements	2x 375 kW
Design Output of inverter for thee(3)-phase requirements	2x 275 kW
Design Output Rectifier of Auxiliary Generators	2x850 kW
Design Output Rectifier of Take-Home Generator	2x350 kW
AFE converters for connection to the AC grid	2x7520 kVA

Propulsion Motors

The propulsion system of the innovative Zero-Emission by Design ferry should comply with the all enforced maritime regulations, providing increased reliability and safety and operating at high efficiency levels. High power innovative propulsion motors compile the eco-friendly zero emission conceptual design providing space conservation, weight minimization and optimized power that could drive a hydro-dynamically optimized hull design in terms of power minimization. A well-designed high-performance propulsion system should offer the required sustainability and reliability and include all safety features under all circumstances.

The required propulsion demands will be adequately supplied from a pair of two (2) asynchronous motors of a 3MW/1500 RPM Nominal Design Point combined with the corresponding reduction gearbox equipment. The proposed technical data of the asynchronous motors are provided below.[1],[16]

Electrical Motors-Main propulsion

Main propulsion motors, built in accordance with IEC 34 standard.

ELECTRICAL MOTORS TECHNICAL DATA	
Design Output	3000 kW
Nominal speed	+/- 1500 rpm
Voltage	660 VAC
Frequency	60.00 Hz

Cabling system should be designed by following main cable routes on the highest point by avoiding interference with piping and leakage points. Cable routed lengths are to be minimized in terms of voltage drop and interconnection with leakage or moisture sources is to be avoided as far as practical.

The two (2) propulsion Motors are to be cooled with a shaft mounted fan.

Side Thruster Motors

The proposed Electrical Motors (Tunnel thruster motors) are expected to be constructed in accordance with IEC 34 Standard. Assisting the vessel to achieve all possible maneuvers, the Side Thrusters are designed to be in operation for a short duration while side berthing. Two bow thrusters of 125 kW will be istalled.[1] Technical data are provided as follows.

ELECTRICAL MOTOR (SIDE TRUSTER)	
Design Output	125 kW
Nominal speed	+/- 1200 rpm
Voltage	660 V
Frequency	60.00 Hz

The Side Thruster Motors are to be also cooled with a shaft mounted fan, like the propulsion Motors.

One-line diagram of incorporated Energy Distribution System

The onboard electric power plant has shown great development in terms of easy operation, flexibility and sustainability. Integration of all required components: propulsion motors, power electronics, battery storage, auxiliary engines and automation system is a challenging approach that makes such a *custom-made design* an attractive solution with respect to its reliability, reduced maintenance costs and power efficient transition.

At this phase of the preliminary design, the preliminary single-line diagram of twin-hull *Ro Pax* is presented including, B.E.S.S, Propulsion Motors, Hotel Load requirements, Shore Connection System, Three (3)-Phase Consumers, Auxiliary Generators, Emergency Generator., power conversion equipment, Switchboards & Electric Breakers. The nominal characteristics of the above are summarized in the following table and are depicted in the single line diagram.[1]

Table 7: Power Equipment of One-Line Diagram of ferry

MAIN EQUIPMENT	**MAIN DATA**
Batteries	2 x 2.8 MWh
Propulsion Motors	2 x 3.0 MW
Hotel Switchboard	2 x 175 kW / 230 VAC
Side Thrusters	2x125 kW
Three (3)-Phase Consumers	2 x 125 kW/ 440 VAC
Auxiliary Generators	2 x 1000kVA/690 V AC
Take Home Generator	1 x 350kW
Shore Connection System	6563 kVA (5,250kW)/7.2kV

One-Line Diagram of Preliminary Design of Vessel

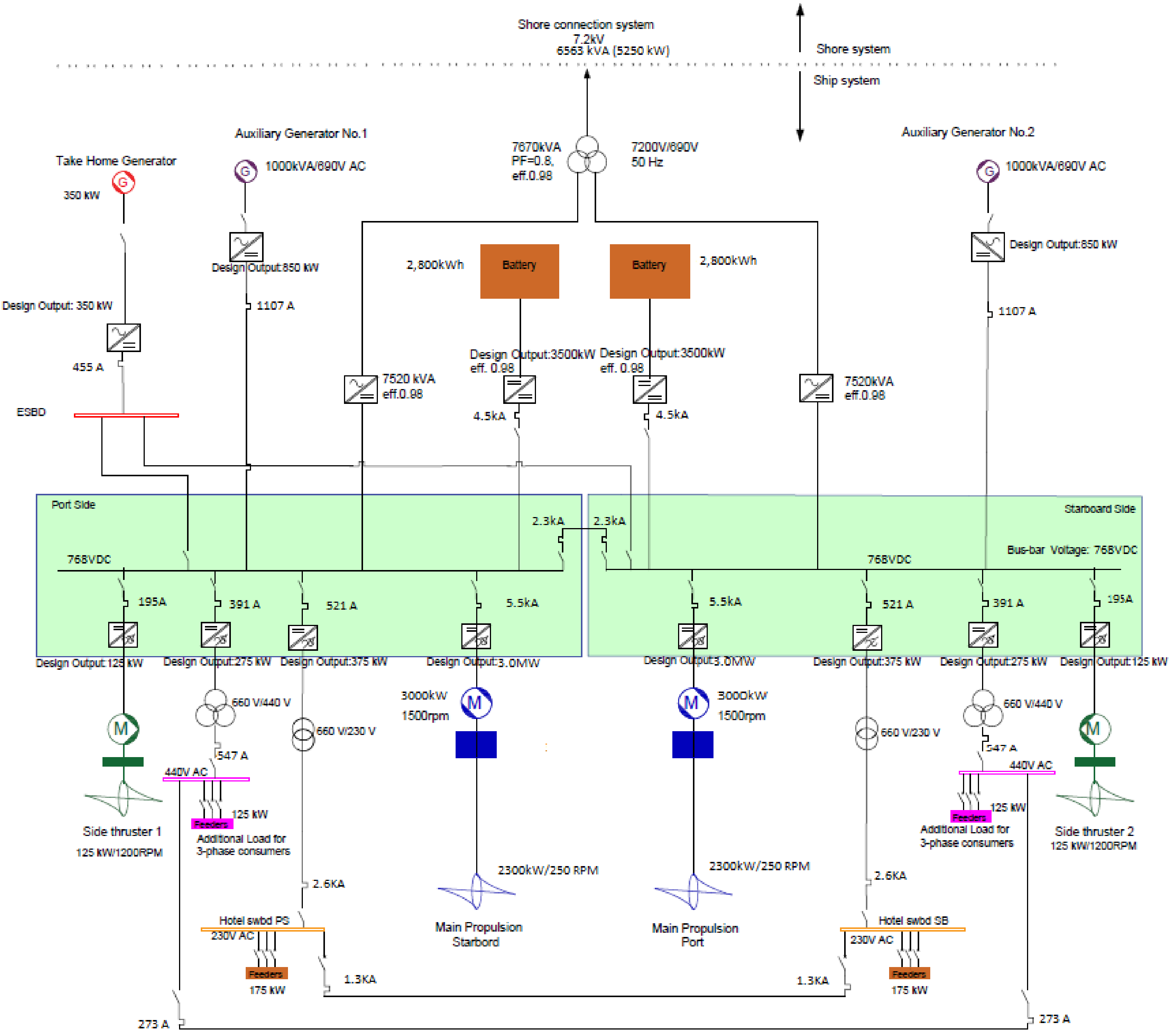


Figure 15: One-Line Diagram

Battery Room Design Installation Criteria

Significant design challenges are currently emerging in this phase of the feasibility study to ensure reliability, safety and flexibility of the onboard power plant regarding the installation of the Battery Rooms where the Battery Racks will be safely accommodated. The regulatory guidelines highlight performance and operational criteria for such energy storage systems incorporating regular robustness and ensuring reliable trip on sea. Compliance with NFPA 70E guideline for battery rooms design is required, as well as, specifying environment control and ventilation as highlighted in Occupational Safety and Health Standards (OSHA). The main design criteria of the ferry's Battery Rooms are described below [24]. The Battery Room should ensure safety of transportation and accommodation from electrical, fire, explosion, chemical or other hazards of the installed Battery system for crew, passengers and craft at all costs.[1]

Architectural Requirements-Design Concept

- The Battery System should be comprised and protected inside the two (2) separated Battery Rooms, constructed with A-60 walls, installed above vessel's highest Waterline. Easy access and escape from all areas is to be ensured.
- • The positioning of the battery room must be in a close proximity to the load centers (UPS modules). Proper code clearances must be maintained in and around battery racks for required maintenance support and life safety systems. Egress aisles, exit ways and maintenance aisles must also be maintained.
- • An overhead hoist or equivalent portable material handling equipment for the handling of batteries should be considered.

Floors Construction

- Alignment with vessels structural elements and Battery Rooms stiffeners is to be ensured. Weight minimization and expansion joints shall be avoided.
- The batteries should be installed on absolutely stable the floor. Foundation of each battery rack is to be equipped with appropriate vibration damping system. Battery racks are expected to have passed vibration test according to classification requirements.
- Subsidence of the floor at points of load shall not take place, as this will cause settling and tilting of the batteries with consequent straining of the battery connection.

Ceilings & Walls

- The ceilings should be flat to ensure that the release of hydrogen gas cannot be trapped in pockets.
- Skylights and false ceilings shall not be used.

- Ceilings shall be given the same paint treatment as walls. Walls shall be continuous from floor to ceiling and be securely anchored.
- Windows shall not be provided in battery rooms.

Doors

- Doors are expected to be constructed every abt. Seven (7) m circumferentially of the Battery Rooms to allow easy maintenance, observation and evacuation in case of casualty. Doors leading outdoor should be fire proof and arranged near emergency exits of the Battery Rooms Deck.
- The battery room door shall have the applicable fire and security rating and shall be not less than 800 mm wide and 2000 mm high.
- The inside surfaces of the door shall be protected by an approved light- colored, acid resistant paint.

Battery Room Layout and proposed Locations

With regards to battery installation room, battery storage systems are to be arranged in such a way, that each cell or crate of cells is accessible from the top and at least one side. It is also to be ensured that they are suitably secured to move with the ship's motion and according to Rules and Regulations for the Classification of Ships, Part 6 Control, Electrical, Refrigeration and Fire, Chapter 2 Electrical Engineering, Section 12 Batteries, mechanical exhaust ventilation systems are expected to be utilized.

The following table summarizes the abbreviations, embedded energy and main dimensional information which will be utilized from this phase and on.

BATTERY ROOMS ENERGY AND DIMENSIONAL INFORMATION			
Battery Room tag	Abbreviations	Embedded estim. energy	Preliminary Dimensions(LxBxH)
Battery Room No.1 serving Port side	BR1	2,800 kWh	17,000 mmx3,200mmx3,000mm
Battery Room No.2 serving Starboard Side	BR2	2,800 kWh	17,000 mmx3,200mmx3,000mm

The depicted locations of the Side of General Arrangement of the vessel are as follows.

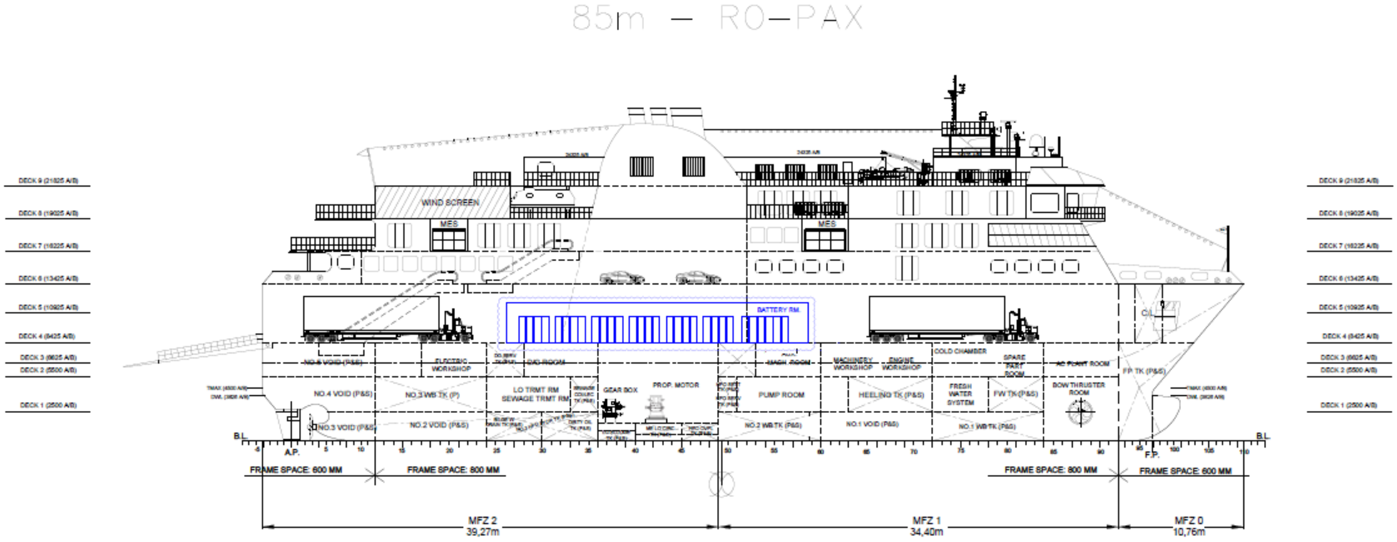


Figure 16: Proposed locations of Battery Rooms, P/S Side depicted General Arrangement (Profile View) of ferry

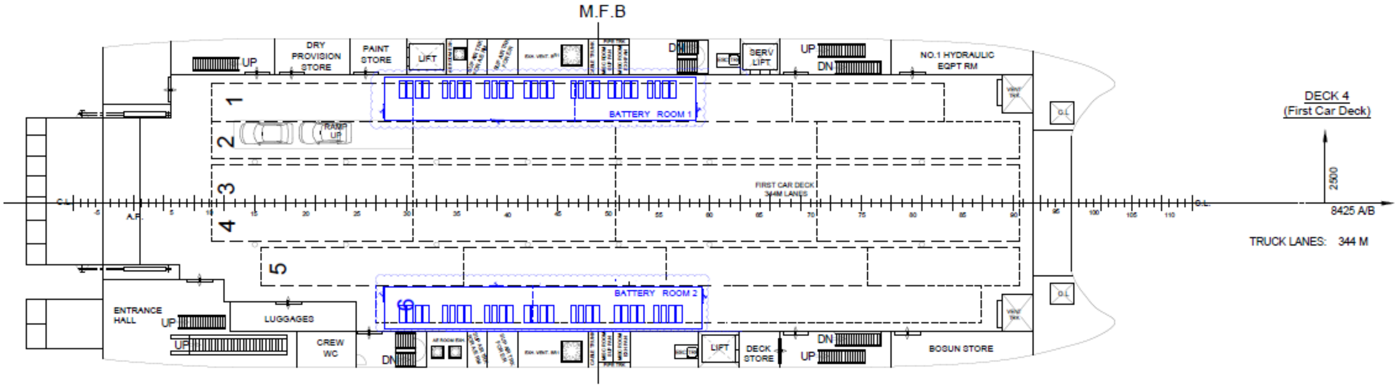


Figure 17: Proposed locations of Battery Rooms, P/S Side on Deck 4 (8,425mm A/B) of ferry

Hybrid Mode: Extended Operation with Auxiliary Generator Engines

Power requirements of vessel are expected to be served adequately through the B.E.S.S dedicated to provide robustness, reliability and redundancy. In case of power extension demand, the vessel will be capable to incorporate Hybrid Mode operation: Auxiliary Generators will be available to operate as auxiliary power supply equipment to ensure safety of trip.

A reliable Energy Management System is expected to monitor and manipulate all optimal load sharing among suppliers and consumers, providing full integration of Battery and Energy System of ferry. The Energy Management System will be capable of protecting against over-or under-voltage, while corresponding alarm indication or shutdown should be also prevented, regarding the severity of risk.

Proposed locations of the two (2) Auxiliary Engines are depicted on the following images on DECK 2(5500 mm A/B) of ferry.[1]

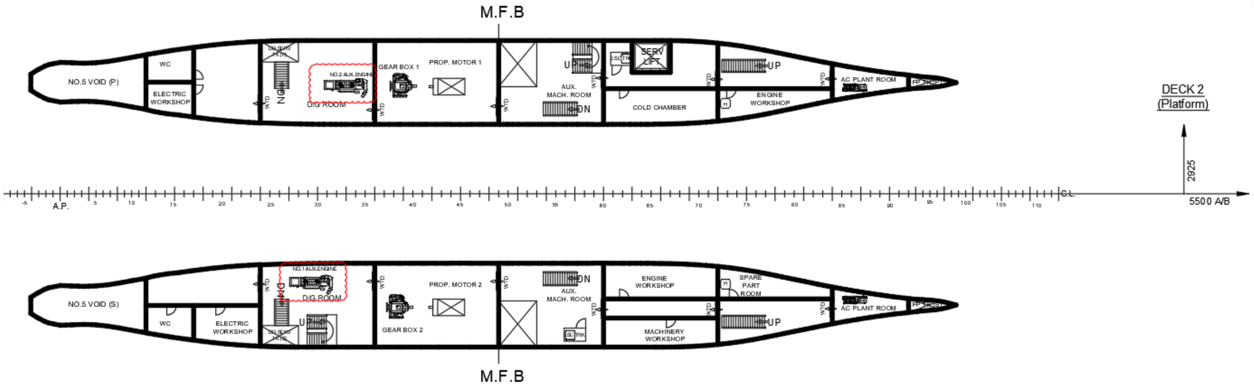


Figure 18: Proposed locations of Auxiliary Generators' Rooms in Deck 2(5,500 mm A/B) of ferry

Emergency Room Generator Design

Emergency source of power is essentially to be provided and expected to be in full compliance with the requirements described in SOLAS II-1, Part D, Regulation 42, Emergency source of electrical power in passenger ships and in Rules and Regulations for the Classification of Ships (July 2017), Part 6, Chapter 2, Electrical Engineering. The Emergency Generator would serve and restore operation on the main propulsion plant and auxiliary machinery and ensure safety and accomplishment of trip. It is expected to be located in an independent Emergency Generator Room, where also the Emergency Switch Board is expected to be installed. An automatic starting up system would permit the emergency generator to carry its full rated load. The proper power electronic conversion equipment has also been considered.

Location of Emergency Switch Board and Emergency Generator are depicted as follows on the corresponding Deck.[1]

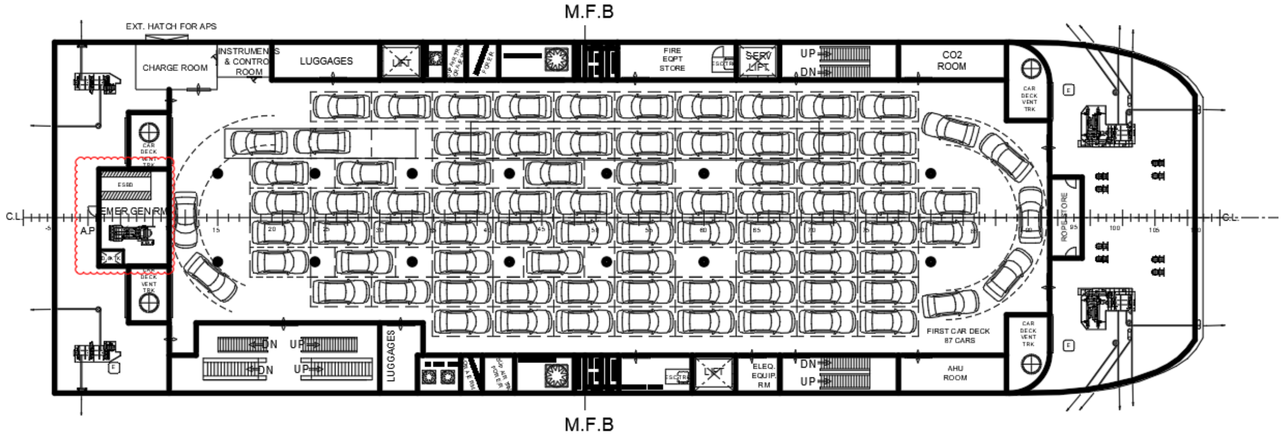


Figure 19: Proposed locations of Emergency Generator's Rooms in Deck 6(13,425 mm A/B) of ferry

Charge Room Design

With respect to the onboard *Shore Connection-Charging Station*, this shall be compromised of two (2) separate rooms: the first one containing the Switch Board of Energy Power System and the second containing the Control & Instruments equipment required for the B.E.S.S. The charging process will require high voltage power supply at quay of 7.2 kV and a total of 5.3 MW from the related port infrastructure.

Regarding Room No.1, it is expected to be equipped with shore connection cable reception hatch and passage is to be ensured with a door leading to Room No.2. Additionally, the three (3)-winding transformer for the safe voltage downgrade from the grid to the vessel's consumers is expected to be installed inside this room. An escape-door will also be utilized in case of emergency.

Regarding Room No.2, it is expected to be equipped with a main door to open deck and another on leading to Room No.1.[1]

CHARGE ROOMS	**MINIMUM PRELIMINARY REQUIRED DIMENSIONS (TOP VIEW)**
Shore Connection Room	6 m x 3.5 m
Instruments & Control Room	3 m x 2.5 m

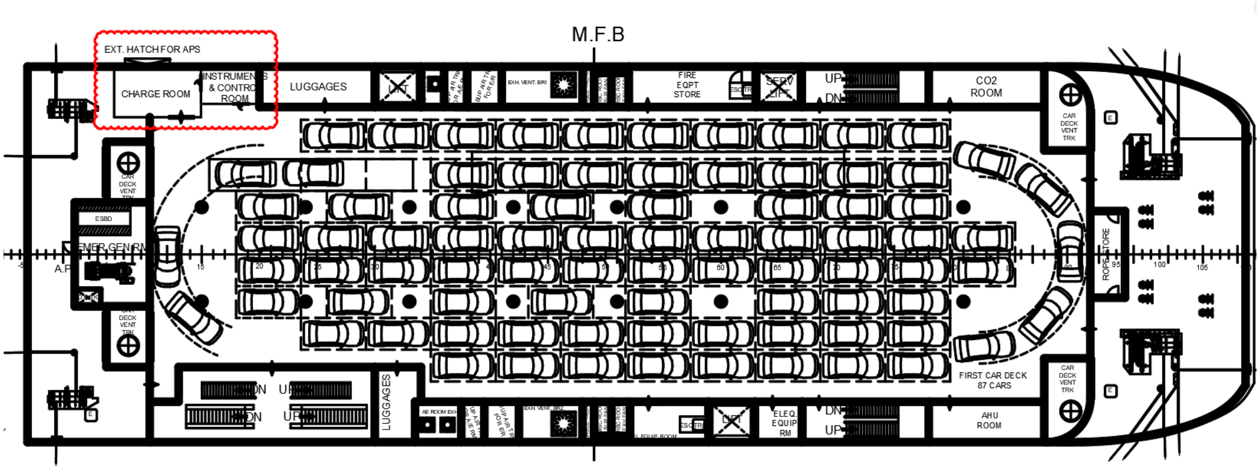


Figure 20: Proposed locations of Shore Connection, Control & Instruments on Deck 6 (13,425 mm A/B) of Vessel

Ventilation of Battery Rooms

Proper Battery individual design should ensure safety measures to prevent a thermal runaway with electronic automatic means. In case of internal thermal runaway, provided a robust construction of each cell, the Power Management System should deal with the runaway in a controlled manner by interfering with an instant shut down of Battery Strings. Also, it will permit the redundant modules to supply with required power without affecting the systems high-power density. Direct cell-to-cell interconnection allows optimized use of the condensed power system and limited heat generation is ensured by design.

Calculating the mean ventilation flow rate at this phase of the design is essential with respect to the prevention of concentration of unwanted gases able to provoke fire incident or even explosion. This risk is related to the number of batteries, their charge rate, and the size of the room. The latter parameters are fundamental for the designing of the required ventilation system of the Battery Rooms to monitor and dislodge the derivatives of battery electrolysis.

The ventilation is supposed to be maintained through the Battery Ventilation Exhausts, dedicated to lead the forced air from the cooling system and any residuals of any wanted residual gases, in each side of the vessel, proximately to the Battery Rooms as depicted in the following images.[1]

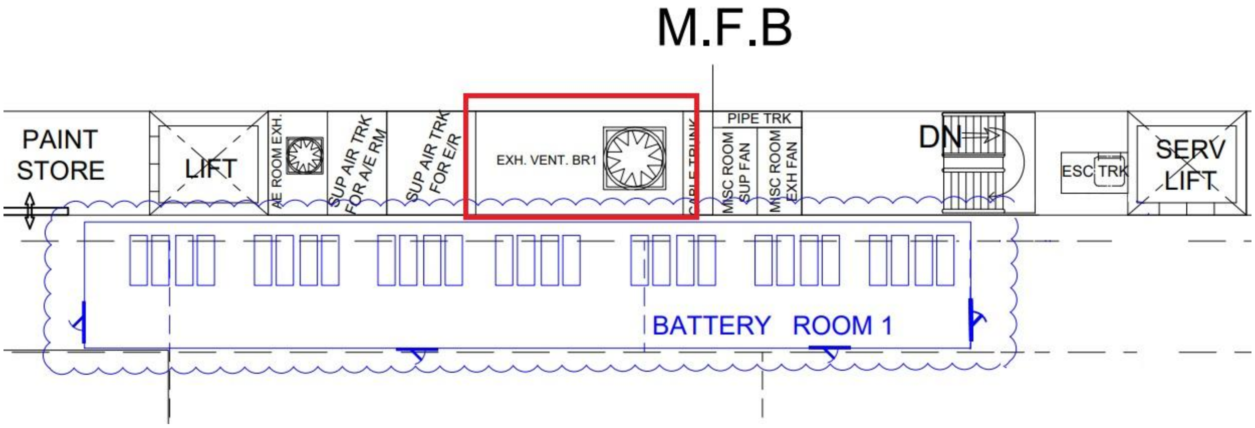


Figure 21: Proposed locations of Exhaust Ventilation System of Battery Room No.1

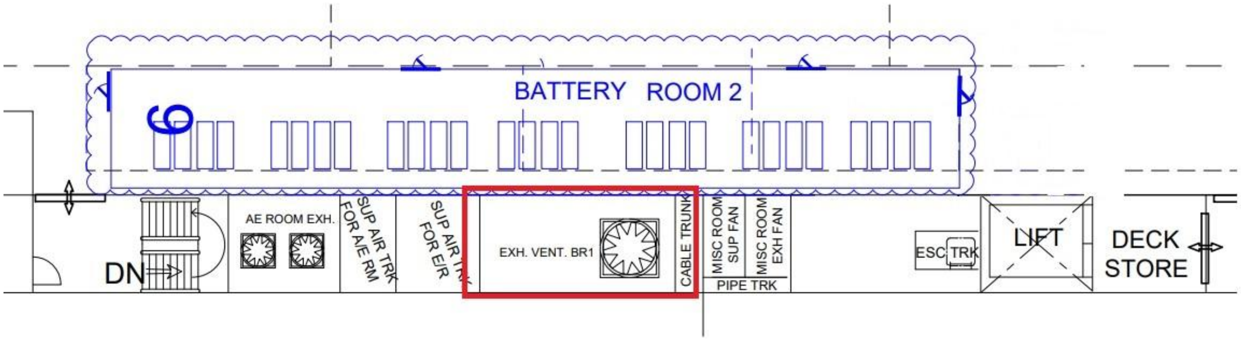


Figure 22: Proposed locations of Exhaust Ventilation System of Battery Room No.2

In case of a thermal runaway, the installation of an appropriate fan in the ventilation path should ensure ousting overboard all hazardous products.

Fire Protection measures

All passenger ships are to be provided with the fire safety measures required by the International Convention for the Safety of Life at Sea, 1974, as amended (SOLAS - International Convention for the Safety of Life at Sea). All required fire detection and alarms are expected to be installed in compliance with Rules and Regulations for the Classification of Ships, Part 6, Chapter 2, Section 17.

Fire resistant rated **A-60 insulation walls, floor and ceilings** protecting the Battery System, as wells as, several fire doors opening to outdoors are to be provided

Battery rooms need to have direct proximity to a range of safety measures in order to mitigate advert results of fire incident. Specifically, utilization and proximity to **fire pump supply** is required on the corresponding deck of the Battery Rooms.

Installation of **local alarms** may seem beneficial for fire protection. **UMS notation** may also be installed on the bridge on Deck 8 (19025mm A/B) of the ferry.

Concerning local firefighting methods, **water mist fire protection** (**or alternatively foam-based extinguishing systems or inert gas suppression systems,** are expected to be installed throughout the Battery Rooms. Additionally, **smoke, local fire and heat detectors** would prevent the advert consequences of a fire incident. **Emergency escape breathing devices** are also to be provided.

The Battery Rooms, Charge Room (No.1 & No.2) and Control Fire Center will include relative **signal or a readily available documentation** describing the location of the B.E.S.S, the types of installed batteries, nominal voltage level, location of electrical disconnects. A counterpart of the above is expected to be installed on the Charge Room/ Instruments and Control Room.

Relative measures of fire protection such as heat, smoke, local fire detectors, water mist fire protection and escape fire doors are assumed to be installed inside both Charge Room/ Instruments and Control Room as well.

All kinds of fire detectors (heat, smoke and local fire) are to be installed in separate loops on vessel’s monitoring system.

Fire protection measures are depicted on the following images for the Battery Rooms and the Charging/Instruments and Control Room. In this case of the *Ro Pax* innovative design**, a safety fire center** would adequately satisfy the requirements of an emergency incident, while operating, controlling and monitoring when it is required regarding emergency safety and fire-fighting methods. This may be found installed on

Second Passenger Deck (Deck 8-19025mm A/B). It is depicted below in its proposed location.[1]

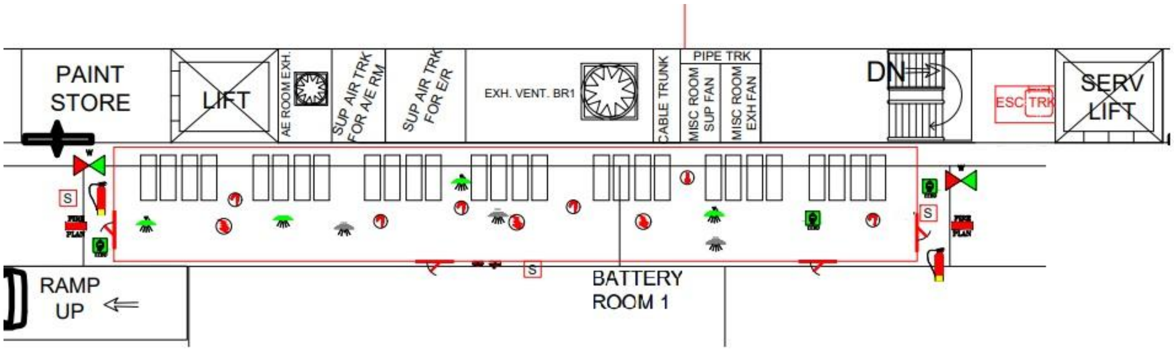


Figure 23: Proposed fire protection System of Battery Room No.1

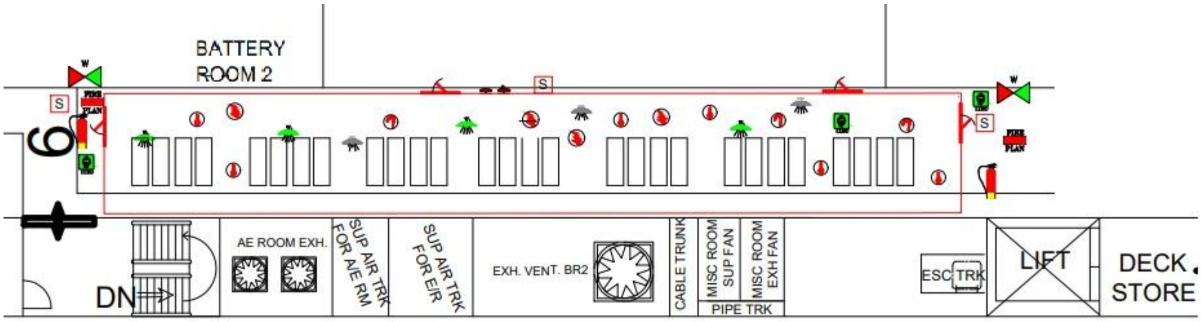


Figure 24: Proposed fire protection System of Battery Room No.2

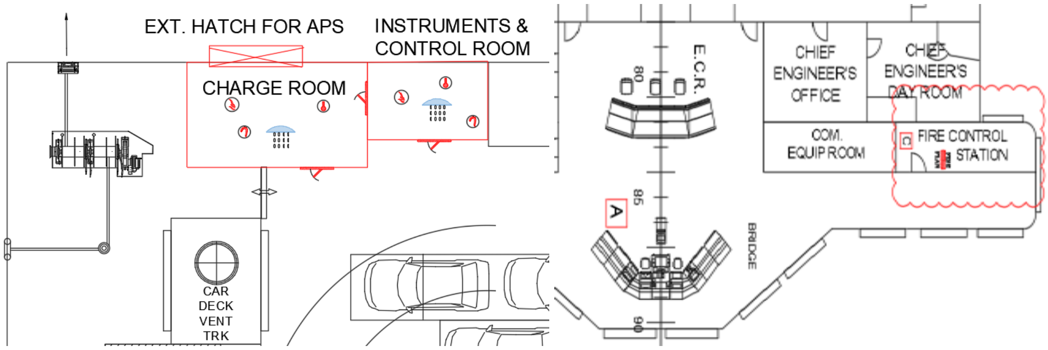


Figure 25: Proposed fire protection for Charge Room/Instruments and Control Room and Fire Control Station

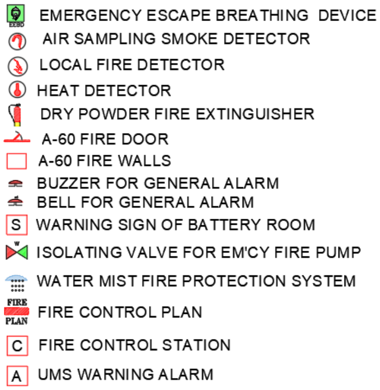


Figure 26: Proposed fire protection measures and signs

Battery Cooling

While temperature extremes and variations are strongly affecting performance, durability and lifespan of batteries, a reliable thermal management of the battery system is crucial to the operation of ferry. A well-designed battery thermal management system is beneficial in terms of optimizing performance and safety. The Battery Packs are to be cooled by an automatic forced air-cooling method system (alternatively/simultaneously water-cooling methods could be used in terms of high temperature extremes) guarantying smooth and reliable operation.

A Sophisticated thermal management approach ensures to keep the battery cells cool and extend battery life mainly in the summer months for such a design able to sufficiently serve coastal requirements.[1]

Orderly evacuation and abandonment in case of casualty

Classification requirements underline that the escape routing arrangements in case of casualty such as stairways, ladders and corridors as crew spaces and in case of other spaces to which the crew normally have access are to be arranged in such a way, so as to provide ready means of escape to a deck from which disembarkation may be accomplished.

At least two means of escape, as widely separated as possible, are to be provided from each section of accommodation spaces, service spaces and control stations. More specifically:

- The normal means of access to the accommodation and service spaces below the open deck are to be arranged so that it is possible to reach the open deck without passing through intervening spaces containing a possible source of fire.
- The second means of escape may be through portholes, or hatches of adequate size, leading to the open deck.
- No dead-end corridors having a length of more than 7 m are accepted.

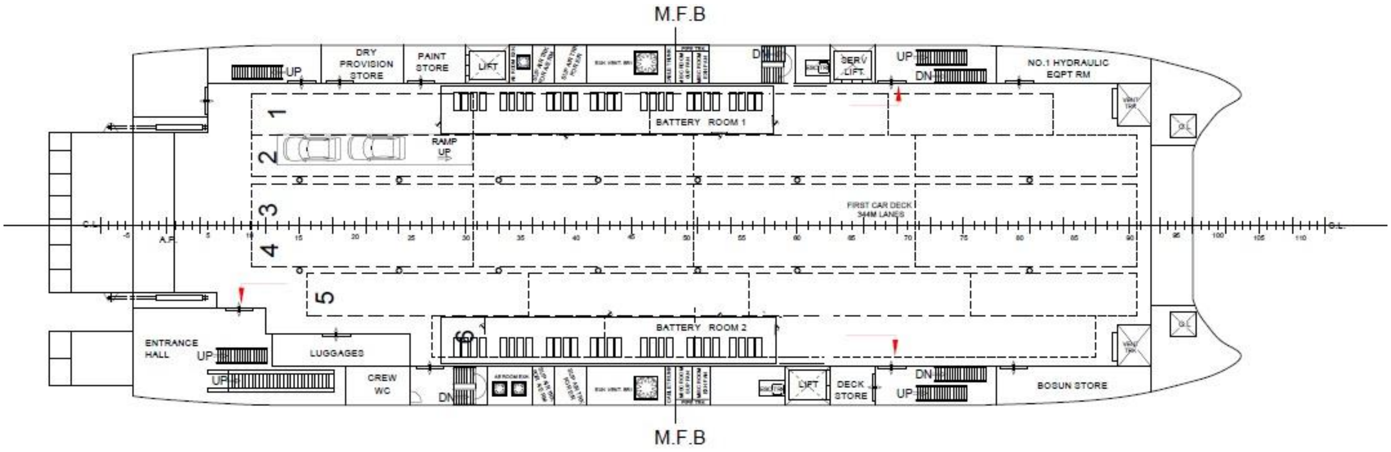


Figure 27: Proposed Escape Routes to Deck of Disembarkation from Deck 4 (8,425 mm)

At least two means of escape are to be provided from machinery spaces, with the exception of a small size of the machinery space makes it impractical. Escape is to be provided through steel ladders that are as widely separated as possible.

Vertical Fire Zones are expected to serve orderly evacuation and concentration until abandonment.

The proposed escape routes are depicted on each corresponding deck in the following images.[1]

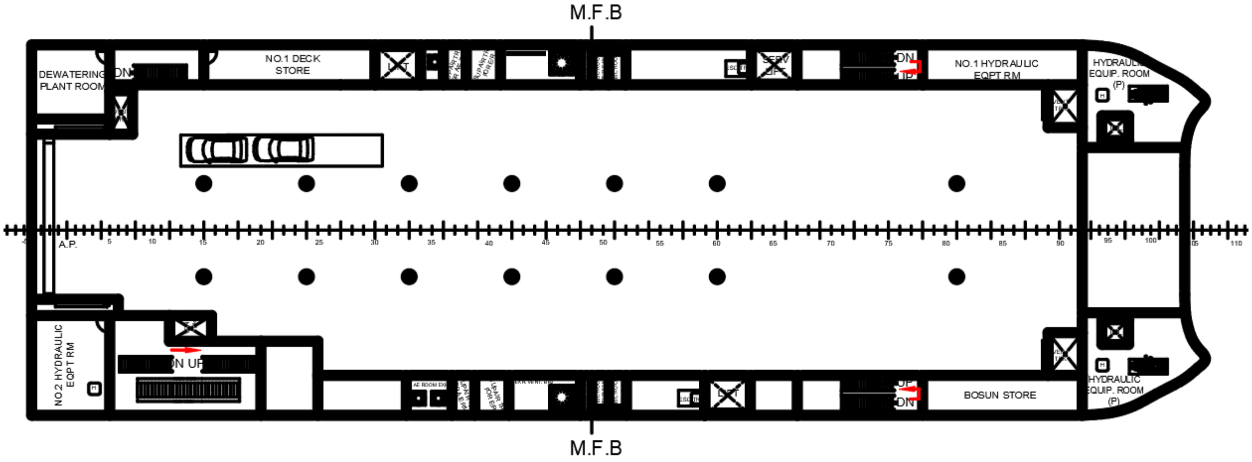


Figure 28: Proposed Escape Routes to Deck of Disembarkation from Deck 5 (10,925 mm)

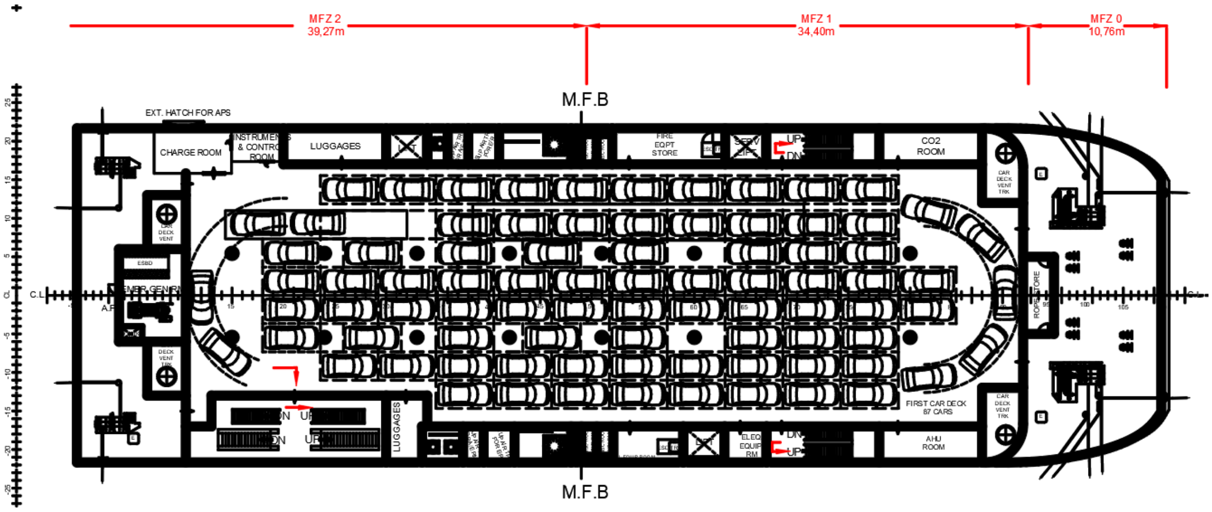


Figure 29: Proposed Escape Routes to Deck of Disembarkation from Deck 6 (13,425 mm)

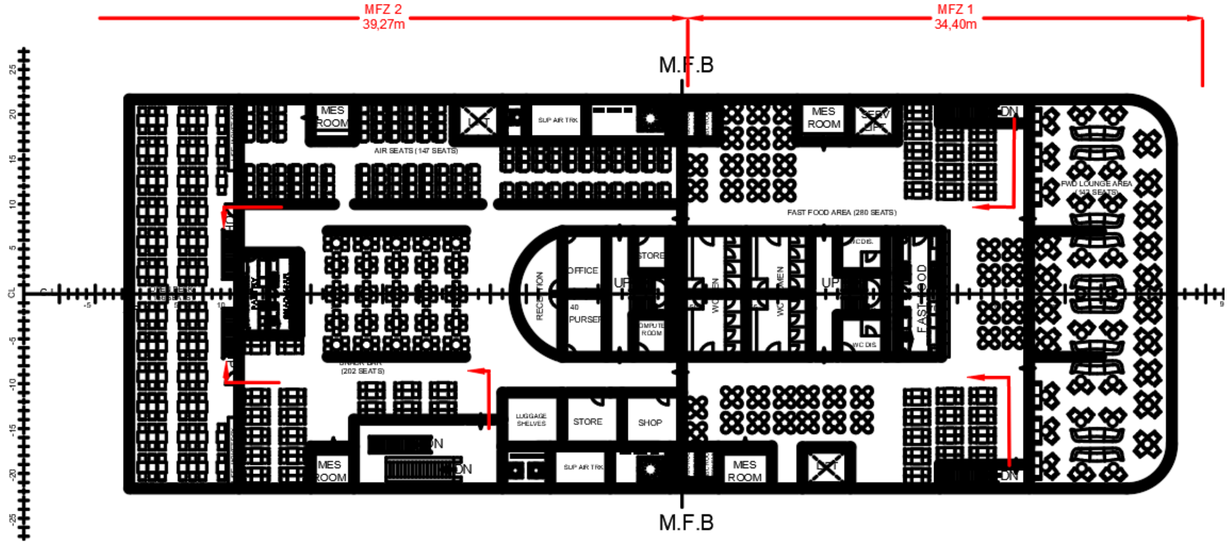


Figure 30: Proposed Main Vertical Fire Zones on Deck 7 (16,225 mm)

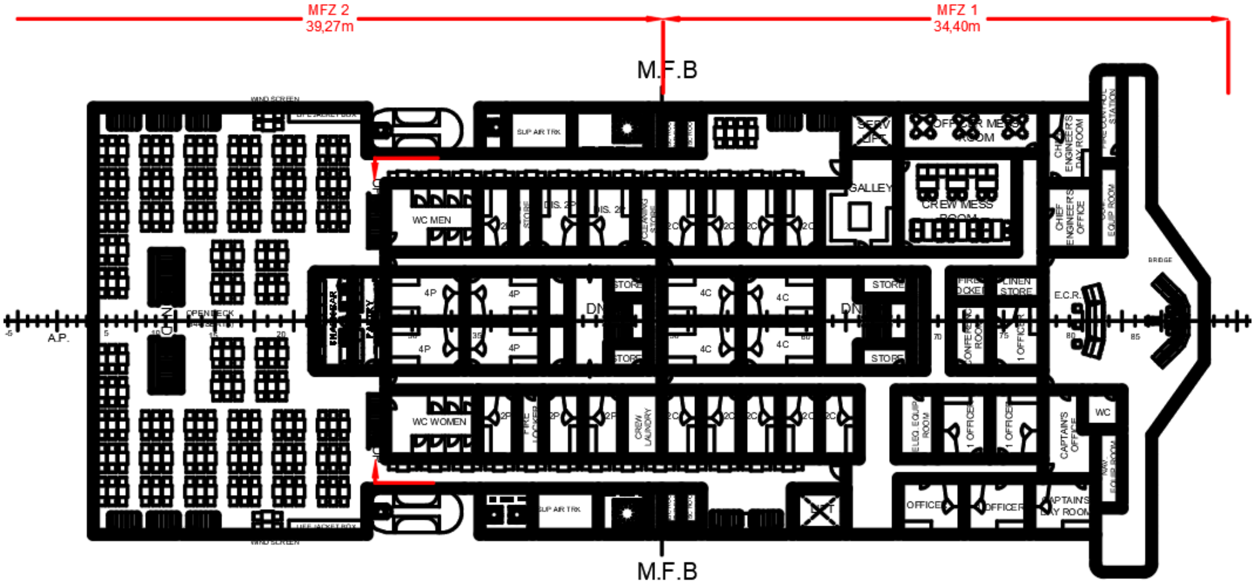


Figure 31: Proposed Main Vertical Fire Zones on Deck 8 (19,025 mm)

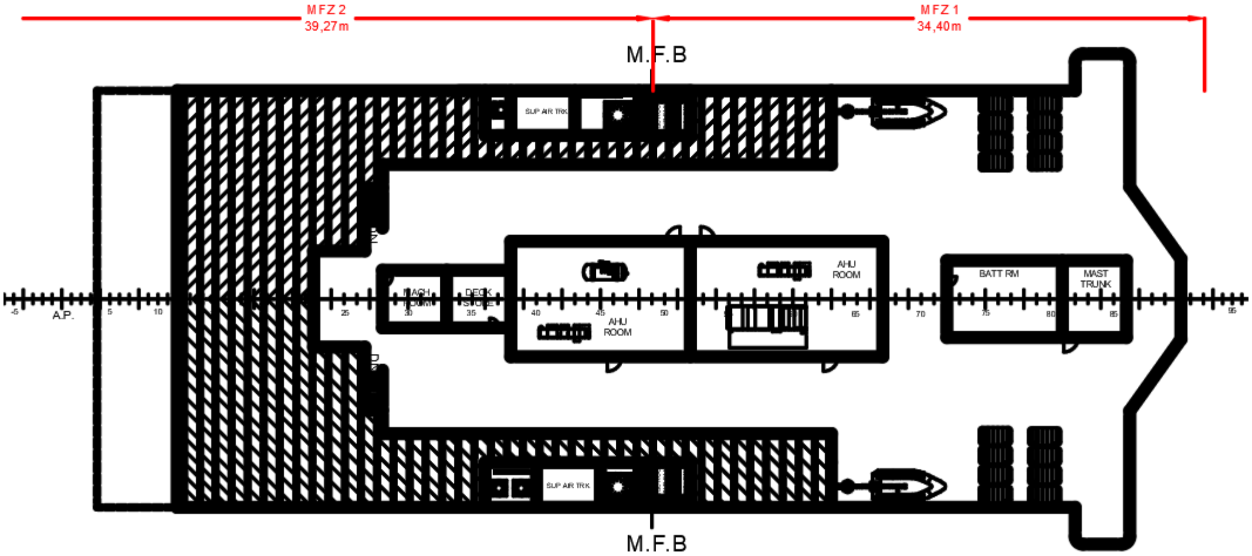


Figure 32: Proposed Main Vertical Fire Zones on Deck 9 (21,825 mm)

Solar Panels

In order to achieve an even better environmental profile and an extra source of power it is investigated the case of installing solar panels on board.
The available area on the ferry located obviously on the upper deck and it is schetck on the figure below.

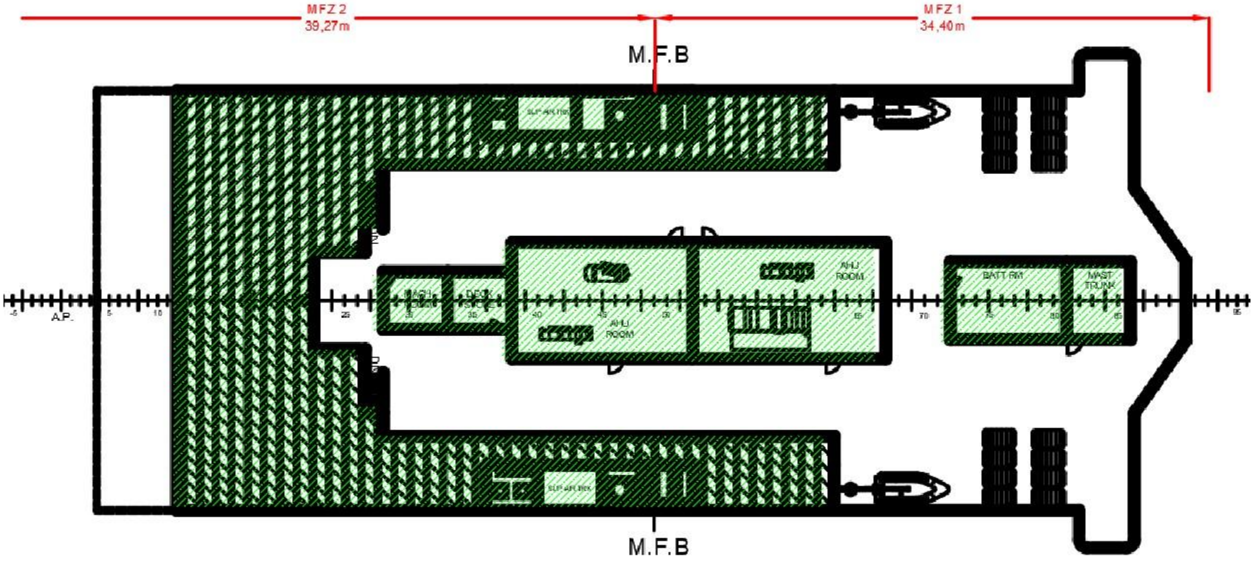


Figure 33: Proposed area for the installation of the solar panels

It was calculated that in this area can be installed solar panels with area about 709 m^2. Considering that the solar panels satisfy the standards for the marine environment, their specific power is 200 W/m^2 , so the total output power will be 141.78 kW.

For the south Evian Gulf the area of operation, the Total photovoltaic energy output of the system is 200 MWh per year. During July the average daily production of electricity is 1025 kWh. The data of the irradiation extracted from the Global Solar Atlas application.[18]

Therefore the installation of solar panels offers an extra eco friendly source of electrical energy. Given also the fact that an Energy Storage System is already installed, the energy produced is continuously supply the storage system. Although this extra energy is useful, it's only a small rate compared to the total energy requirements of the vessel.

It is more effective to invest in more sufficient ground based solar systems that can provide electricity to the shore side charging infrastructure.

Environmental and Social impact

Maritime industry has been in an age of strict environmental regulations in order to reduce its environmental footprint. Maritime transport is the most environmentally friendly type of transport mode (maritime transport accounts for 3.5% to 4% of all climate change emissions, primarily carbon dioxide). However, air pollution and greenhouse gases from ship emissions are increasing because of the growing maritime traffic. Also if we study the ship as unit it produces much more emissions than other means of transport. This problem becomes more visible in ports and coastal areas, such as coast to coast mid range routes where e-ferries can operate.

Battery powered ferries is the only reliable zero emission option, especially when the local grid is supplied from renewable energy sources. They doesn't produce emissions causing air pollution neither emissions contributing to the climate change phenomenon. Another big advantage of electric propulsion is their low noise and vibration operation. This is very important for the passenger, the crew and also for the marine ecosystem.

E-ferries' minimum environmental footprint and their silent operation are very beneficial for the environment, the coastal communities and environmental sensitive areas with touristic interest, such as the Greek archipelago.

Economic study

VESSEL RETROFIT COST

Purpose of this thesis is the investigation of feasibly running an vessel on batteries and its benefits compared to current way of operation. It is also considered that the diesel powered catamaran vessel converted into a battery powered one and the old machinery can be sold. [2]

INSTALLATION COST	
Battery cost per kWh (500$/kWh)	
Battery system cost (5600kW)	€ 2,352,000.00
BMS – 50% of batteries' cost ($)	€ 1,176,000.00
Battery Inverter (200€/kW)	€ 818,180.00
Motor Driver (250€/kW)	€ 1,363,640.00
Electric Motor (60€/kW)	
2 x Electric motors of 3000 kW	€ 360,000.00
SUM	€ 6,069,820.00

SALES OF EXISTING MACHINERY	
Used Medium Speed Diesel Engines (40€/kW)	
2 x Main Engines of 3000kW	€ 240,000.00
Used Electric Generators (35€/kW)	€ 12,250.00
SUM	€ 252,250.00

FINAL COST OF RETROFIT	€ 5,817,570.00

OPERATION AND FUEL SAVINGS COMPARISON

FUEL COST COMPARISON FOR 1 YEAR OPERATION	
Days Working	215
Trips Per Day	8

WITH BATTERIES	
Required Energy Per Trip (kWh)	4188.6
Total Required Energy for 1 Year Operation (kWh)	7,204,417.35
Price of kWh from Utility Grid (€/kWh)	0.05
Total cost (€)	€ 360,221.00

WITH EXISTING MACHINERY	
Main Engine Efficiency	0.55
Electric Generators Efficiency	0.9
Main engines Annual Cruising kWh	3,351,376.35
Main engines Annual Stand-by kWh	1,120,167.85
Auxiliary engine Annual Stand-by kWh	795,125.13
Auxiliary engines Annual cruising kWh	602,000.00
SFOC according to TIER –II protocol (g/kWh)	203
Price of Marine VLSFO per tn (incl VAT**)	580
Price of Marine Diesel Oil per tn (incl VAT**)	612
Total cost (€)	€ 588,044.00

Benefit from Fuel Saving in 1 Year of operation (€)	€ 227,824.00

OPERATION AND MAINTENANCE COST COMPARISON FOR 1 YEAR	
WITH BATTERIES	
Fixed Operation & Maintenance is 2% of the PCS cost (€) per year	17438
Variable O&M is ($/kWh)	1
variable O&M expenses for installed energy (€)	5,040.00
Total O&M Cost Per Year (€)	€ 22,478.00

WITH EXISTING MACHINERY	
Maintenance cost: 12.6€/HP	
Total Installed Power = 2 x 4079 HP	
Total O&M Cost Per Year (€)	€ 102,787.40

TOTAL BENEFIT FROM O&M EXPENSES (€)	€ 80,309.50

ECONOMICAL/FINANCIAL

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 .
Benefit from fuel and O&M costs may be considered as the only revenues in the analysis (in order to have a clear on the comparison of running the vessel on batteries)
The residual value of equipment bought is estimated 65% of their initial price:[2]

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

Contingencies costs are estimated 10% of project value.

In this project takes place the calculation of the Financial Net Present Value(FNPV) and the internal rate of return(IRR).of the vessel's retrofit in order to use completely electric energy for all the demands needed for the transportation to each port.[2]

NPV rate is estimated 6%.

Different scenarios are presented below.The first scenario is for without funding, in case the industry decides to invest to the retrofit purchasing all the construction cost. As presented in the next page this doesn't seem to be the optimal option. The next scenarios presents funding for the retrofit investment. The final scenario is about increasing the passenger’s ticket price.

The following table shows the FRR and FNPV of our investment in case the shipping industry decides to cover all the cost the installation of the retrofit

	NPV:		discount rate 6%						
Calculation of Return of Investment	Year	0	1	2	3	4	5	6	7
		Construction							
Investing Cost(excluding contigencies)(€)	-5817568	- 5817568							
Benefit from fuel and O&M Cost(€)	1999974		308133.0	325112.3	342776.0	361148.8	380256.7	400126	420784.47
Revenue(€)									
Residual Value of investment(€)	2075525	0	0	0	0	0	0	0	3308072.7
FNPV©-Before EU Grant/Net Cash Flow(€)	-1525978	-5817568.	308132.9	325112.3	342776.0	361148.88	380256.66	400125	3728857.2
IRR	0%								

Since FNPV<0 and IRR is 0% the best solution to find this project profitable (within seven years) is financing a percentage of the construction cost.

In this financial analysis the annual net cash flow are mainly the benefits of the electric use and the cost is reduced, because of the monthly income not spent to diesel fuel.

In the next tables, NPV is calculated and it is the main factor to find this project profitable. The different scenarios are being examined are 10,20,30 %.

The results are presented in the next tables.

Financing rate of the construction cost: 10 %

	NPV:		discount rate 6%						
Calculation of Return of Investment	Year	0	1	2	3	4	5	6	7
0	0	Construction	operation						
Investing Cost(excluding contigencies)(€)	- 5235811.351	- 5235811.351	0	0	0	0	0	0	0
Benefit from fuel and O&M Cost(€)	1999974.076	0	308132.9992	325112.3444	342776.0219	361148.8838	380256.6612	400125.995	420784.467
Revenue(€)	0	0	0	0	0	0	0	0	0
Residual Value of investment(€)	2075525.748	0	0	0	0	0	0	0	3308072.718
FNPV©-Before EU Grant/Net Cash Flow(€)	-977150.93	- 5235811.351	308132.9992	325112.3444	342776.0219	361148.8838	380256.6612	400125.995	3728857.185
IRR	1.94%								

Financing rate of the construction cost: 20 %

	NPV:		discount rate 6%						
Calculation of Return of Investment	Year	0	1	2	3	4	5	6	7
		Construction	operation						
Investing Cost(excluding contigencies)(€)	-4654054.535	-4654054.535	0	0	0	0	0	0	0
Benefit from fuel and O&M Cost(€)	1886768.00	0	308132.9992	325112.3444	342776.0219	361148.8838	380256.6612	400125.995	420784.467
Revenue(€)	0	0	0	0	0	0	0	0	0
Residual Value of investment(€)	2075525.748	0	0	0	0	0	0	0	3308072.718
FNPV©-Before EU Grant/Net Cash Flow(€)	-428323.74	-4654054.535	308132.9992	325112.3444	342776.0219	361148.8838	380256.6612	400125.995	3728857.185
IRR	4.07%								

Financing rate of the construction cost: 30 %

	NPV:		discount rate 6%						
Calculation of Return of Investment	Year	0	1	2	3	4	5	6	7
		Construction	operation						
Investing Cost(excluding contigencies)(€)	-4072297.718	-4072297.718	0	0	0	0	0	0	0
Benefit from fuel and O&M Cost(€)	1886768.00	0	308132.9992	325112.3444	342776.0219	361148.8838	380256.6612	400125.995	420784.467
Revenue(€)	0	0	0	0	0	0	0	0	0
Residual Value of investment(€)	2075525.748	0	0	0	0	0	0	0	3308072.718
FNPV©-Before EU Grant/Net Cash Flow(€)	120503.45	-4072297.718	308132.9992	325112.3444	342776.0219	361148.8838	380256.6612	400125.995	3728857.185
IRR	6.59%								

According to the analysis above, the project appears to be financially sustainable, as the investment cost is covered by 30% by financing sources and its cumulated net cash flow during operation is positive during the entire evaluation period.

In case the project can't find the required funding, a solution would be to increase the ticket's price. It is considered that the completeness of the passengers all year long is 25% in order to approach the low traffic during winter. The maximum capacity of the vessel is 1175 passengers. The ticket's price increase will be 0.6 Euros.

The calculations are presented below.

Ticket's price increase 0.6 €

	NPV:		discount rate 6%						
Calculation of Return of Investment	Year	0	1	2	3	4	5	6	7
		Construction							
Investing Cost(excluding contigencies)(€)	-5817568.17	- 5,817,568							
Benefit from fuel and O&M Cost(€)	2005732.01		309,136.23	326,125.61	343,799.42	362,182.52	381,300.63	401,180.40	421,849.42
Revenue(€)	1692298.93		303150	303150	303150	303150	303150	303150	303150
Residual Value of investment(€)	2,075,525.75	0	0	0	0	0	0	0	3,308,072.72
FNPV©-Before EU Grant/Net Cash Flow(€)	75962.33	-5817568.2	612286.2322	629275.6097	646949.4198	665332.5158	684450.6295	704330.403	4033072.137
IRR	6%								

ECONOMICAL ANALYSIS OF THE INSTALLATION OF SOLAR PANELS

On this point we are investigating the case of installing solar panels on board. The financial analysis will be held for a seven year period time in order to keep up with the analysis above. Benefit from electricity costs may be considered as the only revenues in the analysis (in order to have a clear on the comparison gaining extra energy from the panels)

Solar Panels' Savings	
Total Output Energy per year [kWh]	*220,000.00 kWh*
Electricity cost saving for 1 year operation	*€ 11,000.00*
Panel's cost (1200€/m^2)	*€ 850,680.00*

From the NPV analysis, which presented below, results that the installation of solar panels is not a profitable option without extra funding or discount. That's because the price of electricity is low and the revenues based on the savings of electricity are small compared with the cost of the solar panels. This analysis for example would have much better results on a diesel powered vessel as the reduction of fuel consumption is critical.

solar panel's analysis

	NPV:		discount rate 6%						
Calculation of Return of Investment	Year	0	1	2	3	4	5	6	7
		Construction	operation						
Investing Cost(excluding contigencies)(€)	-850680	-850680	0	0	0	0	0	0	0
Benefit from electricity(€)	59559.55	0	11000	11110	11221.1	11333.311	11446.644	11561.110	11676.721
Residual Value of investment(€)	373609.01	0	0	0	0	0	0	0	595476
FNPV©-Before EU Grant/Net Cash Flow(€)	-369359.74	-850680	11000	11110	11221.1	11333.311	11446.644	11561.110	607152.72
IRR	-3.41%								

Summary

This feasibility study focuses on the installation of the Battery Energy Storage System and the design of the propulsion system of the 85 m twin hull ferry.[1]

The fully electric ferry design is suitable to achieve coast-to-coast needs. With its Battery System offers high availability, reduced maintenance load, radiated noise and vibrations, as wells as, zero-emission operation and increased survivability. The Battery System will be capable to allow a full recharge while at Loading/Unloading operations through an Automatic Charging Station from the land

The vessel is designed to serve coastal needs up to 15 Nautical miles. Service speed of craft is designed at 14.8 knots. Is expected to make eight one-way trips daily, operating for a total 215 days annually. During each one-way trip, the vessel consumes abt. 4.189 MWh energy from the battery system (it is assumed all annual cycles follow the described profile). The capacity of the B.E.E.S. installed is 5600kWh.

While a careful maintenance plan is expected to be followed, the Battery System is designed for at least seven (7) years of continuous operation, resulting in 1287 cycles/year. The Nominal Voltage of the installed Battery System is estimated at 768 VDC.

Preliminary single-line diagram of ferry is presented including, B.E.S.S, Propulsion Motors, Hotel Load requirements, Shore Connection System, Three (3)-Phase Consumers, Auxiliary Generators, Emergency Generator, power conversion equipment, Switchboards & Electric Breakers.

Efficient propulsion will be served from pair asynchronous motors of a Design operating point of 3MW/1500 RPM with corresponding.

Tunnel thruster motors will be used to achieve all possible maneuvers, designed to be in operation for a short duration while side berthing.

The Battery System should be accommodated and protected inside the two (2) separated Battery Rooms, constructed with A-60 walls, installed above vessel's highest waterline. Easy access and escape from all areas is to be ensured. Preliminary Fire control plan has been carried out including all required means to prevent the advert consequences of a fire incident.

Power requirements of vessel are expected to be served adequately through the B.E.S.S dedicated to provide robustness, reliability and redundancy, while in case of power extension demand, the vessel will be capable to incorporate Hybrid Mode operation: Auxiliary Generators will be available to operate as auxiliary power supply equipment to ensure safety of trip. Emergency Generator Engine has been selected. Emergency Generator Room and Switchboard has been designed.

Ventilation supposed to be maintained through the Battery Ventilation Exhausts, dedicated to lead the cooling system and any residuals of any wanted residual gases, proximately to the Battery Rooms.

Preliminary evacuation and abandonment plan has been conducted.

Conclusions and recommendations

The project of the electric ships seems to be feasible and beneficial for industry and society. In terms of engineering it's a reliable option that already operates successfully in northern Europe. Electric propulsion is distinguished by simplicity, low noise and low maintenance.

The cost of the retrofit is still expensive choice, but the benefits that come from it are important as well. Even though batteries cost is the biggest expense in the retrofit, the future predictions are estimating that there will be still a great decline in battery prices. Generally, the price cost of the engines batteries (and marine batteries) has been decreased to the 1/3 cost from the initial cost before two years(2017). Also the cost of Battery Management System is expected to decrease.

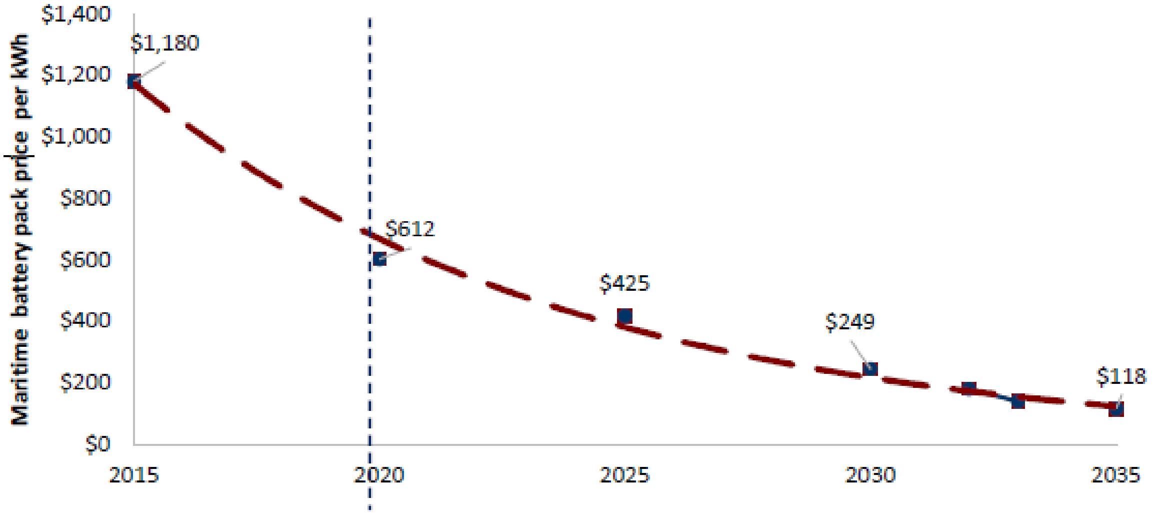


Figure 34: Expected marine electric vessel battery pack price forecast to 2035

Source: E-Ferry project, Leclanché; Liebreich Associates

The initial cost for the electric ferry, including shoreside equipment, are higher than those of an equivalent existing diesel ferry. The vessel and propulsion system are simpler, resulting in some savings. However, the battery system, shoreside infrastructure and typical electrical connection fee more than absorb any savings. Although when it comes to the operating costs, however, the advantage of the diesel ferry reverses, with operating costs for an electric ferry much lower. The biggest avoided cost is the diesel itself. There are further savings from maintenance, with the e-ferry requiring less attention, and lower crew costs due the simplicity of its control and operating systems. A significant additional cost, however, is the need to replace the batteries after around a decade of operation. Also there are additional benefits which even they don‘t get into account on this study, although they have strong impact on the general attractiveness of the project, such as the avoidance of environmental fees, external costs avoidance, flexibility in machinery arrangements etc. The depreciation is expected to happen in 9 years.

Unlike almost any other available option, the electrification of ferries offers a path all the way to zero emissions for those routes where they can be implemented from a route length perspective. In order to get there, the supply chain would need to transition to zero-emissions, as well as the electricity on which they are run. As the proportion of renewable energy increases over time, this becomes an increasingly feasible proposition. technology in the future. Appropriate infrastructure must be installed in the ports in order to accommodate these ships. Such innovative and environmentally friendly projects can absorb funding from EU and Green Climate funds.

Greece should converge to the electric propulsion and should use the power generation from renewable resources of energy.

Finally, it is important to note that even though this study concludes that retrofitting a conventional vessel into an all-electric battery powered one without external funding or increase of the ticket’s prices isn’t a profitable investment at present, the continuous development and improvements of battery technologies during the last years is evident. If this trend continues battery technology in the maritime industry is going to be a very promising solution for the future.

Recommendations for future perusal

It is recommended for further detailed future perusal to investigate the following related topics:

- Feasibility studies for other type of vessels. Some type of vessels to consider are anchor handling tugs, supply ships, pilot boats, pleasure crafts and other vessels that operate in short distances.
- Investigation for other routes in Greece. Because of its geography, Greece offers many short routes that electricity could be an option.

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