National Technical University of Athens School of Naval Architecture and Marine Engineering Division of Marine Engineering

Diploma Thesis

ʻʻ Techno-economical feasibility study on the retrofit of a conventional fishing boat into a battery-powered one ʻʻ

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Abstract

Global warming and increasing pollution of the environment have forced the humanity to take the necessary measures to address the ecological and environmental disaster, as soon as possible. The emissions and pollutants of all means of energy production hold a large amount of the total pollution and regulations are adopted to minimize the effect. The marine industry, trying to comply with emission limits, makes significant efforts to adopt different sources of energy than diesel fuels. Improved battery technologies, as well as high fuel prices, led to investigations of full electric and hybrid propulsion systems.

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

The boat under investigation is "President", which is an auxiliary fish farming, but no specific duty is provided. The investigation will take place for short cruising time and harbor duty, concerning recharge time at one port. The daily operational profile will be 2 trips per day, 300 days per year, including a 70 minutes stay at port.

The results of the investigation are presented, and the corresponding outcome is analyzed. It is obvious that better battery technologies and lower costs of retrofit will make such investments more efficient, with lower risks. The electricity production in Greece is not the optimum, as significant pollution is observed, but hopefully in future electricity will be generated from renewable sources, claiming to be a 100% zero-emission transportation mean.

Key words: Battery-ship, all-electric ship, shipping emissions, regulatory framework, retrofit methodology, future vessel, investment analysis, health costs of air pollution, DNV-Gl, ABS, battery-powered, green ships

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Chapter 1

Introduction

1.1 Background of study

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

In many cities a large source of air pollution comes from both coastal and inland ports. Container ships, switcher locomotives, tugboats, fishing boats, cargo-handling equipment, and trucks collectively release vast amounts of pollution. Pollutant emissions from shipping have continued to rise, while emissions from land-based sources have gradually come down due to dedicated efforts to achieve green production. This situation led the International Maritime Organization to develop and settle rules for ship emissions in ports and nearby coastlines (Emission Control Areas), all types of boats need to comply with.

Humanity by necessity is being forced to reduce its carbon footprint and invest in operations aimed at limiting emissions and improving resource efficiency in order to achieve sustainable growth. The concept of the all-electric-ship seems an ideal clean solution, despite the significant pollution observed by electricity production in Greece, due to limited renewable sources. Future developments will lead to more green energy, emerging the overall objective of battery-ship design, which is to apply an extremely energy efficient design concept and demonstrate a 100% electric, emission free boat.

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, operational performance, absence of vibrations, smaller starting times of the engines and safety in critical situations. Furthermore, adopting autonomous electricity production may prove to be vital for the economic feasibility of a boat, as socio-political instability can cause significant fluctuations on diesel prices.

Nowadays, batteries have not been utilized on a large scale in maritime and offshore applications. Main reason has been that the specific power and energy density of the available batteries have not been able to meet the needs of such applications. Short life time expectations have also been a challenge. Lead-acid and Nickel Cadmium batteries with a very limited capacity compared to weight and size exist on many modern vessels today in different uninterruptible power supply and clean power applications. These are however not intended for continuous use in high power operation and are mostly installed as auxiliary devices. The use of batteries is changing due to the emergence and maturation of new technologies such as lithium-ion batteries with a much higher energy density and cycle-ability than lead-acid or Nickel Cadmium batteries. It is clear that further developments and better efficiency will apply in future, making battery powered vessels really attractive projects.

1.2 Problem statement and objectives

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

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

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

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

Design of a shore charging connection system and transformer stations to interconnect with public electricity grid and the new accurate electrical infrastructure of the vessels, to ensure appropriate function.

Evaluating social benefit from the reduction of ships' emissions and pollution.

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

1.3 Structure of study

This study is structured as follows:

Chapter 2: Battery System
Chapter 2 describes battery's functions and how to evaluate each battery's technology characteristics. In addition, the most important battery technologies are presented in order to help us evaluate the appropriate battery chemistry for the allelectric ship. Series/parallel configurations are described, as long as basic battery definitions.

Chapter 3: Legal and Regulatory Framework
Rules and regulations with whom we need to comply in order to launch the all-electric ship are presented. The technical design of the battery system and its arrangement in the vessel is described based on the "DNV-GL Guideline for Large Maritime Battery Systems" and on ABS_Use Of Lithium Batteries in The Marine and Offshore Industries. There has been a comparison between these regulations and the most important parts are presented, as part of the case study, to ensure safe operation of the vessel.

Chapter 4: Emissions and Air Pollution
The environmental effects of conventionally powered shipping are analyzed. More specifically, the most common and harmful types of pollutants found on the emissions of diesel engines on ships are listed, while the effects that these pollutants have on the climate, the eco-system and human health are described. ECAs and Tier I-III standards are explained, as well as green gas emissions aspects.

Chapter 5: Design Methodology
In this chapter, the retrofit design philosophy for the particular case study in which the present dissertation focuses, as well as the methodology developed for the sizing of the battery system are presented. Its inputs and equations are described and the characteristics of battery model used are presented.

Chapter 6: Electrical Infrastructure
Shore side and ship side network is presented. A recalculation of electric data sheet and apparent power calculation is done, in addition to cables and bus-bars sizing and the corresponding results are presented.

Chapter 7: Case Study
Results from the implementation of the methodology in case study are presented. Number of batteries installed according to operational profile are calculated. Available space for batteries is discussed and annual consumption of diesel and electricity are presented and compared.

Chapter 8: Economic Analysis
The economic investment is presented and the differences of conventional and full-electric costs are compared. An economic feasibility study is developed.

Chapter 9: Conclusions and Recommendations
Conclusions on vessel's retrofit and recommendations for future investigation are presented.

Chapter 2

Battery System

2.1 Getting to know the battery

One of the most common ways to store energy is a battery system, which can provide fuel/emission free operation for a vessel, reduced noise and acceptable efficiency. The basic principle of a battery is the Galvanic Cell. Galvanic Cells are devices that use a chemical reaction to create electricity (oxidation reduction reaction). The electrochemical reaction takes place between two metals of different affinities, called electrodes. The electrode with a weaker pull for electrons releases electrons to the wire (oxidized) and that electrode is called anode (more active). Thus, the solution of anode is getting positively charged. The electrode with a strong pull for electrons gains electrons (reduced) and is the cathode (less active). The solution of cathode gets negatively charged. The source of voltage is the electric potential difference between the positive electrode, cathode, and the negative one, anode. Positive and negative electrodes are defined from their standard potential difference (difference with reference electrode, hydrogen-porous platinum), the more negative is the negative one and the less negative is the positive [1]. Upon discharge, a flow of electrons is initiated by chemical reactions from the anode to the cathode, which produces an electric current in the external circuit, of the opposite direction Figure 2.1 (b) [2]. Positive charges move from the anode to the cathode. The separator makes it possible, without the passage of other molecules.

After discharge, if the reaction is reversible, the battery can be charged once again to create the desired electric potential difference between the anode and the cathode, as shown in Figure 2.1 (c). The components that complete the cell are:

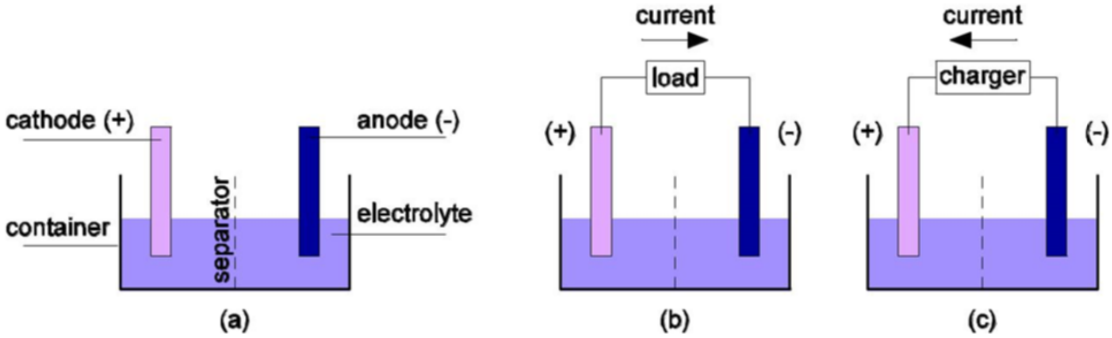


FIGURE 2.1: (a) Typical battery setup and its components and current flow direction during (b) connection with load - discharge or (c) connection with charger - charge.

- The anode, which is the "negative" half of the battery cell. The chemical reaction at the anode (oxidation) releases electrons that flow to the cathode through an external circuit and is usually made up of a thin copper substrate that is coated with the active anode material.
- The cathode, which is the "positive" half of the battery cell. The chemical reaction at the cathode (reduction) absorbs electrons that flow from the anode. It is made up of a substance that is coated with the active material.
- The separator acts as a means of insulation in this procedure, preventing the electrodes from coming into physical contact and allows for positive charges to move from the anode to the cathode in the electrolyte.
- The electrolyte can be liquid, water, alkalis, acids or solvents with dissolved salts and its usage is to transport the ions between the anode and the cathode.

Each and every one of the above materials is part of the cell of a battery and is responsible for the good operation of the cell. The most beneficial combination of the components makes a high quality battery, including high energy, power density, cycles of life, safety and reliability and, inevitably, has an impact on the final price of the battery.

Batteries are classified in two major categories:

- **Primary batteries:** The chemical reactions found on these batteries are irreversible and thus cannot be recharged. They can be used only in a single cycle operation. When the supply of reactants in the battery is exhausted, the battery stops producing current.

- **Secondary batteries:** These batteries are rechargeable and require an external electric current by a DC source to restore reactants to their fully charged state. The current triggers the chemical reactions to operate in reverse bringing the battery to state of high energy, so they can be used in multi cycle operation. Batteries used in marine applications are primarily rechargeable.

2.2 Series and parallel battery configurations

In some applications, a single cell may be adequate to meet the energy and power needs of a load, while for others, in order to achieve the desired voltage and current requirements or power, multiple cells need to be organized into battery modules and multiple battery modules into battery packs and strings. A typical connection is shown in Figure 2.2.

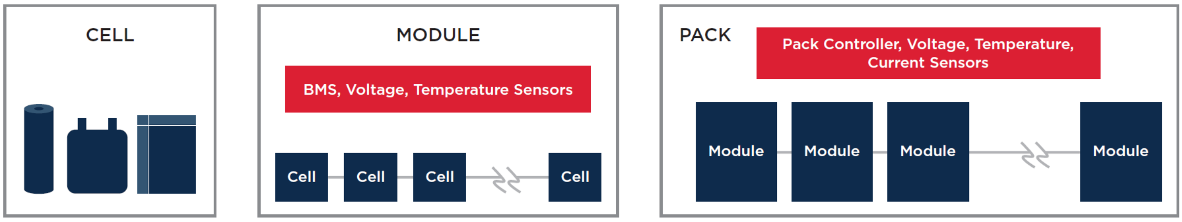


FIGURE 2.2: Battery basic figures.

As long as the power and capacity demands of the vessel are concerned, we design the battery system so as to correspond to the desired use. Depending on the configuration of the cells in the module, high voltage or high current modules can be achieved. If the battery cells are connected in parallel, the battery module will have the same voltage of one cell and the module can provide high current to the load (parallel impedance) equal to the sum of currents of each cell (No of cells x I per cell), as well as increased capacity equal to the sum of the capacities of each cell. Such modules are appropriate for applications where fast charge or discharge is required and are often called "high power modules".

Parallel connection
Cell: I = current (A), V = voltage (V), C = capacity (Ah)
Module of 4 cells: $i_m = 4 * I, V_m = V, C_m = 4 * C$

On the other hand if cells are connected in series, the battery module will have small discharge rates (impedance in series) equal to the current of one cell and high voltages

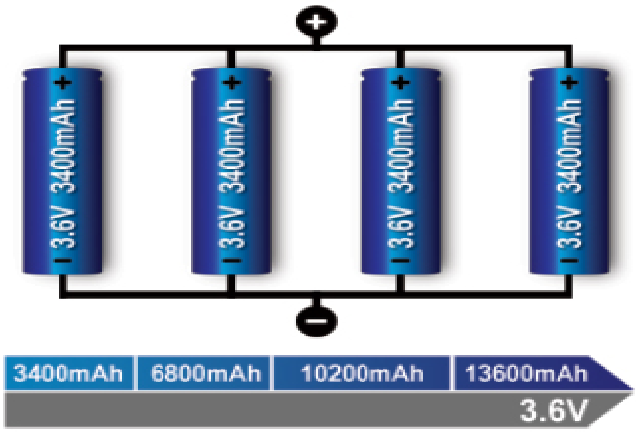


FIGURE 2.3: Parallel connection of four cells (4p).

can be provided to the load equal to the sum of the voltage of each cell but with reduced capacity, equal to the capacity of one cell (connecting cells with same capacity). Such modules are appropriate for applications where the battery system should provide energy to the system for an extended period of time and are often called "high energy modules". The modules are connected into sub-packs. The sub-packs (or modules if there are no sub-packs) are connected into strings (counting voltages, capacities and currents in the same way) and a number of parallel strings makes the battery pack. A battery system may consist of one or more packs.

Series connection
Cell: I = current (A), V = voltage (V), C = capacity (Ah)
Module of 4 cells: $i_m = I, V_m = 4 * V, C_m = C$

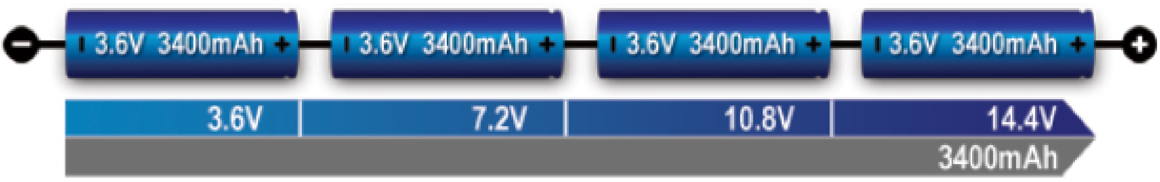


FIGURE 2.4: Series connection of four cells (4s).

Series/Parallel Connection

The series/parallel configuration shown in Figure 2.5 enables design flexibility and achieves the desired voltage and current ratings with a standard cell size. The total power is the sum of voltage times current; a 3.6V (nominal) cell multiplied by 3,400mAh produces 12.24Wh. Four 18650 Energy Cells of 3,400mAh each can be connected in series and parallel as shown to get 7.2V nominal and a total of 48.96Wh. A combination with 8 cells would produce 97.92Wh [3].

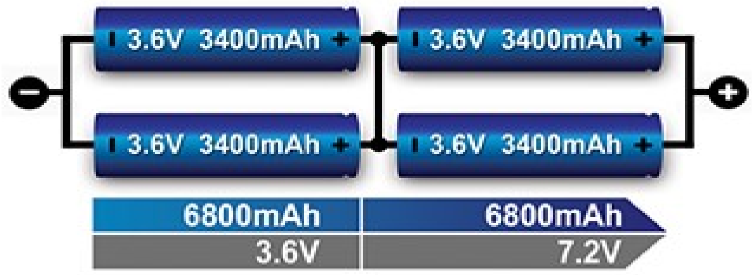


FIGURE 2.5: Series/ Parallel connection of four cells (2s2p).

Depending on the marine application, high energy or high power battery modules and packs are being used. In some applications the main focus is on high energy density and low cost. For other applications a very stable chemistry and long life is the main focus. Other applications can have a focus on power capabilities for charge or discharge or the ability to accept high current pulses for charge and discharge. According to battery manufacturer Kokam, high power battery systems are appropriate for propulsion purposes and high energy battery systems are appropriate for fully electric vessel applications. Alternative energy - power combinations are required from the battery system according to the use case and the application, see Figure 2.6.

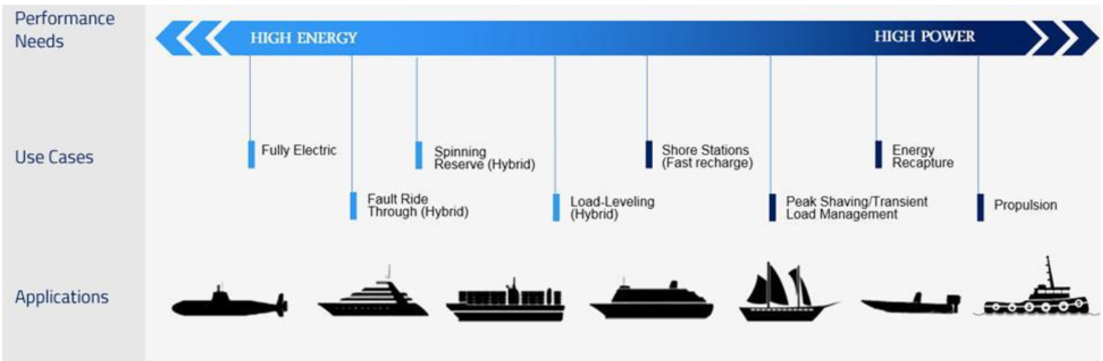


FIGURE 2.6: Battery system performance needs relative to use cases and marine applications.

Battery cells for maritime usage come in three main formats, cylindrical, large format prismatic and soft pouch. Some important characteristics of these three cell types are given on Table 2.1.

Property	**Cylindrical**	**Soft pouch**	**Prismatic**
Enclosure	Steel or aluminum	Multi-layer laminate pouch	Aluminum Plastic Steel
Cell vent mechanism	Fixed direction at specific pressure	Packaging failure vents at low pressure	Fixed direction at specific pressure
Mechanical current interrupt device (CID)	Can be included in header	Non existent	Can be included in header

Table 2.1: Characteristics of cell types, or form factors, applicable for maritime use.

2.3 Battery definitions and what they mean

Batteries are described or evaluated using a set of parameters that reflect their performance. The key parameters will help in understanding the fundamental terminology used to describe, classify and compare different types of batteries used in hybrid and/or electric power operations [4] [5]:

Cell:
A battery cell is a single electrochemical unit in its simplest form, typically packaged in: a) metal cylinders, b) flat, rectangular metal or plastic cases, or c) heat sealed foil pouches. Secondary Cells: The battery cells which are rechargeable are called secondary, whereas the ones that cannot be recharged, primary.

Cell Drift:
The condition where two or more cells are in the state of imbalance. If not corrected by a Battery Management system this effect can lead to a potential safety hazard.

Battery Module and Battery Pack:
A module consists of several cells generally connected in either series or parallel. A battery pack is then assembled by connecting modules together, again either in series or parallel.

Thermal Runaway:
The condition in which a cell enters a self-heating state where the heat generated is greater than the heat dissipated.

C- and E- rates:
In describing batteries, discharge current is often expressed as a C rate in order to normalize against battery capacity, which is often very different between batteries. A C-rate is a measure of the rate at 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.

Battery Classifications:
Not all batteries are created equal, even batteries of the same chemistry. The main trade-off in battery development is between power and energy: batteries can be either high-power or high-energy, but not both. Often manufacturers will classify batteries using these categories. Other common classifications are High Durability, meaning that the chemistry has been modified to provide higher battery life at the expense of power and energy.

Nominal Voltage (V):
The reported or reference voltage of the battery, also sometimes thought of as the normal voltage of the battery.

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

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

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

- **Calendar fade:**
  The reduction of capacity with the passage of time firstly due to the extension of direct interface between electrode and electrolyte and secondly because of the loss of active material.

- **Cycling fade:**
  The reduction of capacity due to successive charge/discharge cycles which result in the alternation of electrode's structure and mechanical fatigue.

Degradation due to both cycling and calendar effects is highly dependent on temperature. The higher the temperature the more rapidly the cell will degrade, with additional risks presented at low temperatures. Exposure to temperatures outside of the rated operating range poses significant risk of reduced lifespan.

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. Energy is calculated by multiplying the discharge power (in Watts) by the discharge time (in hours). Like capacity, energy decreases with increasing C-rate.

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 cycles and by other conditions such as temperature and humidity. The higher the DOD, the lower the cycle life.

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. Along with the energy consumption of the vehicle, it determines the battery weight required to achieve a given electric range.

Specific power (W/kg):
The maximum available power per unit mass. Specific power is a characteristic of the battery chemistry and packaging. It determines the battery weight required to achieve a given performance target.

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. Along with the energy consumption of the vehicle, it determines the battery size required to achieve a given electric range.

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

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

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

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:
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:
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. A fully charged battery system has a SOC of 100%, while a fully discharged battery system has a SOC of 0%. SOC is generally calculated using current integration to determine the change in battery capacity over time. More specifically, determination of SOC is a complex calculation that depends on closely monitoring power in and out of the battery as well as voltage and temperature. However, these calculations must be calibrated specifically for a given battery cell type, are highly temperature dependent and must also factor in non-linear effects of different power levels and voltage or SOC ranges. The complicated nature of this calculation thus points to the need for a highly developed Battery Management System.

State of Health (SOH):
As the cell is charged and discharged repeatedly, the ability to accumulate ions at the negative electrode will gradually decrease. The State of Health (SOH) reflects the general condition of the battery and the ability to deliver the specified performance compared to a new battery. This primarily refers to a reduction in the total amount of energy that the battery can store or release, a reduced capacity.

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

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

Open-circuit voltage (V):
The voltage between the battery terminals with no load applied. The open- circuit voltage depends on the battery state of charge, increasing with state of charge. The resistance within the battery, generally different for charging and discharging, also dependent on the battery's state of charge. As internal resistance increases, the battery efficiency decreases and thermal stability is reduced as more of the charging energy is converted into heat.

Watts and Volt-Amps (VA):
Watt is real power that is being metered; VA is the apparent power that is affected by a reactive load. On a purely resistive load, watt and VA readings are alike; a reactive load such as an inductive motor or fluorescent light causes a phase shift between voltage

and current that lowers the power factor (pf) from the ideal one (1) to 0.7 or lower. The sizing of electrical wiring and the circuit breakers must be based on VA power.

Cold cranking amps (CCA):
Starter batteries, also known as SLI (starter light ignition) are marked with CCA. The number indicates the current in ampere that the battery can deliver at -18$^oC(0^oF)$.

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 power (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, Figure 2.7. Conceptually, the horizontal axis describes how much energy is available, while the vertical 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 X-axis can be delivered at the power (per mass) on the Y-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.

2.4 Lead acid batteries

Invented by the French physician Gaston Planté in 1859, lead acid was the first rechargeable battery for commercial use. Despite its advanced age, the lead chemistry continues to be in wide use today. There are good reasons for its popularity; lead acid is dependable and inexpensive on a cost-per-watt base. There are few other batteries that deliver bulk power as cheaply as lead acid, and this makes the battery cost-effective for automobiles, golf cars, forklifts, marine and uninterruptible power supplies (UPS) [6].

The grid structure of the lead acid battery is made from a lead alloy. Pure lead is too soft and would not support itself, so small quantities of other metals are added

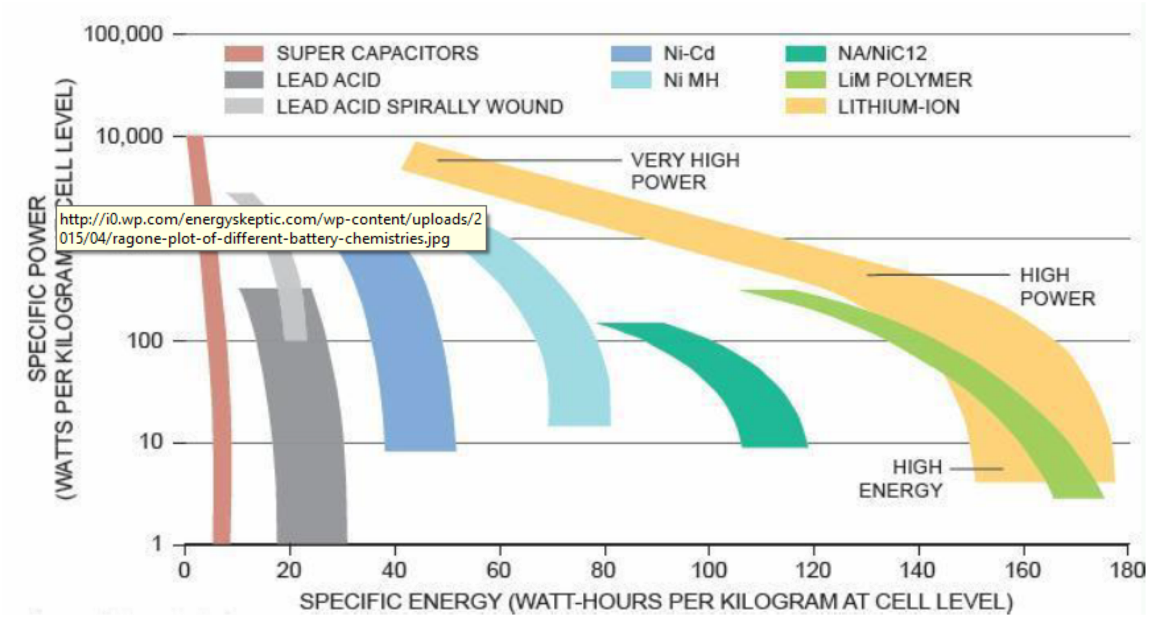


FIGURE 2.7: Specific power and specific energy of different battery chemistries (source Johnson Controls).

to get the mechanical strength and improve electrical properties. The most common additives are antimony, calcium, tin and selenium. These batteries are often known as "lead-antimony" and "lead-calcium."

Adding antimony and tin improves deep cycling but this increases water consumption and escalates the need to equalize. Calcium reduces self-discharge, but the positive lead-calcium plate has the side effect of growing due to grid oxidation when being overcharged. Modern lead acid batteries also make use of doping agents such as selenium, cadmium, tin and arsenic to lower the antimony and calcium content.

Lead acid is heavy and is less durable than nickel- and lithium-based systems when deep cycled. A full discharge causes strain and each discharge/charge cycle permanently robs the battery of a small amount of capacity. This loss is small while the battery is in good operating condition, but the fading increases once the performance drops to half the nominal capacity. This wear-down characteristic applies to all batteries in various degrees.

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

Charging a lead acid battery is simple, but the correct voltage limits must be observed. Choosing a low voltage limit shelters the battery, but this produces poor performance and causes a buildup of sulfation on the negative plate. A high voltage limit improves performance but forms grid corrosion on the positive plate. While sulfation can be reversed if serviced in time, corrosion is permanent. Lead acid does not lend itself to fast charging and with most types, a full charge takes 14–16 hours. The battery must always be stored at full state-of-charge. Low charge causes sulfation, a condition that robs the battery of performance. Adding carbon on the negative electrode reduces this problem but this lowers the specific energy.

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

Advantages	Inexpensive and simple to manufacture; low cost per watt-hour Low self-discharge; lowest among rechargeable batteries High specific power, capable of high discharge currents Good low and high temperature performance
Limitations	Low specific energy; poor weight-to-energy ratio Slow charge; fully saturated charge takes 14-16 hours Must be stored in charged condition to prevent sulfation Limited cycle life; repeated deep-cycling reduces battery life Flooded version requires watering Transportation restrictions on the flooded type Not environmentally friendly

Table 2.2: Advantages and limitations of lead acid batteries.

2.5 Nickel based batteries

For 50 years, portable devices relied almost exclusively on nickel-cadmium (NiCd). This generated a large amount of data, but in the 1990s, nickel-metal-hydride (NiMH) took over the reign to solve the toxicity problem of the otherwise robust NiCd. Many of the characteristics of NiCd were transferred to the NiMH, offering a quasi-replacement as these two systems are similar. Because of environmental regulations, NiCd is limited to specialty applications today[7].

2.5.1 Nickel-Cadmium (NiCd)

Invented by Waldemar Jungner in 1899, the nickel-cadmium battery offered several advantages over lead acid, then the only other rechargeable battery; however, the materials for NiCd were expensive. Developments were slow, but in 1932, advancements were made to deposit the active materials inside a porous nickel-plated electrode. Further improvements occurred in 1947 by absorbing the gases generated during charge, which led to the modern sealed NiCd battery.

For many years, NiCd was the preferred battery choice for two-way radios, emergency medical equipment, professional video cameras and power tools. In the late 1980s, ultra-high capacity NiCd with capacities that were up to 60 percent higher than the standard NiCd emerged. Packing more active material into the cell achieved this, but the gain was shadowed by higher internal resistance and reduced cycle count.

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

2.5.2 Nickel-Metal-Hydride (NiMH)

Research on nickel-metal-hydride started in 1967; however, instabilities with the metal-hydride led to the development of the nickel-hydrogen (NiH) instead. New hydride alloys discovered in the 1980s eventually improved the stability issues and today NiMH provides 40 percent higher specific energy than the standard NiCd.

Nickel-metal-hydride is not without drawbacks. The battery is more delicate and trickier to charge than NiCd. With 20 percent self-discharge in the first 24 hours after charge and 10 percent per month thereafter, NiMH ranks among the highest in the class. Modifying the hydride materials lowers the self- discharge and reduces corrosion of the alloy, but this decreases the specific energy. Batteries for the electric power train make use of this modification to achieve the needed robustness and long lifespan.

Advantages	Rugged, high cycle count with proper maintenance Only battery that can be ultra-fast charged with little stress Good load performance; forgiving if abused Long shelf life; can be stored in a discharged state, needs priming before use Simple storage and transportation; not subject to regulatory control Good low-temperature performance Economically priced; NiCd is the lowest in terms of cost per cycle Available in a wide range of sizes and performance options
Limitations	Relatively low specific energy compared with newer systems Memory effect; needs periodic full discharges and can be rejuvenated Cadmium is a toxic metal. Cannot be disposed of in landfills High self-discharge; needs recharging after storage Low cell voltage of 1.20V requires many cells to achieve high voltage

TABLE 2.3: Advantages and limitations of NiCd batteries.

2.6 Lithium based batteries

Pioneering work of the lithium battery began in 1912 under G.N. Lewis, but it was not until the early 1970s that the first non-rechargeable lithium batteries became commercially available. Attempts to develop rechargeable lithium batteries followed in the 1980s but failed because of instabilities in the metallic lithium used as anode material (The metal-lithium battery uses lithium as anode; Li-ion uses graphite as anode and active materials in the cathode.) [8].

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 could 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. The key to the superior specific energy is the high cell voltage of 3.60V. Improvements in the active materials and electrolytes have the potential to further boost the energy density. Load characteristics are good

Advantages	30–40 percent higher capacity than a standard NiCd Less prone to memory than NiCd, can be rejuvenated Simple storage and transportation; not subject to regulatory control Environmentally friendly; contains only mild toxins Nickel content makes recycling profitable Wide temperature range
Limitations	Limited service life; deep discharge reduces service life Requires complex charge algorithm. Sensitive to overcharge Does not absorb overcharge well; trickle charge must be kept low Generates heat during fast charge and high-load discharge High self-discharge Coulombic efficiency only about 65% (99% with Li-ion)

TABLE 2.4: Advantages and limitations of NiMH batteries.

and the flat discharge curve offers effective utilization of the stored energy in a desirable and flat voltage spectrum of 3.70–2.80V/cell.

Li-ion is a low-maintenance battery, an advantage that most other chemistries cannot claim. The battery has no memory and does not need exercising (deliberate full discharge) to keep it in good shape. Self-discharge is less than half that of nickel-based systems and this helps the fuel gauge applications. The nominal cell voltage of 3.60V can directly power mobile phones, tablets and digital cameras, offering simplifications and cost reductions over multi-cell designs. The drawbacks are the need for protection circuits to prevent abuse, as well as high price. Lithium-ion uses a cathode (positive electrode), an anode (negative electrode) and electrolyte as conductor. (The anode of a discharging battery is negative and the cathode positive). The cathode is metal oxide and the anode consists of porous carbon. During discharge, the ions flow from the anode to the cathode through the electrolyte and separator; charge reverses the direction and the ions flow from the cathode to the anode. Li ion batteries come in many varieties but all have one thing in common – the “lithium-ion” catchword. Although strikingly similar at first glance, these batteries vary in performance and the choice of active materials gives them unique personalities.

Lithium-ion batteries will unavoidably degrade with use. As the cell is charged and discharged repeatedly, the ability to accumulate ions at the negative electrode will

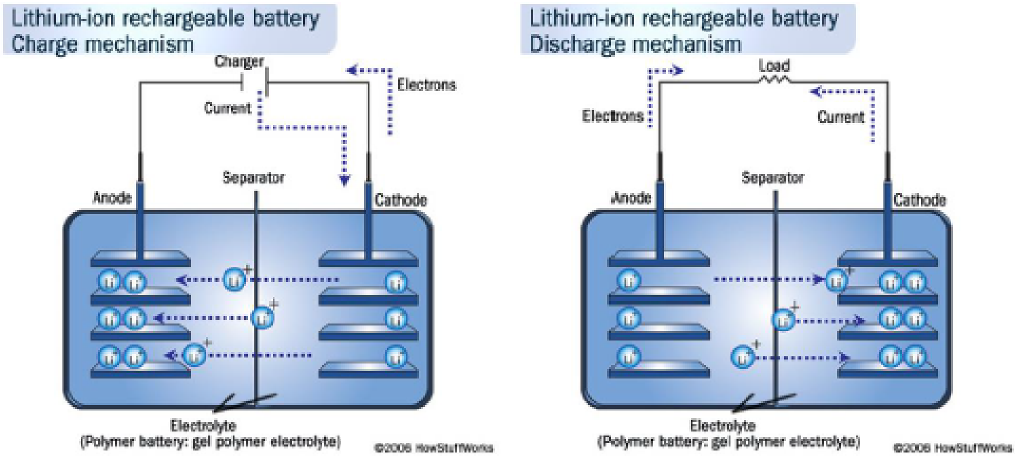


FIGURE 2.8: Basic principles and components of a lithium-ion battery.

gradually decrease. The State of Health (SOH) reflects the general condition of the battery and the ability to deliver the specified performance compared to a new battery. This primarily refers to a reduction in the total amount of energy that the battery can store or release, a reduced capacity; but for some applications reduction in power capability (due to increasing internal resistance) may be equally or even more important.

The traits of a battery, such as how much energy it can store or how fast it can charge or discharge, are dependent on the cell composition, which includes design parameters as well as chemistry. A battery can be based on a variety of commonly used lithium-ion chemistries which represent different battery characteristics. Maritime battery systems will typically be built of several thousands of cells, and as such it is vital that each cell operates consistently with all other cells. This requires both that the battery BMS is able to successfully control and operate each cell in a balanced manner, and equally that cells are manufactured of good and equal quality. Lesser quality batteries are available on the market as the result of cheaper production methods, but are associated with greater risk – of unwanted failures like shorter lifespan, inconsistent voltage, inconsistent capacity or in worst cases internal failures that can lead to fire. Advantages and limitations of Li-ion batteries are presented, Table 2.5.

2.6.1 Lithium-Cobalt-Oxide ($LiCoO_2$)

Its high specific energy makes Li-cobalt the popular choice for mobile phones, laptops and digital cameras. The battery consists of a cobalt oxide cathode and a graphite carbon anode. The cathode has a layered structure and during discharge, lithium ions

Advantages	High specific energy and high load capabilities with Power Cells Long cycle and extend shelf-life; maintenance-free High capacity, low internal resistance, good coulombic efficiency Simple charge algorithm and reasonably short charge times Low self-discharge (less than half that of NiCd and NiMH)
Limitations	Requires protection circuit to prevent thermal runaway if stressed Degrades at high temperature and when stored at high voltage No rapid charge possible at freezing temperatures (<0°C, <32°F) Transportation regulations required when shipping in larger quantities

TABLE 2.5: Advantages and limitations of Li-ion batteries.

move from the anode to the cathode. The flow reverses on charge. The drawback of Li-cobalt is a relatively short life span, low thermal stability and limited load capabilities (specific power).

The drawback of Li-cobalt is a relatively short life span, low thermal stability and limited load capabilities (specific power). Like other cobalt-blended Li-ion, Li-cobalt has a graphite anode that limits the cycle life by a changing solid electrolyte interface (SEI), thickening on the anode and lithium plating while fast charging and charging at low temperature. Newer systems include nickel, manganese and/or aluminum to improve longevity, loading capabilities and cost. Li-cobalt should not be charged and discharged at a current higher than its C-rating.

The hexagonal spider graphic , Figure 2.9, summarizes the performance of Li-cobalt in terms of specific energy or capacity that relates to runtime; specific power or the ability to deliver high current; safety; performance at hot and cold temperatures; life span reflecting cycle life and longevity; and cost. Other characteristics of interest not shown in the spider webs are toxicity, fast-charge capabilities, self-discharge and shelf life.

Lithium Cobalt Oxide: $LiCoO_2$ cathode (~60% Co), graphite anode Short form: LCO or Li-cobalt. Since 1991	
Voltages	3.60V nominal; typical operating range 3.0–4.2V/cell
Specific energy (capacity)	150–200Wh/kg. Specialty cells provide up to 240Wh/kg.
Charge (C-rate)	0.7–1C, charges to 4.20V (most cells); 3h charge typical. Charge current above 1C shortens battery life.
Discharge (C-rate)	1C; 2.50V cut off. Discharge current above 1C shortens battery life.
Cycle life	500–1000, related to depth of discharge, load, temperature
Thermal runaway	150°C (302°F). Full charge promotes thermal runaway
Applications	Mobile phones, tablets, laptops, cameras
Comments	Very high specific energy, limited specific power. Cobalt is expensive. Serves as Energy Cell. Market share has stabilized.

TABLE 2.6: Characteristics of lithium cobalt oxide.

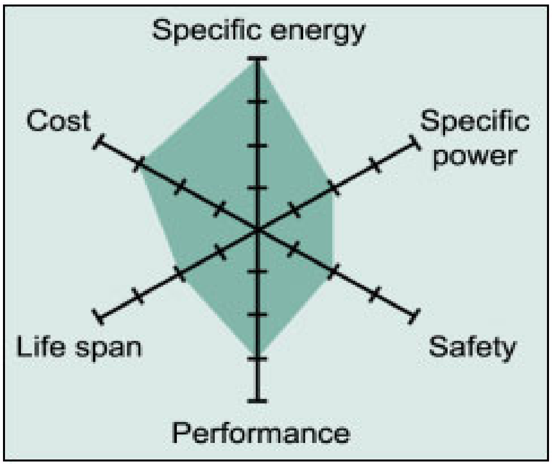


FIGURE 2.9: Snapshot of an average Li-cobalt battery.

2.6.2 Lithium-Manganese-Oxide ($LiMn_2O_4$)

Li-ion with manganese spinel was first published in the Materials Research Bulletin in 1983. In 1996, Moli Energy commercialized a Li-ion cell with lithium manganese oxide as cathode material. The architecture forms a three-dimensional spinel structure that improves ion flow on the electrode, which results in lower internal resistance and improved current handling. A further advantage of spinel is high thermal stability and enhanced safety, but the cycle and calendar life are limited.

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

Li-ion research gravitates heavily towards combining Li-manganese with cobalt, nickel, manganese and/or aluminum as active cathode material. In some architecture, a small amount of silicon is added to the anode. These three active metals, as well as the silicon enhancement can conveniently be chosen to enhance the specific energy (capacity), specific power (load capability) or longevity. While consumer batteries go for high capacity, industrial applications require battery systems that have good loading capabilities, deliver a long life and provide safe and dependable service.

Lithium Manganese Oxide: $LiMn_2O_4$ cathode. graphite anode Short form: LMO or Li-manganese (spinel structure) Since 1996	
Voltages	3.70V (3.80V) nominal; typical operating range 3.0–4.2V/cell
Specific energy (capacity)	100–150Wh/kg
Charge (C-rate)	0.7–1C typical, 3C maximum, charges to 4.20V (most cells)
Discharge (C-rate)	1C; 10C possible with some cells, 30C pulse (5s), 2.50V cut-off
Cycle life	300–700 (related to depth of discharge, temperature)
Thermal runaway	250°C (482°F) typical. High charge promotes thermal runaway
Applications	Power tools, medical devices, electric powertrains
Comments	High power but less capacity; safer than Li-cobalt; commonly mixed with NMC to improve performance.

Table 2.7: Characteristics of lithium manganese oxide.

Figure 2.10 shows the spider web of a typical Li-manganese battery. The characteristics appear marginal but newer designs have improved in terms of specific power, safety and life span. Pure Li-manganese batteries are no longer common today; they may only be used for special applications.

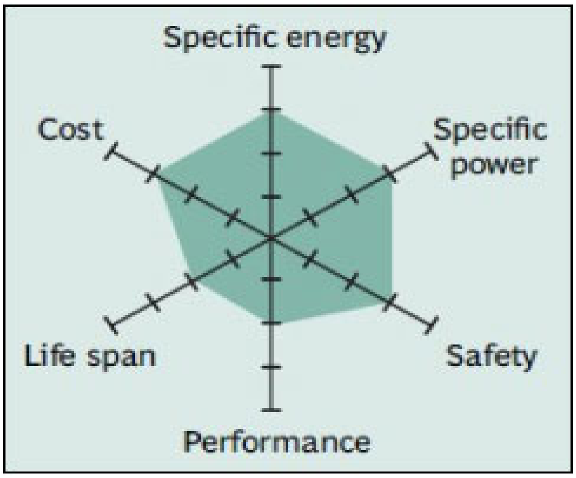


FIGURE 2.10: Snapshot of a pure Li-manganese battery.

2.6.3 Lithium-Nickel-Manganese-Cobalt-Oxide ($LiNiMnCoO_2$ or NMC)

One of the most successful Li-ion systems is a cathode combination of nickel-manganese-cobalt (NMC). Similar to Li-manganese, these systems can be tailored to serve as Energy Cells or Power Cells. For example, NMC in an 18650 cell for moderate load condition has a capacity of about 2,800mAh and can deliver 4A to 5A; NMC in the same cell optimized for specific power has a capacity of only about 2,000mAh but delivers a continuous discharge current of 20A. A silicon-based anode will go to 4,000mAh and higher but at reduced loading capability and shorter cycle life. Silicon added to graphite has the drawback that the anode grows and shrinks with charge and discharge, making the cell mechanically unstable.

The secret of NMC lies in combining nickel and manganese. An analogy of this is table salt in which the main ingredients, sodium and chloride, are toxic on their own but mixing them serves as seasoning salt and food preserver. Nickel is known for its high specific energy but poor stability; manganese has the benefit of forming a spinel structure to achieve low internal resistance but offers a low specific energy. Combining the metals enhances each other strengths.

NMC is the battery of choice for power tools, e-bikes and other electric powertrains. The cathode combination is typically one-third nickel, one-third manganese and one-third cobalt, also known as 1-1-1. This offers a unique blend that also lowers the raw material cost due to reduced cobalt content. Another successful combination is NCM with 5 parts nickel, 3 parts cobalt and 2 parts manganese (5-3-2). Other combinations using various amounts of cathode materials are possible.

Lithium Nickel Manganese Cobalt Oxide: $LiNiMnCoO_2$. cathode, graphite anode Short form: NMC (NCM, CMN, CNM, MNC, MCN similar with different metal combinations) Since 2008	
Voltages	3.60V, 3.70V nominal; typical operating range 3.0–4.2V/cell, or higher
Specific energy (capacity)	150–220Wh/kg
Charge (C-rate)	0.7–1C, charges to 4.20V, some go to 4.30V; 3h charge typical. Charge current above 1C shortens battery life.
Discharge (C-rate)	1C; 2C possible on some cells; 2.50V cut-off
Cycle life	1000–2000 (related to depth of discharge, temperature)
Thermal runaway	210°C (410°F) typical. High charge promotes thermal runaway
Cost	~$420 per kWh (Source: RWTH, Aachen)
Applications	E-bikes, medical devices, EVs, industrial
Comments	Provides high capacity and high power. Serves as Hybrid Cell. Favorite chemistry for many uses; market share is increasing.

TABLE 2.8: Characteristics of lithium nickel manganese cobalt oxide (NMC).

Battery manufacturers move away from cobalt systems toward nickel cathodes because of the high cost of cobalt. Nickel-based systems have higher energy density, lower cost, and longer cycle life than the cobalt-based cells but they have a slightly lower voltage.

New electrolytes and additives enable charging to 4.4V/cell and higher to boost capacity. Figure 2.11 demonstrates the characteristics of the NMC.

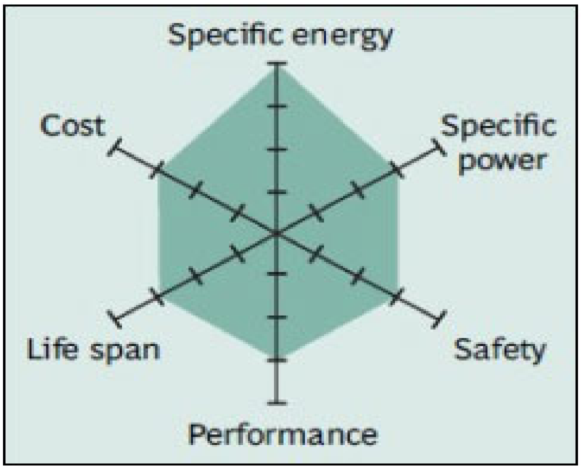


FIGURE 2.11: Snapshot of NMC.

2.6.4 Lithium-Iron-Phosphate ($LiFePO_4$)

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

Li-phosphate is more tolerant to full charge conditions and is less stressed than other lithium-ion systems if kept at high voltage for a prolonged time. As a trade-off, its lower nominal voltage of 3.2V/cell reduces the specific energy below that of cobalt-blended lithium-ion. With most batteries, cold temperature reduces performance and elevated storage temperature shortens the service life, and Li-phosphate is no exception. Li-phosphate has a higher self-discharge than other Li-ion batteries, which can cause balancing issues with aging. This can be mitigated by buying high quality cells and/or using sophisticated control electronics, both of which increase the cost of the pack. Cleanliness in manufacturing is of importance for longevity. There is no tolerance for moisture, lest the battery will only deliver 50 cycles.

Li-phosphate is often used to replace the lead acid starter battery. Four cells in series produce 12.80V, a similar voltage to six 2V lead acid cells in series. Vehicles charge lead acid to 14.40V (2.40V/cell) and maintain a topping charge. Topping charge is applied to maintain full charge level and prevent sulfation on lead acid batteries.

With four Li-phosphate cells in series, each cell tops at 3.60V, which is the correct full-charge voltage. At this point, the charge should be disconnected but the topping charge continues while driving. Li-phosphate is tolerant to some overcharge; however, keeping the voltage at 14.40V for a prolonged time, as most vehicles do on a long road trip, could stress Li-phosphate. Cold temperature also reduces performance of Li-ion and this could affect the cranking ability in extreme cases. Figure 2.12 summarizes the attributes of Li-phosphate.

Lithium Iron Phosphate: $LiFePO_4$ cathode, graphite anode Short form: LFP or Li-phosphate Since 1996	
Voltages	3.20, 3.30V nominal; typical operating range 2.5–3.65V/cell
Specific energy (capacity)	90–120Wh/kg
Charge (C-rate)	1C typical, charges to 3.65V; 3h charge time typical
Discharge (C-rate)	1C, 25C on some cells; 40A pulse (2s); 2.50V cut-off (lower that 2V causes damage)
Cycle life	1000–2000 (related to depth of discharge, temperature)
Thermal runaway	270°C (518°F) Very safe battery even if fully charged
Cost	~$580 per kWh (Source: RWTH, Aachen)
Applications	Portable and stationary needing high load currents and endurance
Comments	Very flat voltage discharge curve but low capacity. One of safest Li-ions. Used for special markets. Elevated self-discharge.

TABLE 2.9: Characteristics of lithium iron phosphate.

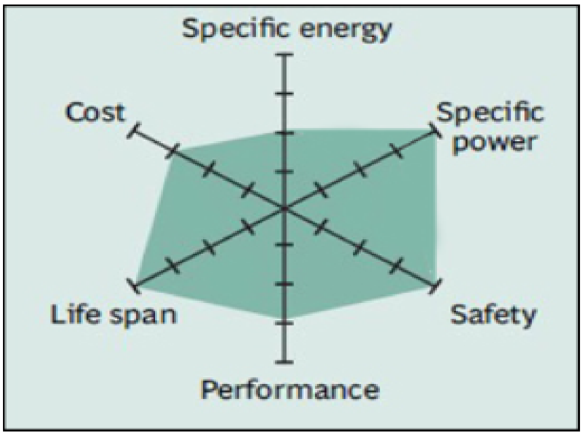


FIGURE 2.12: Snapshot of a typical Li-phosphate battery.

2.6.5 Lithium-Nickel-Cobalt-Aluminum-Oxide ($LiNiCoAlO_2$)

Lithium nickel cobalt aluminum oxide battery, or NCA, has been around since 1999 for special applications. It shares similarities with NMC by offering high specific energy, reasonably good specific power and a long life span. Less flattering are safety and cost. Figure 2.13 summarizes the six key characteristics. NCA is a further development of lithium nickel oxide; adding aluminum gives the chemistry greater stability.

High energy and power densities, as well as good life span, make NCA a candidate for EV powertrains. High cost and marginal safety are negatives.

Lithium Nickel Cobalt Aluminum Oxide: $LiNiCoAlO_2$ cathode (~9% Co), graphite anode Short form: NCA or Li-aluminum. Since 1999	
Voltages	3.60V nominal; typical operating range 3.0–4.2V/cell
Specific energy (capacity)	200-260Wh/kg; 300Wh/kg predictable
Charge (C-rate)	0.7C, charges to 4.20V (most cells), 3h charge typical, fast charge possible with some cells
Discharge (C-rate)	1C typical; 3.00V cut-off; high discharge rate shortens battery life
Cycle life	500 (related to depth of discharge, temperature)
Thermal runaway	150°C (302°F) typical, High charge promotes thermal runaway
Cost	~$350 per kWh (Source: RWTH, Aachen)
Applications	Medical devices, industrial, electric powertrain (Tesla)
Comments	Shares similarities with Li-cobalt. Serves as Energy Cell.

TABLE 2.10: Characteristics of lithium nickel cobalt aluminum oxide .

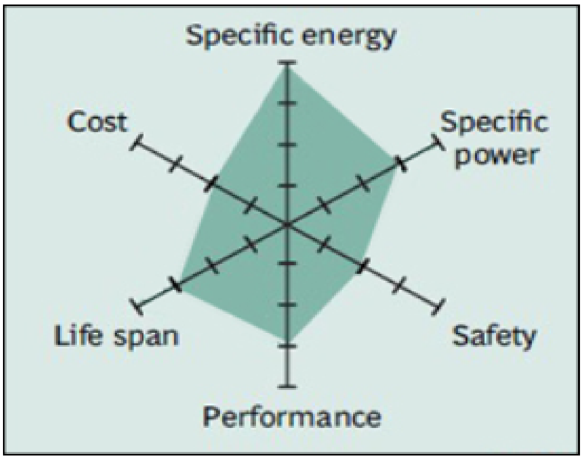


FIGURE 2.13: Snapshot of NCA.

2.6.6 Lithium-Titanate ($Li_4Ti_5O_{12}$)

Batteries with lithium titanate anodes have been known since the 1980s. Li-titanate replaces the graphite in the anode of a typical lithium-ion battery and the material forms into a spinel structure. The cathode can be lithium manganese oxide or NMC. Li-titanate has a nominal cell voltage of 2.40V, can be fast charged and delivers a high discharge current of 10C, or 10 times the rated capacity. The cycle count is said to be higher than that of a regular Li-ion. Li-titanate is safe, has excellent low-temperature discharge characteristics and obtains a capacity of 80 percent at –30^oC (–22^oF).

Lithium Titanate: Can be lithium manganese oxide or NMC; $Li_4Ti_5O_{12}$ (titanate) anode Short form: LTO or Li-titanate	Commercially available since about 2008.
Voltages	2.40V nominal; typical operating range 1.8–2.85V/cell
Specific energy (capacity)	50–80Wh/kg
Charge (C-rate)	1C typical; 5C maximum, charges to 2.85V
Discharge (C-rate)	10C possible, 30C 5s pulse; 1.80V cut-off on LCO/LTO
Cycle life	3,000–7,000
Thermal runaway	One of safest Li-ion batteries
Cost	~$1,005 per kWh (Source: RWTH, Aachen)
Applications	UPS, electric powertrain (Mitsubishi i-MiEV, Honda Fit EV), solar-powered street lighting
Comments	Long life, fast charge, wide temperature range but low specific energy and expensive. Among safest Li-ion batteries.

Table 2.11: Characteristics of lithium titanate.

LTO (commonly Li4Ti5O12) has advantages over the conventional cobalt-blended Li-ion with graphite anode by attaining zero-strain property, no SEI film formation and no lithium plating when fast charging and charging at low temperature. Thermal stability under high temperature is also better than other Li-ion systems; however, the battery is expensive. At only 65Wh/kg, the specific energy is low, rivalling that of NiCd. Li-titanate charges to 2.80V/cell, and the end of discharge is 1.80V/cell. Figure 2.14 illustrates the characteristics of the Li-titanate battery. Typical uses are electric powertrains, UPS and solar-powered street lighting.

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

2.6.7 Lithium-Polymer (LiPo)

The term polymer is commonly used to describe certain type of lithium-based battery that may or may not be polymer based. These typically include pouch and prismatic cells. Lithium-polymer differs from other battery systems in the type of electrolyte used. The original polymer used a solid (dry) polymer electrolyte that resembles a plastic-like film. This insulator allows the exchange of ions (electrically charged atoms) and replaces the traditional porous separator that is soaked with electrolyte.

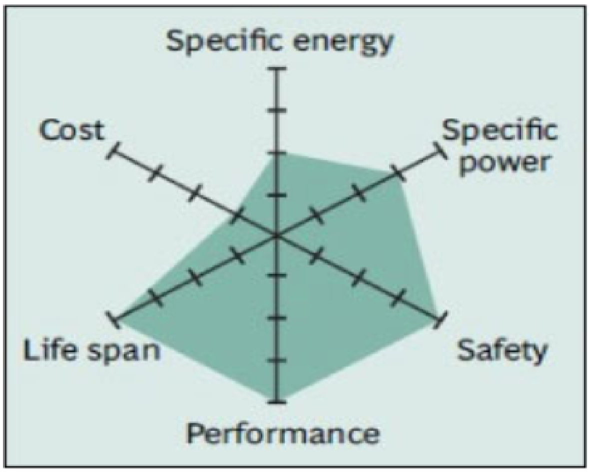


FIGURE 2.14: Snapshot of Li-titanate.

A solid polymer has poor conductivity at room temperature, and the battery must be heated to 60^oC (140^oF) and higher to enable current flow. Large polymer batteries for stationary applications were 45 installed that needed heating, but these have since disappeared. To make the modern Li-polymer battery conductive at room temperature, gelled electrolyte has been added. Most Li-ion polymer cells today incorporate a micro porous separator with some moisture. Li-polymer can be built on many systems, the likes of Li-cobalt, NMC, Li phosphate and Li-manganese, and is not considered a unique battery chemistry. The majority of Li-polymer packs are cobalt based; other active material may also be added.

Both systems use identical cathode and anode material and contain a similar amount of electrolyte. Li-polymer is unique in that a micro porous electrolyte replaces the traditional porous separator. Li-polymer offers slightly higher specific energy and can be made thinner than conventional Li-ion, but the manufacturing cost is said to be higher than cylindrical design. While a standard Li-ion needs a rigid case to press the electrodes together, Li-polymer uses laminated sheets that do not need compression. A foil-type enclosure reduces the weight by more than 20 percent over the classic hard shell.

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

2.7 Summary

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

Battery systems can be optimized for high energy storage capacity, as is often required for all-electric applications, or for high power applications, as in hybrids, where the purpose of the battery system is to cover peak loads and even out the generator loads. Some applications will require a combination of both energy and power.

The characteristics of the four commonly used rechargeable battery systems are being compared on Table 2.12, showing average performance ratings at time of publication. Li-ion is divided into different types, named by their active materials, which are cobalt, manganese, phosphate and titanate.

Missing from in the list is the popular lithium-ion-polymer that gets its name from the unique separator and electrolyte system. Most are a hybrid version that shares performance with other Li-ion.

Amongst all of these batteries, lead-acid batteries are the oldest and most mature technology on the market. They are the most economical for larger power applications where weight is of little concern. Nickel Cadmium (NiCd) batteries are also matured and well understood technology but relatively low in energy density. They are used where long life, high discharge and economical price are most important. Although NiCd and lead-acid batteries can supply excellent pulse power, they are not environmentally friendly as they contain toxic heavy metals. Nickel Metal Hydrite (NiMH) batteries have a higher energy density to that of NiCd at the expense of reduced cycle life. However, this type of battery does not contain toxic metals. Another drawback of both Nickel based batteries analyzed on the present dissertation is the severe self-discharge effect.

Despite all these characteristics, there is a huge development in lithium-ion batteries over the past few years and adoption of high-quality batteries at electric and hybrid vehicles and large-scale grid systems, which makes li-ion battery systems the most viable and promising option for maritime applications.

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

TABLE 2.12: Characteristics of commonly used rechargeable batteries.

Different types of li-ion batteries offer different features, with trade-offs between specific power, specific energy, safety, cost, lifespan and performance. For example, a chemistry that optimizes safety compromises other features such as specific energy and power. This fact makes some of them more appealing for different type of applications. An important tool in finding the optimal battery for each application is a spider web diagram [9] in which all these factors are taken into consideration, Figure 2.15.

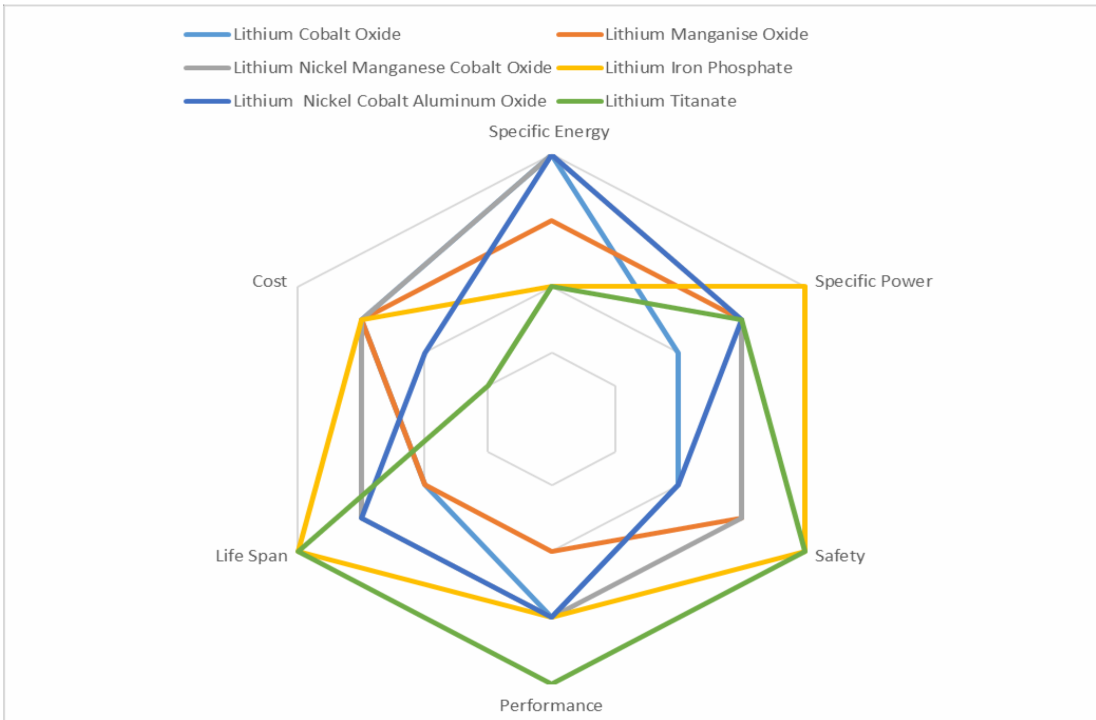


FIGURE 2.15: Qualitative spider web diagram describing key features of LI-ion batteries.

While Li-aluminum (NCA), Li-cobalt-oxide ($LiCoO_2$) and Li-Nickel-Manganese-Cobalt-Oxide (NMC) are the clear winners by storing more capacity than other systems, this only applies to specific energy for Li-aluminum, providing low level of safety and increased cost. In terms of specific power, Li-phosphate (LFP) is superior with lower specific energy but really good lifespan and good performance. Li-manganese (LMO) is one of the most affordable choices, but the short lifespan counterbalances this advantage. Li-titanate (LTO) may have low capacity but this chemistry outlives most other batteries in terms of life span and also has the best cold temperature performance. Major disadvantage of Li-titanate (LTO) is the low specific energy and the extremely high cost. Lithium Cobalt Oxide (LCO) has a high specific energy, low cost and a moderate performance. However, it is highly unfavorable in all the other aspects as it has a low specific power, low safety, and a low lifespan.

Lithium-ion batteries offer significant advantages over other traditional battery chemistries such as lead acid, NiCd and NiMH:

- **Specific Energy (watt-hours/kg):** Lithium-ion batteries offer a much higher specific energy and capacity compared to other traditional batteries. Their low internal resistance makes a lithium-ion battery more suitable for high power applications.

- **Light Weight:** Lithium-ion batteries are one-third of the weight of lead acid batteries, and are smaller in size than other rechargeable batteries of similar capacity. Lithium-ion batteries are practical in applications in which physical specifications such as space, weight and total energy storage are considered important.

- **Faster Charging:** The lower internal resistance of the lithium-ion chemistries when compared to that of traditional batteries allows for charging with lower losses and heat gain. This advantage can result in faster overall charging times for batteries of comparable capacity, however a variety of factors influence the ultimate result. Some lithium-ion chemistries have symmetrical charge and discharge rates while others are asymmetrical with the discharge current several times that of the allowable charge current.

- **Self-discharge:** All batteries are subject to losses in the form of self-discharge, which can be an important issue for batteries where longer term energy storage is required. The self discharge rate for lithium-ion batteries is typically lower than that for other battery types and for other energy storage technologies.

- **Low Memory Effect:** Memory effect is a phenomenon observed in rechargeable batteries in which they lose their maximum energy capacity when repeatedly recharged after being only partially discharged. This memory effect is common in rechargeable batteries such as NiCd and NiMH. Lithium-ion batteries have little or no memory effect.

- **Low Maintenance:** Lithium-ion batteries typically require little maintenance, whereas lead acid batteries require maintenance every 3-6 months, and NiCd and NiMH batteries require a full discharge periodically so that they do not exhibit a memory effect. A process known as cell balancing is important to the deployment and efficient utilization of lithium-ion battery technologies. Although cell balancing is incorporated into the BMS and typically does not require operator intervention or supervision, it may potentially impact the availability of the battery system as cells must be off line during the rebalancing process. This loss of capacity may be an important factor depending upon the service involved.

- **Cycle Life:** The cycle life is much higher for lithium-ion batteries when compared with other traditional batteries. For lithium-ion batteries, the cycle life is impacted by the depth of discharge (DoD). A shallow DoD prolongs cycle life.
- **Cell Voltage:** : Lithium-ion cells have a chemistry that results in a higher open circuit voltage than traditional cells.
- **Flat Discharge:** Lithium-ion chemistries have a relatively flat discharge curve, consequently they are capable of delivering constant power at a relatively constant current for a large portion of their discharge curve.
- **Toxicity:** Lithium-ion batteries when disposed of are environmentally friendly compared to traditional batteries. The toxicity limits for lithium-ion batteries are low.

Figure 2.16 provides comparison on the energy and power density of different battery chemistries. It is apparent that lithiumion batteries have a higher energy density on a mass basis, as well as on volumetric basis than other battery types [10].

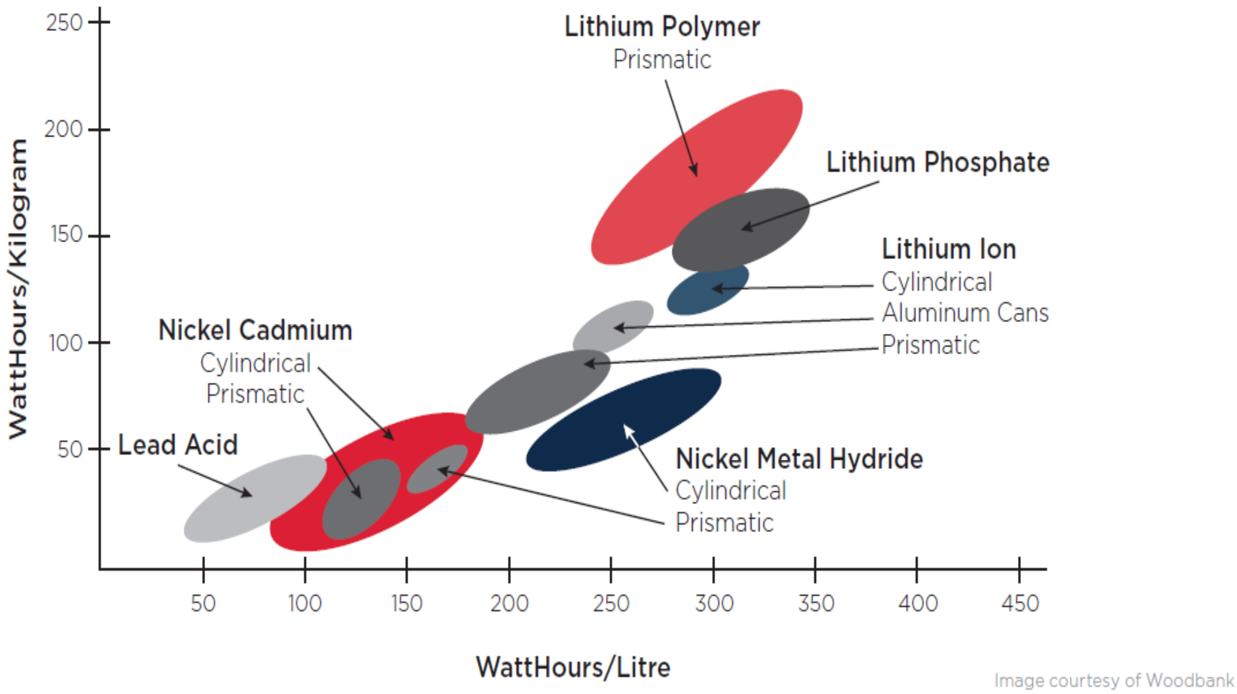


FIGURE 2.16: Energy Density Comparisons.

The maritime-focused systems have mainly been based on Li-ion cells with NMC (Nickel Manganese Cobalt Oxide) cathodes and graphite anodes. Systems based on iron-phosphate cathodes have also been used. Both the NMC and iron-phosphate chemistries represent a good compromise between the most important parameters of safety, energy, power density, cycle life and cost.

In future, we expect different types of Li-ion batteries to apply on maritime and industry systems, having better performance, safer functions and reliability, with respect to the environment. Such batteries are Lithium-air (Li-air), Lithium-metal (Li-metal) and Lithium-sulfur (Li-S), promising higher specific energy, better life cycle and lighter and smaller constructions. Thus, batteries will be cheaper with high performance, leading to an extremely developing use in marine applications and reducing the emissions in the environment.

Chapter 3

Legal and Regulatory Framework

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

The vessel under retrofit consideration of this dissertation must ensure the same safety and integrity level as before, when powered from conventional internal combustion engines. Battery safety has become a primary concern and potential competitive differentiator for all stake holders of battery powered and hybrid ships.

The technical design of the battery system and its arrangement in the vessel is described based on the "DNV-GL : Guideline for Large Maritime Battery Systems"[11] and on "ABS : Use Of Lithium Batteries in The Marine and Offshore Industries"[12]. These handbooks were chosen by the writer of the present disertation and the Supervisor J. Prousalidis in order to mention the most dangerous and vulnerable aspects of vessel's retrofit.

There has been a comparison between these regulations and the most important parts are presented, as part of the case study, to ensure safe operation of the vessel, normal operation of all main and auxiliary machines, and emergency issues.

3.1 Feasibility studies

It is recommended to undertake feasibility studies, before deciding to use a maritime battery system.

The purpose of the feasibility study is to evaluate alternative solutions as appropriate for the case considered. Expected operational modes and operational profiles, relevant load cycles, targeted system life etc. need to be considered in the feasibility studies. Evaluation of strengths and weaknesses (e.g. SWOT analyses) of alternative solutions with respect to technical issues, environmental aspects and economy are relevant in this phase. The results of the feasibility studies, which should include a rough sizing of the whole power system with related engines and batteries, will be used to determine whether the project should go ahead to the next phase.

Compared to traditional batteries with water based electrolytes such as lead acid and nickel cadmium batteries, lithium ion batteries have two to eight times as much energy per weight unit. The high energy density as well as the use of a flammable electrolyte makes a safe design more challenging. Lithium based battery systems depend on a well designed and tested electronic control system for safe operations.

3.2 Battery system

The battery system consists of one or more battery packs including all required systems for the intended purpose. This chapter outlines the recommendations made from the FMECA analysis for cells, modules, subpacks and packs. Figure 3.1 illustrates the battery system and sub-system definitions.

3.2.1 Cells

A cell is the smallest electro chemical unit.

3.2.1.1 Internal short circuit

Internal short-circuits have been a significant cause for thermal events. An internal short-circuit means that an electrically conducting bridge has been formed between the positive and the negative electrodes inside the battery cell. The majority of such

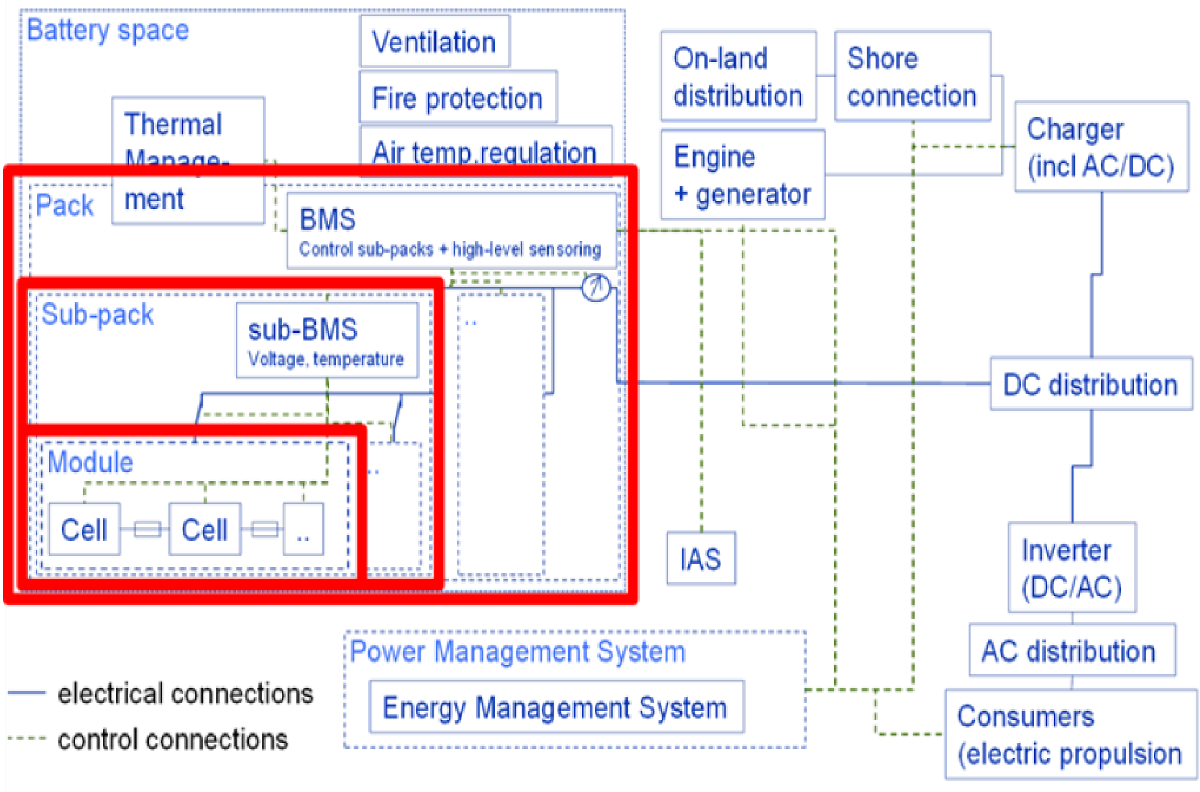


FIGURE 3.1: Battery System and related sub-systems.

internal-short-circuits do not result in a thermal event. A thermal event can happen if the impedance of the internal short-circuit is high enough to create sufficient heat, but low enough to allow sufficient current to pass and that the conductive bridge is strong enough to not break down when current is flowing. In addition, the heating must occur in a location where a high local temperature can induce chain reactions resulting in a cell thermal runaway. Cell level thermal events are usually impossible to foresee.

It is recommended that the manufacturer of a battery system shall monitor the battery cells regarding their self-discharge properties such that potential faults can be detected. A quality regime at the battery system manufacturer shall include rules and documentation with respect to internal short-circuit tolerance of the used cells, e.g. internal production quality documentation and nail test results.

3.2.1.2 High Impedance

To check the AC impedance of individual cells prior to assembly into battery modules, the standard method is to use a Milliohmmeter implementing a 1 kHz AC test signal for precise measurements of extremely low resistances (for instance Agilent 4338B

Milliohmmeter). This procedure is usually an inline test to check the supplier quality. It is important to keep in mind that this is an AC impedance test. For the usage of the batteries in a battery pack, the DC impedance is usually more important. The DC impedance will also DNV GL – 10/03/2014 No. 2013-1632, Rev. V1.0 – www.dnvgl.com Page 21 incorporate capacitive elements originating from electrochemical reactions and diffusion processes. Testing the DC impedance of at least modules prior to commencing usage of the battery system is necessary.

If a cell or cell connection has high impedance it will result in increased heat production during operation. If one cell is exposed to higher temperature, the impedance growth in this cell will be higher than the impedance growth for cells at a lower temperature. This generates a positive feedback effect with the potential to severely affect the life and performance of the battery pack. If the heat production is high enough this can also have severe safety implications since thermal events can be initiated.

The impedance in a cell or a group of cells can be calculated by Ohm's law by dividing the voltage by the current, provided the voltage and current are measured at the same time. Then the impedance of one group of cells can be compared to the impedance of another group of cells.

3.2.1.3 Electrolyte leakage

Leakage of electrolyte is a possibility, especially from pouch cells. Electrolyte can have a sweet smelling organic solvent odor. Electrolyte leakages are detected via electrical insulation measurements provided that the battery system insulation measurement strategy is designed to detect such leakages. In the case of undetected breaches in cell packaging, leaking and evaporating carbonate solvents can be detected with sensors sensitive to these species. Other detection methods can be increased self-discharge rate, loss of power, increased impedance, detection of organic compound fumes etc. In case of electrolyte leakage, the battery manufacturers MSDS should indicate methods for cleaning the spill. Pouch cells exposed to electrolyte should be permanently taken out of use as cells may have experienced damage that could be very difficult to detect.

3.2.2 Modules

A module is an assembly of cells including some level of electronic control.

3.2.2.1 Battery management system control failure

It is important to ensure that the High-level BMS can detect critical failures of Sub-BMS and switch off the related module/sub-packs.

3.2.2.2 Short circuits

Basic fusing strategy should follow a cascade, so that an external short circuit causes the main fuse to blow (component easiest to exchange).

- All fuses need to be tested and certified against maximum system voltage to avoid arcing.
- If a module or sub-pack does not have specific fusing capabilities, the supplier needs to demonstrate the safety by an external short circuit test at different voltages and temperatures (see available standards UL/UN transportation, IEC62281/1).
- In order to avoid short circuits, each exchangeable unit (module or sub-pack) must have preventive design measures against accidental shorts (screwdriver etc.) and intrusion of potential conductive particles.

3.2.2.3 Temperature sensor failure, voltage sensor failure

Voltage sensors to be installed for every cell or parallel cells in a series of connected cells.

- Temperature sensors must be placed in such a way that temperature differences between any cells exceeding 5^oC for more than 5 minutes are detected.
- The density of temperature sensors need to be high enough to enable safe battery pack operation, even with one failed sensor per battery module.
- To prevent safety or other critical issues, voltage sensors require some form of redundancy.
- Temperature sensors also need some redundancy with plausibility checks.
- If there is a failure in a voltage sensor, it is possible to further operate the battery pack provided that the cell voltage(s) for each of the cells with failed sensors can be calculated from other measurements (such as module level).

- The accuracy of the voltage measurement needs to take into account safety, energy content estimation and balancing requirements.
- Inadequate design and/or location of battery voltage or temperature sensor wires can pose a fire hazard. Such sensor wires should have a suitable cross section to avoid the possibility of excess heat buildup in case of a short circuit going through the sensor wires. In addition a proper separation of the different sense wires on the BMS is required.

3.2.2.4 Loss of cooling

It is recommended that the battery system shall be operable at minimum requested discharge rate (e.g. needed during limphome mode, steering speed) without external cooling in case the cooling system is needed under normal operation conditions.

3.2.3 Sub-packs

A sub-pack is an assembly of one or more modules. This is the smallest unit that can be electrically isolated. Depending on the system architecture, each sub-pack can have internal relays/contactors which can interrupt main power connection.

Recommendations:

The sub-pack architecture shall foresee, in case:

a) the sub-pack does not contain one or several relays: an exchangeable fuse and a main power connectors with a minimum rating of IP20 in state (touch proof).

b) the sub-packs does contain one or several relays: the main power con nectors shall have integrated High Voltage InterLock (HVIL) contact (last make/first break type contact) which opens the relay/relays.

Large plastic parts (above 200 g weight) should be material marked, e.g. CE mark ing.

All plastic parts within a battery system should preferably be of low-smoke zero halogen material (e.g. no PVC cable coating). Reference is made also to offshore material standards.

Unauthorized access to the internals of battery sub-packs must be inhibited as far as possible.

The main components of a battery system (e.g. sub-packs or control units) shall be protected against unauthorized mechanical access (e.g. by tamper-proof screws or crimp seals).

All components of the battery system shall be properly marked and reflect their specific danger potential. Relevant operators and personnel shall be trained accord ingly.

The responsible operator of a battery system shall have a competence requirement scheme for construction, operation and maintenance of the system.

The battery sub packs shall have sufficient protection mechanisms against intrusion by software and unwanted calibration access to the battery system.

The battery sub packs shall include contactors on both + and - sides. The rat ing of the contactors shall include sufficient margin with respect to the maximum expected current during normal operation.

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

The battery system shall be able to detect major and potentially dangerous connec tor high impedance and shall have implemented adequate warnings and/or failure messages for the rest of the system in case such failure is detected. Large impedance differences in parallel strings will cause different current distribution in the strings.

The battery system shall include segregation possibility of its cooling system in case of cooling medium leakage and given the medium is a liquid which imposes potential damage to the system or its environment.

3.2.4 Packs

A battery pack consists of one or more sub-packs that can work for the intended purpose as a standalone unit.

3.2.4.1 High level sensor failure

It is recommended that all battery related control systems shall have access to and make use of data from all relevant sensors included in the battery system which are important for critical controls.

3.2.4.2 Voltage and temperature imbalance

The principle behind a passive balancing system is that bleed resistors are used to remove energy from the cells with the highest state of charge. Usually the bleed resistors are activated only at high states of charge. With an active balancing system, energy is transferred from cells with high state of charge to cells with low state.

All cell voltages shall be monitored and the difference in cell voltage should not exceed a specified limit.

- For a fully balanced battery system, all cell voltages are within a specified limit.
- The available energy is limited by the cell with the lowest voltage. In an imbalanced system, this will cause reduced capacity.
- The SOH and SOC should be compensated to account for the capacity loss due to pack imbalance.

When temperature imbalance is considered, it is important to consider that virtually every battery control parameter is temperature dependent. Variation in temperature across the battery pack will therefore influence performance, safety and expected life time. Individual temperature difference should therefore be monitored. Usually the maximum cell to cell temperature difference is specified and it is often recommended that a maximum difference of 5 degrees Celsius should not be exceeded during normal operation.

3.2.4.3 Emergency shutdown

The battery system is to be fitted with an emergency shutdown mechanism adjacent to, but outside of the battery space. The emergency shutdown circuit is to be hardwired and independent of any control, monitoring, and alarm system circuits. If the battery system is used to provide power for propulsion of the asset, there should be an additional emergency shutdown arrangement on the navigation bridge and the centralized control station (CCS) or enclosed operating station (EOS).

3.3 Battery system design

3.3.1 Design and procurement

When the ship building contract is signed, the responsibility and further design work is normally transferred to the yard. The yard prepares procurement packs for the various system components. It is recommended that potential battery providers are consulted at this phase.

Main priorities for a battery system for maritime applications are safety, reliability and sufficient life for the system to be economically feasible. All components in the battery systems must be of good quality to secure a safe and reliable system. The integration and testing of the complete battery system is of similar importance as the quality of its single components. It is recommended that a safety assessment of the battery space is initiated in the design phase.

It is crucial to fully understand the duty cycles of the application as well as understanding the key requirements of the application for battery selection and optimum performance.

3.3.1.1 Li-ion battery cells

Li-ion based systems require that the voltage, current and temperature of each single cell in the system is monitored at all times. The voltage and current limits are temperature dependent. A proper system design requires that proper action can be taken if cell parameters are outside the manufacturer's recommendation. To decrease system complexity, temperature monitoring can include some predicted values based on measurements for a group of cells. We recommend redundancy in systems when predictive or correlated temperature measurements are used. Cells connected in parallel will have the same voltage and cells connected in series the same current.

There are a large number of manufacturers of different variants of Li-ion cells. Cell chemistries are optimized for different applications. In some applications the main focus is on high energy density and low cost. For other applications a very stable chemistry and long life is the main focus. Other applications can have a focus on power capabilities for charge or discharge or the ability to accept high current pulses for charge and discharge.

There is disparity in product quality between cell manufacturers. Automated production, proper process control, and robust cell design are all crucial elements to ensure good battery cell quality. It is important to base the battery pack on cells with equal properties since the system has to be designed with the weakest cell in mind. Cells with a large variation in properties will mandate overdesign for portions of the battery system and make cell balancing more challenging.

For maritime applications it is important to choose a cell with properties that can provide an optimum combination of safety, life, performance and cost for the application in question. A thorough understanding of all these aspects is required by the team doing the battery system design. To ensure this understanding, independent cell testing or advice from independent third parties who have done neutral testing may be required. See Appendix D for further input on cell testing.

3.3.1.2 Electrical system

When the cells are assembled into modules, custom supportive materials are added around the cells. The thermal management system, which could be based on either passive cooling or active cooling with air or liquid, is installed and the cells are electrically connected in the specified configuration. The battery cell terminals may either be of a screw type, welded or clamped.

The modules are connected into sub-packs. The sub-packs (or modules if there are no sub-packs) are connected into strings and a number of parallel strings makes the battery pack. A battery system may consist of one or more packs. The electrical connections between the different aggregate levels of the battery system may be connected using cables, bus bars or a combination of these. Low contact impedance for the electrical connections is crucial to avoid over-heating and control the fire risk, as well as maximum efficiency. Several parallel strings will decrease the risk of overheating from increased contact impedance. DNV GL – 10/03/2014 No. 2013-1632, Rev. V1.0 – www.dnvgl.com Page 8 can also ease the detection of elevated levels of contact impedance in the electrical connections resulting in increased safety of the system.

Electrical protections, such as fuses and contactors, should be present at multiple levels within the battery, such as within each module or at the string level. Other key components electrical system on string level are contactors, fuses, current sensors, pre-charge circuits and service disconnect breakers. It is recommended that each battery string has a separate current sensor in order to detect increased impedance that can lead to overheating.

The electrical connections between the different aggregate levels of the battery system may be connected using cables, bus bars or a combination of these. Low contact impedance for the electrical connections is important to avoid over-heating and control the fire risk, as well as maximum efficiency. Several parallel strings will decrease the risk of overheating from increased contact impedance. It can also ease the detection of elevated levels of contact impedance in the electrical connections resulting in increased safety of the system.

Battery systems generate and store Direct Current (DC) electricity at a voltage level that will change as the battery operates. Power converters are necessary to interface this electricity with the ship power distribution system. In the case of a DC distribution system being used on the ship, a DC-DC converter (or 'chopper') will typically be used to control voltage levels. This can also be done at the pack or module level to produce some advantages. In the case of an Alternating Current (AC) ship power distribution system, a bi-directional inverter must be used to convert the DC electricity from the battery. In these AC arrangements it is also advantageous to have a voltage transformer on the battery interconnection. Power electronic components are expensive and will also have losses and thus these losses should be considered at an early stage of designing the system.

The power converter, whether DC or AC, is responsible for the majority of battery control with regard to orchestrating charging and discharging operations. The ship Power Management System (PMS) interfaces with the battery through the power converter to command charge or discharge functions. Information from the battery, such as status, SOC, and available power level, is calculated and transmitted by the Battery Management System to the PMS. The PMS then evaluates system load, operational criteria, battery status and input from personnel to make decisions regarding what the power generating equipment should do. The PMS also presents available power and energy levels to crew. It is important that the BMS and PMS systems are well integrated, both in terms of software and hardware.

3.3.1.3 Electronic control system

The electronic control system is frequently referred to as the Battery Management System (BMS). Voltage and temperature sensors are usually part of the module. It is recommended to consider some level of redundancy for these fundamental measurements, depending on the safety criticality of the system. The module may also include an electronic circuit board that controls the cells in the module via continuous checks and assessments. A key principle when locating sensors is to make the system in such a way that malfunctioning sensors may be detected. The module level BMS is part of the total battery electronic system. The system may include additional sensor inputs such as current sensors and additional temperature sensors as well as other system specific sensors. It is recommended that each battery string has a separate current sensor in order to detect increased impedance that can lead to overheating. In addition, for systems containing a large number of strings, a group of strings can have a common current sensor. A “Master-BMS” usually controls the assembled battery system and communicates with the external power management system. It is crucial to ensure that the communication between the master BMS and the power management system for the actual application is properly specified for normal operation as well as for situations where a problem has occurred.

If a problem occurs in a battery system it may either be due to components or manufacturing failures. Software faults or inadequacies can also be a major source of problems. For problem solving and fault analyses it is important that all critical components in a battery system can be identified. All software and firmware version numbers and settings must be tracked. All critical components should have their unique number which should be traceable from the manufacturer of the component to final installation in a battery pack. The pack supplier should administer the database identifying the components used for the different modules and packs.

3.3.2 Design and construction

Recommendations for the design and construction of battery system and battery modules:

3.3.2.1 General

i) The exposed battery casing (for cells and modules) is to be constructed of durable, flame-retardant, moisture resistant materials, which are not subject to deterioration in the marine environment and at the temperature to which it is likely to be exposed.

ii) The battery module enclosures are to have a degree of protection not lower than IP44.

iii) The battery system is to be fitted with an emergency shutdown mechanism adjacent to, but outside of the battery space. The emergency shutdown circuit is to be hardwired and independent of any control, monitoring, and alarm system circuits. If the battery system is used to provide power for propulsion of the asset, there should be an additional emergency shutdown arrangement on the navigation bridge and the centralized control station (CCS) or enclosed operating station (EOS).

iv) If the battery system is to be used as part of the emergency source of electrical power, it is not to be installed in the same space as the emergency switchboard. If the battery bank is used in conjunction with an emergency power source (e.g., emergency diesel generator), it should not be located in same space as the emergency power source. Both spaces are to be readily accessible and as near as practical.

v) Battery cells of different physical characteristics, chemistries, and electrical parameters are not to be used in the same electrical circuit. vi) The battery system is to have means by which it can be electrically isolated for maintenance purposes. This isolation mechanism is to be independent of the emergency shutdown arrangement.

vii) The casing of a cell, module, battery pack, and battery systems are to be provided with a pressure-relief mechanism/arrangement to prevent rupture or explosion. The individual modules are also to have arrangements to prevent spilling of electrolyte.

viii) All outgoing circuits of the battery system are to be protected against overload and short-circuit, excluding the emergency batteries used for engine starting.

3.3.2.2 Control, Monitoring, Alarm and Safety Systems

i) Control, monitoring, and safety systems are to have self-check facilities. In the event of failure to the systems or power supply, an alarm is to be activated.

ii) The safety system is to be designed so as to limit the consequence of failures. It is to be constructed on the fail-safe principle.

iii) Sensors for safety functions are to be independent from sensors used for other purposes (e.g., for alarm system).

iv) The sensors are to be designed to withstand the local environment. The enclosure of the sensor and the cable entry are to be appropriate to the space in which they are located. Any malfunctioning in the sensors is to be detectable.

3.3.2.3 Battery chargers

i) Battery chargers used for essential, emergency, and transitional sources of power are to meet the requirements specified in 4-8-3/5.9 of the Steel Vessel Rules, as applicable.

ii) The battery charger is to operate within the limits (i.e., charging and discharging) set in the BMS as specified by the battery cell manufacturer.

iii) The battery charger is to be designed to maintain charging within the voltage, current, and temperature limit for the battery as specified by the battery cell manufacturer.

iv) The battery charger is to be interfaced with and controlled by the BMS.

3.4 Battery space

The battery space is the physical installation room including walls, floor, ceiling, and all functions and components which contribute to keep the battery system in the defined space at a specified set of environmental conditions (e.g. temperature or moisture level). Guidelines for large maritime battery sysyems propose a number of construction and installation instructions:

i) Battery spaces are not to be located forward of the collision bulkhead of the vessel. Special cases may be considered for powering loads located forward of collision bulkhead.

ii) Battery spaces are not to contain any heat sources or high fire risk objects.

iii) Battery spaces are not to contain any equipment (including cables and pipes) supporting essential services as defined in 4-8-1/7.3.3 of the Steel Vessel Rules or 4-1-1/3.5 of the MODU Rules, so as to prevent loss of such essential services in the event of an incident such as thermal runaway.
Note: This requirement does not apply to cables supplying power to and from the battery system itself.

iv) The rated capacity of the battery system is to be determined for the ambient temperature conditions in 4-1-1/Table 8 of the Steel Vessel Rules or 4-1-1/Table 2 of the

MODU Rules. Where the expected ambient temperatures are different from those in the applicable table, the rating of the battery system is to be based on the actual ambient temperature.

v) If the battery system is installed in an environmentally controlled space, the applicable requirements in 4-8-3/1.17.2 of the Steel Vessel Rules or 4-3-1/17.3.1 of the MODU Rules are to be complied with.

vi) High ambient temperature in the battery space is to be monitored and alarmed at a continuously manned location.

vii) The battery space is to be installed with appropriate means to vent gases, which may be generated during an abnormal situation, from the battery space to open deck.

viii) The Battery System location and arrangement plan should clearly show the battery pack with respect to the space it is being installed in as well as the clearance of distances between any other equipment in the room and the battery pack.

ix) Battery spaces are to be mechanically ventilated and discharges from the exhaust fans are to be led to a place on the open deck where such discharges will not cause a fire or explosion hazard or toxic hazard to nearby personnel. The ventilation of the battery space is to have sufficient capacity to minimize the possibility of accumulation of flammable vapors, especially during an abnormal condition. Refer to 4-8-4/5.3.1(b) of the Steel Vessel Rules or 4-3-3/3.7.3(a) of the MODU Rules for ventilation system requirements for the battery space. The ventilation ducting for the battery space is to be separate from the HVAC systems used to ventilate other spaces on the vessel.

x) The battery space is to be fitted with flammable gas detection, appropriate to the battery chemistry being used. The gas detection is to give an alarm at a continuously manned location and automatically disconnect the battery system if the concentration of gas in the battery space reaches 30% LEL.

3.4.1 Ventilation and accumulation of flammable gases

It is necessary to ensure proper detection of gases that may be emitted from the battery system in the event of a serious fault conditioning, relief and ventilation to prevent the formation of explosive atmospheres. Design therefore needs to consider realistic parameters for the battery system under consideration. This includes flammable gases from decomposition of the electrolyte due to temperature rise in a cell, in addition to hydrogen and other gases that can be created via electrolysis or other processes in case water comes in contact with the battery electrical systems.

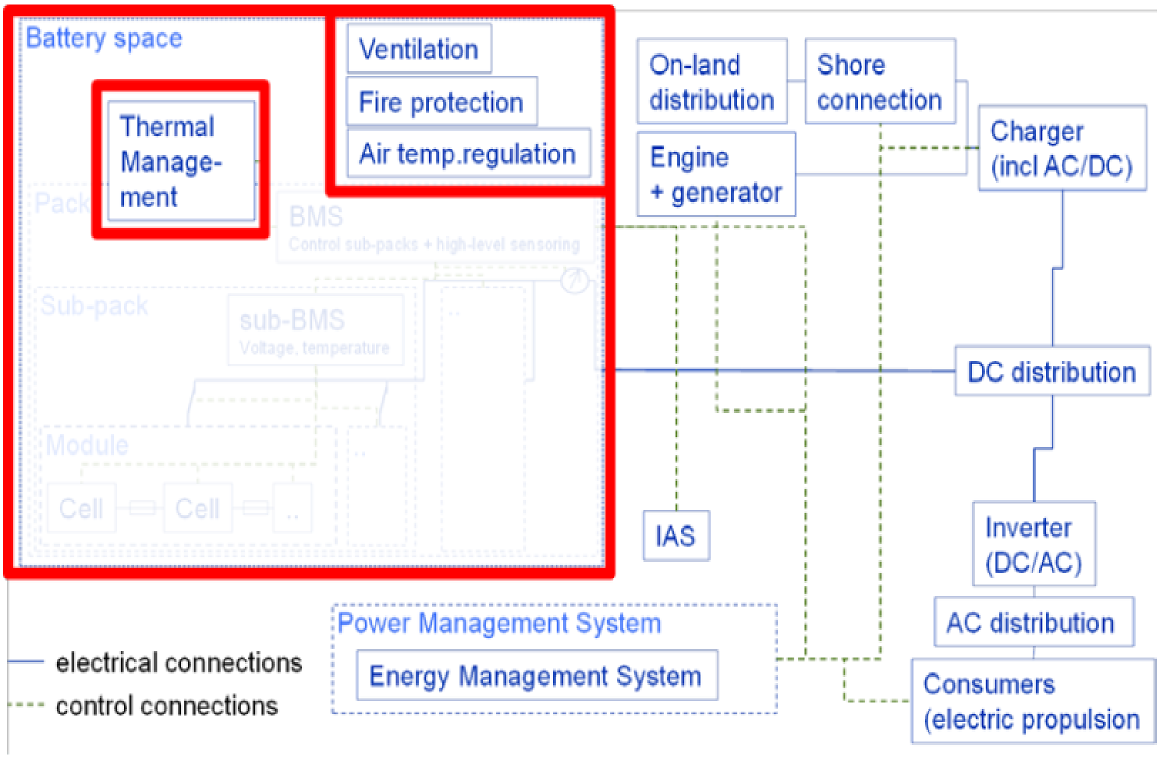


FIGURE 3.2: Illustration of Battery Space.

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

3.4.2 Fire protection

As far as the fire protection of battery space is concerned, it has to be considered as an Auxiliary Machinery Space or a Machinery Space other than category A as defined in SOLAS Regulation II-2 and is subject to the structural fire protection requirements listed therein.

The battery space is to be fitted with a suitable Fixed Fire Extinguishing System (FFES) recommended by the vendor and appropriate to the battery chemistry used. A fixed system is to have provisions (i.e., selection of proper metallic material for nozzles, grounding methods) to prevent a buildup of static electricity at nozzle during release of extinguishing agent. The FFES is to comply with the provisions of Part 4, Chapter 7 of the Steel Vessel Rules or Part 5 of the MODU Rules, to the extent applicable, and is to adequately consider the potential fire loads involved (e.g., size of the batteries, battery chemistry used, specific materials involved, etc.). Technical validation of the system is to be carried out in accordance with the procedures outlined in the ABS Guidance Notes on Alternative Design and Arrangements for Fire Safety and sufficient documentation to verify the same is to be submitted along with arrangements and details of the system for review.

Portable fire extinguishers are to be provided as required in 4-7-2/1.7 of the Steel Vessel Rules or 5-2-4/1 of the MODU Rules.

The battery space is to be provided with fume-tight door to prevent escape of combustible gasses, deck drain, and not to be adjacent to spaces with combustible/flammable materials, berthing compartments, or machinery spaces of Category A except for emergency generator starting batteries located in an adjacent space to the emergency generator.

With respect to rooms adjacent to the battery space, normal good quality fire detection and fire extinguishing should be sufficient in order to prevent a fire spreading from adjacent rooms to the battery space. It is recommended to check the relevant external fire scenarios and whether the segregation from the battery space is sufficient to maintain the required integrity.

With respect to thermal events originating in the battery space, early detection and increased cooling power will help to keep any fire under control.

The following safety strategy with respect to a battery fire is anticipated:

- Electrical and thermal control through BMS without option for manual override of safety functions.
- Cell thermal runaway shall be kept confined at lowest possible level, therefore:

a) The design of a module/sub-pack shall inhibit propagation from cell to cell.

b) If 2a) cannot be guaranteed, the module/sub-pack outer surface shall not exceed a critical temperature level of approx. 130 ^oC during a thermal event. No flames shall be visible

c) If 2b) cannot be guaranteed, the battery space must inhibit propagation between modules/subpacks as well as surrounding materials catching fire.

- Fire within several sub-packs must be assumed to be out of control. Vessel evacuation cannot be excluded.

Strategy with respect to fire outside the battery space:

- Any fire shall not lead to temperature above 70^oC within battery modules for more than 30 min.
- If the cell temperature has exceeded the battery manufacturer's maximum temperature, the battery system needs to be re-certified by the battery supplier before it can be put back into use.
- Fire classes applied on walls, doors etc. shall protect the battery system, e.g. by A60 fire separation, which indicates the duration the doors and walls must be able to withstand a given type of fire.
- If possible, decrease SOC to reduce the risk for a thermal event in the battery system.

It is recommended that the maximum cell temperatures over lifetime shall be monitored. This gives an indication on whether the system can be used further or needs exchange after a critical fault involving high temperatures.

The responsible operators for a battery system shall have sufficient training to be able to decide when and in which catses the fire extinguishing in the battery space shall be deactivated.

3.5 Battery management system (BMS)

The battery system is to have a Battery Management System (BMS). The BMS is to comply with the requirements in Section 4-9-3 of the Steel Vessel Rules. Appropriate computer-based system category for BMS is to be assigned in accordance with 4-9-3/7 of the Steel Vessel Rules. The BMS is to be considered as a computer-based system with system Category II or III. The exact category is dependent on the risk assessment for all operational scenarios (e.g., intended use for battery system, etc.). The relevant software design requirements and ABS Surveyor witness requirements for Category II or III systems are to be complied with.

The BMS is to, at a minimum, monitor the battery cell voltage, cell temperature, and battery string current and is to be continuously powered and an alarm is to be given in the event of failure of the normal power supply.

The following conditions are to result in an individual or group audible and visual alarm to be displayed in a continuously manned location:

- Cell overvoltage
- Cell undervoltage
- Cell voltage unbalance
- Cell over-temperature
- Battery module/pack ground fault
- Failure of communication with asset's Power Management System (PMS)
- Tripping of mechanism that provides electrical isolation
- Failure/shutdown of the battery system or failure of any of the individual modules

The safety system is to be activated automatically in the event of identified conditions that could lead to damage of the lithium battery system. Activation of any automatic safety actions is to activate an alarm in a continuously manned location.

A software-based feature/mechanism is to be installed to prevent the crew from overriding or ignoring critical BMS system alarms and shutdown. Manual override of safety functions is not permitted.

More information about BMS are being provided in previous section 3.3.1.3 of Electronic Control System.

3.6 Installation and commissioning

The Battery System installation and sea-trial/commissioning procedures submitted for review is to address the following:

- Testing of the following safety functions and associated alarms: cell balancing detection/protection, overvoltage detection/protection, undervoltage detection/protection, emergency shutdown arrangement, ground fault detection, loss of communication detection/protection.
- Testing of the expected performance functions of the battery system on the particular asset.
- Testing of protective functions in the battery space, as applicable to asset specific installation. iv) Correct interface between the battery system and the DC-bus or battery charger, as applicable.

3.7 Operation and maintenance

The Battery System Operations and Maintenance manual submitted for review is to address normal and emergency operating procedures and maintenance procedures for the use of the battery system. The emergency procedures are to include those that should be taken in events such as fires, overheated batteries, etc. A Battery System maintenance schedule is to be provided for review and maintained on board, providing information on:

- Load profiles
- Charging procedure
- Normal operation procedures of the battery system included minimum levels of battery capacity
- Emergency operation procedures of the battery system
- Estimated battery deterioration (ageing) rate curves
- Operating instructions for normal and degraded operating modes

- Details of the user interface
- Transfer of control (if more than one control station, or local control are implemented)
- Test facilities
- Failure detection and identification facilities, automatic and manual
- Data security
- Access restrictions
- Special areas requiring user attention
- Procedures for start-up
- Procedures for restoration of functions
- Procedures for data back-up where applicable

A plan for systematic maintenance and function testing shall be kept on-board including:

- Verification of the SOH (remaining lifetime of the batteries).
- Test of all instrumentation, automation and control systems affecting the battery system
- Test intervals to reflect the consequences of failure involving a particular system. Functional testing of critical alarms should not exceed 3 month intervals. For non-critical alarms, the longest intervals are normally not to surpass 12 months
- Acceptance criteria
- Fault identification and repair
- List of the supplier's service net

3.8 Buttery system testing for maritime applications

Investigation of battery suitability should minimize the testing required to create a dataset that can be used to assess and determine the risks that will threaten battery performance in its intended application. The maritime market represents a new battery application that may involve conditions or intended uses that provide exceptions to traditional automotive practices, which have informed much of battery testing procedures to date. The purpose of risk based testing is not necessarily to characterize the battery in detail, but to assess the effect of environment or duty cycle on lifetime and throughput and assign risks to that performance.

Battery system(s) testing are to follow the approved sea trial/commissioning procedures and are to include at least the following items:

- Visual inspection
- Operational tests
- Tests of all the alarms and safety functions
- Emergency shutdown operation
- Fire protection systems
- Fire and Gas detection systems
- Simulation of communication failure
- Correct operation of ventilation, cooling, gas detection system, fire detection system, fire extinguishing system, etc., where provided

The following tables show examples for the range of test procedures which can be applied to a battery system for maritime applications by the battery system manufacturer. For more tests see Appendix A . The tests are distinguished between TT (Type Test) and RT (Routine Test). The definitions are as follows:

- Type Test (TT): Conformity test made on one or more items representative of the production.
- Routine Test (RT): Conformity test made on each individual item during or after production.

No.	*Test*	*Type Test*	*Routine Test*	*Reference*
1	External short-circuit test	x		IEC 62619 7.2.1
2	Impact test	x		IEC 62619 7.2.2
3	Drop test	x		IEC 62619 7.2.3
4	Thermal abuse test	x		IEC 62619 7.2.4
5	Overcharge test	x		IEC 62619 7.2.5
6	Forced discharge test	x		IEC 62619 7.2.6
7	Internal short-circuit test/Propagation test	x		IEC 62619 7.3.2/7.3.3
8	Overcharge control of voltage	x		IEC 62619 8.2.2
9	Overcharge control of current	x		IEC 62619 8.2.3
10	Overheating control	x		IEC 62619 8.2.4
11	Battery system/BMS safety function tests		x	Section 2/5
12	Type tests for control, monitoring and safety equipment	x		4-9-8/Table 1 of the *Steel Vessel Rules*
13	Unit Certification tests for control, monitoring and safety equipment.		x	4-9-8/Table 2 of the *Steel Vessel Rules*

Note: Battery systems may comply with requirements in an alternative standard provided it has been determined by ABS as being not less effective. Where applicable, requirements may be imposed by ABS in addition to those in the alternative standard so that the intent of the Rules is met.

Table 3.1: Type and Routine Tests.

Chapter 4

Emissions and Air Pollution

International shipping is relatively efficient when compared to other modes of transport in terms of emissions footprint per amount of transport work, however environmental pollution caused by maritime transportation is increasing due to its rapid development. Currently, the international maritime transport is responsible for not more than 11% of the green house gasses (GHG) produced by all transport sectors. Still, shipping GHG emissions are significant (over one million CO2 per year in absolute figures) and tend to rise owing to an anticipated expansion of global trade in the future (ICCT, 2013). Studies show that in a business as usual scenario, shipping GHG emissions are expected to double or even triple until 2050 (Buhaug et al., 2009) [13].

NO_X: are outcome of the combustion process in diesel engines. Marine fuel's quality depends from its content of sulphur. The combustion of sulphur-containing fuel leads to SO2 emissions.

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

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

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

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

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

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

The contribution of shipping to air pollution is al-so significant due to the high energy demands and usage of low quality marine fuels which result in significant amounts of dominant air emissions such as sulphur oxides (SO_X), nitrogen oxides (NO_X) and particulate matter (PM). Hence, since the 70% of global shipping emissions occur within a distance of 400 km from land (Endresen et al., 2003) ships are potentially important contributors to air pollution impacts.

4.1 Climate and environment

Air pollution and climate change are intertwined. Several air pollutants are also climate forcers, which have a potential impact on climate and global warming in the short term (i.e. decades). Tropospheric O_3 and black carbon (BC), a constituent of PM, are examples of air pollutants that are short-lived climate forcers and that contribute directly to global warming. Other PM components, such as organic carbon (OC), ammonium ($NH_{4\,+}$), sulphate ($SO_{4\,2-}$) and nitrate ($NO_{3\,-}$), have a cooling effect. In addition, changes in weather patterns due to climate change may change the transport, dispersion, deposition and formation of air pollutants in the atmosphere.

As far as the climate has dirrect connection with the environment, air pollution has several important environmental impacts and may directly affect vegetation, as well as the quality of water and soil and the ecosystem services that they support. Ground-level ozone (O_3) damages agricultural crops, forests and plants by reducing their growth rates. Other pollutants, such as nitrogen oxides (NO_X, the sum of nitrogen monoxide (NO) and nitrogen dioxide (NO_2)), sulphur dioxide (SO_2) and ammonia (NH_3), contribute to the acidification of soil, lakes and rivers, causing biodiversity loss. In addition to causing acidification, NH_3 and NO_X emissions also disrupt terrestrial and aquatic ecosystems by introducing excessive amounts of nutrient nitrogen. This leads to eutrophication, which is an oversupply of nutrients that can lead to changes in species diversity and to invasions of new species.

The overall impacts of (any) emissions on climate are complex, and are summarized conceptually for the shipping sector in Figure 4.1. Emissions give rise to changes in the abundance of trace species in the atmosphere. Through atmospheric processes, these emission species may undergo atmospheric reactions, alter microphysical processes or be absorbed/removed by various sinks (land and water surfaces) through wet and dry deposition. These changes may then affect the radiative balance of the atmosphere through changes in the abundance of trace species, in atmospheric composition, and in the properties of clouds and aerosols. Such changes in radiative forcing may then affect climate in a variety of ways, e.g., global and local mean surface temperature, sea level, changes in precipitation, snow and ice cover, etc. In turn, these physical impacts have societal impacts through their effects on agriculture, forestry, energy production, etc. Ultimately, all of these effects have a social cost, which can be very difficult to quantify. Clearly, as one steps through these impacts, they become more relevant but correspondingly more complex and uncertain in quantitative terms [14].

4.2 Human

Air pollution is a major concern of new world, which has a serious toxicological impact on human health. It has a number of different emission sources, but transportations and industrial processes contribute the major part of air pollution. According to the World Health Organization, six major air pollutants include particle pollution, ground-level ozone, carbon monoxide, sulfur oxides, nitrogen oxides, and lead. Long and short term exposure to air suspended toxicants has a different toxicological impact on human including respiratory and cardiovascular diseases and long-term chronic diseases such as cancer [15].

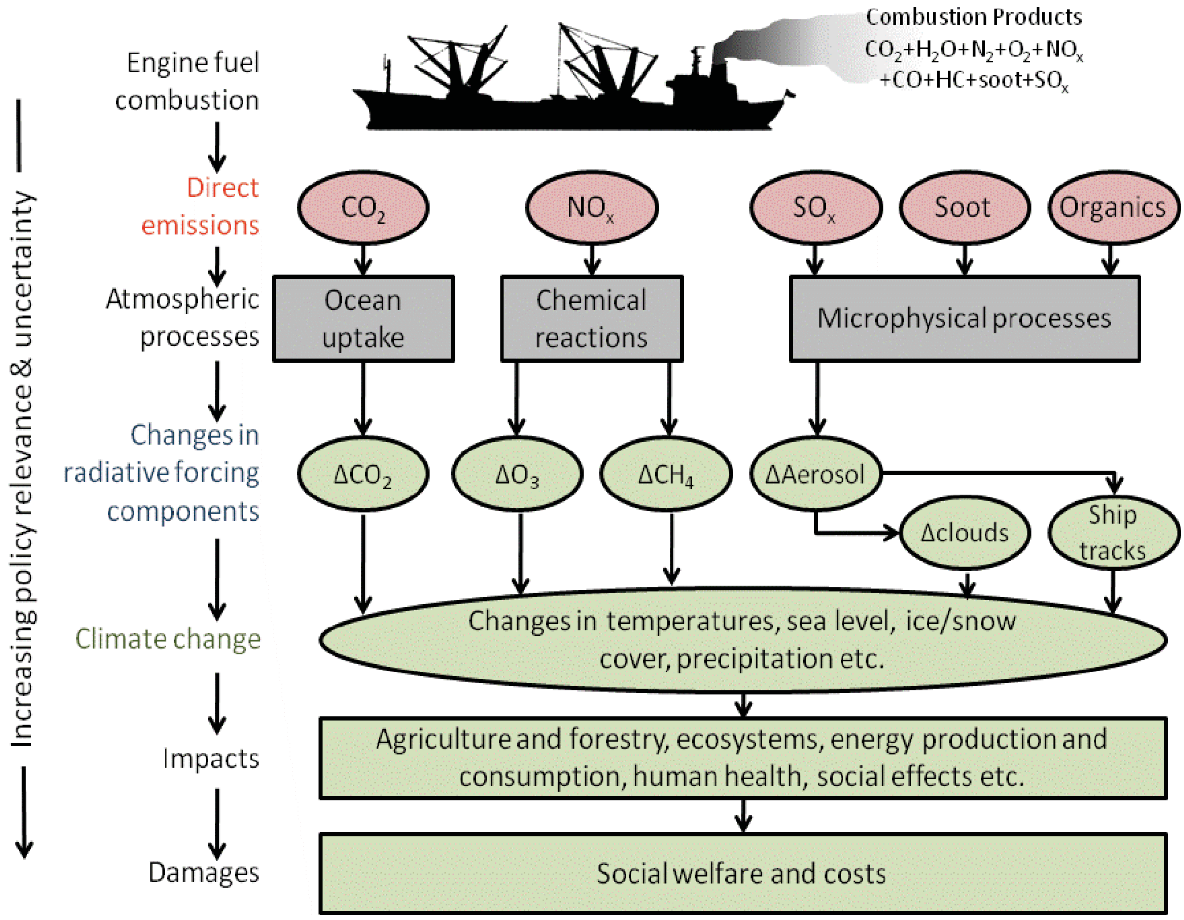


FIGURE 4.1: Schematic diagram of the overall impacts of emissions from the shipping sector on climate change (from Lee et al., 2009a).

Several reports have revealed the direct association between exposure to the poor air quality and increasing rate of morbidity and mortality mostly due to cardiovascular and respiratory diseases. Mortality reflects reduction of life expectancy attributed to premature deaths due to air pollution, while morbidity relates to occurrences of illness and years lived with a disease or disability that may require hospitalization.

Air pollution is considered as the major environmental risk factor in the incidence and progression of some diseases such as asthma, lung cancer, ventricular hypertrophy, Alzheimer's and Parkinson's diseases, psychological complications, autism, retinopathy, fetal growth, and low birth weight

Common organs and bodily functions that can be harmed are [16]:

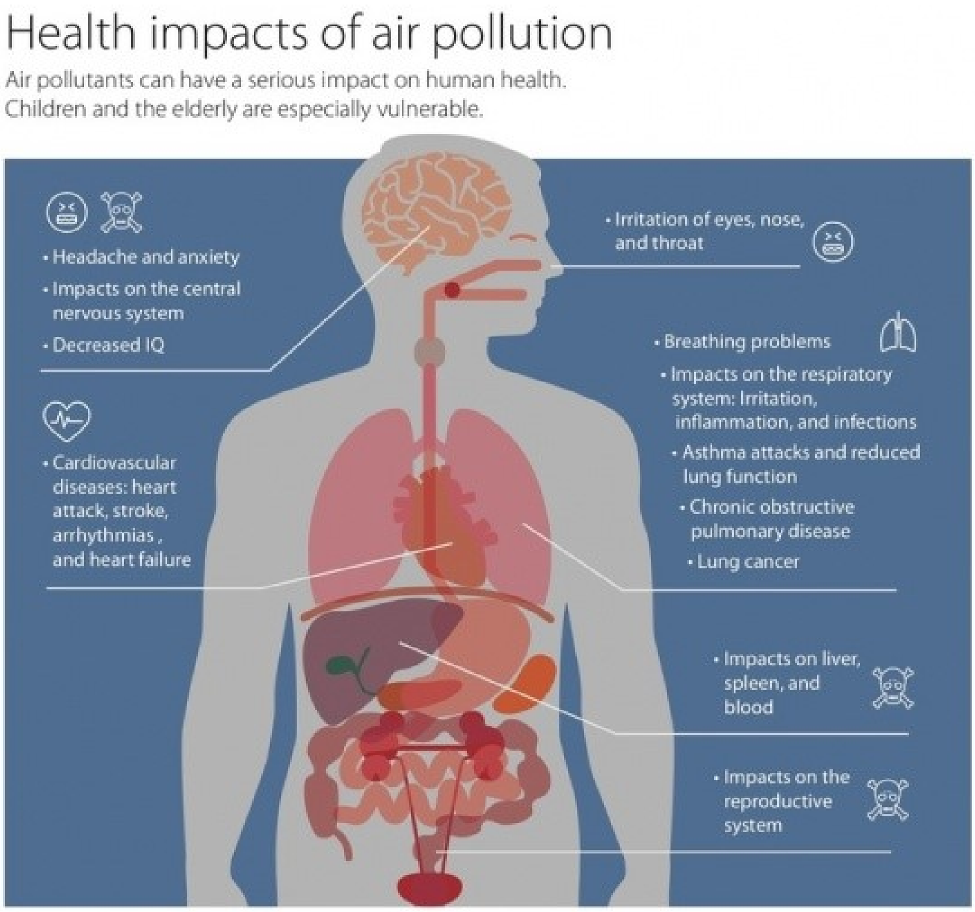


FIGURE 4.2: Impacts of air pollution on human health.

- Respiratory system
- Cardiovascular damage
- Fatigue, headaches and anxiety
- Irritation of the eyes, nose and throat
- Damage to reproductive organs
- Harm to the liver, spleen and blood
- Nervous system damage
- Urinary system
- Digestive system
- Neuropsychiatric complications

It is without any doubt that air pollution is a major threat to humans. Exposure to air pollution is now considered by the World Health Organization (WHO). Ships emit considerable amounts of pollutants, not only when sailing, but also during their stay in ports. This is of particular importance for harbor cities because ship emissions contribute to all these problems mentioned on human health, in addition to the environment. The International Maritime Organisation has settle rules for low ship's emissions in ports and near specific coast lines, trying to protect human health and environment.

4.3 Economic impacts

The effects of air pollution on health, crops and forests yields, ecosystems, the climate and the built environmental also entail considerable market and non-market costs. The market costs of air pollution include reduced labor productivity, additional health expenditure, and crop and forest yield losses. The Organisation for Economic Cooperation and Development (OECD) projects these costs to reach about 2% of European gross domestic product (GDP) in 2060 (OECD, 2016), leading to a reduction in capital accumulation and a slowdown in economic growth [17].

Non-market costs (also referred to as welfare costs) are those associated with increased mortality and morbidity (illness causing, for example, pain and suffering), degradation of air and water quality and consequently ecosystems health, as well as climate change.

The European Commission estimated that total health-related external costs in 2010 were in the range of EUR 330–940 billion, including direct economic damages of EUR 15 billion from lost work days, EUR 4 billion from healthcare costs, EUR 3 billion from crop yield loss and EUR 1 billion from damage to buildings (European Commission, 2013a).

The potential total economic consequences of both market and non-market impacts of ambient air pollution are very significant and underscore the need for strong policy action.

4.4 Prevention of air pollution from ships

4.4.1 Emission control areas and Tier I-III standards

Although air pollution from ships does not have the direct cause and effect associated with, for example, an oil spill incident, it causes a cumulative effect that contributes to the overall air quality problems encountered by populations in many areas, and also affects the natural environment, such as tough acid rain.

The potential total economic consequences of both market and non-market impacts of ambient air pollution are very significant and underscore the need for strong policy action.

IMO ship pollution rules are contained in the "International Convention on the Prevention of Pollution from Ships", known as MARPOL 73/78, including Annex VI titled "Regulations for the Prevention of Air Pollution from Ships". It was first adopted in 1997 and limits the main air pollutants contained in ships exhaust gas, including sulphur oxides (SO_x) and nitrous oxides (NO_x), and prohibits deliberate emissions of ozone depleting substances (ODS). MARPOL Annex VI also regulates shipboard incineration, and the emissions of volatile organic compounds (VOC) from tankers.

The IMO emission standards are commonly referred to as Tier I-III standards. The Tier I standards were defined in the 1997 version of Annex VI, Protocol (Tier I)—The "1997 Protocol" to MARPOL, which includes Annex VI, becomes effective 12 months after being accepted by 15 States with not less than 50% of world merchant shipping tonnage. On 18 May 2004, Samoa deposited its ratification as the 15th State (joining Bahamas, Bangladesh, Barbados, Denmark, Germany, Greece, Liberia, Marshal Islands, Norway, Panama, Singapore, Spain, Sweden, and Vanuatu). At that date, Annex VI was ratified by States with 54.57% of world merchant shipping tonnage. Accordingly, Annex VI entered into force on 19 May 2005 [18].

Following entry into force of MARPOL Annex VI on 19 May 2005, the Marine Environment Protection Committee (MEPC), at its 53rd session (July 2005), agreed to revise MARPOL Annex VI with the aim of significantly strengthening the emission limits in light of technological improvements and implementation experience. As a result of three years examination, MEPC 58 (October 2008) adopted the revised MARPOL Annex VI and the associated NOx Technical Code 2008, which entered into force on 1 July 2010.

The main changes to MARPOL Annex VI are a progressive reduction globally in emissions of SO_x, NO_x and particulate matter and the introduction of emission control areas (ECAs) to reduce emissions of those air pollutants further in designated sea areas.

Under the revised MARPOL Annex VI, the global sulphur cap will be reduced from current 3.50% to 0.50%, effective from 1 January 2020, subject to a feasibility review to be completed no later than 2018.

MEPC 70 (October 2016) considered an assessment of fuel oil availability to inform the decision to be taken by the Parties to MARPOL Annex VI, and decided that the fuel oil standard (0.50% sulphur limit) shall become effective on 1 January 2020.

The limits applicable in ECAs for SO_x and particulate matter were reduced to 0.10%, from 1 January 2015.

Progressive reductions in NO_x emissions from marine diesel engines installed on ships are also included, with a "Tier II" emission limit for engines installed on a ship constructed on or after 1 January 2011; and a more stringent "Tier III" emission limit for engines installed on a ship constructed on or after 1 January 2016 operating in ECAs (North American Emission Control Area and the U.S. Caribbean Sea Emission Control Area). Marine diesel engines installed on a ship constructed on or after 1 January 1990 but prior to 1 January 2000 are required to comply with "Tier I" emission limits, if an approved method for that engine has been certified by an Administration.

The revised NO_x Technical Code 2008 includes a new chapter based on the agreed approach for regulation of existing (pre-2000) engines established in MARPOL Annex VI, provisions for a direct measurement and monitoring method, a certification procedure for existing engines and test cycles to be applied to Tier II and Tier III engines.

MEPC 66 (April 2014) adopted amendments to regulation 13 of MARPOL Annex VI regarding the effective date of NO_x Tier III standards.

The amendments provide for the Tier III NO_x standards to be applied to a marine diesel engine that is installed on a ship constructed on or after 1 January 2016 and which operates in the North American Emission Control Area or the U.S. Caribbean Sea Emission Control Area that are designated for the control of NO_x emissions.

In addition, the Tier III requirements would apply to installed marine diesel engines when operated in other emission control areas which might be designated in the future for Tier III NO_x control. Tier III would apply to ships constructed on or after the date of adoption by the Marine Environment Protection Committee of such an emission control area, or a later date as may be specified in the amendment designating the NO_x Tier III emission control area.

Further, the Tier III requirements do not apply to a marine diesel engine installed on a ship constructed prior to 1 January 2021 of less than 500 gross tonnage, of 24 m or over in length, which has been specifically designed and is used solely, for recreational purposes [19].

Existing Emission Control Areas include [20]:

- The Baltic Sea area (regulation 14.3.1 of MARPOL Annex VI and regulation 1.11.2 of MARPOL Annex I, SOx adopted 1997 / entered into force 2005, NOx: 2016/2021):

  The Baltic Sea area means the Baltic Sea proper with the Gulf of Bothnia, the Gulf of Finland and the entrance to the Baltic Sea bounded by the parallel of the Skaw in the Skagerrak at specific coordinates.

- The North Sea area (regulation 14.3.1 of MARPOL Annex VI and regulation 1.14.6 of MARPOL Annex V, SOx: 2005/2006, NOx: 2016/2021):

  The North Sea area means the North Sea proper including seas therein with the boundary between:

  1. the North Sea southwards and eastwards by specific coordinates;

  2. the Skagerrak, the southern limit of which is determined east of the Skaw by specific coordinates;

  3. the English Channel and its approaches eastwards and northwards by specific coordinates;

- The North American area (regulation 14.3.2 and appendix VII of MARPOL Annex VI, NOx & SOx: 2010/2012):

  The North American area comprises:

  1. the sea area located off the Pacific coasts of the United States and Canada, enclosed by geodesic lines connecting specific coordinates

  2. the sea areas located off the Atlantic coasts of the United States, Canada, and France (Saint-Pierre-et-Miquelon) and the Gulf of Mexico coast of the United States enclosed by geodesic lines connecting the specific coordinates;

3. the sea area located off the coasts of the Hawaiian Islands of Hawai'i, Maui, Oahu, Molokai, Niihau, Kauai, Lanai, and Kahoolawe, enclosed by geodesic lines connecting specific coordinates;

- The Unites States Caribbean sea area (regulation 14.3.3 and appendix VII of MARPOL Annex VI, NOx & SOx: 2011/2014).

The NO_x emission limits of Regulation 13 of MARPOL Annex VI apply to each marine diesel engine with a power output of more than 130 kW installed on a ship. A marine diesel engine is defined as any reciprocating internal combustion engine operating on liquid or dual fuel. There are two exceptions: engines used solely for emergencies and engines on a ships operating solely within the waters of the state in which they are flagged. The later exception only applies if these engines are subject to an alternative NO_x control measure.

NO_x emission limits are set for diesel engines depending on the engine maximum operating speed (n, rpm), as shown on Table 4.1 and presented graphically in Figure 4.3. Tier I and Tier II limits are global, while the Tier III standards apply only in NO_x Emission Control Areas.

Tier	Date	NOx Limit, g/kWh		
		n < 130	130 ≤ n < 2000	n ≥ 2000
Tier I	2000	17.0	$45 \cdot n^{-0.2}$	9.8
Tier II	2011	14.4	$44 \cdot n^{-0.23}$	7.7
Tier III	2016†	3.4	$9 \cdot n^{-0.2}$	1.96
† In NOx Emission Control Areas (Tier II standards apply outside ECAs).				

TABLE 4.1: NO_x emission limits

Annex VI regulations include caps on sulfur content of fuel oil as a measure to control SO_x emissions and, indirectly, PM emissions (there are no explicit PM emission limits). Special fuel quality provisions exist for SO_x Emission Control Areas (SO_x ECA or SECA). The sulfur limits and implementation dates are listed on Table 4.2 and illustrated in Figure 4.4.

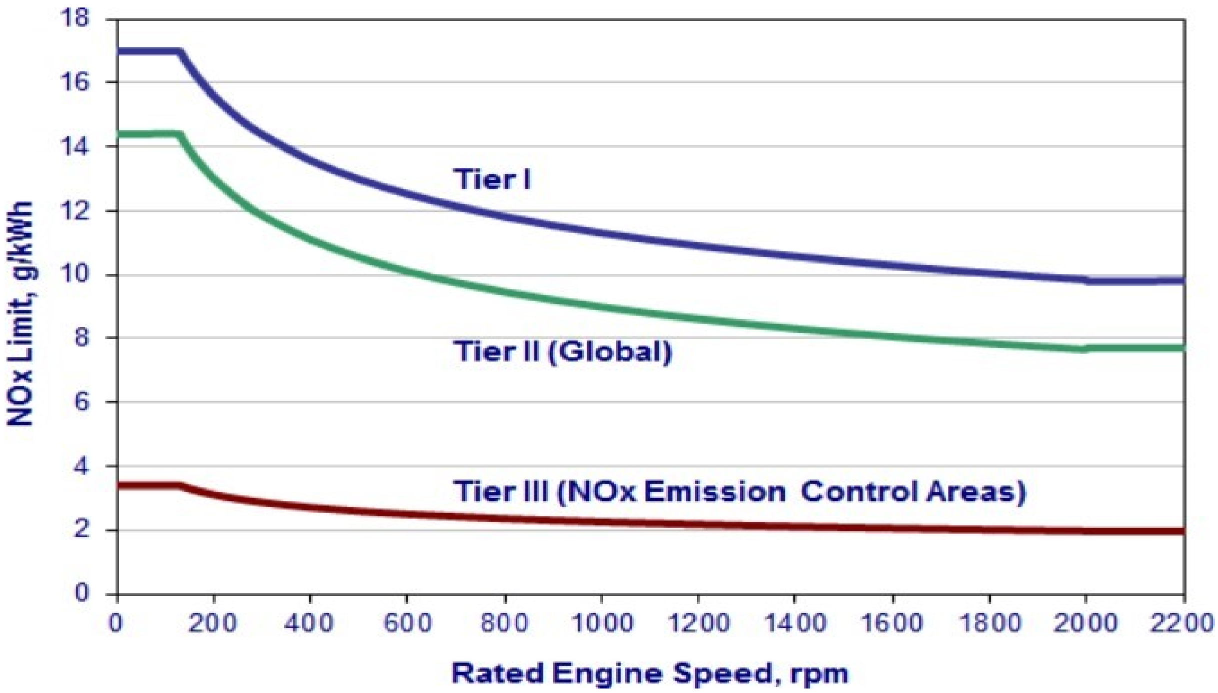


FIGURE 4.3: NO_x emission limits VS engine speed.

Date	Sulfur Limit in Fuel (% m/m)	
	SOx ECA	Global
2000	1.5%	4.5%
2010.07	1.0%	
2012		3.5%
2015	0.1%	
2020		0.5%

TABLE 4.2: SO_x emission limits

4.4.2 Greenhouse gas emissions

MARPOL Annex VI, Chapter 4 introduces two mandatory mechanisms intended to ensure an energy efficiency standard for ships: (1) the Energy Efficiency Design Index (EEDI), for new ships, and (2) the Ship Energy Efficiency Management Plan (SEEMP) for all ships [21].

- The EEDI is a performance-based mechanism that requires a certain minimum energy efficiency in new ships.
- The SEEMP establishes a mechanism for operators to improve the energy efficiency of ships.

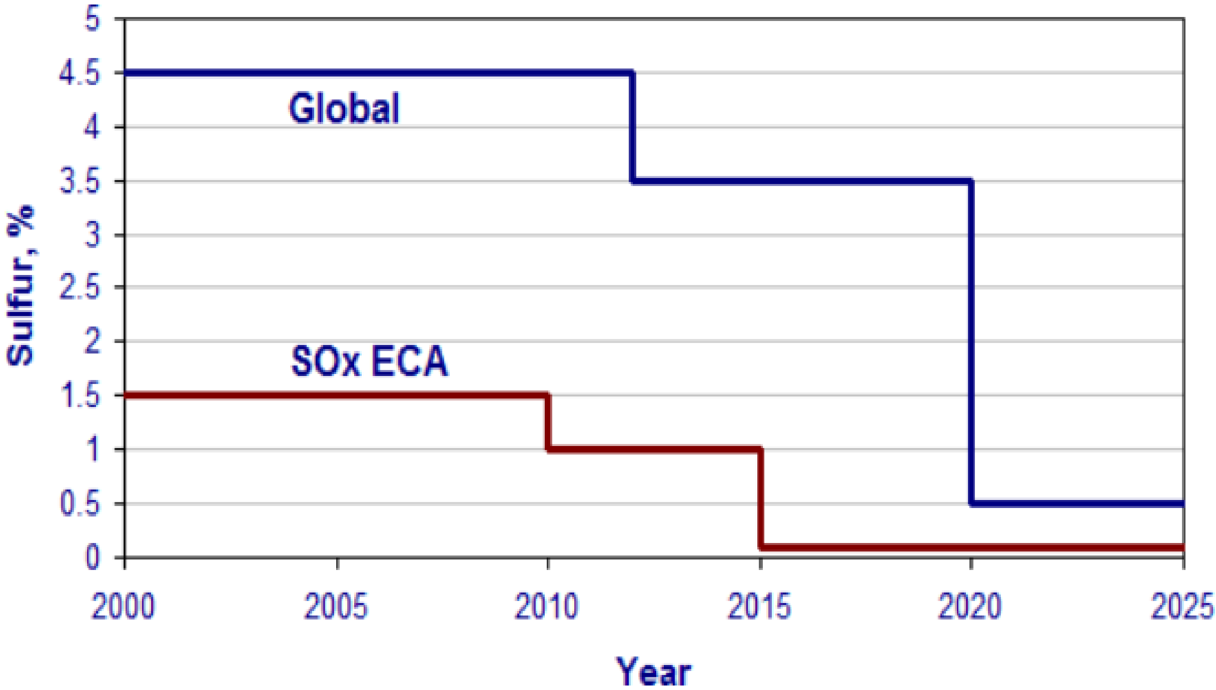


Figure 4.4: Sulfur emission limits VS year.

Energy Efficiency Design Index (EEDI)

The EEDI for new ships is the most important technical measure and aims at promoting the use of more energy efficient (less polluting) equipment and engines. The EEDI requires a minimum energy efficiency level per capacity mile (e.g. tonne mile) for different ship type and size segments. Since 1 January 2013, following an initial two year phase zero, new ship design needs to meet the reference level for their ship type. The level is to be tightened incrementally every five years, and so the EEDI is expected to stimulate continued innovation and technical development of all the components influencing the fuel efficiency of a ship from its design phase. The EEDI is a non-prescriptive, performance-based mechanism that leaves the choice of technologies to use in a specific ship design to the industry. As long as the required energy efficiency level is attained, ship designers and builders are free to use the most cost-efficient solutions for the ship to comply with the regulations. The EEDI provides a specific figure for an individual ship design, expressed in grams of carbon dioxide (CO_2) per ship's capacity-mile (the smaller the EEDI the more energy efficient ship design) and is calculated by a formula based on the technical design parameters for a given ship.

The CO_2 reduction level (grams of CO_2 per tonne mile) for the first phase is set to 10% and will be tightened every five years to keep pace with technological developments of new efficiency and reduction measures. Reduction rates have been established until the period 2025 and onwards when a 30% reduction is mandated for applicable ship types calculated from a reference line representing the average efficiency for ships built between 2000 and 2010. The EEDI is developed for the largest and most energy intensive segments of the world merchant fleet and embraces emissions from new ships covering the following ship types: tankers, bulk carriers, gas carriers, general cargo ships, container ships, refrigerated cargo carriers and combination carriers. In 2014, MEPC adopted amendments to the EEDI regulations to extend the scope of EEDI to: LNG carriers, ro-ro cargo ships (vehicle carriers), ro-ro cargo ships; ro-ro passenger ships and cruise passenger ships having non-conventional propulsion. These amendments mean that ship types responsible for approximately 85% of the CO_2 emissions from international shipping are incorporated under the international regulatory regime.

Since 2012, Marine Environment Protection Committee (MEPC) adopted/approved or amended following important guidelines aimed at assisting the implementation of the mandatory regulations on Energy Efficiency for Ships in MARPOL Annex VI:

- 2014 Guidelines on survey and certification of the Energy Efficiency Design Index (EEDI), as amended
- 2014 Guidelines on the method of calculation of the attained Energy Efficiency Design Index for new ships, as amended
- 2013 Guidelines for calculation of reference lines for use with the Energy Efficiency Design Index (EEDI)
- 2013 Guidelines for calculation of reference lines for use with the Energy Efficiency Design Index (EEDI) for cruise passenger ships having non-conventional propulsion
- 2013 Interim guidelines for determining minimum propulsion power to maintain the manoeuvrability of ships in adverse conditions, as amended
- 2016 Guidelines for the development of a Ship Energy Efficiency Management Plan (SEEMP)
- 2013 Guidance on treatment of innovative energy efficiency technologies for calculation and verification of the attained EEDI
- Urinary system
- Interim Guidelines for the calculation of the coefficient fw for decrease in ship speed in a representative sea condition for trial use

- Neuropsychiatric complications

The above Guidelines and resolutions are available on the official website of IMO.

Ship Energy Efficiency Management Plan (SEEMP) and Energy Efficiency Operational Indicator (EEOI)

The Ship Energy Efficiency Management Plan (SEEMP) is an operational measure that establishes a mechanism to improve the energy efficiency of a ship in a cost-effective manner. The SEEMP also provides an approach for shipping companies to manage ship and fleet efficiency performance over time using, for example, the Energy Efficiency Operational Indicator (EEOI) as a monitoring tool. The guidance on the development of the SEEMP for new and existing ships incorporates best practices for fuel efficient ship operation, as well as guidelines for voluntary use of the EEOI for new and existing ships (MEPC.1/Circ.684). The EEOI enables operators to measure the fuel efficiency of a ship in operation and to gauge the effect of any changes in operation, e.g. improved voyage planning or more frequent propeller cleaning, or introduction of technical measures such as waste heat recovery systems or a new propeller. The SEEMP urges the ship owner and operator at each stage of the plan to consider new technologies and practices when seeking to optimise the performance of a ship.

Chapter 5

Design Methodology

5.1 Retrofit philosophy

Next step into vessel's electrification process is the investigation of battery systems' sizing. This is the most influential issue to be figured out. An approach to determine required power output, would be to calculate ship's main machineries' consumptions and translate these measurements into required installed energy (kWh). Imprecise data of fuel consumptions kept on board, at some of our inspections on vessels, prohibited this choice in fear of over/under estimating ship's power demands. The most precise way to calculate hulls and its' appendages resistance is through CFD modelling. Lack of enough data, though, combined with the rise of retrofit total cost, kept us off from trying to redesign ships propulsion system. It was preferred for our calculation methodology to build an energy balance sheet based on ship's operational profile in accordance with the existing diesel engines' nominal output and electrical load balance.

The vessel being considered for retrofit is "President". It is a fishing boat with main particulars mentioned on Table 5.1.

The machinery space consists of two diesel main engines coupled with a gearbox. A genset is also installed, tasked with covering the electrical loads of the boat.

The main goal of this retrofit is the complete electrification of the boat, i.e. the replacement of the main diesel engines, as well as the gensets of the boat by batteries. These batteries are going to cover both propulsion and electrical loads of the ship. Batteries' cost will be the highest expense for this retrofit, they will be vessel's sole source of power and they are not light. We wouldn't want an expensive ship, carrying more batteries

Main Particulars	
Length OA	20.88 m
Breadth	6.6 m
Depth	3.1 m

Table 5.1: Main particulars of "President".

than needed (batteries are a steady weight, unlike fuel) nor a vessel being obliged to miss some voyages because it didn't have enough installed energy compared to time available for charging.

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

The number of battery modules needed and their arrangement in the vessel depends, as well, from market available battery solutions. When battery system is installed, it will power directly hoteling, function and propulsion loads of the ship. While at berth, it will be recharged between trips and after the end of the shift from a shore side system, developed at one port of duty. Furthermore, we will consider the scenario that the power needed at the port of charge will be provided directly from the shore connection, reducing the total amount of installed energy on board.

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

Few changes will be caused in ship's electrical AC distribution network, as it will be converted in a DC one. Our target is the retrofit of existing low cost vessels, therefore, we need to keep in mind that battery storage systems are, even today, quite expensive choices for these categories of routes.

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

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

Local societies' welfare and health by decreasing environment's further pollution are the most aspiring reasons for this retrofit. In order to achieve the desired outcome, we need to design an efficient system with safety for the environment, but also for the crew. For this reason, we will investigate remaining energy on board after failure, to ensure the ability for safe return at port.

5.2 Battery characteristics

The battery modules used on the retrofit are manufactured by Valence and the specific model is going to be the U-Charge U27-36XP of the XP Series. U-Charge® XP is a range of 12, 18 and 36 volt Lithium Iron Magnesium Phosphate battery modules, offering intrinsic safety with twice the run-time and less than half the weight of similarly sized sealed lead-acid batteries. The specific model was chosen as it provides the most economical solution for this specific application. Main characteristics of U-Charge XP Series are given on Table 5.2.

The sizing of battery modules is a major parameter of the retrofit. The time of recharging, as well as the safety margin and the operational profile of the batteries, including lifecycles and charge/discharge limits will be taken into consideration.

Installing a very small battery system would require to be charged from lower operating DOD to 100% DOD after every trip. But charging fully every time will result to extend shift duration. Moreover, the batteries will last for a shorter period of time as cycles per day will be significantly increased, in addition to the reduced capacity of the batteries.

Specifications		U1-12XP	U24-12XP	U27-12XP	UEV-18XP	U27-36 XP
Nominal Module Voltage		12.8 V	12.8 V	12.8 V	19.2 V	38.4 V
Nominal Capacity (C/5, 23°C)		40 Ah	110 Ah	138 Ah	69 Ah	45Ah
Weight (approximate)		6.5 kg	15.8 kg	19.5 kg	14.9 kg	19.6kg
Dimension incl. Terminals LxWxH (mm)		197x131x182	260x172x225	306x172x225	269x148x245	306x172x225
BCI Group Number		U1R	Group 24	Group 27	N/A	Group 27
Terminals, Female-Threaded		M6 x 1.0	M8 x 1.25	M8 x 1.25	M8 x 1.25	M8 x 1.25
Specific Energy		79 Wh/kg	89 Wh/kg	91 Wh/kg	89 Wh/kg	91 Wh/kg
Energy Density		110 Wh/l	139 Wh/l	148 Wh/l	124 Wh/l	148 Wh/l
Standard Discharging @ 25°C	Max. Continuous Load Current	80 A	150 A	150 A	120 A	90 A
	Peak Load Current (30 sec).	120 A	300 A	300 A	200 A	135 A
	Cut-off Voltage	10 V	10 V	10 V	15 V	30 V
Standard Charging	Max. Charge Voltage	14.6 V	14.6 V	14.6 V	21.9 V	43.8 V
	Float Voltage	13.8 V	13.8 V	13.8 V	20.7 V	41.4 V
	Charge Time c/2 *	2.5 hrs	2.5 hrs	2.5 hrs	2.5 hrs	2.5 hrs
DC internal resistance (max)		15 mΩ	6 mΩ	5 mΩ	10 mΩ	25 mΩ
Equivalent Lithium Content Per Module (g)		48.6	127.98	160.38	121.5	160.38
Part Number		1004434	1004425	1004428	1004431	1005219

TABLE 5.2: Characteristics of U-Charge XP modules.

Figure 5.1 depicts the total capacity of the batteries at 100% DOD in percentage of the initial capacity as a function of the cycles that the battery system has served.

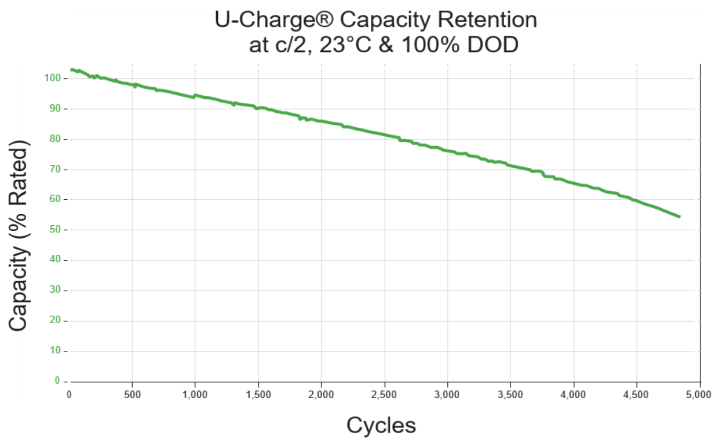


FIGURE 5.1: Capacity as function of cycles at 100% DOD.

The battery modules will result in lower capacity in a significant amount of their life expectancy. It is vital for the operational and economical planning of the retrofit to ensure proper performance and reliability of the battery system.
Figure 5.2 presents a typical DOD profile of a battery system, charging at C/2 (nominal) rate and end of life at 80% of initial capacity.

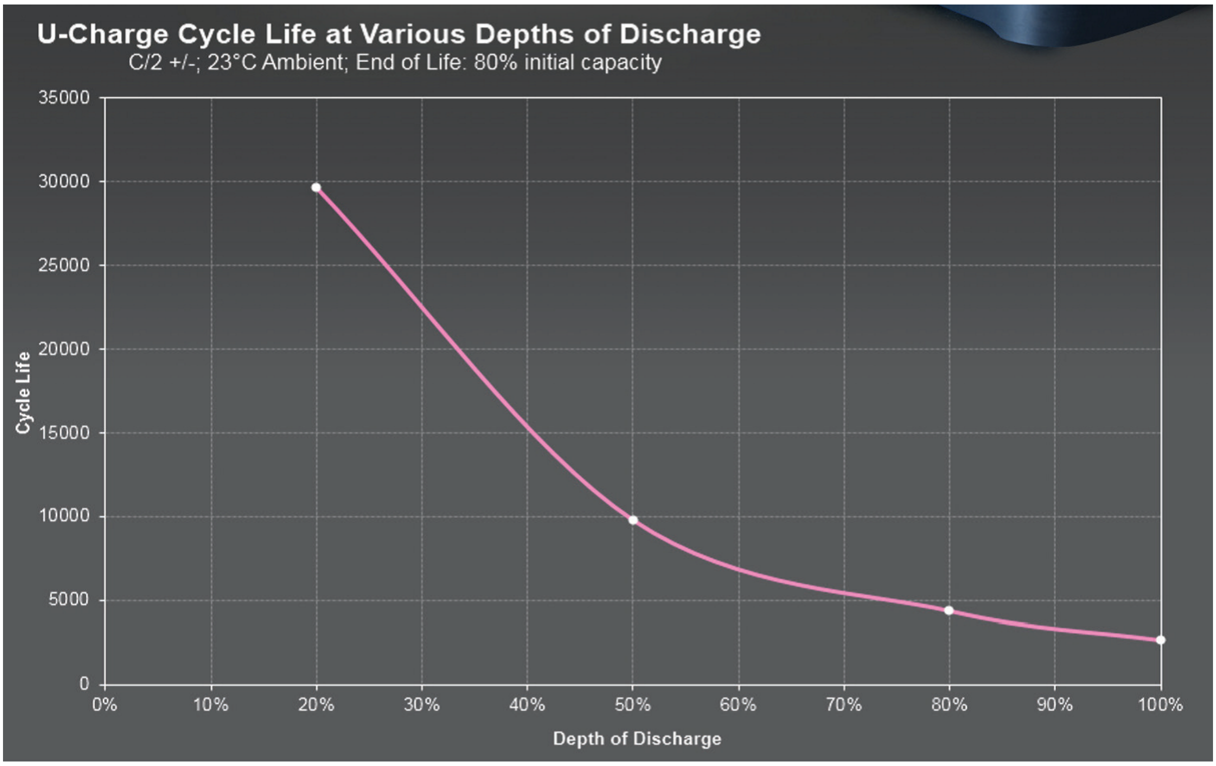


FIGURE 5.2: Cycles as function of DOD.

The vessel is going to be recharged for specific time after every trip. In order to install less batteries we need to reduce the total charging time. This can be done by installing batteries that can be charged with high currents (at bigger C rate). If the system is charged with higher currents than those proposed by the manufacturer, the total life expectancy of the system will decrease. Furthermore, if we discharge the batteries in higher currents the capacity will decrease.
Figure 5.3 depicts the total capacity of the batteries in percentage of the initial capacity as a function of the discharge C rate for a U-Charge XP module of 12 V.

The system with less batteries generally results in slightly lower volume, weight and price. The performance of the modules, though, the life expectancy of the system and safety reasons leads us to a bigger number of batteries and packs.

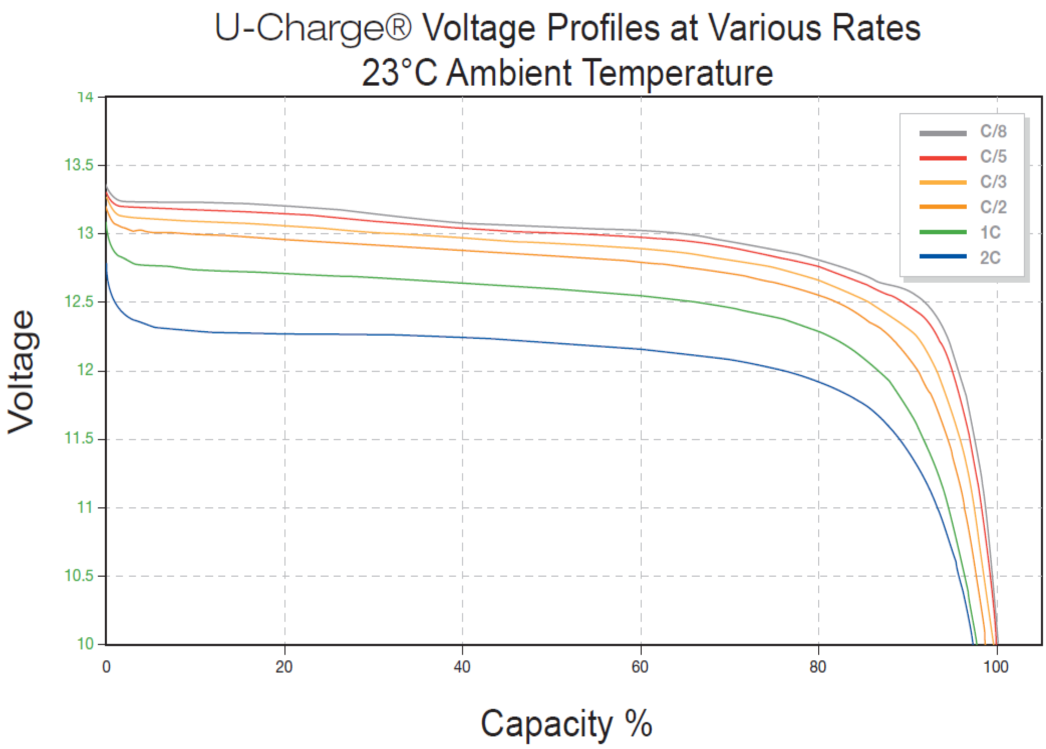


FIGURE 5.3: Capacity according to C rate.

5.3 Model inputs and equations

The required data to calculate our energy balance loads needed for the retrofit are the following:

Concerning vessel's characteristics before the retrofit:

- Number of Main Engines for propulsion and their nominal output.
- No of Operating Main Engines for propulsion
- Main Engine Load Factor for Cruise, Maneuver and Stand-by at Port
- Electrical Load Balance at Sea
- Electrical Load Balance at Port
- Electrical Load Balance at Maneuver
- System's AC Voltage (V)

Concerning vessel's characteristics after the retrofit:

- Electric Motors Efficiency number
- Electric motor's power output
- Electric motor's voltage
- System's DC Voltage (V)

Concerning route characteristics:

- Time Cruising (min)
- Time at Berth (min)
- Time at Maneuver (min)
- Required no. of trips per day

Concerning battery module's characteristics:

- Nominal Charging/Discharging Voltage
- Nominal Charging/Discharging current for max lifecycles
- Module's dimensions
- Capacity
- Volume
- Weight
- Nominal D.O.D.
- C-Rate

5.3.1 Ship side calculations and battery system sizing

Vessel's shift itinerary will be divided into trips and voyages as defined below:

$$trip = 2 * Voyages + Port + Stand - by + Maneuver + Seaportsatsea$$

$$T_{\text{per trip}} = 2 * T_{\text{CRUISING}} + T_{\text{PORT}} + T_{\text{MANEUVER}} + T_{\text{STN-BY}} + T_{\text{SEAPORTS}}$$

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

$$E_{\text{PR/TRIP}} = [P_{\text{THRUST}} * N_{\text{THRUST}} * \left(2 * L_{\text{fcr}} * \frac{T_{\text{CRUISING}}}{60} + L_{\text{fmn}} * \frac{T_{\text{MANEUVER}}}{60}\right) * \frac{1}{n_{\text{EL.MOTOR}}}], \ (kWh)$$

where, P_{THRUST}: Electric motor nominal power output (kW)
N_{THRUST}: No of electric motors operating while cruising
L_{fmn}: Main engine load factor at maneuver(%)
L_{fcr}: Main engine load factor at cruising(%)
T_{CRUISING}: Time cruising (min)
T_{MANEUVER}: Time at maneuver (min)
$n_{\text{EL.MOTOR}}$: Electric motors efficiency

The energy demand for hoteling/electrical loads, $E_{\text{HOT/TRIP}}$, for one trip is:

$$E_{\text{HOT/TRIP}} = [2 * P_{\text{HOT/SEA}} * \frac{T_{\text{CRUISING}}}{60}] + [P_{\text{HOT/MANEUVER}} * \frac{T_{\text{MANEUVER}}}{60}] + [P_{\text{HOT/PORT}} * \frac{T_{\text{PORT}}}{60}] + [P_{\text{HOT/STN-BY}} * \frac{T_{\text{STN-BY}}}{60}] + [P_{\text{HOT/PORT}} * \frac{T_{\text{SEAPORTS}}}{60}], \ (kWh)$$

where, $P_{\text{HOT/SEA}}$: Electric Load Balance at Sea (kW)
$P_{\text{HOT/PORT}}$: Electric Load Balance at Birth (kW)
$P_{\text{HOT/MANEUVER}}$: Electric Load Balance at Maneuver (kW)
$P_{\text{HOT/STN}}$: Electric Load Balance at Stand-by (kW)
T_{MANEUVER}: Time at maneuver (min)
T_{CRUISING}: Time cruising (min)
T_{PORT}: Time at birth (min)
T_{SEAPORTS}: Time using port load on sea, collecting cargo (min)
$T_{\text{STN-BY}}$: Time of stand-by at sea (min)

The energy demand , E_{TRIP}, for one trip is:

$$E_{\text{TRIP}} = E_{\text{PR/TRIP}} + E_{\text{HOT/TRIP}}, \ (kWh)$$

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

$$E_{\text{TOTAL/DAY}} = E_{\text{TRIP}} * N_{\text{TRIPS}}, \ (kWh)$$

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

From total energy per day the stand-by operation at port has to be removed from the final trip. The minimum installed energy on board, $E_{MIN.INSTALLED}$, for fulfilling the number of trips per shift/day while operating at nominal DOD for maximum lifecycles, will be calculated according to time available for charging each time at port:

$$E_{\text{MIN.INSTALLED}} = \frac{E_{\text{TOTAL/DAY}}}{((N_{\text{TRIPS}} - 1) * f + DOD)}, \ (kWh)$$

$$f = \left(\frac{C1}{C2}\right) * \frac{(T_{\text{PORT}} - T_{\text{PLUG}})}{T_{100}}$$

where, DOD: Depth of Discharge of Battery system for maximum life-cycles (%)
f: a parameter used to estimate how the different charging currents and time needed to connect the vessel to the charging station impacts the charging load transferred on board (%)
T_{100}: Total time needed to completely charge the battery pack at nominal charging current
T_{plug}: Total time needed to plug-in and then plug-off the charging station
T_{port} :Total time spent on port
C1 : Charging current
C2: Nominal charging current

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

$$N_{\text{BT.SERIES}} = \frac{V_{\text{SYST}}}{V_{\text{BT}}}$$

where, V_{SYST}: System's main bus bar's voltage (V)
V_{BT}: Battery module's nominal voltage (V)

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

$$N_{\text{BT.PARAL}} = \frac{E_{\text{MIN.INSTALLED}}}{(N_{\text{BT.SERIES}} * V_{\text{BT}} * Ah_{\text{BT}})}$$

where, $N_{BT.PARAL}$: No of batteries connected in parallel
$N_{BT.SERIES}$: No of batteries connected in series
Ah_{BT}: Battery module's nominal capacity (Ah)

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

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

$$N_{\text{BT.TOTAL}} = N_{\text{BT.SERIES}} * N_{\text{PARALLEL}}$$

$$E_{\text{INSTALLED}} = N_{\text{BT.TOTAL}} * V_{\text{BT}} * Ah_{\text{BT}},\ (kWh)$$

In order to ensure safe return to the port after failure of one battery pack the remaining energy, which is calculated by:

$$E_{\text{REMAIN}} = (1 - DOD) * E_{\text{INSTALLED}} * N_{\text{REMAINPACK}},\ (kWh)$$

where, $N_{\text{REMAINPACK}} = \frac{1}{2}$ if there are 2 battery packs
$N_{\text{REMAINPACK}} = \frac{3}{4}$ if there are 4 battery packs

must be greater than E_{VOYAGE}

$$E_{\text{VOYAGE}} = \frac{E_{\text{TRIP}}}{2},\ (kWh)$$

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

$$W_{\text{TOTAL}} = N_{\text{BT.TOTAL}} * W_{\text{BT}},\ (tn)$$

$$\nabla_{\text{TOTAL}} = N_{\text{BT.TOTAL}} * \nabla_{\text{BT}},\ (m^3)$$

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

Daily cycles considered for the estimation of battery system's life expectancy are calculated by the following formula:

$$Cycles_{\text{DAILY}} = INT\left[Percentage_{\text{chrg}} * (N_{\text{TRIPS}} - 1) + (1 - Percentage_{\text{remain}})\right] + 1$$

The term +1 on the above equation is ignored if the decimal part of the parenthesis is less than 0.10.

$$LifeExpectancy = \frac{Cycles_{\text{NOMINAL}}}{N_{\text{op}} * Cycles_{\text{DAILY}}},\ (years)$$

where, $Cycles_{\text{DAILY}}$: battery cycles per day
$Cycles_{\text{NOMINAL}}$: nominal number or cycles if system is operated at nominal values
$Percentage_{\text{chrg}}$: percentage of battery recharge per trip

Percentage$_{remain}$: percentage of battery capacity remaining after last trip
N_{op}: number of operation days per year

The shore side calculations methodology is described below:

The shore substation has to provide certain kW of power. The voltage of the previous AC network is 220/380V. According to inverter's manufacturer the AC to DC current is transformed from 380V to 500V, and vice versa. The voltage of the secondary coil of the transformer is then 380V, which will be converted to 500V for the DC network of the boat. To ensure the proper voltage for the charge of the batteries and avoid overheating of cables, the shore supply will not recharge the batteries as modules ($V_{\text{DC-SEC}} = V_{\text{CHRG}} * N_{\text{BT.SERIES}}$), as the demanded DC voltage, $V_{\text{DC-SEC}}$, will exceed the voltage of our system. The discharge of batteries will take place as battery modules, while the recharge for each battery separately. The BMS system of each battery will adjust the appropriate recharge voltage demand (max of 43.8 V) and the constant current(proposed 23 A). This is due to the fact that, while recharging, the shore power supply will deliver the demanded load for the port duty of the boat (V_{SYST}=500V).

The P_{SUB} is calculated from the nominal charge voltage and current, proposed from the manufacturer of the batterie.

$$P_{\text{SUB}} = \frac{I_{\text{NOM.CHRG}} * V_{\text{CHRG}} * N_{\text{BT.TOTAL}}}{1000} + El.PortLoad, \ (kW)$$

$$I_{\text{NET}} = \frac{P_{\text{SUB}} * 1000}{V_{\text{SYST}}}, \ (A)$$

where, $I_{\text{NOM.CHRG}}$: the proposed charge current of the battery module (A)
El.PortLoad: the demand of electric load of boat at port (kW)
V_{CHRG}: the proposed charge voltage of the battery module (V)

This current (I_{NET}) feeds the electrical network. The current is calculated as DC because there will be a rectifier to transform the AC current of the substation. In the power demand equation we sum the El.Port-load because, as mentioned, the power demand at the port of charge will be provided directly from the shore connection.

The annual electricity consumption was calculated according the daily demand, the range of load and the time of use. Different load was taken into consideration, according to different state of operation (port, stand-by at port) and at the end of the shift the extra load for fully recharge the batteries, without providing load for the operation of vessel at port.

5.3.2 Emissions and pollutants

The retrofit vessel has a 6 cylinder, 4 cycle, water cooled high speed diesel engine (MITSUBISHI S6B3-MPTK, 345KW) and the quantification of the volume of emissions saved in the atmosphere is based on guidelines of TIER-I protocol, according to the manufacturer Appendix B.

The Tier I approach is based on the premise that the quantities of fuel sold for shipping activities are available by fuel type, from nationally collected data. Fuel data needs to be split by NFR code: national navigation (usually navigation statistics), international (bunkers), fishing (usually available as separate statistics) and military.

For a single trip the emissions can be expressed as:

$$EM_{\mathrm{TRIP}} = EM_{\mathrm{MAIN}} + EM_{\mathrm{AUX\text{-}LOW}} + EM_{\mathrm{AUX\text{-}HIGH}}$$

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

$$EM_{\mathrm{TRIPi}} = \sum_{m} (FC_{\mathrm{m}} * EF_{\mathrm{i,m}})$$

where, $\mathrm{EM}_{\mathrm{TRIPi}}$: emission of pollutant i in kilograms
FC_{m}:mass of fuel type m (tonnes)
$\mathrm{EF}_{\mathrm{i,m}}$:fuel consumption-specific emission factor of pollutant i and fuel type m [kg/tonne]
m: fuel type (bunker fuel oil, marine diesel oil, marine gas oil, gasoline)

In order to use the above equations we need to know the fuel consumption of the vessel. We have an estimated consumption from the manufacturer Appendix B, which we are going to investigate.

FUEL CONSUMPTION METHOD (Mitsubishi S6B3-MPTK)

The fuel consumption varies according to test condition, specification and application of each customer. To obtain the fuel consumption based on the most typical test condition, we adopted average fuel consumption recommended by ISO 8178 (E3 standard test cycle for propulsion application and D2 for auxiliary applications). The fuel consumption values published in this marine product guide were calculated taking each steady-state mode into account.

E2 –Test cycle for "constant-speed main propulsion" applications (including diesel-electric drive and all controllable –pitch propeller installations).

E3 – Test cycle for "propeller-law-operated main and propeller-law operated auxiliary engine" application.

D2 – Test cycle for "constant-speed auxiliary engine" application.

Mode number	1	2	3	4
Power (%)	100	75	50	25
Weighting factor	0.20	0.50	0.15	0.15

TABLE 5.3: Weighting factors of type E3 ISO 8178 test cycles.

Mode number	1	2	3	4	5
Power (%)	100	75	50	25	10
Weighting factor	0.05	0.25	0.30	0.30	0.10

TABLE 5.4: Weighting factors of type D2 ISO 8178 test cycles

Fuel consumption is based on ISO 3046/1 with 5% tolerance at rated power, weighing 836 g/liter based on the regulations of JIS (Japanese Industrial Standards) and a LHV of 42,780 kJ/kg, excluding pumps [22].

The above estimation includes different operations of the engine in various loads and weighting factors. No more data could be found for this specific engine. The project on which we are working, considers a constant load factor (0.9) for propulsion operation only. The electric infrastructure is calculated for this demand, so taking this average consumption for the calculation of fuel consumption would not be representative. It was considered preferable to find another engine with same/similar characteristics to evaluate the annual fuel demand. The same method was used for the auxiliary engine, too. The selection was made from a marine engine selection guide of Caterpillar marine power systems. The main egine's data were taken from C18 (IMO1) and for the auxiliary engine C2.2 and C4.4 models were used.

FUEL CONSUMPTION METHOD (Caterpillar C18)

A Rating (Unrestricted Continuous)
Typical applications: For vessels operating at rated load and rated speed up to 100% of the time without interruption or load cycling (80% to 100% load factor). Typical

applications could include but are not limited to vessels such as freighters, tugboats, bottom trawlers, or deep river tugboats [23].

The specific fuel oil consumption is given in litres per hour so we calculate:

$$FC = SFOC * T_{\text{day}} * DAYS_{\text{oper}} * p * 0.001,\ (tn)$$

where, FC: fuel oil consumption per year
SFOC: specific fuel oil consumption ($\frac{lt}{h}$)
T_{day}: time of operation for one day (hours)
$DAYS_{\text{oper}}$: number of operation days per year
p: fuel density ($\frac{tn}{m^3}$)

It has to be mentioned that the FC is an approximation according to the data we have and not an accurate value.

5.3.3 Investment appraisal

Net present value (NPV) is the difference between the present value of cash inflows and the present value of cash outflows over a period of time. NPV is used in capital budgeting to analyze the profitability of a projected investment or project. It is calculated by this equation:

$$NPV = \sum_{i=1}^{n} \frac{A_{\text{i}}}{(1+r)^i} - C_0$$

Chapter 6

Electrical Infrastructure

6.1 Shore side

The shore side power network configurations utilized for charging the batteries while the vessel is at berth is presented.

There are, mainly, two alternative Connect Management System solutions on the market:

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

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

An AC shore connection system includes a main substation equipped with a MV switchboard supplying the shore side substations and shore side substations supplying the connection points between the vessels and the port, equipped with:

- An isolation transformer of Dyn configuration for adapting the utility grid MV to the connection voltage, with the neutral point grounded (possibly through a grounding resistance)

- The outgoing switchboard supplying the plugs of the point of connection between the port and the vessel

The standards propose similar configurations for both the HVSC and the LVSC systems. The main difference between the two configurations consists of the earthing equipment and its relevant interlocks used in the High Voltage systems to avoid residual charges.

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

According to "DNV-GL Guideline for Large Maritime Battery Systems", the charging system and other relevant systems shall detect the connection to shore power and activation of propulsion shall be inhibited in this case. Note that some applications will need propulsion power even when connected to shore power. In those cases safety measures must be taken to avoid unintended un-plugging of the charging interface.

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

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

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

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

In case the maximum charging power of the system is more than 1 MW an HV shore connection must be adopted. An earthing switch must be added after the outgoing circuit breaker, for earthing trapped charges in the HV connection cable. The power supply of the vessel presented in this case study will not exceed 1 MW (calculated in the following chapter) and the shore connection system will be a LV system. Figure 6.1 presents a typical Dyn connection [24].

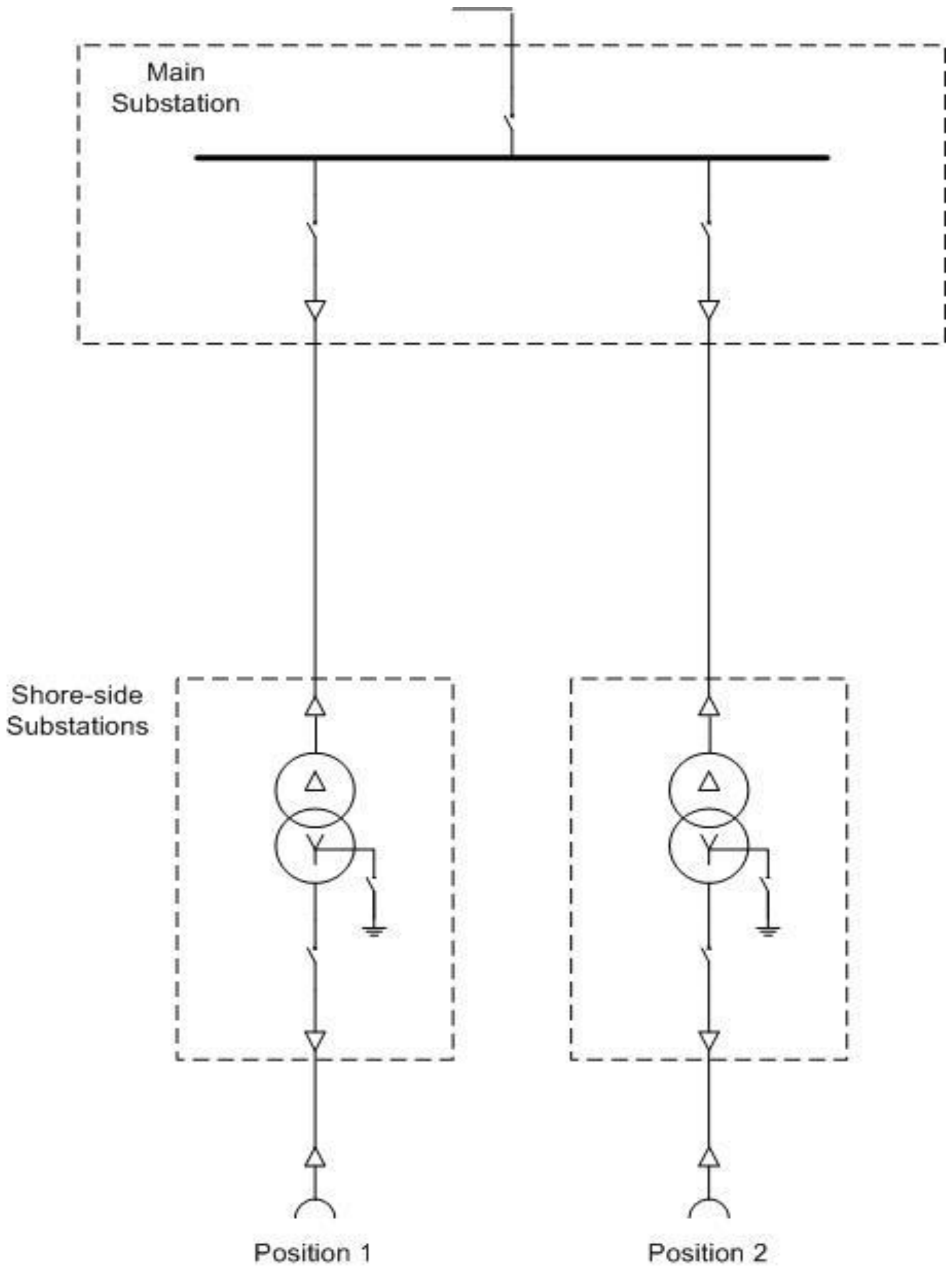


Figure 6.1: Shore side configuration for an AC LV shore connection.

6.2 Ship side

In this chapter we redefine the electric balance sheet of the vessel by increments on power demand of the consumers, as no Energy Efficiency Degree is taken into consideration. In addition, Power Factor is included in the calculations, as DC electric power will finally be converted, by inverters, in AC, in order to be consumed by the electric devices of the vessel. It is of high importance that the calculated balance sheet will be accurate, as underestimating the power demands will lead to low installed energy on board, affecting the normal function of the vessel and the duration of the investment. On the other hand, overestimating will lead to more expensive investment and extra weight on the boat. When balance sheet is recalculated, a research will take place for cables and buses and the new electric diagram will be presented.

6.2.1 Basic electrical balance sheet

The electric balance sheet consists of four main operating modes:

1. normal route
2. maneuvering
3. port
4. stand by

The loads of the vessel have been grouped into certain categories:

- Electric consumptions of machinery room
- Electric consumptions of hotel rooms
- Electric consumptions of vessel
- Electric consumptions of navigation

Each consumer has a nominal power. The nominal power, in addition to the following data, is given on the electric balance sheet. Energy Efficiency Degree, n, is taken into consideration and the nominal absorbed power is calculated:

$$P_{\text{nm abs}} = \frac{P_{\text{nm}}}{n}$$

Due to luck of enough data of the electric devices, we will use Table 6.1 to calculate the EED, which can be taken as function of the nominal load of the consumers [25].

Φορτίο	**Βαθμός αποδόσεως**
P ≥40 kW	0.95
40 kW ≥ P ≥20 kW	0.90
20 kW ≥ P ≥5 kW	0.85
P ≤ 5 kW	0.80

Table 6.1: EED as function of nominal load.

The total absorbed power is given by the number of each installed device, N, multiplied with the nominal absorbed power. Hence, the installed power is given:

$$P_{\text{ins}} = N * P_{\text{nm abs}}$$

The number of consumers which are in operation in every operation mode is given with N' and the corresponding operating factor with f_s:

$$f_{\text{s}} = \frac{\text{mean load in 24 hours}}{\text{nominal load}}$$

The mean absorbed operation power in each mode is calculated:

$$P_{\text{op}} = \frac{P_{\text{nm}}}{n} * N' * f_{\text{s}} = P_{\text{nm abs}} * N' * f_{\text{s}}$$

As mentioned in previous chapter the emergency electric balance sheet will not be recalculated, as it is approved for the specific vessel and it consists of batteries. The electric balance sheet of the vessel has been recalculated according to the given balance sheet Appendix C and is presented on Table 6.2:

	ΚΑΤΑΝΑΛΩΤΕΣ	η	N	Εγκατεστημένη Ισχύς			Ισχυς Κανονικης Πορείας			Ισχύς Ελιγμών			Ισχύς εν όρμω			Ισχύς Αναμονής		
				$P_{ον.αποδ}$	$P_{ον.απορροφ.}$	$P_{εγκατ.}$	N΄	f_s	$P_{λειτ.}$	N΄	f_s	$P_{λειτ.}$	N΄	f_s	$P_{λειτ.}$	N΄	f_s	$P_{λειτ.}$
				KW	KW	KW			KW			KW			KW			KW
	ΗΛΕΚΤΡΙΚΕΣ ΚΑΤΑΝΑΛΩΣΕΙΣ ΜΗΧΑΝΟΣΤΑΣΙΟΥ																	
1	Αντλία πυρκαγιάς	0.85	1	5.50	6.47	6.471	0	0.85	0.00	0	0.85	0.00	1	0.20	1.29	0	0.00	0.00
2	Υδροστατικη Αντλια γερανου	0.90	1	22.00	24.44	24.44	1	0.00	0.00	1	0.00	0.00	1	0.90	22.00	0	0.00	0.00
3	Αντλια σεντινών	0.85	1	5.50	6.47	6.471	1	0.00	0.00	1	0.00	0.00	1	0.10	0.65	0	0.00	0.00
4	Αντλια ερματος	0.85	1	5.50	6.47	6.471	1	0.00	0.00	1	0.00	0.00	1	0.20	1.29	0	0.00	0.00
5	Υδρ. Αντλια καπακιων	0.80	1	3.00	3.75	3.75	1	0.00	0.00	1	0.00	0.00	1	0.20	0.75	0	0.00	0.00
6	Ανεμιστήτας Μηχ/σίου	0.80	2	2.20	2.75	5.5	2	0.85	4.68	2	0.85	4.68	2	0.20	1.10	2	0.20	1.10
7	Φωτισμός Μηχ/σίου	0.80	1	0.288	0.360	0.36	1	1	0.36	1	1	0.36	1	1	0.36	1	1.00	0.36
								KW	**5.04**		**KW**	**5.04**		**KW**	**27.45**		**KW**	**1.46**
	ΗΛΕΚΤΡΙΚΕΣ ΚΑΤΑΝΑΛΩΣΕΙΣ ΧΩΡΩΝ ΕΝΔΙΑΙΤΗΣΗΣ																	
1	Φωτισμός	0.80	1	0.06	0.08	0.075	1	1	0.08	1	1	0.08	1	1	0.08	1	1.00	0.08
								KW	**0.08**		**KW**	**0.08**		**KW**	**0.08**			**0.08**
	ΗΛΕΚΤΡΙΚΕΣ ΚΑΤΑΝΑΛΩΣΕΙΣ ΠΛΟΙΟΥ																	
1	Εργατης αγκυρων	0.85	1	5.50	6.47	6.471	1	0.00	0.00	1	0.40	2.59	1	0.00	0.00	1	0.00	0.00
2	Αντλια ποσιμου νερου	0.80	1	2.57	3.21	3.213	1	0.50	1.61	1	0.50	1.61	1	0.50	1.61	1	0.50	1.61
3	Αντλια λυματων	0.80	1	1.50	1.88	1.875	1	0.00	0.00	1	0.00	0.00	1	0.50	0.94	0	0.00	0.00
4	Αντλια υγιεινης	0.80	1	3.70	4.63	4.625	1	0.40	1.85	1	0.40	1.85	1	0.40	1.85	1	0.40	1.85
5	Ηλεκτρικη θερμανση νερου	0.80	1	3.00	3.75	3.75	1	0.10	0.38	1	0.20	0.75	1	0.5	1.88	1	0.50	1.88
6	Ανορθωτης βαρουλκων	0.80	1	2.50	3.13	3.125	1	0	0.00	1	0.00	0.00	1	0	0.00	0	0.00	0.00
7	Φωτισμός χωρου τιμονιου	0.80	1	0.18	0.23	0.225	1	1	0.23	1	1	0.23	1	1	0.23	1	1.00	0.23
8	Φωτισμός αποθηκης	0.80	1	0.12	0.15	0.15	1	1	0.15	1	1	0.15	1	1	0.15	1	1.00	0.15
9	Φωτισμος κατ/ματων	0.80	1	0.66	0.83	0.825	1	1	0.83	1	1	0.83	1	1	0.83	1	1.00	0.83
10	Φωτισμος γεφυρας	0.80	1	0.05	0.07	0.068	1	1	0.07	1	1	0.07	1	1	0.07	1	1.00	0.07
11	Φωτισμος χωρου αμπαριου	0.80	1	0.12	0.15	0.15	1	1	0.15	1	1	0.15	1	1	0.15	1	1.00	0.15
12	Φωτισμος χωρων συσσ/των	0.80	5	0.06	0.08	0.375	5	1	0.38	5	1	0.38	5	1	0.38	5	1.00	0.38
13	Φωτισμος χωρου αντ. πυρ.αναγκης	0.80	1	0.06	0.08	0.075	1	1	0.08	1	1	0.08	1	1	0.08	1	1.00	0.08
	ΗΛΕΚΤΡΟΝΙΚΑ																	
14	Φορτιστης/ Ανορθωτης μπαταριων	0.80	1	2.50	3.13	3.125	1	0.20	0.63	1	0.20	0.63	1	0.2	0.63	1	0.20	0.63
	ΝΑΥΣΙΠΛΟΙΑ							**KW**	**6.32**		**KW**	**9.29**		**KW**	**8.76**		**KW**	**7.82**
1	Λειτουργίες Ναυσιπλοιας	0.80	1	1.60	2.000	2	1	1.00	2.00	1	1.00	2.00	1	0.5	1.00	1	1.00	2.00
								KW	**2.00**		**KW**	**2.00**		**KW**	**1.00**		**KW**	**2.00**
	Σύνολο							**KW**	**13.43**		**KW**	**16.40**		**KW**	**37.28**		**KW**	**11.36**

Table 6.2: Electric balance sheet.

6.2.2 Active and reactive power calculation

The layout of a ship's Electric Balance Sheet leads to the calculation of the required electrical power per operating mode, and then to the selection of the size and number of required batteries. In this section, the concepts of active and reactive power are developed, which are related to the Power Factor (PF) of the consumers, and a methodology for their calculation is presented.

Generally, active power is the useful power generated and consumed in a power grid. This power is consumed in ohmic resistances (eg lighting, heating, etc.), which is usually the bulk of the electrical loads. The effective power is calculated from the following equations:

$$P = V * I * cos\phi \qquad \text{(1 phase)}$$
$$P = \sqrt{3} * V * I * cos\phi \qquad \text{(3 phase)}$$

where $cos\phi$ is the Power Factor and V is line to line voltage.

In addition to the resistors, in a network there are other consumers, such as motors, which produce mechanical rotary or linear motion consuming electrical energy. Typical large coil assemblies (often called winding of electrical machines), which do not require significant power consumption, but require a significant amount of reactive power, are typically required for these consumers. Reactive power can be calculated from the following equations:

$$Q = V * I * sin\phi \qquad \text{(1 phase)}$$
$$Q = \sqrt{3} * V * I * sin\phi \qquad \text{(3 phase)}$$

where $sin\phi = \sqrt{(1 - cos^2\phi)}$ and and V is line to line voltage.

In order to understand the meaning of reactive power, it must be stressed that the circulation of both active and reactive power is via conductors, switches, etc., which also do not have ideal behavior, they are thermally charged and involve a risk of malfunction or destruction. The problem, therefore, is that, in addition to the useful power, in some cases there is a considerable amount of reactive power, obviously at the expense of the former. The problem with the reactive power, demanded mainly by electric motors, is that, on the one hand, some devices must produce it, and on the other hand it must pass through the same paths as the active power, necessarily restricting the latter. Despite the fact that our new power distribution network will be a DC one, we need both, active and reactive power, as we need the whole demanded power that batteries need to produce. So, what is needed is the Apparent Power (vector sum) demand calculated from the following equations:

$$S = V * I \qquad \text{(1 phase)}$$
$$S = \sqrt{3} * V * I \qquad \text{(3 phase)}$$

or alternatively

$$S = \frac{P}{cos\phi}$$
$$S = \frac{Q}{sin\phi}$$

Table 6.3 presents the calculations for the apparent power. The following assumptions have been made:

1) Appliances - facilities such as fuel heaters, kitchens, hobs, lighting panels and navigation aids are considered as resistive loads.

2) The PF is taken equal to 1 for resistive loads and equal to 0.85 for motors.

3) It is considered that inverters and rectifiers transform the hole power from KW to KVA, and vice versa, reduced only from the efficiency factor.

6.2.3 Cables and bus-bars

Cables used on board shall be non-flammable and watertight. Non-flammable are cables that do not ignite to create or transmit the fire, but they are destroyed by high temperatures. Their insulation is usually made from ethyl propylene or polyvinyl chloride.

In order to calculate the standard diameter of the supply cables of the devices, it is first necessary to calculate the value of the current to be drawn by these cables in order to ensure their safe and uninterrupted operation. Diameter is selected based on a standard table of standard cables, Appendix D.

	ΚΑΤΑΝΑΛΩΤΕΣ	V	ΣΙ cosφ	Εγκατεστημένη Ισχύς			Φαινόμενη Απορροφούμενη Ισχύς Μονάδας	Κανονική Πορεία			Ελιγμών			Εν Όρμω			Αναμονής		
								fs	Ισχύς Λειτουργίας Μονάδας	Φαινόμενη Ισχύς Μονάδας	fs	Ισχύς Λειτουργίας Μονάδας	Φαινόμενη Ισχύς Μονάδας	fs	Ισχύς Λειτουργίας Μονάδας	Φαινόμενη Ισχύς Μονάδας	fs	Ισχύς Λειτουργίας Μονάδας	Φαινόμενη Ισχύς Μονάδας
				$P_{ον.αποδ.}$	$P_{ον.απορροφ.}$	$P_{εγκατ.}$	$P_{ον.απορροφ.}$		(P)	(S)		(P)	(S)		(P)	(S)		(P)	(S)
		Volt		KW	KW	KW	KVA		KW	KVA		KW	KVA		KW	KVA		KW	KVA
	ΗΛΕΚΤΡΙΚΕΣ ΚΑΤΑΝΑΛΩΣΕΙΣ ΜΗΧΑΝΟΣΤΑΣΙΟΥ																		
1	Αντλία πυρκαγιάς	380	0.85	5.50	6.47	6.47	7.61	0.85	5.50	6.471	0.85	5.50	6.47	0.20	1.29	1.52	0.00	0.00	0.00
2	Υδροστατικη Αντλια γερανου	380	0.85	22.00	24.44	24.44	28.76	0.00	0.00	0.000	0.00	0.00	0.00	0.90	22.00	25.88	0.90	22.00	25.88
3	Αντλια σεντινών	380	0.85	5.50	6.47	6.47	7.61	0.00	0.00	0.000	0.00	0.00	0.00	0.10	0.65	0.76	0.10	0.65	0.76
4	Αντλια ερματος	380	0.85	5.50	6.47	6.47	7.61	0.00	0.00	0.000	0.00	0.00	0.00	0.20	1.29	1.52	0.20	1.29	1.52
5	Υδρ. Αντλια καπακιων	380	0.85	3.00	3.75	3.75	4.41	0.00	0.00	0.000	0.00	0.00	0.00	0.20	0.75	0.88	0.20	0.75	0.88
6	Ανεμιστήτας Μηχ/σίου	380	0.85	2.20	2.75	5.50	3.24	0.85	2.34	2.750	0.85	2.34	2.75	0.20	0.55	0.65	0.20	0.55	0.65
7	Φωτισμός Μηχ/σίου	220	1	0.29	0.36	0.36	0.36	1	0.36	0.360	1	0.36	0.36	1	0.36	0.36	1.00	0.36	0.36
	ΗΛΕΚΤΡΙΚΕΣ ΚΑΤΑΝΑΛΩΣΕΙΣ ΧΩΡΩΝ ΕΝΔΙΑΙΤΗΣΗΣ																		
1	Φωτισμός	220	1	0.06	0.08	0.08	0.08	1	0.08	0.075	1	0.08	0.08	1	0.08	0.08	1.00	0.08	0.08
	ΗΛΕΚΤΡΙΚΕΣ ΚΑΤΑΝΑΛΩΣΕΙΣ ΠΛΟΙΟΥ																		
1	Εργατης αγκυρων	380	0.85	5.50	6.47	6.47	7.61	0.00	0.00	0.000	0.40	2.59	3.04	0.00	0.00	0.00	0.00	0.00	0.00
2	Αντλια ποσιμου νερου	380	0.85	2.57	3.21	3.21	3.78	0.50	1.61	1.890	0.50	1.61	1.89	0.50	1.61	1.89	0.50	1.61	1.89
3	Αντλια λυματων	380	0.85	1.50	1.88	1.88	2.21	0.00	0.00	0.000	0.00	0.00	0.00	0.50	0.94	1.10	0.00	0.00	0.00
4	Αντλια υγιεινης	380	0.85	3.70	4.63	4.63	5.44	0.40	1.85	2.176	0.40	1.85	2.18	0.40	1.85	2.18	0.40	1.85	2.18
5	Ηλεκτρικη θερμανση νερου	220	1	3.00	3.75	3.75	3.75	0.10	0.38	0.375	0.20	0.75	0.75	0.50	1.88	1.88	0.50	1.88	1.88
6	Ανορθωτης βαρουλκων	380	0.85	2.50	3.13	3.13	3.68	0.00	0.00	0.000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	Φωτισμός χωρου τιμονιου	220	1	0.18	0.23	0.23	0.23	1.00	0.23	0.225	1.00	0.23	0.23	1.00	0.23	0.23	1.00	0.23	0.23
8	Φωτισμός αποθηκης	220	1	0.12	0.15	0.15	0.15	1.00	0.15	0.150	1.00	0.15	0.15	1.00	0.15	0.15	1.00	0.15	0.15
9	Φωτισμος κατ/ματων	220	1	0.66	0.83	0.83	0.83	1.00	0.83	0.825	1.00	0.83	0.83	1.00	0.83	0.83	1.00	0.83	0.83
10	Φωτισμος γεφυρας	220	1	0.05	0.07	0.07	0.07	1.00	0.07	0.068	1.00	0.07	0.07	1.00	0.07	0.07	1.00	0.07	0.07
11	Φωτισμος χωρου αμπαριου	220	1	0.12	0.15	0.15	0.15	1.00	0.15	0.150	1.00	0.15	0.15	1.00	0.15	0.15	1.00	0.15	0.15
12	Φωτισμος χωρων συσσ/των	220	1	0.06	0.08	0.38	0.08	1.00	0.08	0.075	1.00	0.08	0.08	1.00	0.08	0.08	1.00	0.08	0.08
13	Φωτισμος χωρου αντ. πυρ.αναγκης	220	1	0.06	0.08	0.08	0.08	1.00	0.08	0.075	1.00	0.08	0.08	1.00	0.08	0.08	1.00	0.08	0.08
	ΗΛΕΚΤΡΟΝΙΚΑ																		
14	Φορτιστης/ Ανορθωτης μπαταριων	220	0.85	2.50	3.13	3.13	3.68	0.20	0.63	0.735	0.20	0.63	0.74	0.20	0.63	0.74	0.20	0.63	0.74
	ΝΑΥΣΙΠΛΟΙΑ																		
1	Λειτουργίες Ναυσιπλοιας	220	1	1.60	2.00	2.00	2.00	1.00	2.00	2.000	1.00	2.00	2.00	0.50	1.00	1.00	1.00	2.00	2.00

Table 6.3: Apparent power calculations.

I_{line} is called line current and is the current coming out of the source system, leaking the power cables and feeding the consumer systems (loads).

The intensity of the I_{line} is calculated for the load P of the relations:

$$I_{\text{line}} = \frac{P}{V} \qquad \text{(DC)}$$

$$I_{\text{line}} = \frac{P}{V * cosf} \qquad \text{(AC-1 phase)}$$

$$I_{\text{line}} = \frac{P}{\sqrt{3} * V * cosf} \qquad \text{(AC-3 phase)}$$

Current intensity is taken from:

$$I = I_{\text{line}}, \quad \text{for resistive loads}$$

$$I = I_{\text{line}} * 1.25, \quad \text{for motors}$$

Table 6.4 presents the calculations for the diameter of the supply cables. The increment on power demand from DC to AC, or vice versa, is due to inverters (rectifiers) efficiency (98%). The following assumptions have been made:

1) Appliances - facilities such as fuel heaters, kitchens, hobs, lighting panels and navigation aids are considered as resistive loads.

2) The PF is taken equal to 1 for resistive loads and equal to 0.85 for motors.

3) The 380V-AC power supplies are considered as 3 phase and the 220V-AC as 1 phase.

4) The cross section of 1.0 mm^2 from table, is not used (we go to its 1.5 mm^2).

5) It is considered that inverters and rectifiers transform the hole power from KW to KVA, and vice versa, reduced only from the efficiency factor.

All consumers are separated in electric panels. In order to calculate the size of bus sections we need to know the power demand of each panel. Table 6.5 presents the corresponding loads.

			ΚΑΛΩΔΙΑ ΚΑΤΑΝΑΛΩΤΩΝ ΓΙΑ ΡΕΥΜΑ AC								ΚΑΛΩΔΙΑ ΚΑΤΑΝΑΛΩΤΩΝ ΓΙΑ ΡΕΥΜΑ DC							
	ΚΑΤΑΝΑΛΩΤΕΣ	N	V	Φαινόμενη Απορροφούμενη Ισχύς Μονάδας	Ιγ	Συντελ. προσαύξησης	Ιεπιλ	Ιτυπ	Ιασφ	S	V	Απορροφούμενη Ισχύς Μονάδας	Ιγ	Συντελ. προσαύξησης	Ιεπιλ	Ιτυπ	Ιασφ	S
			Volt	KVA	A		A	A	A	mm^2	Volt	KW	A		A	A	A	mm^2
	ΗΛΕΚΤΡΙΚΕΣ ΚΑΤΑΝΑΛΩΣΕΙΣ ΜΗΧΑΝΟΣΤΑΣΙΟΥ																	
1	Αντλία πυρκαγιάς	1	380	7.61	11.57	1.25	14.46	20	20	3*2.5	500	7.77	15.54	1.25	19.42	27	25	3*4
2	Υδροστατικη Αντλια γερανου	1	380	28.76	43.69	1.25	54.62	84	80	3*25	500	29.35	58.69	1.25	73.36	84	80	3*25
3	Αντλια σεντινών	1	380	7.61	11.57	1.25	14.46	20	20	3*2.5	500	7.77	15.54	1.25	19.42	27	25	3*4
4	Αντλια ερματος	1	380	7.61	11.57	1.25	14.46	20	20	3*2.5	500	7.77	15.54	1.25	19.42	27	25	3*4
5	Υδρ. Αντλια καπακιων	1	380	4.41	6.70	1.25	8.38	14	16	3*1.5	500	4.50	9.00	1.25	11.25	14	16	3*1.5
6	Ανεμιστήτας Μηχ/σίου	2	380	3.24	4.92	1.25	6.14	14	16	3*1.5	500	3.30	6.60	1.25	8.25	14	16	3*1.5
7	Φωτισμός Μηχ/σίου	1	220	0.36	1.64	1.00	1.64	14	16	3*1.5	-	-	-	-	-	-	-	-
	ΗΛΕΚΤΡΙΚΕΣ ΚΑΤΑΝΑΛΩΣΕΙΣ ΧΩΡΩΝ ΕΝΔΙΑΙΤΗΣΗΣ																	
1	Φωτισμός	1	220	0.08	0.34	1.00	0.34	14	16	3*1.5	-	-	-	-	-	-	-	-
	ΗΛΕΚΤΡΙΚΕΣ ΚΑΤΑΝΑΛΩΣΕΙΣ ΠΛΟΙΟΥ																	
1	Εργατης αγκυρων	1	380	7.61	11.57	1.25	14.46	20	20	3*2.5	500	7.77	15.54	1.25	19.42	27	25	3*4
2	Αντλια ποσιμου νερου	1	380	3.78	5.74	1.25	7.18	14	16	3*1.5	500	3.86	7.71	1.25	9.64	14	16	3*1.5
3	Αντλια λυματων	1	380	2.21	3.35	1.25	4.19	14	16	3*1.5	500	2.25	4.50	1.25	5.63	14	16	3*1.5
4	Αντλια υγιεινης	1	380	5.44	8.27	1.25	10.33	14	16	3*1.5	500	5.55	11.10	1.25	13.88	20	20	3*2.5
5	Ηλεκτρικη θερμανση νερου	1	220	3.75	17.05	1.00	17.05	20	20	3*2.5	-	-	-	-	-	-	-	-
6	Ανορθωτης βαρουλκων	1	380	3.68	5.59	1.25	6.98	14	16	3*1.5	500	3.75	7.50	1.25	9.38	14	16	3*1.5
7	Φωτισμός χωρου τιμονιου	1	220	0.23	1.02	1.00	1.02	14	16	3*1.5	-	-	-	-	-	-	-	-
8	Φωτισμός αποθηκης	1	220	0.15	0.68	1.00	0.68	14	16	3*1.5	-	-	-	-	-	-	-	-
9	Φωτισμος κατ/ματων	1	220	0.83	3.75	1.00	3.75	14	16	3*1.5	-	-	-	-	-	-	-	-
10	Φωτισμος γεφυρας	1	220	0.07	0.31	1.00	0.31	14	16	3*1.5	-	-	-	-	-	-	-	-
11	Φωτισμος χωρου αμπαριου	1	220	0.15	0.68	1.00	0.68	14	16	3*1.5	-	-	-	-	-	-	-	-
12	Φωτισμος χωρων συσσ/των	5	220	0.08	0.34	1.00	0.34	14	16	3*1.5	-	-	-	-	-	-	-	-
13	Φωτισμος χωρου αντ. πυρ.αναγκης	1	220	0.08	0.34	1.00	0.34	14	16	3*1.5	-	-	-	-	-	-	-	-
	ΗΛΕΚΤΡΟΝΙΚΑ																	
14	Φορτιστης/ Ανορθωτης μπαταριων	1	220	3.68	16.71	1.00	16.71	20	20	3*2.5	-	-	-	-	-	-	-	-
	ΝΑΥΣΙΠΛΟΙΑ																	
1	Λειτουργίες Ναυσιπλοιας	1	220	2.00	9.09	1.00	9.09	14	16	3*1.5	-	-	-	-	-	-	-	-
	ΚΙΝΗΤΗΡΕΣ																	
1	Ηλεκτρικοί Κινητήρες	2	380	403.51	613.07	1.10	674.37	4*192	4*200	4*(3*95))	500	411.74	823.49	1.10	905.84	5*224	5*224	5*(3*120))
	SHORE SIDE																	
1	Shore connection	2	380	338.97	515.01	1.10	566.51	3*192	3*200	3*(3*95)	500	332.19	664.38	1.10	730.82	4*192	4*200	4*(3*95)

Table 6.4: Calculations of cables for AC and DC currents.

									Κανονική Πορεία				Ελιγμών				Εν Όρμω				Αναμονής			
	ΚΑΤΑΝΑΛΩΤΕΣ	η	ΣΙ cosφ	N	Εγκατεστημένη Ισχύς $P_{ον.αποδ.}$	$P_{ον.απορροφ}$	$P_{εγκατ.}$	Φαινόμενη Απορροφούμενη Ισχύς Μονάδας $P_{ον.απορροφ.}$	N΄	f_s	$P_{λειτ.}$	Φαινόμενη Ισχύς Λειρουργίας $P_{Σ.λειτ.}$	N΄	f_s	$P_{λειτ.}$	Φαινόμενη Ισχύς Λειρουργίας $P_{Σ.λειτ.}$	N΄	f_s	$P_{λειτ.}$	Φαινόμενη Ισχύς Λειρουργίας $P_{Σ.λειτ.}$	N΄	f_s	$P_{λειτ.}$	Φαινόμενη Ισχύς Λειρουργίας $P_{Σ.λειτ.}$
					KW	KW	KW	KVA			KW	KVA			KW	KVA			KW	KVA			KW	KVA
	ΖΥΓΟΙ 500V																							
	ΚΕΝΤΡΙΚΟΣ ΠΙΝΑΚΑΣ ΜΗΧΑΝΟΣΤΑΣΙΟΥ 500V																							
1	Αντλία πυρκαγιάς	0.85	0.85	1	5.50	6.47	6.47	7.612	0	0.85	0.00	0.000	0	0.85	0.00	0.000	1	0.20	1.29	1.522	1	0.00	0.00	0.000
2	Αντλια σεντινών	0.85	0.85	1	5.50	6.47	6.47	7.612	1	0.00	0.00	0.000	1	0.00	0.00	0.000	1	0.10	0.65	0.761	0	0.00	0.00	0.000
3	Αντλια ερματος	0.85	0.85	1	5.50	6.47	6.47	7.612	1	0.00	0.00	0.000	1	0.00	0.00	0.000	1	0.20	1.29	1.522	0	0.00	0.00	0.000
4	Υδρ. Αντλια καπακιων	0.80	0.85	1	3.00	3.75	3.75	4.412	1	0.00	0.00	0.000	1	0.00	0.00	0.000	1	0.20	0.75	0.882	0	0.00	0.00	0.000
5	Ανεμιστήτας Μηχ/σίου	0.80	0.85	2	2.20	2.75	5.50	3.235	2	0.85	4.68	5.500	2	0.85	4.68	5.500	2	0.20	1.10	1.294	2	0.20	1.10	1.294
6	Αντλία λυματων	0.80	0.85	1	1.50	1.88	1.88	2.206	1	0.00	0.00	0.000	1	0.00	0.00	0.000	1	0.50	0.94	1.103	0	0.00	0.00	0.000
7	Ανορθωτης βαρουλκων	0.80	0.85	1	2.50	3.13	3.13	3.676	1	0.00	0.00	0.000	1	0.00	0.00	0.000	1	0.00	0.00	0.000	0	0.00	0.00	0.000
										Sum=	4.68	5.500		Sum=	4.68	5.500		Sum=	6.02	7.086		Sum=	1.10	1.294
	ΖΥΓΟΙ 380V																							
	ΥΠΟΠΙΝΑΚΑΣ ΓΕΡΑΝΟΥ																							
1	Υδροστατικη Αντλια γερανου	0.90	0.85	1	22.00	24.44	24.44	28.758	1	0.00	0.00	0.000	1	0.00	0.00	0.000	1	0.90	22.00	25.882	0	0.00	0.00	0.000
										Sum=	0.00	0.000		Sum=	0.00	0.000		Sum=	22.00	25.882		Sum=	0.00	0.000
	ΥΠΟΠΙΝΑΚΑΣ ΑΝΤΛΙΩΝ ΠΟΣΙΜΟΥ ΝΕΡΟΥ ΚΑΙ ΥΓΙΕΙΝΗΣ																							
1	Αντλια υγιεινης	0.80	0.85	1	3.70	4.63	4.63	5.441	1	0.40	1.85	2.176	1	0.40	1.85	2.176	1	0.40	1.85	2.176	1	0.40	1.85	2.176
2	Αντλια ποσιμου νερου	0.80	0.85	1	2.57	3.21	3.21	3.779	1	0.50	1.61	1.890	1	0.50	1.61	1.890	1	0.50	1.61	1.890	1	0.50	1.61	1.890
										Sum=	3.46	4.066		Sum=	3.46	4.066		Sum=	3.46	4.066		Sum=	3.46	4.066
	ΥΠΟΠΙΝΑΚΑΣ ΕΡΓΑΤΗ ΑΓΚΥΡΩΝ																							
1	Εργατης αγκυρων	0.85	0.85	1	5.50	6.47	6.47	7.612	1	0.00	0.00	0.000	1	0.40	2.59	3.045	1	0.00	0.00	0.000	0	0.00	0.00	0.000
										Sum=	0.00	0.000		Sum=	2.59	3.045		Sum=	0.00	0.000		Sum=	0.00	0.000
	ΣΥΝΟΛΟ ΓΙΑ ΖΟΙΓΟ 500V										**8.131**	**9.566**			**10.719**	**12.611**			**31.479**	**37.034**			**4.556**	**5.360**
											KW	**VA**			**KW**	**VA**			**KW**	**VA**			**KW**	**VA**
	ΖΥΓΟΙ 220V																							
	ΚΕΝΤΡΙΚΟΣ ΠΙΝΑΚΑΣ ΜΗΧΑΝΟΣΤΑΣΙΟΥ																							
1	Φωτισμός Μηχ/σίου	0.80	1.00	1	0.29	0.36	0.36	0.360	1	1	0.36	0.360	1	1.00	0.36	0.360	1	1.00	0.36	0.360	1	1.00	0.36	0.360
2	Φωτισμός Ενδιαίτησης	0.80	1.00	1	0.06	0.08	0.08	0.075	1	1	0.08	0.075	1	1.00	0.08	0.075	1	1.00	0.08	0.075	1	1.00	0.08	0.075
3	Φωτισμός χωρου τιμονιου	0.80	1.00	1	0.18	0.23	0.23	0.225	1	1	0.23	0.225	1	1.00	0.23	0.225	1	1.00	0.23	0.225	1	1.00	0.23	0.225
										Sum=	0.66	0.660		Sum=	0.66	0.660		Sum=	0.66	0.660		Sum=	0.66	0.660
	ΥΠΟΠΙΝΑΚΑΣ ΓΕΦΥΡΑΣ																							
1	Φωτισμός αποθηκης	0.80	1.00	1	0.12	0.15	0.15	0.150	1	1	0.150	0.150	1	1.00	0.150	0.150	1	1.00	0.15	0.150	1	1.00	0.15	0.150
2	Φωτισμος κατ/ματων	0.80	1.00	1	0.66	0.83	0.83	0.825	1	1	0.825	0.825	1	1.00	0.825	0.825	1	1.00	0.83	0.825	1	1.00	0.83	0.825
3	Φωτισμος γεφυρας	0.80	1.00	1	0.05	0.07	0.07	0.068	1	1	0.068	0.068	1	1.00	0.068	0.068	1	1.00	0.07	0.068	1	1.00	0.07	0.068
4	Φωτισμος χωρου αμπαριου	0.80	1.00	1	0.12	0.15	0.15	0.150	1	1	0.15	0.150	1	1.00	0.15	0.150	1	1.00	0.15	0.150	1	1.00	0.15	0.150
5	Φωτισμος χωρων συσσ/των	0.80	1.00	5	0.06	0.08	0.38	0.075	5	1	0.38	0.375	5	1.00	0.38	0.375	5	1.00	0.38	0.375	5	1.00	0.38	0.375
6	Φωτισμος χωρου αντ. πυρ.αναγκης	0.80	1.00	1	0.06	0.08	0.08	0.075	1	1	0.08	0.075	1	1.00	0.08	0.075	1	1.00	0.08	0.075	1	1.00	0.08	0.075
7	Φορτιστης/ Ανορθωτης μπαταριων	0.80	0.85	1	2.50	3.13	3.13	3.676	1	0.20	0.63	0.735	1	0.20	0.63	0.735	1	0.20	0.63	0.735	1	0.20	0.63	0.735
8	Ηλεκτρικη θερμανση νερου	0.80	1.00	1	3.00	3.75	3.75	3.750	1	0.10	0.38	0.375	1	0.20	0.75	0.750	1	0.50	1.88	1.875	1	0.50	1.88	1.875
										Sum=	2.64	2.753		Sum=	3.02	3.128		Sum=	4.14	4.253		Sum=	4.14	4.253
	ΥΠΟΠΙΝΑΚΑΣ ΝΑΥΣΙΠΛΟΙΑ																							
1	Λειτουργίες Ναυσιπλοιας	0.80	1.00	1	1.60	2.00	2.00	2.000	1	1.00	2.00	2.000	1	1.00	2.00	2.000	1	0.50	1.00	1.000	1	1.00	2.00	2.000
										Sum=	2.00	2.000		Sum=	2.00	2.000		Sum=	1.00	1.000		Sum=	2.00	2.000
	ΣΥΝΟΛΟ ΓΙΑ ΖΟΙΓΟ 200V										**5.303**	**5.413**			**5.678**	**5.788**			**5.803**	**5.913**			**6.803**	**6.913**
											KW	**VA**			**KW**	**VA**			**KW**	**VA**			**KW**	**VA**
	ΓΕΝΙΚΟ ΣΥΝΟΛΟ										**13.434**	**14.979**			**16.397**	**18.399**			**37.282**	**42.947**			**11.359**	**12.273**
											KW	**VA**			**KW**	**VA**			**KW**	**VA**			**KW**	**VA**

Table 6.5: Power demands of panels.

For the main bus bar calculation we consider the power demand from batteries operation, which exceeds the demand from the shore side supply.

$$I_{\text{line}} = \frac{756.425 * 1000}{500} = 1512.849 \ \ A$$
$$I = 1.1 * I_{\text{line}} = 1512.849 * 1.1 = 1664.134 \ \ A$$

For the bus-bars calculations we consider an extra 10% for safety margin reasons and the standard diameter of the supply cables of the buses is selected by the connection bar table, Appendix D.

From the table mentioned, the cross section of the main bus is selected to be 1600 mm^2. The cables leading to the bus bars and the cross sections of the buses are calculated and presented on Table 6.6, except the shore side cables, the anchor worker, drinking water pump cables, hygiene pump and crane pump cables, calculated on Table 6.4. Crane and anchor pumps are calculated for nominal loads, in order to be able to work in full load, if necessary. The nominal load of hygiene pump also exceeds the mean absorbed operation power of the panel, so the dimension of this bus is calculated according to the hygiene pump nominal absorbed power. The main bar of 220V consists of two leading cables, so the cross section of the bar is calculated with double the power mentioned in the column (Power kVA).

The data of Table 6.6 are calculated according to the mean absorbed operation power (P_{op}, calculated Table 6.5), with the exceptions mentioned above, while the data of consumers, Table 6.4, according to nominal absorbed power ($P_{\text{nm abs}}$).

The list of inverters and rectifiers is presented on table 6.7. These data have been calculated for nominal loads, except the 220V inverters and the shore side rectifiers, which are for operation loads, increased by 10%.

Πίνακες	Ισχύς (kVA)	DC-->AC Efficiency	Απαιτούμενη Ισχύς (KW)	Ρεύμα γραμμής +10% προσαύξηση (A)	Διατομή Καλωδίου (mm^2)	Ασφαλιστική διάταξη	Κύριος Ζυγός Πίνακα (mm^2)
Επίπεδο τάσης 220V							
Υποπίνακας Γέφυρας (AC)	4.25	-	-	21.264	3*4	25 A	100
Υποπίνακας Ναυσιπλοίας (DC)	-	-	2.000	10.000	3*1.5	16 A	100
Μετασχηματιστής 220/24V AC-->DC	3.68	-	-	18.382	3*2.5	20 A	-
Κεντρική μπάρα 220V (AC μετα inverter στα 220V)(2x)	3.46	-	-	9.978	3*1.5	16 A	100
Επίπεδο τάσης 380V							
Υποπίνακας Γερανού (AC)	28.76	-	-	48.063	-	-	100
Υποπίνακας Αντλιών Πόσιμου Νερού κ Υγιεινής	5.44	-	-	9.094	-	-	100
Υποπίνακας Εργάτη Αγκυρών (AC)	7.61	-	-	12.723	-	-	100
Μετασχηματιστές 380/220V (AC)(2x)	3.46	-	-	5.777	3*1.5	16 A	-
Επίπεδο τάσης 500V							
Κεντρική μπάρα(Κεντρικος μηχαν/σιου) (DC)	37.03	0.98	37.790	83.138	3*35	80 A	100
Κεντρικός Πίνακας Μπαταριών (DC)	-	-	756.425	1664.134	3(3*70) per pack	480 A	1600
Κεντρική μπάρα 220V (DC πριν inverter στα 500V)(2x)	3.46	0.98	3.527	7.759	3*1.5	16 A	-

Table 6.6: Electric panels.

Inverters DC-->AC	N	Ισχύς (kVA)	DC-->AC Efficiency	Απαιτούμενη Ισχύς (kW)
Ηλεκτρικοί Κινητήρες	2	403.51	0.98	823.49
Ζυγός 220V	2	3.80	0.98	7.76
Αντλία Λυμάτων	1	2.21	0.98	2.25
Αντλία Έρματος	1	7.61	0.98	7.77
Αντλία Πυρκαγιάς	1	7.61	0.98	7.77
Αντλία Κυτών	1	7.61	0.98	7.77
Αντλία Καλυμάτων Κύτους	1	4.41	0.98	4.50
Ανεμιστήρας Μηχανοστασίου	2	3.24	0.98	6.60
Εργάτης Αγκυρών	1	7.61	0.98	7.77
Αντλία Γερανού	1	28.76	0.98	29.35
Αντλία Υγιεινής	1	5.44	0.98	5.55
Αντλία Πόσιμου Νερού	1	3.78	0.98	3.86
Rectifiers AC-->DC	N	Ισχύς (kW)	AC-->DC Efficiency	Απαιτούμενη Ισχύς (kVA)
Shore connection system (AC-->DC)	2	365.41	0.98	745.73
Sum				**1660.16**

Table 6.7: Inverters-Rectifiers.

Chapter 7

Case Study

7.1 Data analysis

Vessel's main equipment before retrofit is shown:

Main Diesel Engines	2 x MITSUBISHI S6B3-MPTK 463 BHP 1940 RPM
Power generator	1 x DOOSAN AD034TI 42 KW

Table 7.1: Equipment in machinery room.

As mentioned, the chosen battery for the retrofit of the vessel is Valence U27-36XP. Battery modules characteristics are shown on Table 7.2.

As far as the trip is concerned, no data are available. A usual operation of fishing boat is considered. A 19 minute voyage for getting out of the port and go on the open sea is assumed. A stand-by operation is following for 120 minutes to get the cargo and 10 minutes of port load at sea is considered (seaports) in order to load the cargo from the sea and get ready to go back to the port. Another 19 minutes of voyage and 5 minutes of maneuvering complete the trip. Next, 30 minutes of port operation are following (while charging) and 40 minutes of stand-by operation at port to complete the demanded charge of batteries, Figure 7.1.

Valence U27-36XP		
Nominal Module Voltage		38.4 V
Nominal Capacity (C/5, 23°)		46.2 Ah
Dimension		306 x 172 x 255 mm
Weight		19.6 kg
Volume		0.11 m^3
Specific Energy		91 Wh/kg
Price		1100 $
Energy Density		148 Wh/lt
Standard Discharging @25°C)	Max Cont. Current	90 A
	Peak Load Current (30sec)	135 A
	Cut-off Voltage	30 V
Standard Charging	Max Charge Voltage	43.8 V
	Float Voltge	41.4 V
	Rec.Current C/2	23 A
Charging time from 100% DOD --> 0% DOD (h)		2.5

Table 7.2: Battery module specifications.

7.2 Retrofit calculations

There has been a calculation of vessel's demands in power, in all operational modes, in previous chapter, Table 6.5. Required energy per trip is considered with power demand of electric load in port of recharge, being delivered directly from the shore side system. A 4 minute time duration for plug-in and plug –off of the boat is considered. The loads of the calculated electric balance sheet have been increased by the inverters efficiency, as the batteries need to support these loses in order to achieve the demanded power on consumers. The propulsion loads are estimated according to main engine's nominal power, the load factors and the number of operating engines. These loads have also been increased by the electric motors efficiencies, the power factors and the inverters efficiency. The total energy demand to be installed is increased 10% for safety margin reasons. The trip's information are presented on Table 7.3, as well as the corresponding electric demands from batteries.

Concerning the power demands of vessel's function, different scenarios are presented according to the recharge time at port, Table 7.4, Table 7.5, Table 7.6.

Scenario 5 is chosen with 4 packs of batteries for the following reasons:

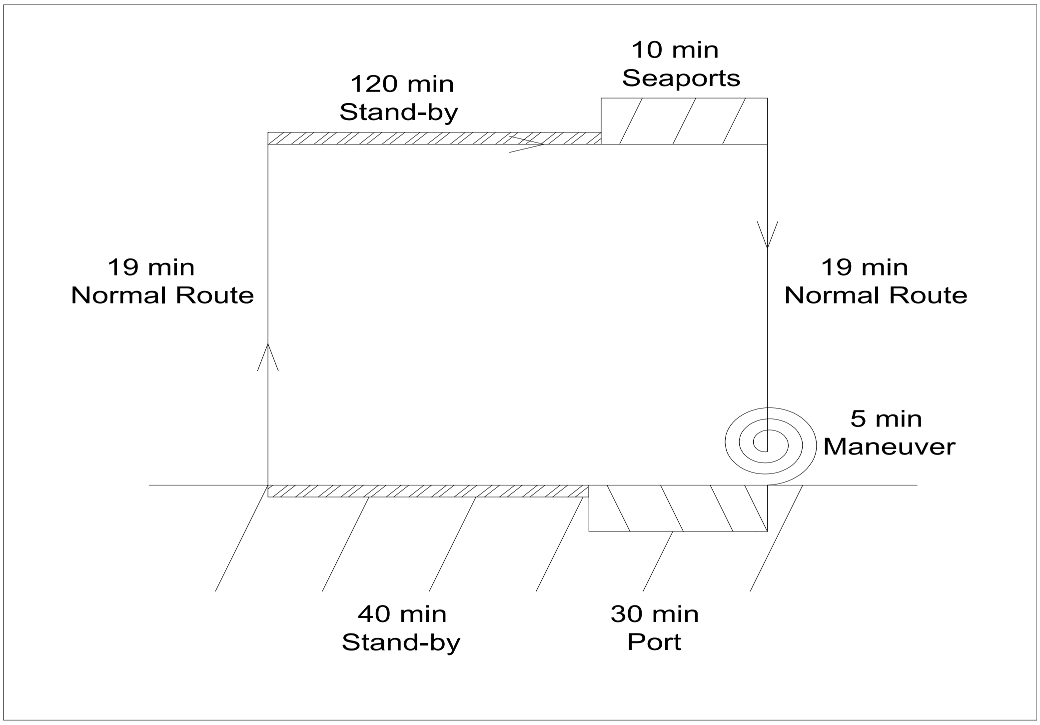


FIGURE 7.1: Voyage diagram.

- The energy after failure of one pack is: $E_{\text{VOYAGE}} = \frac{E_{\text{TRIP}}}{2} = 282\,kWh > E_{\text{REMAIN}} = 245.88\,kWh$. To ensure redundancy we will add 2x14=28 more batteries to add 49.7 kWh at the already existing batteries for emergency (8.64 kWh), Appendix C, to provide $E'_{\text{REMAIN}} = 304.19\,kWh$.

- $\nabla_{\text{TOTAL}} = 7.295 + 0.332 = 7.626\,m^3$. This volume can be fitted in the diesel oil tanks of the vessel, as examined in following table, even with a low permeability coefficient.

- $W_{\text{TOTAL}} = 12.012 + 0.546 = 12.558\,tn$. This weight is higher than the sum of the diesel oil in the vessel's tanks (2 tons higher). Such amount of weight is considered negligible to affect the operation load of the vessel. This speculation is approved from the naval architect of the boat.

- The above life expectancy is estimated for operation at 70% DOD, Figure 5.2.

- The discharge current of batteries is $I = \frac{P_{\text{max}}}{V * N_{\text{total}}} = \frac{756.425}{500*616} = 2.45$ (A), which corresponds to $\frac{C}{18}$, so from Figure 5.3 we can assume that no capacity is lost from high currents, as module of 38.4 V will behave in similar way.

A complete updated electric diagram was redesigned for the new all-electric boat, Appendix E.

Trip Information	
Electrical Load at Normal Route (KW)	14.979
Electrical Load-Batteries at Normal Route (KW)	15.285
Electrical Load in Maneuver (KW)	18.399
Electrical Load-Batteries in Maneuver (KW)	18.774
Electrical Load at Port (kW)	42.947
Electrical Load-Batteries at Port (kW)	43.823
Electrical Load at Stand-by (KW)	12.273
Electrical Load-Batteries at Stand-by (KW)	12.523
Main Engine Load factor-Maneuver	0.7
Main Engine Load Factor-Normal Route	0.9
Main Engine Nominal Power (KW)	345
No of Operating Main Engines at Sea	2
DC-->AC Inverter Efficiency	0.98
Electric Motors Efficiency	0.95
ΣI (cosφ) of electric motor	0.9
Propulsion Load Normal Route (kW)	621.00
Electrical Prop Load Normal Route (kW)	741.14
Propulsion Load Maneuver (kW)	483.00
Electrical Prop Load Maneuver (kW)	576.44
Time of Maneuver(min)	5
Time of Normal Route (min)	19
Time at stand-by	120
Time at Port (min)	30
Time operating seaports at sea (min)	10
Electrical Load-Batteries at stand by (kWh)	25.05
Electric Load-Batteries at Port (kWh)	21.91
Electric Load-Batteries at Seaports (kWh)	7.30
Electric Load-Batteries at Normal Route (kWh)	239.53
Electric Load-Batteries at Maneuver (kWh)	49.60
Energy/trip (kWh)	563.94
Trips/day	2
DOD	0.7
System dc voltage (V)	500

Table 7.3: Trip information.

Senario	Charging time/trip (min) *	Charging %Capacity	energy demand (kWh) increased 10%	n series	N parralel		N total		Installed energy (kWh)	
					2 Bat. Arrays	4 Bat. Arrays	2 Bat. Arrays	4 Bat. Arrays	2 Bat. Arrays	4 Bat. Arrays
1	50	0.307	1232.456	14	50	52	700	728	1241.86	1291.53
2	55	0.340	1192.954	14	50	52	700	728	1241.86	1291.53
3	60	0.373	1155.906	14	48	48	672	672	1192.18	1192.18
4	65	0.407	1121.089	14	46	48	644	672	1142.51	1192.18
5	70	0.440	1088.309	14	44	44	616	616	1092.83	1092.83
6	75	0.473	1057.391	14	44	44	616	616	1092.83	1092.83

TABLE 7.4: Batteries selection t1.

Senario	Energy after failure in 1 array at DOD		Weight (kg)		Volume (L)		Price ($ K)	
	2 Bat. Arrays	4 Bat. Arrays	2 Bat. Arrays	4 Bat. Arrays	2 Bat. Arrays	4 Bat. Arrays	2 Bat. Arrays	4 Bat. Arrays
1	186.278	290.594	13650	14196	8289.540	8621.122	770.000	800.800
2	186.278	290.594	13650	14196	8289.540	8621.122	770.000	800.800
3	178.827	268.241	13104	13104	7957.958	7957.958	739.200	739.200
4	171.376	268.241	12558	13104	7626.377	7957.958	708.400	739.200
5	163.925	245.887	12012	12012	7294.795	7294.795	677.600	677.600
6	163.925	245.887	12012	12012	7294.795	7294.795	677.600	677.600

TABLE 7.5: Batteries selection t2.

Senario	Cycles per Day	Life Expectancy (2 trps/300 days) years	Max Shore Side Power (KW)		Shore Consumed Energy per year kWh
			2 Bat. Arrays	4 Bat. Arrays	4 Bat. Arrays
1	1	18.333	749.003	777.211	411150.51
2	1	18.333	749.003	777.211	393529.99
3	1	18.333	720.796	720.796	384189.47
4	1	18.333	692.589	720.796	367948.94
5	1	18.333	664.382	664.382	362748.42
6	1	18.333	664.382	664.382	347887.89

TABLE 7.6: Batteries selection t3.

The exact amount of volume and weight of the diesel tanks of the vessel is calculated in order to ensure enough space for the installation of the batteries. As shown on Table 7.7, the total number of batteries can be fitted in the diesel oil tanks. Considering different permeability coefficients and ventilation issues, the diesel oil daily service tanks can also be used to achieve the desired space, if necessary. These tanks are highlighted with red line on the vessel's General Arrangement, Appendix E.

Tanks of conventional Fishing Boat "President"						
Diesel Oil Tank (2x)	Length	2	m	Volume	11.52	m^3
	Width	2.4	m			
	Height	1.2	m	Weight	10.14	tn
Diesel Oil Daily Service Tank (2x)	Length	1.5	m	Volume	0.63	m^3
	Width	0.65	m			
	Height	0.75	m	Weight	0.56	tn
Total Volume					**12.15**	**m^3**
Total Weight					**10.69**	**tn**

Table 7.7: Diesel oil tanks.

7.3 Consumption and emissions

The consumption of the conventional vessel is calculated according to methodology mentioned in previous chapter 5.3.2, Table 7.8.

Main			Auxiliary Low			Auxiliary High		
SFOC	lt/h	82.2	SFOC	lt/h	6.3	SFOC	lt/h	11
$T_{per\ day}$	h	1.43	$T_{per\ day}$	h	6.10	$T_{per\ day}$	h	1.33
$DAYS_{oper}$	number	300	$DAYS_{oper}$	number	300	$DAYS_{oper}$	number	300
p	tn/m^3	0.88	p	tn/m^3	0.88	p	tn/m^3	0.88
FC_{day}	tn	0.104	FC_{day}	tn	0.034	FC_{day}	tn	0.013
FC_{annual}	**tn**	**31.10**	**FC_{annual}**	**tn**	**10.15**	**FC_{annual}**	**tn**	**3.87**
Total daily fuel consumption (tn)							**0.15**	
Total annual fuel consumption (tn)							**45.12**	

Table 7.8: Fuel consumption.

The emission factors for calculating the pollutants were taken from ”European Environment Agency” [26], Appendix B. These data were selected for MDO/MGO consumption, according to Tier I standards, Table 7.9.

The quantification of greenhouse gases pollutants are estimated according to ”IPCC 2006” [27], Table 7.10.

Engine	Fuel Type	NO_x EF (kg/tn)	NMVOC EF (kg/tn)	PM_{10} EF (kg/tn)	$PM_{2.5}$ EF (kg/tn)	CO* (kg/tn)	SO_x* (kg/tn)
Main/ Auxiliary	MDO/ MGO	78.5	2.8	1.5	1.4	7.4	20

TABLE 7.9: Emission factors for Tier I.

Engine	Phase	Fuel Type	CO_2 (kg/tn)	CH_4 (kg/tn)	N_20* (kg/tn)
Main/ Aux	Sea	MDO/MGO	3190	0.18	1.3
	Port				

TABLE 7.10: Emission factors for greenhouse gasses.

The total annual emissions are calculated according these data, Table 7.11.

	NO_x EF	NMVOC EF	$PM_{2.5}$ EF	PM_{10} EF	CO*	SO_x*	CO_2	CH_4	N_20*
Sum for 1 Day (kg)	11.8069	0.4211	0.21	0.23	1.113	3.008	479.80	0.0271	0.196
Total Annual Emissions (tn)	**3.54**	**0.13**	**0.06**	**0.07**	**0.33**	**0.90**	**143.94**	**0.008**	**0.06**

TABLE 7.11: Total annual emissions of conventional vessel.

Electricity in Greece is produced with several methods and some of them emit gasses and pollutants, same as diesel oil and gasoline. Collecting some information for the electricity production, it is obvious that these emissions are not negligible, especially from use of fossil fuels and coal [28]. The electricity production in Greece has a significant pollution effect because of the wide use of natural gas and lignite [29], Appendix B. Another important issue is not only the electricity production, but also the gasses emitted during manufacture of batteries. It is really important to investigate the environmental effects and the pollution caused while processing and manufacturing raw materials of battery. Considering that the use of renewable technologies is going to further expand in Europe, and consequently to Greece during next years, there will be a more environmentally friendly operation of an all-electric boat.

Despite the fact that electricity is not, at least not yet, a zero emission source of energy, it is without any doubt that pollution at ports and coastlines will have a zero effect from all-electric boats. Significant amounts of pollutants will not emit in these areas, improving the quality of air and reducing illnesses and environmental destruction, caused by ships and boats.

Chapter 8

Economic Analysis

8.1 Retrofit and functional cost estimation

The final installation cost of the Li-ion battery system is calculated with the extra 28 battery modules of emergency included to the final cost,Table 8.1.

The operation and maintenance cost of both a conventional and an all-electric boat with a Li-ion battery system and their net difference are shown,Table 8.2.

The annual cost of operation for a conventional and an all-electric boat, as well as their net difference is calculated,Table 8.3.

The investment is going to span in a time period of 18 years as shown on Table 7.6, so the future oil and electricity prices must be predicted. The present value of marine diesel oil was assumed after consulting with professor I.Prousalidis. The electricity price was assumed according to the professional invoice for adjustable charges at night zone [30].

Because of the 10% increase of installed energy on board due to safety margin reasons, the final DOD percentage is reduced as shown on Table 8.4. It is then possible to recalculate the lifespan of the battery system. From Figure 5.2, a new life expectancy is assumed to be about 23 years (7000 cycles). Hence, it is safe to assume a 20 year period of operation of the vessel, without install new batteries on board.

Predicting the future price of fuel oil is a difficult task due to the unpredictability of the oil market. With that said all future predictions point to an increase of fuel price [31]. In the present dissertation an annual 3.5% steady increase was assumed as a reasonable

INSTALLATION COST			
	Price per unit	**Price per kW**	**Price (€)**
Initial Cost of Batteries	1100 $	-	708400
Battery Management System	60% of batterries cost	-	425040
Inverters-Rectifiers	-	200 €	332032
Gearbox (x2)	12000 €	-	24000
Cables and bus-bars	5000 €	-	5000
Electric Motor (x2)	-	140 €	96600
Other/Labor	10% of total cost	-	159107.2
Total			1750179.2
SALES OF EXISTING MACHINERY			
	Price per unit	**Price per kW**	**Price (€)**
Existing Main Engine (x2)	-	50 €	34500
Gearbox (x2)	4800 €	-	9600
Existing Electric Generator	-	40 €	1766
Total			45866
Initial Cost of Investment (€)			**1704313**

TABLE 8.1: Vessel's retrofit final cost with Li-ion battery system.

estimation. The estimation of electricity prices in Greece was a more difficult task as there was a lack of available sources covering this subject. Finally, an annual steady rise of 1% was assumed. The savings from fuel of the retrofit vessel are calculated, Table 8.5.

OPERATION & MAINTENANCE COSTS PER YEAR			
WITH BATTERIES			
	Price per unit	**Price per kWh**	**Price (€)**
Fixed Operation & Maintenance costs	1% of Batteries cost	-	6559
Variable Operation & Maintenace costs	-	0.5 €	546
Total			7106
WITH EXISTING MACHINERY			
	Price per unit	**Price per HP**	**Price (€)**
Installed Power of Engines	-	12.6 €	11659
Total			11659
Total Operation & Maintenace Savings per Year (€)			**10795**

Table 8.2: Maintenance savings from all electric boat.

FUEL COST COMPARISON FOR 1 YEAR OPERATION			
WITH BATTERIES			
	Consumption (kWh)	**Price per kWh**	**Price (€)**
Total required energy for 1 year operation	362748	0.0444 €	16102
Total costs of electricity			16102
WITH EXISTING MACHINERY			
	Consumption (tn)	**Price per tn**	**Price (€)**
Total required fuel for 1 year operation	45.12	550 €	24817
Total cost of fuel			24817
Total Fuel Cost Savings for 1st Year (€)			**8715**

Table 8.3: Fuel costs comparison.

Scenario 5- 4 pack		
Installed energy (kWh)		
1092.83		
after [x] charge energy of battery will be (kwh)	[x] charge	before [x] charge battery will have (%)
1009.7381	1	0.4840
926.6430	2	0.4079

TABLE 8.4: State of battery between trips.

	YEAR 1	YEAR 2	YEAR 3	YEAR 4	YEAR 5	YEAR 6	YEAR 7	YEAR 8	YEAR 9	YEAR 10
Price of MDO (€/tn)	550.0	569.3	589.2	609.8	631.1	653.2	676.1	699.8	724.2	749.6
Total cost of fuel (€)	24817	25685.7	26584.7	27515.16	28478.19	29474.93	30506.55	31574.28	32679.38	33823.16
Price of kWh from the Grid (€/kWh)	0.0444	0.0448	0.0453	0.0457	0.0462	0.0467	0.0471	0.0476	0.0481	0.0485
Total cost of electricity (€)	16102	16263.43	16426.06	16590.32	16756.22	16923.79	17093.02	17263.95	17436.59	17610.96
Total Fuel Cost Savings (€)	8715	9422.272	10158.64	10924.84	11721.97	12551.14	13413.53	14310.33	15242.79	16212.2
	YEAR 11	YEAR 12	YEAR 13	YEAR 14	YEAR 15	YEAR 16	YEAR 17	YEAR 18	YEAR 19	YEAR 20
Price of MDO (€/tn)	775.8	803.0	831.1	860.2	890.3	921.4	953.7	987.1	1021.6	1057.4
Total cost of fuel (€)	35007.0	36232.21	37500.34	38812.85	40171.3	41577.3	43032.5	44538.64	46097.5	47710.91
Price of kWh from the Grid (€/kWh)	0.0490	0.0495	0.0500	0.0505	0.0510	0.0515	0.0521	0.0526	0.0531	0.0536
Total cost of electricity (€)	17787	17964.94	18144.59	18326.04	18509.3	18694.39	18881.33	19070.15	19260.85	19453.46
Total Fuel Cost Savings (€)	17220	18267.27	19355.75	20486.82	21662.01	22882.91	24151.17	25468.5	26836.65	28257.45

TABLE 8.5: Fuel and electricity costs estimation for a 20-year period.

8.2 Net present value estimation

As mentioned, the battery modules do not need to be replaced at the 20 years period. The residual value of the batteries was assumed as 20% of their price for recycling purposes and the rest equipment as 60% of the initial value.

For the Net Present Value estimation a discount rate of 6% was assumed. The negative financial net present value of the investment, Table 8.6, shows that the project requires EU assistance or an external fund to make it viable. The Discount Rate at 6% is not an optimistic estimation, so we need to take into consideration different rates of this value to evaluate the investment. The prediction for the diesel and electricity price, is also a parameter to affect the investment. On Figure 8.1 there is an estimation of the minimum percentage of initial quantity and the amount of funding needed for the investment, so that can be considered as marginally acceptable (NPV=0). An estimation has also been occurred for electricity rise rate at 1.5% and 2.5% for diesel oil. The results of the diagram show that at least 50% of the initial investment should be funded, even with a discount rate lower than 3%.

	Discount Rate 6%	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
Costs	-1704312.8	-1704313	0	0	0	0	0	0	0	0	0	0
Savings		0	19509.9	20217.50	20953.86	21720.07	22517.20	23346.37	24208.75	25105.55	26038.01	27007.43
Residual Value of Invetsment		0	0	0	0	0	0	0	0	0	0	0
Net Cash Flow		-1704312.8	19509.9	20217.5	20953.9	21720.1	22517.2	23346.4	24208.75	25105.6	26038.0	27007.43
Value Adjustment		1	1.06	1.1236	1.191016	1.262477	1.338226	1.418519	1.5036303	1.593848	1.689479	1.790848
NPV per year		-1704313	18405.59	17993.5	17593.27	17204.33	16826.16	16458.27	16100.205	15751.54	15411.86	15080.81
			Year 11	Year 12	Year 13	Year 14	Year 15	Year 16	Year 17	Year 18	Year 19	Year 20
Costs			0	0	0	0	0	0	0	0	0	0
Savings			28015.1	29062.50	30150.98	31282.05	32457.23	33678.14	34946.40	36263.72	37631.87	39052.68
Residual Value of Invetsment			0	0	0	0	0	0	0	0	0	754377.8
Net Cash Flow			28015.1	29062.5	30151.0	31282.0	32457.2	33678.1	34946.40	36263.7	37631.9	793430.5
Value Adjustment			1.898299	2.012196	2.132928	2.260904	2.396558	2.540352	2.6927728	2.854339	3.0256	3.207135
NPV per year			14758.02	14443.17	14135.96	13836.08	13543.27	13257.27	12977.849	12704.77	12437.82	247395.4
NPV	**-1167998**											

Table 8.6: Net present value of 20 year period investment.

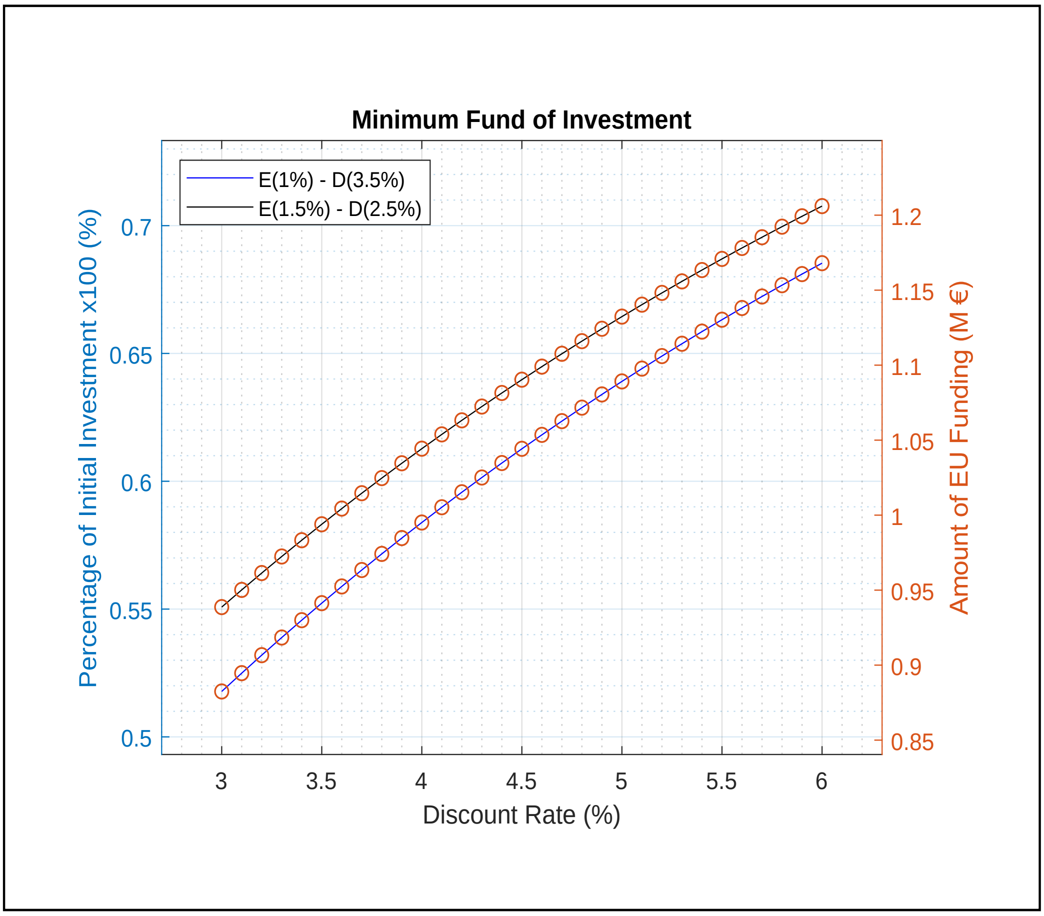


FIGURE 8.1: Minimum acceptable fund.

Chapter 9

Conclusions and Recommendations

9.1 Conclusions

- The retrofit of an existing vessel is not feasible without external financial aid.
- External financial aid, such as European funds, could help to create a more attractive environment for investors.
- The battery system can be easily fitted inside the fuel oil tanks.
- Fuel cost savings are not high and cannot outbalance battery system's expenses taking into account system's life expectancy, despite the wide period.
- Batteries' price is the biggest expenditure and also the cost of inverter's is a high one. If there is a contest for both, the price will significantly diminish.
- Four independent battery packs plus 28 battery modules are installed to ensure vessel's safety and reliability in accordance to the regulations, in case of failure of one pack.
- The weight of the battery packs is quite high, but not enough to be considered significant, increasing the demand of propulsion load.
- The new DC network is recalculated, providing a reliable distribution network with a Low Voltage shore connection.
- An extra 10% of installed energy is installed on board to ensure redundancy during vessel's operation.

- Specific regulations and guidelines are being adopted, providing reliable operation and safety for all the crew and passengers.

An all-electric boat, without any doubt, will benefit the environment.It will help in reducing the amount of pollutants emitted locally, at port of duties and all the nearby coastlines. In addition, there will be significant reduce at noise, especially in a populated port city. Another thing to consider is that an all-electric vessel will help in the reduction of carbon footprint as well as the emission of other pollutants nationally. The annual amount of pollutants produced by on-shore power supply and the amount of pollutants generated by onboard power generation is significant. Despite that, though, there is reduction from a conventional boat with traditional propulsion system. If Greece focuses in evolving its infrastructure by incorporating greener energy generation technologies, these benefits could become even greater.

The all-electric boat is an expensive boat, as proved. The NPV was negative, resulting in low expectations for the retrofit of a vessel. Without any fund, the investment could not be feasible as the cost of retrofit is very high and cannot be compensated by the fuel savings and operation and maintenance costs. The EU seems to be able to provide large amounts for green energy, making the retrofit discussion really attractive for future implementations, not only for existing boats, but also for new ones.

Thinking about the future of electric boats and vehicles, it is obvious that further developments on battery chemistries are expected to be massive from every aspect i.e. specific energy, shape, charging time, pollution. A great decline in battery prices is about to come which, combined with better and more efficient electric motors, will make retrofit a really competitive and green investment, attracting ship owners of larger and more expensive ships. ,

9.2 Recommendations

The retrofit of a vessel has a significant cost, mainly because of the high cost of the batteries. Further investigations for different battery chemistries and improvements of the existing types is of major importance, in order to improve the performance of batteries, lower their weight and their size and reduce the total cost. This will lead to a feasible investment, with low risk and benefits for the ship owner and the environment.

A really important issue is the space where the batteries will be installed. The battery room has to be a dedicated room to host the batteries. During vessel's operation a lot of heat will be realeased from batteries, increasing the temperature of the room. Proper ventilation is vital for regular operation of batteries and safe function of the boat. It is an issue which needs further investigation, as no significant research has been made.

Following what has been said, development of appropriate rules and recommended practices is necessary for the safe implementation of any of these technologies in the future. There has been a comparison on ABS and DNV-GL guidelines on this diploma thesis to mention the most dangerous and vulnerable aspects of vessel's retrofit. Existing guidelines do not specify standards and appropriate installation and operation methods, in order to ensure normal operation and safety.

Emissions from vessels contribute to the environmental problem that ports and industrial cities face. Retrofit of boats with batteries is a really promising alternative to minimize the pollution but, as discussed, electricity production in Greece emits significant amounts of pollutants. Greece should augment the proportion of power generation from renewable resources. In addition to this, measuring the emissions from a battery-boat it has to be taken into account that significant pollutants are exposed to atmosphere during construction of batteries. These values need to be measured and considered in the electrification process and estimations of an electric vessel. In that way, the first 100% zero-emission vessels can be launched.

Finally, a suitable and reliable shore side system has to be developed, to ensure safe operation and redundancy on power demand.

Appendix A

Battery System Tests

Test	Comments	Component	TT/RT
External Short Circuit with no BMS	UN38.3/IEC62281	Module, Sub pack	TT
External short with operable BMS	Could also be performed with a complete string, requires a controller with breakers/relays	Sub pack	TT
Internal Thermal Event	Propagation on pack level. IEC62619 is assumed to cover relevant recommendations: - unchanged module/pack structure (mechanical/electrical) - SOC 100%, all cells balanced - Normal temperature (alternative: max operation temperature) - passive/charging/discharging status - single cell set off on purpose (thermal element or other, cell location to be discussed) - etc.	Sub pack	TT
Overcharge with no BMS	UN38.3/IEC62281	Sub pack	TT
Emergency stop function	-	Battery system	RT
Alarms and shutdowns	-	Battery system	RT
HVIL	-	Battery system	RT
Temperature protection BMS	-	Battery system	RT
Overvoltage protection BMS	-	Battery system	RT
Undervoltage protection BMS	-	Battery system	RT
Sensor failures	-	Battery system	TT
Communication Failure	-	Battery system	RT
Reverse polarity protection	-	Battery system	RT
Nail Test	UL2580	Cell	TT

TABLE A.1: Battery system safety tests.

Test	Comments	DUT	TT/RT
Cell balancing	According to specification	Battery system	RT
SOC validation	Validate the measured SOC	Battery system	RT
Charging behavior	According to specification	Battery system	RT
Discharge behavior	According to specification	Battery system	RT
Capacity check	According to specification	Battery system	RT

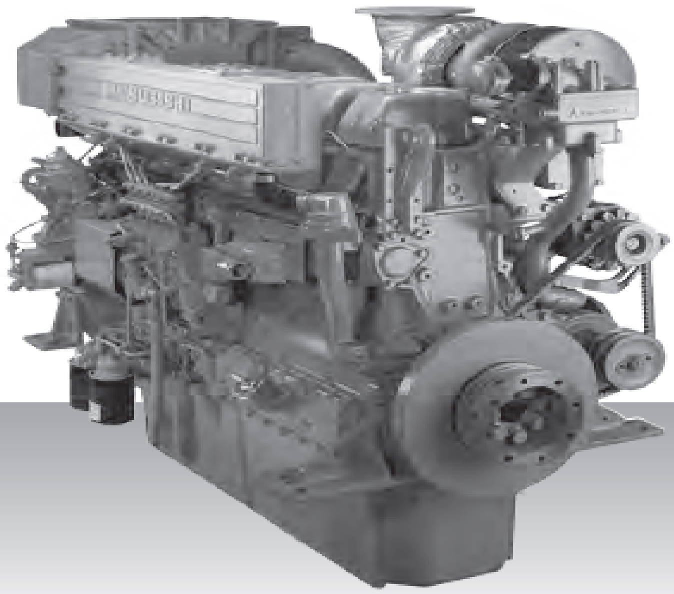
Table A.2: Battery system performance tests.

Appendix B

Main engines and emission factors

Propulsion - IMO Tier I / non emission
High speed - Engine

S6B3-MPTK



6-cylinder, 4-cycle, water cooled diesel engine,
wih direct-injection, turbocharger and air-cooler.

Bore x stroke (mm) : 135 x 170
Displacement (l) : 14.60

Commercial rating

kW	bhp	rpm	Rating	Fuel cons. l/hr*	Emission
345	463	1,940	UCD	59.6	IMO-T1
380	510	2,000	HD	68.0	IMO-T1
415	557	2,065	MD	on request	IMO-T1

*Average fuel consumption according to ISO, see page 6.
Specifications / data subject to change without prior notice.

TABLE B.1: Data of main engines.

Table 3-2 Tier 1 emission factors for ships using marine diesel oil/marine gas oil

Tier 1 default emission factors					
	Code	Name			
NFR Source Category	1.A.3.d.i	International navigation			
Fuel	Marine diesel oil/marine gas oil (MDO/MGO)				
Not applicable	Aldrin, Chlordane, Chlordecone, Dieldrin, Endrin, Heptachlor, Heptabromo-biphenyl, Mirex,				
Not estimated	NH3, Benzo(a)pyrene, Benzo(b)fluoranthene, Benzo(k)fluoranthene, Indeno(1,2,3-cd)pyrene, Total 4 PAHs				
Pollutant	**Value**	**Unit**	**95% confidence interval**		**Reference**
			Lower	**Upper**	
NOx	78.5	kg/tonne fuel	0	0	Entec (2007). See also note (2)
CO	7.4	kg/tonne fuel	0	0	Lloyd's Register (1995)
NMVOC	2.8	kg/tonne fuel	0	0	Entec (2007). See also note (2)
SOx	20	kg/tonne fuel	0	0	Note value of 20 should read
TSP	1.5	kg/tonne fuel	0	0	Entec (2007)
PM10	1.5	kg/tonne fuel	0	0	Entec (2007)
PM2.5	1.4	kg/tonne fuel	0	0	Entec (2007)
Pb	0.13	g/tonne fuel	0	0	average value
Cd	0.01	g/tonne fuel	0	0	average value
Hg	0.03	g/tonne fuel	0	0	average value
As	0.04	g/tonne fuel	0	0	average value
Cr	0.05	g/tonne fuel	0	0	average value
Cu	0.88	g/tonne fuel	0	0	average value
Ni	1	g/tonne fuel	0	0	average value
Se	0.1	g/tonne fuel	0	0	average value
Zn	1.2	g/tonne fuel	0	0	average value
PCB	0.038	mg/tonne fuel	0	0	Cooper (2005)
PCDD/F	0.13	ug I-TEQ/tonne	0	0	Cooper (2005)
HCB	0.08	mg/tonne fuel	0	0	Cooper (2005)

Notes

1. S = percentage sulphur content in fuel; pre-2000 fuels: 0.5 % wt. [source: Lloyd's Register, 1995]. For European Union as specified in the Directive 2005/33/EC:
   a. 0.2 % wt. from 1 July 2000 and 0.1 % wt. from 1 January 2008 for marine diesel oil/marine gas oil used by seagoing ships (except if used by ships crossing a frontier between a third country and a Member State);
   b. 0.1% wt. from 1 January 2010 for inland waterway vessels and ships at berth in Community ports.
2. Emission factor for NO_x and NMVOC are the 2000 values in cruise for medium speed engines (see Tier 2).
3. Reference: 'average value' is between Lloyd's Register (1995) and Cooper and Gustafsson (2004)

Table B.2: Emission factors table.

EnEx
Energy Exchange Group

ΜΗΝΙΑΙΟ ΔΕΛΤΙΟ ΣΥΣΤΗΜΑΤΟΣ ΣΥΝΑΛΛΑΓΩΝ ΗΕΠ ΙΟΥΝΙΟΣ 2018

3. Ενεργειακό Ισοζύγιο ΗΕΠ

	Ιούνιος 2018	% μεταβολή (ως προς 06/2017)	Ιανουάριος - Ιούνιος 2018	% μεταβολή (ως προς 01-06/2017)
ΠΑΡΑΓΩΓΗ ΚΑΙ ΙΣΟΖΥΓΙΟ ΕΙΣΑΓΩΓΩΝ - ΕΞΑΓΩΓΩΝ (MWh)				
ΣΥΝΟΛΟ ΠΑΡΑΓΩΓΗΣ & ΙΣΟΖΥΓΙΟΥ ΕΙΣΑΓΩΓΩΝ - ΕΞΑΓΩΓΩΝ	**4,241,384**	**0.81**	**24,690,131**	**-1.38**
ΑΝΑΛΥΣΗ ΚΑΘ. ΠΑΡΑΓΩΓΗΣ				
ΛΙΓΝΙΤΙΚΗ	1,341,102	2.43	6,818,760	-20.72
ΠΕΤΡΕΛΑΪΚΗ	0	0.00	0	0.00
ΦΥΣΙΚΟΥ ΑΕΡΙΟΥ	1,236,852	-16.62	6,573,326	-13.81
ΥΔΡΟΗΛΕΚΤΡΙΚΗ	350,119	52.83	2,877,148	153.98
ΑΠΕ	764,121	21.77	4,929,145	13.58
ΣΥΝΟΛΟ ΚΑΘ. ΠΑΡΑΓΩΓΗΣ	**3,692,194**	**1.18**	**21,198,378**	**-2.31**

Table B.3: Emission factors for electricity production.

Appendix C

Electric balance sheet

1Γ. ΗΛΕΚΤΡΙΚΟΣ ΙΣΟΛΟΓΙΣΜΟΣ: ΚΑΝΟΝΙΚΗΣ ΠΟΡΕΙΑΣ

1Γ.α ΗΛΕΚΤΡΙΚΕΣ ΚΑΤΑΝΑΛΩΣΕΙΣ ΜΗΧΑΝΟΣΤΑΣΙΟΥ

Α/Α	Ονομασία Ηλεκτρικού Καταναλωτή	Ονομαστική Ισχύς [KW]	Αριθμός Εγκατεστημένων Μονάδων	Συντελεστής Λειτουργίας	Αριθμός Μονάδων σε Λειτουργία	Απορροφούμενη Ισχύς από καταναλωτή
1	Αντλία μετάγγισης καυσίμου	0,750	1	0,10	1	0,075
2	Αντλία πυρκαγιάς	(d)	1	-	-	-
3	Υδρ. Αντλία γερανού	22,000	1	0,00	1	0,000
4	Αντλία σεντινών	5,500	1	0,00	1	0,000
5	Αντλία έρματος	5,500	1	0,00	1	0,000
6	Υδρ. Αντλία καπακιών	3,000	1	0,00	1	0,000
7	Ανεμιστήρας Μηχ/σίου	2,200	2	0,85	2	3,740
8	Φωτισμός Μηχ/σίου	0,288	-	1,00	-	0,288
Συνολική Απορροφούμενη Ισχύς						**4,103**

1Γ.β ΗΛΕΚΤΡΙΚΕΣ ΚΑΤΑΝΑΛΩΣΕΙΣ ΧΩΡΩΝ ΕΝΔΙΑΙΤΗΣΗΣ

Α/Α	Ονομασία Ηλεκτρικού Καταναλωτή	Ονομαστική Ισχύς [KW]	Αριθμός Εγκατεστημένων Μονάδων	Συντελεστής Λειτουργίας	Αριθμός Μονάδων σε Λειτουργία	Απορροφούμενη Ισχύς από καταναλωτή
1	Φωτισμός	0,060	-	1,00	-	0,060
Συνολική Απορροφούμενη Ισχύς						**0,060**

1Γ.γ ΗΛΕΚΤΡΙΚΕΣ ΚΑΤΑΝΑΛΩΣΕΙΣ ΠΛΟΙΟΥ

Α/Α	Ονομασία Ηλεκτρικού Καταναλωτή	Ονομαστική Ισχύς [KW]	Αριθμός Εγκατεστημένων Μονάδων	Συντελεστής Λειτουργίας	Αριθμός Μονάδων σε Λειτουργία	Απορροφούμενη Ισχύς από καταναλωτή
1	Εργάτης αγκύρων	5,500	1	0,00	-	0,000
2	Αντλία πόσιμου νερού	2,570	1	0,50	-	1,285
3	Αντλία λυμάτων	1,500	1	0,00	1	0,000
4	Αντλία υγιεινής	3,700	1	0,40	1	1,480
5	Ηλεκτρική θέρμανση νερού	3,000	1	0,10	1	0,300
6	Ανορθωτής βαρούλκων	2,500	1	0,00	1	0,000

7	Φωτισμός Χώρου Τιμονιού	0,180	-	1,00	-	0,180
8	Φωτισμός Αποθήκης	0,120	-	1,00	-	0,120
9	Φωτισμός Κατ/μάτων	0,660	-	1,00	-	0,660
10	Φωτισμός Γέφυρας	0,054	-	1,00	-	0,054
11	Φωτισμός Χώρου Αμπαριού	0,120	-	1,00	-	0,120
12	Φωτισμός Χώρου Συσσ/τών	0,060	-	1,00	-	0,060
13	Φωτισμός Χώρου Αντλίας πυρ. ανάγκης	0,060	-	1,00	-	0,060
ΗΛΕΚΤΡΟΝΙΚΑ						
14	Φορτιστής / Ανορθωτής Μπαταριών	2,500	1	0,20	1	0,500
Συνολική Απορροφούμενη Ισχύς						**4,819**

Απαιτούμενη Συνολική Ισχύς σε κανονική πορεία.

Γ.α ΗΛΕΚΤΡΙΚΕΣ ΚΑΤΑΝΑΛΩΣΕΙΣ ΜΗΧΑΝΟΣΤΑΣΙΟΥ	4,103 [KW]
Γ.β ΗΛΕΚΤΡΙΚΕΣ ΚΑΤΑΝΑΛΩΣΕΙΣ ΧΩΡΩΝ ΕΝΔΙΑΙΤΗΣΗΣ	0,060 [KW]
Γ.γ ΗΛΕΚΤΡΙΚΕΣ ΚΑΤΑΝΑΛΩΣΕΙΣ ΠΛΟΙΟΥ	4,819 [KW]
ΣΥΝΟΛΟ	**8,982 [KW]**

Στο πλοίο υπάρχει μία (1) ηλεκτρική γεννήτρια DOOSAN, τύπου AD034TI, ονομαστικής ισχύος 44,160 [KW].

Βαθμός φορτίσεως γεννήτριας 8,982/44,160= 0,203 = 20,3 %
Επομένως, η γεννήτρια δύναται να φέρει με ασφάλεια το συνολικό ηλεκτρικό φορτίο του πλοίου.

1Δ. ΗΛΕΚΤΡΙΚΟΣ ΙΣΟΛΟΓΙΣΜΟΣ: ΚΑΤΑΣΤΑΣΗΣ ΕΛΙΓΜΩΝ

1Δ.α ΗΛΕΚΤΡΙΚΕΣ ΚΑΤΑΝΑΛΩΣΕΙΣ ΜΗΧΑΝΟΣΤΑΣΙΟΥ

Α/Α	Ονομασία Ηλεκτρικού Καταναλωτή	Ονομαστική Ισχύς [KW]	Αριθμός Εγκατεστημένων Μονάδων	Συντελεστής Λειτουργίας	Αριθμός Μονάδων σε Λειτουργία	Απορροφούμενη Ισχύς από καταναλωτή
1	Αντλία μετάγγισης καυσίμου	0,750	1	0,00	1	0,000
2	Αντλία πυρκαγιάς	(d)	1	-	-	-
3	Υδρ. Αντλία γερανού	22,000	1	0,00	1	0,000
4	Αντλία σεντινών	5,500	1	0,00	1	0,000
5	Αντλία έρματος	5,500	1	0,00	1	0,000
6	Υδρ. Αντλία καπακιών	3,000	1	0,00	1	0,000
7	Ανεμιστήρας Μηχ/σίου	2,200	2	0,85	2	3,740
8	Φωτισμός Μηχ/σίου	0,288	-	1,00	-	0,288
Συνολική Απορροφούμενη Ισχύς						**4,028**

1Δ.β ΗΛΕΚΤΡΙΚΕΣ ΚΑΤΑΝΑΛΩΣΕΙΣ ΧΩΡΩΝ ΕΝΔΙΑΙΤΗΣΗΣ

Α/Α	Ονομασία Ηλεκτρικού Καταναλωτή	Ονομαστική Ισχύς [KW]	Αριθμός Εγκατεστημένων Μονάδων	Συντελεστής Λειτουργίας	Αριθμός Μονάδων σε Λειτουργία	Απορροφούμενη Ισχύς από καταναλωτή
1	Φωτισμός	0,060	-	1,00	-	0,060
Συνολική Απορροφούμενη Ισχύς						**0,060**

1Δ.γ ΗΛΕΚΤΡΙΚΕΣ ΚΑΤΑΝΑΛΩΣΕΙΣ ΠΛΟΙΟΥ

Α/Α	Ονομασία Ηλεκτρικού Καταναλωτή	Ονομαστική Ισχύς [KW]	Αριθμός Εγκατεστημένων Μονάδων	Συντελεστής Λειτουργίας	Αριθμός Μονάδων σε Λειτουργία	Απορροφούμενη Ισχύς από καταναλωτή
1	Εργάτης αγκύρων	5,500	1	0,40	-	2,200
2	Αντλία πόσιμου νερού	2,570	1	0,50	-	1,285
3	Αντλία λυμάτων	1,500	1	0,00	1	0,000
4	Αντλία υγιεινής	3,700	1	0,40	1	1,480
5	Ηλεκτρική θέρμανση νερού	3,000	1	0,20	1	0,600
6	Ανορθωτής βαρούλκων	2,500	1	0,00	1	0,000

7	Φωτισμός Χώρου Τιμονιού	0,180	-	1,00	-	0,180
8	Φωτισμός Αποθήκης	0,120	-	1,00	-	0,120
9	Φωτισμός Κατ/μάτων	0,660	-	1,00	-	0,660
10	Φωτισμός Γέφυρας	0,054	-	1,00	-	0,054
11	Φωτισμός Χώρου Αμπαριού	0,120	-	1,00	-	0,120
12	Φωτισμός Χώρου Συσσ/τών	0,060	-	1,00	-	0,060
13	Φωτισμός Χώρου Αντλίας πυρ. ανάγκης	0,060	-	1,00	-	0,060
ΗΛΕΚΤΡΟΝΙΚΑ						
14	Φορτιστής / Ανορθωτής Μπαταριών	2,500	1	0,20	1	0,500
Συνολική Απορροφούμενη Ισχύς						**7,319**

Απαιτούμενη Συνολική Ισχύς σε κατάσταση ελιγμών.

Δ.α ΗΛΕΚΤΡΙΚΕΣ ΚΑΤΑΝΑΛΩΣΕΙΣ ΜΗΧΑΝΟΣΤΑΣΙΟΥ 4,028 [KW]

Δ.β ΗΛΕΚΤΡΙΚΕΣ ΚΑΤΑΝΑΛΩΣΕΙΣ ΧΩΡΩΝ ΕΝΔΙΑΙΤΗΣΗΣ 0,060 [KW]

Δ.γ ΗΛΕΚΤΡΙΚΕΣ ΚΑΤΑΝΑΛΩΣΕΙΣ ΠΛΟΙΟΥ 7,319 [KW]

ΣΥΝΟΛΟ **11,407 [KW]**

Στο πλοίο υπάρχει μία (1) ηλεκτρική γεννήτρια, τύπου DOOSAN, ονομαστικής ισχύος 44,160 [KW].

Βαθμός φορτίσεως γεννήτριας 11,407/44,160= 0,258 = 25,8%
Επομένως, η γεννήτρια δύναται να φέρει με ασφάλεια το συνολικό ηλεκτρικό φορτίο του πλοίου.

1Ε. ΗΛΕΚΤΡΙΚΟΣ ΙΣΟΛΟΓΙΣΜΟΣ: ΚΑΤΑΣΤΑΣΗ ΟΡΜΟΥ

1Ε.α ΗΛΕΚΤΡΙΚΕΣ ΚΑΤΑΝΑΛΩΣΕΙΣ ΜΗΧΑΝΟΣΤΑΣΙΟΥ

Α/Α	Ονομασία Ηλεκτρικού Καταναλωτή	Ονομαστική Ισχύς [KW]	Αριθμός Εγκατεστημένων Μονάδων	Συντελεστής Λειτουργίας	Αριθμός Μονάδων σε Λειτουργία	Απορροφούμενη Ισχύς από καταναλωτή
1	Αντλία μετάγγισης καυσίμου	0,750	1	0,20	1	0,150
2	Αντλία πυρκαγιάς	5,500	1	0,20	1	1,100
3	Υδρ. Αντλία γερανού	22,000	1	0,90	1	19,800
4	Αντλία σεντινών	5,500	1	0,10	1	0,550
5	Αντλία έρματος	5,500	1	0,20	1	1,100
6	Υδρ. Αντλία καπακιών	3,000	1	0,20	1	0,600
7	Ανεμιστήρας Μηχ/σίου	2,200	2	0,20	2	0,880
8	Φωτισμός Μηχ/σίου	0,288	-	1,00	-	0,288
Συνολική Απορροφούμενη Ισχύς						**24,468**

1Ε.β ΗΛΕΚΤΡΙΚΕΣ ΚΑΤΑΝΑΛΩΣΕΙΣ ΧΩΡΩΝ ΕΝΔΙΑΙΤΗΣΗΣ

Α/Α	Ονομασία Ηλεκτρικού Καταναλωτή	Ονομαστική Ισχύς [KW]	Αριθμός Εγκατεστημένων Μονάδων	Συντελεστής Λειτουργίας	Αριθμός Μονάδων σε Λειτουργία	Απορροφούμενη Ισχύς από καταναλωτή
1	Φωτισμός	0,060	-	1,00	-	0,060
Συνολική Απορροφούμενη Ισχύς						**0,060**

1Ε.γ ΗΛΕΚΤΡΙΚΕΣ ΚΑΤΑΝΑΛΩΣΕΙΣ ΠΛΟΙΟΥ

Α/Α	Ονομασία Ηλεκτρικού Καταναλωτή	Ονομαστική Ισχύς [KW]	Αριθμός Εγκατεστημένων Μονάδων	Συντελεστής Λειτουργίας	Αριθμός Μονάδων σε Λειτουργία	Απορροφούμενη Ισχύς από καταναλωτή
1	Εργάτης αγκύρων	5,500	1	-	-	-
2	Αντλία πόσιμου νερού	2,570	1	0,50	-	1,285
3	Αντλία λυμάτων	1,500	1	0,50	1	0,750
4	Αντλία υγιεινής	3,700	1	0,40	1	1,480
5	Ηλεκτρική θέρμανση νερού	3,000	1	0,50	1	1,500
6	Ανορθωτής βαρούλκων	2,500	1	0,00	1	0,000

7	Φωτισμός Χώρου Τιμονιού	0,180	-	1,00	-	0,180
8	Φωτισμός Αποθήκης	0,120	-	1,00	-	0,120
9	Φωτισμός Κατ/μάτων	0,660	-	1,00	-	0,660
10	Φωτισμός Γέφυρας	0,054	-	1,00	-	0,054
11	Φωτισμός Χώρου Αμπαριού	0,120	-	1,00	-	0,120
12	Φωτισμός Χώρου Συσσ/τών	0,060	-	1,00	-	0,060
13	Φωτισμός Χώρου Αντλίας πυρ. ανάγκης	0,060	-	1,00	-	0,060
ΗΛΕΚΤΡΟΝΙΚΑ						
14	Φορτιστής / Ανορθωτής Μπαταριών	2,500	1	0,20	1	0,500
Συνολική Απορροφούμενη Ισχύς						**6,769**

Απαιτούμενη Συνολική Ισχύς στον όρμο.

Ε.α ΗΛΕΚΤΡΙΚΕΣ ΚΑΤΑΝΑΛΩΣΕΙΣ ΜΗΧΑΝΟΣΤΑΣΙΟΥ	24,468 [KW]
Ε.β ΗΛΕΚΤΡΙΚΕΣ ΚΑΤΑΝΑΛΩΣΕΙΣ ΧΩΡΩΝ ΕΝΔΙΑΙΤΗΣΗΣ	0,060 [KW]
Ε.γ ΗΛΕΚΤΡΙΚΕΣ ΚΑΤΑΝΑΛΩΣΕΙΣ ΠΛΟΙΟΥ	6,769 [KW]
ΣΥΝΟΛΟ	**31,297 [KW]**

Στο πλοίο υπάρχει μία (1) ηλεκτρική γεννήτρια, τύπου DOOSAN, ονομαστικής ισχύος 44,160 [KW].

Βαθμός φορτίσεως γεννήτριας 31,297/44,160 = 0,709= 70,9 %
Επομένως, η γεννήτρια δύναται να φέρει με ασφάλεια το συνολικό ηλεκτρικό φορτίο του πλοίου.

2. <u>ΗΛΕΚΤΡΙΚΟΣ ΙΣΟΛΟΓΙΣΜΟΣ ΚΑΤΑΝΑΛΩΣΕΩΝ ΑΝΑΓΚΗΣ 24 και 12 VOLTS</u>

2Α. ΣΥΣΣΩΡΕΥΤΕΣ ΑΝΑΓΚΗΣ :

Το πλοίο φέρει, στο Χώρο των συσσωρευτών, δύο συστοιχίες συσσωρευτών, εντός στεγανών κουτιών.

Η κάθε συστοιχία αποτελείται από δύο συσσωρευτές 12 [Volts], 180 AH ο καθένας, συνδεδεμένων σε σειρά.

Συνεπώς η τάση λειτουργίας κάθε συστοιχίας είναι: 2 x 12 = 24 [Volts] και η χωρητικότητα κάθε μίας 180 AH.

Οι συστοιχίες τροφοδοτούν το κύκλωμα ανάγκης του πλοίου, μέσω μεταγωγικού διακόπτη, η κάθε μία χωριστά.

Συνεπώς, η συνολική χωρητικότητα των δύο συστοιχιών είναι : 2 x 180 = 360 AH.

2Β. ΥΠΟΛΟΓΙΣΜΟΣ ΚΑΤΑΝΑΛΩΣΗΣ ΦΩΤΙΣΜΟΥ ΑΝΑΓΚΗΣ

1. **Συνολικός Αριθμός Λαμπτήρων Ανάγκης Μηχανοστασίου 24 [Volts].**

   Το μηχανοστάσιο φέρει τρία (3) φωτιστικά σώματα 24V DC, ισχύος 25 [Watt] το καθένα.

2. **Συνολικός Αριθμός Λαμπτήρων Ανάγκης Χώρου Τιμονιού.**

   Ο χώρος τιμονιού φέρει ένα (1) φωτιστικό σώμα ανάγκης, ισχύος 25 [Watt].

3. **Συνολικός Αριθμός Λαμπτήρων Ανάγκης Αποθήκης.**

   Στην αποθήκη υπάρχει ένα (1) φωτιστικό σώμα ανάγκης, ισχύος 25 [Watt].

4. **Συνολικός Αριθμός Λαμπτήρων Ανάγκης Εξωτερικών Καταστρωμάτων.**

   Υπάρχουν συνολικά τρία (3) φωτιστικά σώματα 24V DC, ισχύος 25 [W] το καθένα και ένας προβολέας ερεύνης, ισχύος 150 [W].

5. **Συνολικός Αριθμός Λαμπτήρων Ανάγκης Γέφυρας.**

   Φέρει δύο (2) φωτιστικά σώματα 24V DC, ισχύος 25 [Watt] το καθένα.

6. **Συνολικός Αριθμός Λαμπτήρων Πλοϊκών Φώτων.**

   Συνολικά τα πλοϊκά φώτα είναι εννέα (9), ισχύος 25 [W] το καθένα.

Στον πιο κάτω πίνακα υπολογίζεται η συνολική απαιτούμενη ηλεκτρική ισχύς ανάγκης.

Appendix D

Tables of connection bars and cables

Nominal cross-section		Continuous service		Half-hour service 30 minutes		Intermittent service Ratio 40 %, Period 10 minutes	
		Current rating	Fuse rating	Current rating	Fuse rating	Current rating	Fuse rating
mm²	AWG/MCM	A max.	A max.	A max.	A max.	A max.	A max.
Single-core cables							
1,0	17	16	16	17	16	19	20
1,5	15	20	20	21	20	24	25
2,5	13	28	25	30	25	36	35
4	11	38	35	40	35	50	50
6	9	48	50	51	50	64	63
10	7	67	63	72	63	91	80
16	5	90	80	98	100	126	125
25	3	120	100	134	125	170	160
35	2	145	125	165	160	209	200
50	0	180	160	211	200	263	250
70	2/0	225	224	272	250	332	315
95	4/0	275	250	344	-	410	-
120	250	320	315	410	-	480	-
150	300	365	-	482	-	553	-
185	400	415	-	564	-	633	-
240	500	490	-	691	-	748	-
300	600	560	-	818	-	855	-
2-core cables							
1,0	17	14	10	14	10	17	16
1,5	15	17	16	18	16	22	20
2,5	13	24	25	25	25	31	25
4	11	32	25	35	35	43	35
6	9	41	35	44	35	56	50
10	7	57	50	63	63	80	80
16	5	76	63	87	80	110	100
25	3	102	100	119	100	149	125
3- or 4-core cables							
1,0	17	11	10	12	10	14	10
1,5	15	14	16	15	16	18	16
2,5	13	20	20	21	20	26	25
4	11	27	25	29	25	37	35
6	9	34	35	37	35	47	35
10	7	47	50	53	50	67	63
16	5	63	63	74	63	92	80
25	3	84	80	102	100	124	125
35	2	101	100	123	125	152	160
50	0	126	125	166	160	192	200
70	2/0	157	160	218	200	240	224
95	4/0	192	200	278	250	294	300
120	250	224	224	337	315	342	315
Multi-core cables							
5 x 1,5	5 x 15	12	10	12	10	16	16
7 x 1,5	7 x 15	10	10	11	10	14	16
10 x 1,5	10 x 15	9	6	10	10	13	10
12 x 1,5	12 x 15	9	6	10	10	12	10
14 x 1,5	14 x 15	8	6	9	6	12	10
16 x 1,5	16 x 15	8	6	9	6	11	10
19 x 1,5	19 x 15	7	6	8	6	11	10
24 x 1,5	24 x 15	7	6	8	6	10	10

AWG: American Wire Gauge
MCM: Mille Circular Mil

TABLE D.1: Current carrying capacity based on maximum conductor operating temperature of 85^{o}C.

Cu-section of connection bus-bars [mm²]	Permitted load [A]
100	200
200	315
300	400
400	630
500	800
600	1000
800	1250
1000	1600
1600	2000
2000	2500
2400	3150
3200	4000

Table D.2: Connection bars.

Appendix E

Vessel's Plans

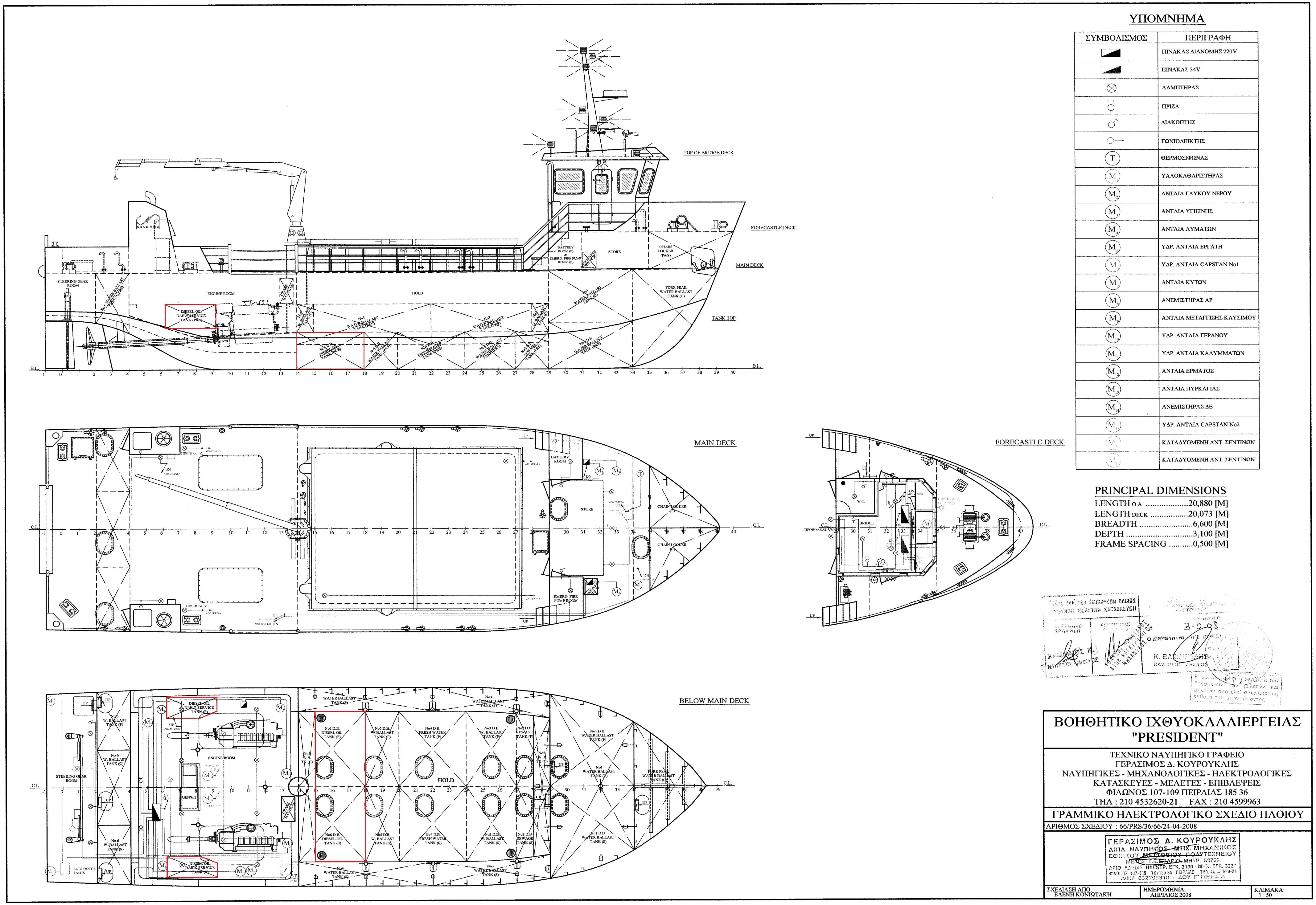


Table E.1: General Arrangement.

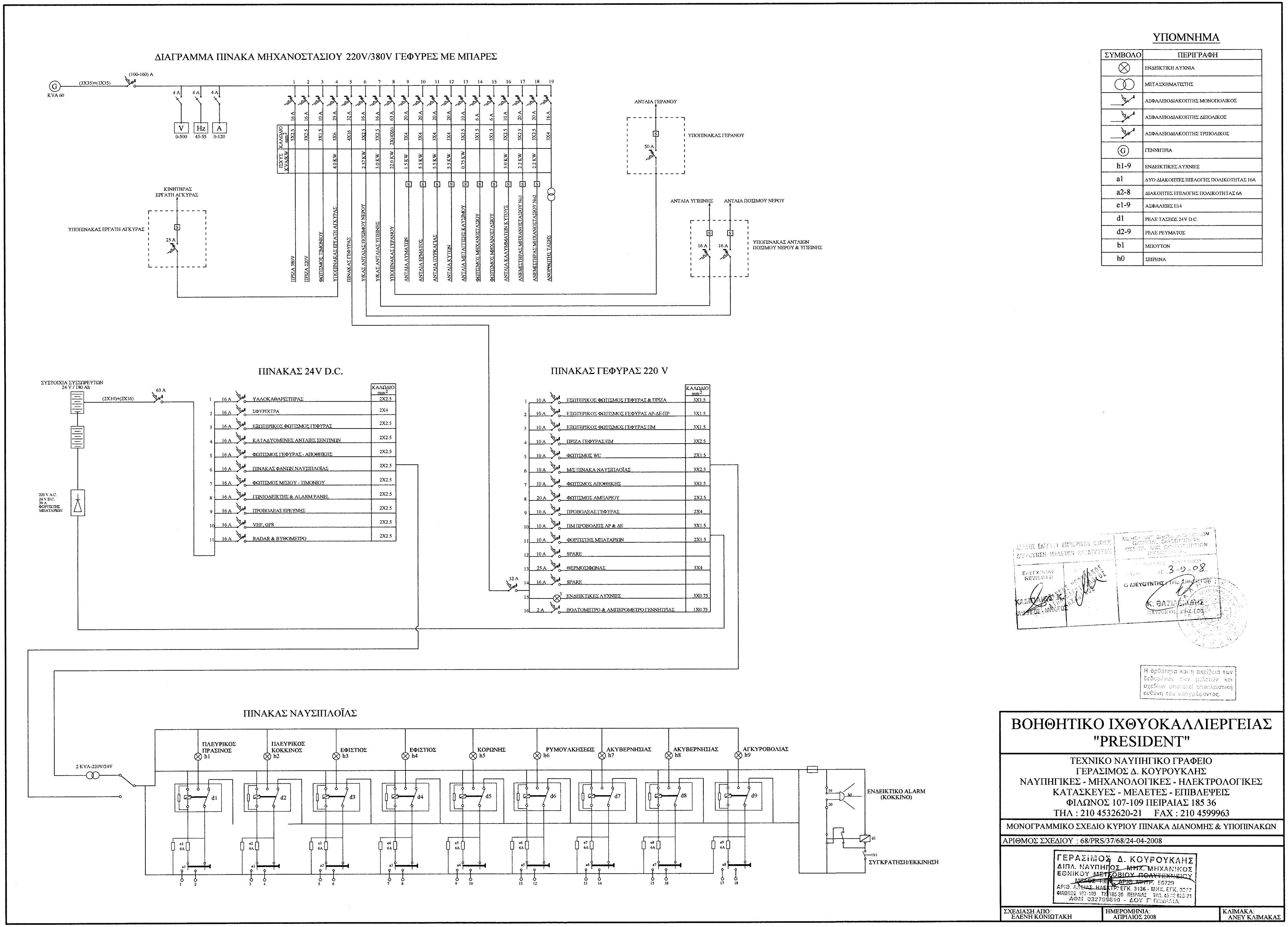


Table E.2: Electric diagram of conventional vessel.

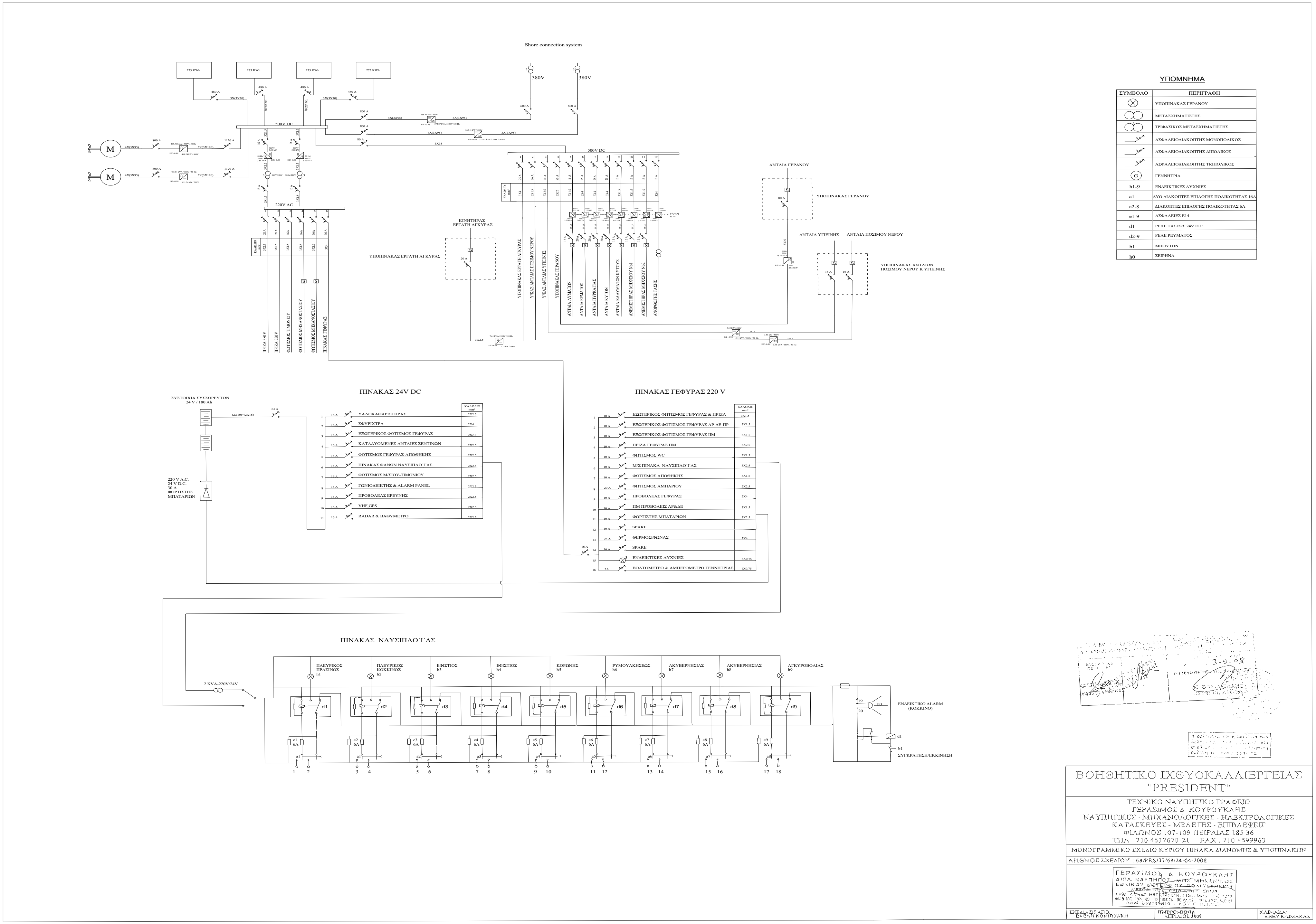


TABLE E.3: Electric diagram of all electric boat.

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