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

Division of Marine Engineering

Diploma Thesis

Preliminary Design of Power System of All Electric Battery Double End Ferry

Rentas Stefanos

Supervisor: J. Prousalidis
Professor N.T.U.A. of Marine Electrical Engineering

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Abstract

Purpose of this thesis is to evaluate the use of batteries in shipping and examine their potential and constraints as the main energy source on an 72 m all-electric ferry. A preliminary general arrangement has been conducted, whereas the electric power system has been designed based on ferry's operating profile and in absolute accordance with the Classification Society rules and requirements. An overview of the regulatory landscape is provided as it applies to the maritime environment. This considers codes, standards, regulations, Class Rules as well as national or international requirements which may be relevant. Safety issues like ventilation and cooling have been taken into account while charging method and necessary port facilities have also been described thoroughly. Finally, an environmental and techno-economic analysis is performed in order to judge and determine if the optimized power control, performance criteria and financial sustainability of the project are achieved.

Introduction

Batteries are widely recognized as one of the most important elements of engineering systems and machinery layouts. When it comes to shipping, however, they have had mainly a supporting role serving emergency systems, safety equipment, communications and other less power demanding applications. Nowadays, the challenge is to evolve and search for new highly efficient and environmentally friendly designs. This task for greater energy efficiency improvements has triggered and inspired the marine community to integrate the great battery power potential into the maritime sector.

In the meanwhile, the international environmental concerns about climate change are growing larger and have led organizations like IMO and local authorities to issue new stricter directives, aiming and promising Greener shipping. Responding to the urgent needs for drastic reduction of toxic gas emissions from marine operations, a series of research and development works were initiated with the ultimate goal of creating an optimized energy management system. Electrical propulsion with battery systems have been recognized as one of the most credible options to address this issue and achieve decarbonization in the marine industry. Charging the battery from the coastal power grid may achieve zero emissions during sailing.

Within this framework, the concept of an all-electric ferry comes naturally into mind as the ideal solution, considering also the fact that fresh naval applications are emerging to make electric propulsion reliable and exceptionally promising. Main advantages are its' flexibility, redundancy, robustness and reduced environmental footprint. However, the quest to all electric New Buildings raises numerous engineering challenges which need to be fully addressed.

To respond to the questions risen, the main objective of this thesis is to investigate and assess the feasibility level of all the above by undertaking the first designing steps of an fully electric double ended RoPax ferry.

Part A – Battery Technology for Maritime

1. Battery Technology

1.1 Basic Principles of Battery Technology

Batteries are valued as devices that store chemical energy and convert it into electrical energy. In general, a battery is comprised of two different poles – a positive electrode called the cathode, and a negative electrode called the anode. Then some material is used inside the battery, called electrolyte, that enables ions to be transferred back and forth between these poles by electrochemical reactions. A separator is placed between the cathode and anode, for insulating purposes in order to prevent internal short circuits. Hence, when the poles are connected by a conducting material, electrons will be forced to flow through the external electrical circuit, and therefore produce electrical energy. In the below figure, the basic components of a battery are illustrated.

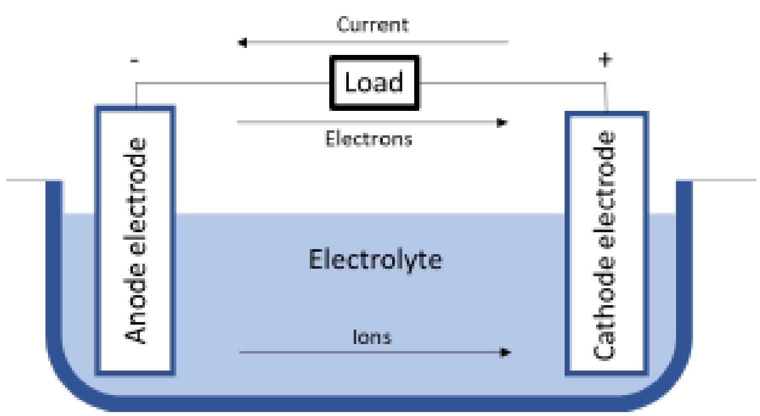


Figure 1.1 – 1: Battery Cell

When these electrochemical processes occur, chemical energy of the system decreases due to its transformation in electrical energy and the potential difference between the anode and the cathode is constantly reduced. Depending on the chemical composition, it may be possible to reverse the chemical reactions and recharge the battery in its' original state, by applying an external electric current. It becomes even clearer, that the specification and material selection of batteries main components will determine the properties and capabilities of the battery system and therefore of the whole project.

The electrochemical unit described above is known as battery cell and may be configured in a series, parallel or a mixture of both to deliver the desired voltage, capacity, or power density. For protection against heat, vibration or external shocks, battery cells electrically connected to one another are arranged in larger groups, defined as Battery modules. Modules may be further grouped together in series and/or parallel combinations to form a battery pack. The battery pack incorporates adequate housing for the battery modules and provides power terminal arrangements. The pack may also incorporate additional protective devices and circuits. Battery packs may also be grouped in series and/or parallel to form a battery system depending upon the expected loads.

1.2 Battery Types

Demand for high-performance rechargeable batteries had become so tangible and ubiquitous in the recent years that its numerous requirements and functions had nearly risen to the status of common knowledge. As a result, new battery types and technologies come forth. Open market offers a variety of products with different type of characteristics and limitations based on the chemical composition, the charge rate and always the cost. Designing the power system of the vessel is more likely, if not for sure, the focal point of this study, and thus choosing the appropriate battery type is crucial. In this section, the most important battery technologies alongside with their specifications and applications are presented in order to help us evaluate the appropriate battery chemistry for the all-electric ship. For any given chemistry, there is most often a wide range of products representing different levels of quality and performance. Thus, it is not feasible or possible to cover the entire spectrum of all technologies, but to just represent the basics.

1.2.1. Lithium-Ion

A lithium-ion (Li-ion) battery is an advanced battery technology that uses lithium ions as a key component of its electrochemistry. During a discharge cycle, lithium atoms in the anode are ionized and separated from their electrons. The lithium ions move from the anode and pass through the electrolyte until they reach the cathode, where they recombine with their electrons and electrically neutralize. In part because of lithium's small size (third only to hydrogen and helium), Li-ion batteries are capable of having a very high voltage and charge storage per unit mass and unit volume. Lithium-ion batteries can consist of different material and chemistries in the electrodes and the electrolyte, as well as manufacturing processes and related materials. Most of the available lithium-ion batteries all use carbon or graphite-based anodes and differs from each other by the cathode chemistry. The cathode materials play a vital role in their electrochemical performance and account for more than 30% of the cost of the entire battery system. Therefore, it is very important to research and develop cathode materials with high performance and low cost

Compared to the other high-quality rechargeable battery technologies, Li-ion batteries have one of the highest energy densities of any battery technology today (100-265 Wh/kg or 250-670 Wh/L). In addition, Li-ion battery cells can deliver up to 3.6 Volts, 3 times higher than technologies such as Ni-Cd or Ni-MH. This means that they can deliver large amounts of current, fact that makes them suitable for high-power applications. They also do not require scheduled cycling to maintain their battery life and have no memory effect, a detrimental process where repeated partial discharge/charge cycles can cause a battery to 'remember' a lower capacity. This is an advantage over both Ni-Cd and Ni-MH, which display this effect. Finally, Li-ion batteries have low self-discharge rate of around 1.5-2% per month, whereas in the same time they don't contain toxic cadmium, which makes them easier to dispose of than Ni-Cd batteries. Due to these advantages, this type has become the most promising and fastest growing battery on the market.

On the other hand, despite their technological promise, Li-ion batteries still have a number of shortcomings, particularly with regards to safety. Li-ion batteries have a tendency to overheat, and can be damaged at high voltages. In some cases, this can lead to thermal runaway and combustion. Another factor limiting their widespread adoption is their excessive cost, which is around 40% higher than Ni-Cd. Addressing these issues, taking into account their applicability and performance, is a key component of this research.

1.2.2. Lead-Acid

In lead acid batteries, H+ ions are the energy carrier. The anode is lead (Pb) electrode, and the cathode is lead dioxide (PbO2). The electrolyte is an aqueous solution of sulfuric acid (H2SO4). The principle is shown in Figure 1.2.2. During discharge, Pb reacts with HSO4- ions, forming PbSO4 and H+ ions. The hydrogen ions are transferred to the cathode, where they react with PbO2 and HSO4-, forming H2O and PbSO4.

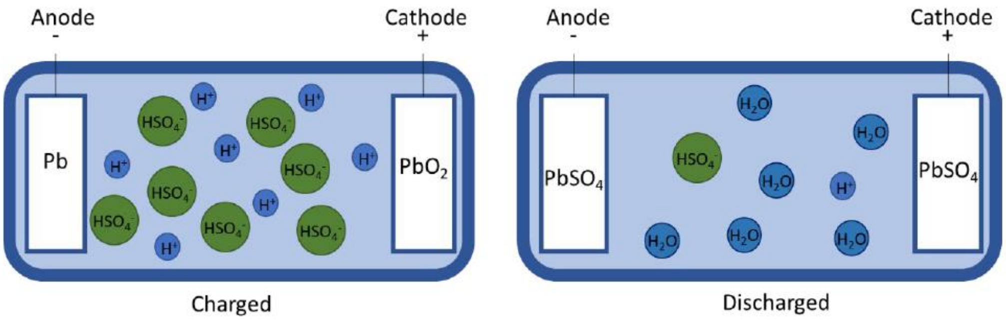


Figure 1.2.2 – 1: Lead-Acid Battery

Lead-acid batteries are supplied worldwide at a very low cost. They are recognized to be safe, since the electrolyte and active materials are not flammable, although they are known to produce hydrogen under charging. Self-discharge rates for this type of batteries are very low, around 2 to 5% of rated capacity per month, which makes them ideal for long-term storage applications.

The main drawback is the low energy density and short service life they produce. The typical energy density is around 30Wh/kg which makes them inadequate for high demanding applications. Meanwhile, depending on the depth of discharge, lead acid for deep-cycle applications provides 200 to 300 discharge/charge cycles which is considered minimum. Performance of lead-acid batteries is also significantly deteriorating in high temperature environments.

1.2.3. Nickel-Based

In these batteries, hydroxide ions (OH-) are used as energy carriers. The available types are nickel cadmium (NiCd), nickel metal hydride (NiMH), nickel iron (NiFe), nickel zinc (NiZn) and nickel hydrogen (NiH). The electrolyte contains an aqueous solution of potassium hydroxide (KOH).

- Nickel cadmium batteries are mature technologies, that are widely used in UPS applications. Nickel hydroxide/nickel oxyhydroxide (Ni(OH)2/NiOOH) is used as cathode material, and cadmium (Cd) in the anode. This technology is economically priced and presents the lowest per cycle cost. Main disadvantages are the low energy density, the memory effect and the explosive environment which is created during charge.

- In nickel metal hydride, nickel hydroxide/nickel oxyhydroxide (Ni(OH)2/NiOOH) is used as cathode material, while for NiMH use a hydrogen absorbing alloy and cadmium hydroxide (Cd(OH)2) in the anode. Pros and cons are very similar to Nickel Cadmium batteries.

- The nickel-iron battery (NiFe) uses nickel oxide-hydroxide (NiOOH) cathode and an iron (Fe) anode. Longevity and resilience are its positive elements, whereas the main drawbacks are the low specific energy of about 50 Wh/kg, the poor low-temperature performance and high self-discharge of 20–40 percent a month.

- Nickel-zinc (NiZn) is similar to nickel-cadmium since it uses nickel oxide hydroxide (NiOOH) as a cathode and an alkaline electrolyte, and of course Zinc (Zn) is the anode. The provided specific energy is 100 Wh/kg and can be cycled 200–300 times. NiZn can be supplied at low cost and is also recyclable due to the absence of toxic substances. High self-discharge rate due to fast growth of dendrites is their weak point.

- The nickel-hydrogen battery combines the positive nickel electrode of a nickel-cadmium battery and the negative electrode. The cells have the disadvantage of relatively high self-discharge rate. Compared with other rechargeable batteries, a nickel-hydrogen battery provides good specific energy of 55-60 watt-hours/kg, and very long cycle life. Although, these amounts are fair, they are significantly lower compared to Lithium-Ion batteries.

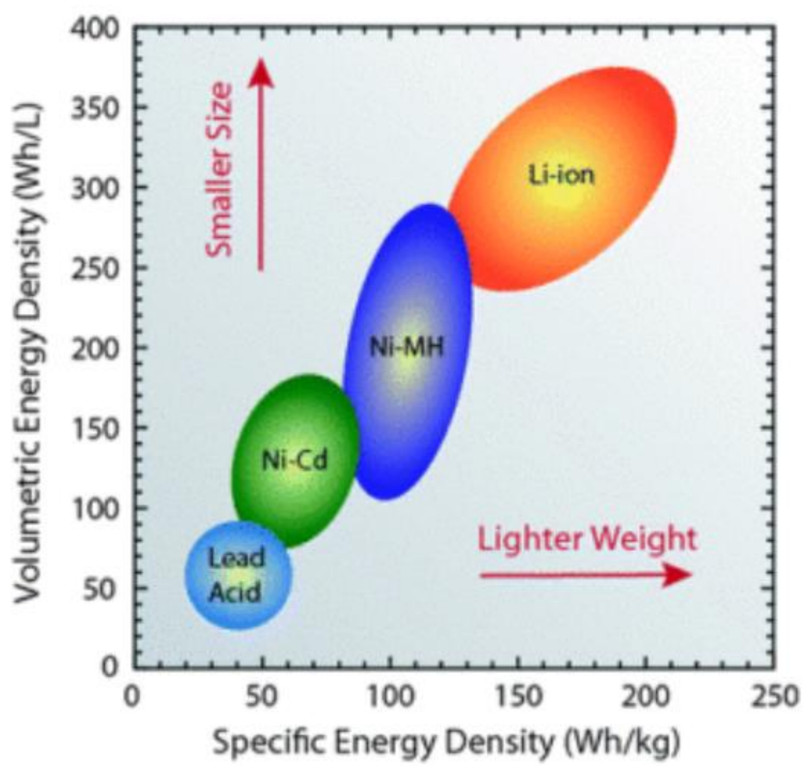


Figure 1.2.3 – 1: A diagram of the specific energy density and volumetric energy density of various battery types.

1.3 Li-On Batteries

Lithium-ion Battery technology distinguishes in terms of shot-trip coastal routes. Its' enhanced incomparable power density and its capability allow a short-term regenerate of high amount of energy while loading/unloading operations take place. Thus, they arise as the most suitable candidate for our project needs. A quick review of the most popular and advanced Li-On Battery technologies is going to be performed in order to assess and select the one which is going to be implemented to our project.

1.3.1 Lithium Iron Phosphate ($LiFePO_4$) – LFP

Lithium Iron Phosphate ($LiFePO_4$) , also called LFP, is one of the more recently-developed rechargeable battery chemistries. Rechargeable lithium iron phosphate batteries use $LiFePO_4$ as the principle cathode material and a graphitic carbon electrode with a metallic backing as the anode.

The major distinction that lithium iron phosphate batteries have from other li-ion batteries is that LFP is capable of delivering a constant voltage and also has a comparatively higher charge cycle, in the range of 2000-3000. LFP batteries are environmentally safe and structurally stable. They have a lower energy density and low discharge rate. They do not heat up easily and are relatively cooler than other batteries. The chemistry of the battery saves it from thermal runaway, and hence it is considered to be one of the most reliable products available in the market.

The LFP battery has been known to withstand harsh conditions and hazard events better than other batteries since they do not explode or catch fire. For example, the key benefits for the application of an LFP in a car are: the high pulse-rate capability of up to 10C and 20C pulse discharge, long cycle life, good thermal stability, enhanced safety, tolerance if abused, and advanced environmental friendliness after being retired. To sum up, although LFP provides lower energy density than NCA and NMC, the low cost, high thermal stability still make it a key player in certain markets.

In conclusion, the main advantages of the LFP batteries are:

- Less ventilation and cooling requirements.
- Best result in terms of safety (less prone to thermal runaway)
- Superior thermal and chemical stability
- Advanced environmental friendliness after being retired
- Long life Cycle

The only drawback compared to others, is considered to be the low specific energy rating.

1.3.2 Lithium Nickel Manganese Cobalt Oxide ($LiNiMnCoO_2$) – NMC

NMC is one of the more recent cathode developments and is the present market leader for large format applications and are increasingly replacing LCO and LMO in consumer electronics. Its strength is the combination of attributes of the constituents of nickel (with a high specific energy, but low stability), cobalt (high specific energy) and manganese (doped in the layered structure to stabilize it).

Depending on the quantities of Nickel, Cobalt and Manganese NMC batteries can possess different properties. Decreasing the relative amount of cobalt in this balance is a major benefit for cost and energy density. However, the same has significant effects on performance and lifetime of the battery. On the other hand, by incorporating more nickel, higher capacity and energy density can be achieved, but this also may lead to lower thermal stability and a shorter life span. Variating the amount of Ni, Mn and Co will affect cost, capacity and stability.

The main advantages of the NMC are the high energy density and capacity by achieving the correct combination of N,M and Co. However, comparing to LFP lower stability and life span is expected. Finally, regarding both LMO and NMC, the containing manganese, have shown to be very sensitive to high temperatures. A distinguished phenomenon related to these technologies has been observed, namely manganese dissolution due to reaction with the electrolyte. Hence, a high internal resistance increase with aging has been observed on these batteries.

1.3.3 Lithium Manganese Oxide ($LiMn_2O_4$) – LMO

A lithium ion manganese oxide battery (LMO) is a lithium ion cell that uses manganese dioxide, as the cathode material. Cathodes based on manganese-oxide components are earth-abundant, inexpensive, non-toxic, and provide better thermal stability. However, the cycling performance of LMO is still considered not satisfactory because of the layered structure which has a tendency to change into spinel structure during Li ion extraction and because Mn leaches out of LMO during cycling.

Basically, the most popular chemistry is the LiMn2O4 which is of spinel type but there are several more based on different compounds like the Layered Li_2MnO_3 , $LiMnO_2$ and Li_2MnO_2 each one with different properties..

The main advantages of the LMO batteries are:

- High temperature stability and safety relative to other Li-ion types as it has integrally high thermal stability thus needs less safety circuitry than cobalt system.
- High-rate capability due to low internal cell resistance which benefits fast charging and high current discharging.

The main disadvantages of the LMO batteries are:

- Limited life cycle
- Low energy density compared to similar Li-On batteries.
- Sensitive to high temperatures.

1.3.4 Lithium Nickel Cobalt Aluminum Oxide ($LiNiCoAlO_2$) – NCA

NCA battery stands for Lithium nickel cobalt aluminum oxide based battery (LiNiCoAlO2) which is an essential cathode material with many vital advantages, such as lower cost and higher specific capacity compared with lithium cobalt and lithium iron phosphate materials. NCA is generally similar to NMC but has some small changes that make it more suitable for certain applications. The addition of a small amount of Al stabilizes the material structure and improves the thermal stability of the material. The $LiNiCo_yAlO_2$ (NCA) material obtained by doping Co and Al elements exhibits exceptional electrochemical properties. Among the series of materials with different ratios of Ni, Co, and Al elements, $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ is the most widely researched material and has attracted full attention and commercialization due to its low cost, nontoxicity, and high-energy density. NCA is a promising cathode material due to its excellent structural stability and high capacity. However, the noticeably irreversible capacity and reduced cycle and rate performance still limit its large-scale application.

1.3.5 Lithium Cobalt Oxide ($LiCoO_2$) – LCO

Lithium cobalt oxide, also known as lithium cobaltate, is the first and the most commercially successful form of layered transition metal oxide cathodes. LCO is a very attractive cathode material because of its relatively high theoretical specific capacity of 274 mAh , high theoretical volumetric capacity , low self-discharge, high dis-charge voltage, and good cycling performance. However, the theoretical capacity of lithium cobalt oxide is high, but the actual capacity is only half of what is theorized. The reason is due to the charging process: when the amount of lithium ions extracted from lithium cobalt oxide material is less than 50%, the morphology and crystal form of the material can be kept stable. However, when the lithium-ion extraction amount increases to 50%, the lithium cobaltate material undergoes a phase change. If charging continues at this time, cobalt will dissolve in the electrolyte and generate oxygen, which affects the stability of the battery cycle life and performance.

Lithium cobaltate has many benefits with its high discharge platform, simple synthesis process, high capacity, and good cycle performance. However, the major limitations are high cost, low thermal stability (the lowest of any commercial cathode material), and fast capacity fade at high current rates or during deep cycling. Thus, it's difficult to guarantee safety when making large LCO batteries.

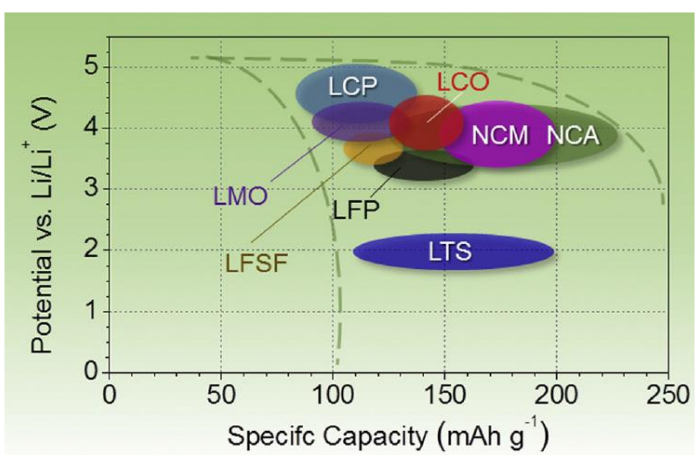


Figure 1.3.4 – 1: A diagram of the specific capacity and potential of the most common Li-On battery types.

1.4 Battery Cost and Comparison

Based on our research, the below summary tables have been conducted in order to highlight the merits and demerits of each cathode material with respect to safety issues, stability, energy density, capacity and off course expense.

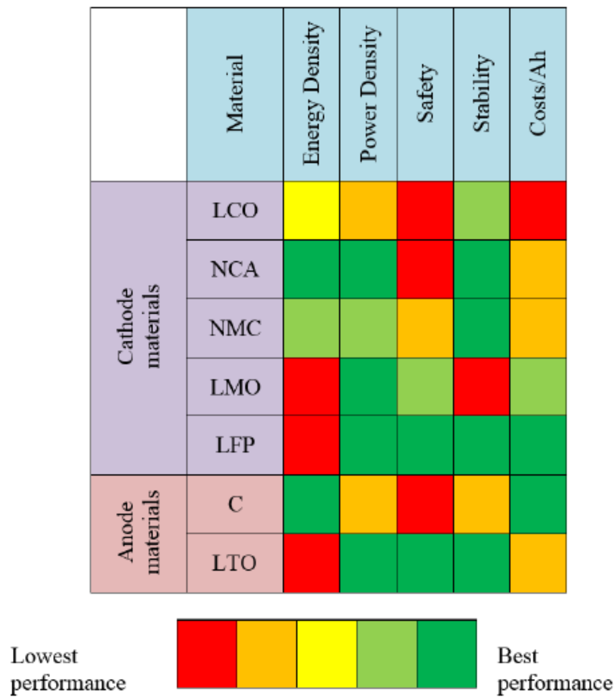


Figure 1. 4 – 1: Comparison between the most common Li-On battery cathode and anode materials..

Lithium Ion Chemistry Comparison	LFP Lithium Iron Phosphate	NMC Lithium Nickel Manganese Cobalt Oxide	LMO Lithium Manganese Oxide (May Contain Cobalt)	NCA Lithium Nickel Cobalt Aluminum Oxide	LCO Lithium Cobalt Oxide
Danger of Thermal Runaway & Fire	NO	YES	YES	YES	YES
Toxic Elements	NO	YES	YES	YES	YES
Landfill Safe	YES	NO	NO	NO	NO
Involves Abusive Mining Practices	NO	YES	YES	YES	YES
Ventilation Required	NO	YES	YES	YES	YES
Cooling Equipment Required	NO	YES	YES	YES	YES
Safety Monitoring Equipment Required	NO	YES	YES	YES	YES
Able To Withstand High Temperature Environments	YES up to 140°	NO	NO	NO	NO

Figure 1.4 – 2: Safety Assessment of the most common Li-On battery cathodes.

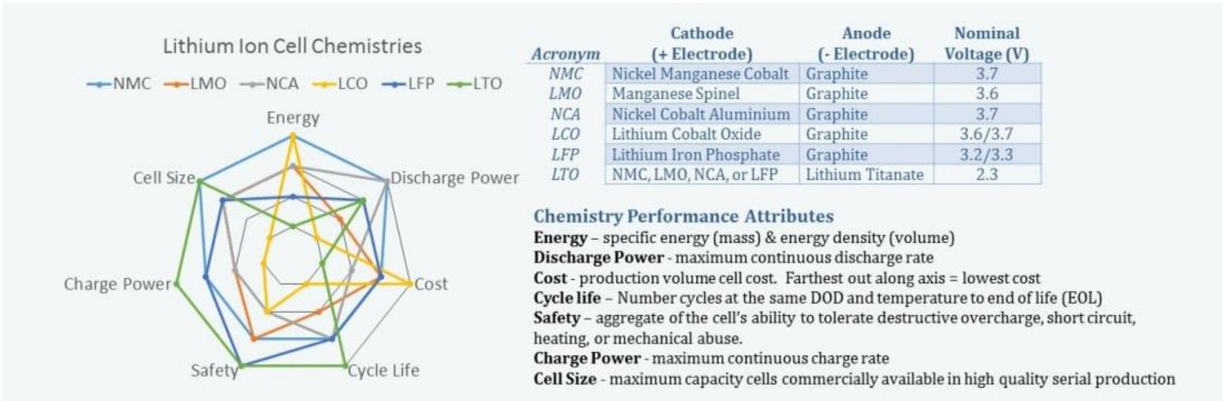


Figure 1.4 – 3: General comparison between the most common Li-On battery types.

In the meanwhile, a variety of different battery vendors has been reached and consulted. Based on preliminary calculations, the required capacity of the battery modules is estimated to be about 2MWh ± 25%. With reference to the above inquiry, a rough estimation of the following items was requested from the manufactures:

1. Purchase cost of the batteries / kWh. → Around 600-700 USD/kWh
2. Installation cost. Rack dimensions, cooling method etc. → Depending on the agreement/Commisioning fees roughly about 25k
3. Maintenance / Operational cost. → Annually 5000k
4. Expected lifetime of the batteries → 10 years
5. Time and requirements for charging → Depends on demand for sailing, and availability on shore power.

The cathode chemistry of the applied battery cells and modules which will comprise the Energy storage system of the vessel, depends merely on the manufacturers standards. The same to be considered, regarding the arrangement and assembly of the battery packs. For instance, a leading figure in innovative and reliable zero-emission solutions for all segments in the maritime industry Corvus Energy undertook the design of the energy storage system of the first all-electric Ferry MF Ambere. The Corvus ESS is made up of arrays of AT6500 battery modules, each of which contains 24 lithium-polymer cells. Advanced cell chemistry – Li-NMC layered pouch cells – are the foundation of the Corvus battery's characteristics that make it ideally suited for the platform. Building on this foundation, Corvus's marine-rated design and battery management system harness the capabilities of the cell in a safe and controllable manner. The Li-NMC battery module is known for its high power-to-weight ratio. The power density of the Corvus battery is 951W/kg, compared with only 41W/kg for a lead-acid battery or 685W/kg for a typical lithium-ion battery.

CORVUS Energy AT6500 Module Specifications

COMPONENT	AT6500-50 AIR-COOLED	AT6500-100 AIR-COOLED	AT6500-50-LQ LIQUID-COOLED	AT6500-100-LQ LIQUID-COOLED
Maximum Voltage	50.4V	100.8V	50.4V	100.8V
Nominal Voltage	44.4V	88.8V	44.4V	88.8V
Minimum Voltage	38.4V	76.8V	38.4V	76.8V
Capacity	150Ah	75Ah	150Ah	75Ah
RMS [1] C-Rate	0.8C [2]	0.8C [2]	1.5C	1.5C
RMS [1] Current	120A	60A	225A	113A
Energy	6.5kWh	6.5kWh	6.5kWh	6.5kWh
Weight	70 kg (154 lb.)	70 kg (154 lb.)	72 kg (158 lb.)	72 kg (158 lb.)
Size	59x33x38 cm (26x13x15 in)	59x33x38 cm (26x13x15 in)	59x33x38 cm (26x13x15 in)	59x33x38 cm (26x13x15 in)

Figure 1.4 – 4: Corvus AT6500 Specification Datasheet

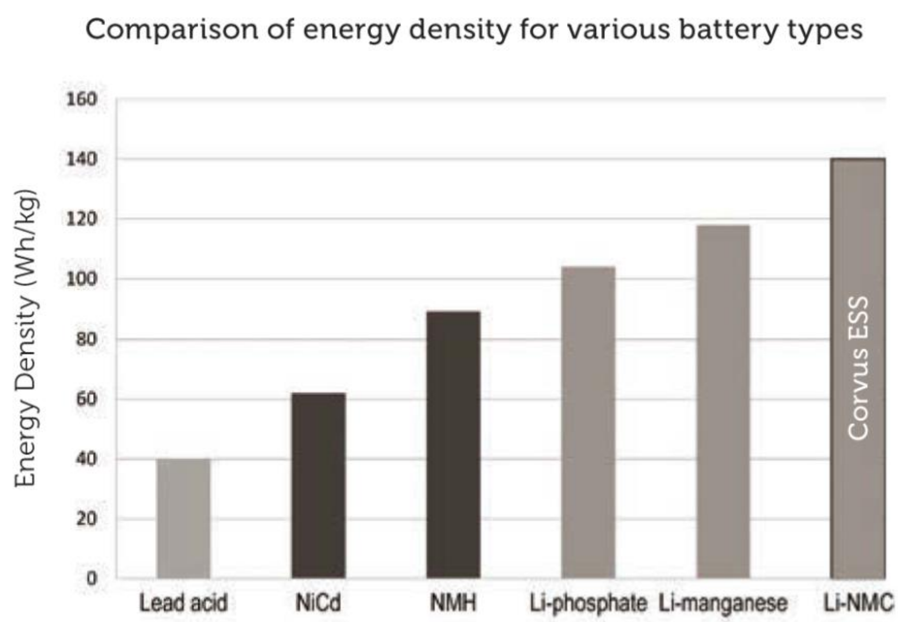


Figure 1.4 – 5: Corvus ESS Li-NMC battery system compared to different Li-On Battery Types.

Taking all the above into consideration, Li-ion batteries have an unmatchable combination of high energy and power density, making it the technology of choice in our project. Various promising anode and cathode materials exist, but many suffer from limited electrical conductivity, slow Li transport, dissolution or other unfavorable interactions with electrolyte, low thermal stability, high volume expansion, and mechanical brittleness. The final design and application will merely rely on the approval and acceptance of the Classification society requirements and with respect to the vendors standards. However, LFP and NMC cathode materials distinguish in terms of safety and power density respectively and that's the main reason why they were already applied in a variety of New Buildings of this field.

2. Maritime Electrification

Full-electric and hybrid electric cars have seen a massive increase in popularity, motivated by rising fuel prices and environmental concerns. The introduction of hybrid technology to reduce energy consumption and emissions has not gained the same attention in the maritime industry yet, but the change has started and more and more ships are being equipped with batteries.

Like the car industry, we divide battery-powered ships into three types:

- Full-electric ships (ES)
- Plug-in hybrid ships (PHES)
- Hybrid ships (HES)

On a full-electric ship, all the power, for both propulsion and auxiliaries, comes from batteries. A plug-in hybrid ship, similar to a plug-in hybrid car (PHEV), is able to charge its batteries using shore power and has a conventional engine in addition. The ship can operate on batteries alone on specific parts of the route, when maneuvering in port, during stand-by operations. A hybrid ship uses batteries to increase its engine performance and does not use shore power to charge its batteries.

2.1 List of All electric and Hybrid Vessels

The important task for the maritime industry is to evaluate the technology, how it performs and how should be integrated in a maritime environment. For our review and consideration, a list of all electric and hybrid ferries, either retrofitted or launched recently is presented below, alongside with all major features and operational specifications.

Name	Type	Built	LOA (m)	Battery - System	Operation Line	Charging
Tycho Brahe and Aurora	Passenger and car ferry	1991	238	640 6.5 kWh batteries installed on top of each ferry in containers. **System: 4160 kWh**	4 km ferry route between Helsingborg (Sweden) and Helsingör (Denmark)	**5 min 30 s at Helsingør 9 min at Helsingborg - Charging Power : 10.5 MW at 10 kV**
Elektra	Passenger and car hybrid ferry	2017	98	The two lithium-ion battery packs each have a capacity of **530 kWh (1MWh total storage)**, one in the forward and one in the aft machinery space.	between Nauvo and Parainen in the Turku archipelago	Charging in 5 Minutes: **5 min 30 s and overnight**
Gloppefjord & Eidsfjord	Passenger and car hybrid ferry	2018	106	Total battery capacity onboard each ferry is two **520kWh PlanB batteries** with Siemens as the electric integrator.	on the Anda-Lote route Nordfjord on the west coast of Norway	**6–7 min and overnight. Charging Power 1,500 kW**
Ampere	Passenger and car all electric ferry	2015	80	**1,000 kWh Li-ion battery system / 450kW electric motors**, one of them driving the thrusters /	It crosses the Sognefjord about 34 times a day	**10 min and overnight - Charging Power: 1.2 MW / 1,250–1,650 A**

Name	Type	Built	LOA (m)	Battery - System	Operation Line	Charging
Movitz	first supercharged ferry	2019	111	The system is powered by super-advanced Nickel-Metal-Hydrid (NiMH) **180 kWh batteries** from the Swedish company Nilar.	On a route between Solna Strand and Gamla Stan Sulesund-Hareid route	Charging in 10 Minutes
P 315 hybrid ferry	Passenger and car Hybrid ferry	2022	100	**1040 Kwh**	the Åland Föglö line in the Åland Archipelago in 2022	(estimate about 5.6 minutes; 80% of the 7 minute shore time)
Tustna	Passenger and car ferry	2019	95,6	The vessel is equipped with a battery system with a storage capacity of approx. **2 x 1000 kWh**,		
Ellen	Passenger and car all electric ferry	2019	60	They are split between two battery rooms below deck and have a capacity of **4.3 MWh**, larger than any other electric vessel.	operates the 22 NM route between the islands of Ærø and Als in Southern Denmark.	***4 MW at 1,000 V***
Norled hybrid Ferry (Festoya)	Passenger and car ferry	2019	114,4	**1582 kWh**	Festøya – Solavågen and Mannheller – Fodnes routes.	The batteries will be recharged from the land grid during the vessels stay at quay which will typically be about 11 minutes
Future of the Fjords	All-electric catamaran	2018	40	**1,800 kWh**	Nærøyfjord, Norway	**2.4 MW at 1 kV - 20 min**
Amherst Island (above) Wolfe Island (below)	Passenger and car ferry	2020	72	**1800 kW**	Kingston and Wolfe Island, as well as Millhaven and Amherst Island,	**1000 V DC, 1600 A**
	Passenger and car ferry	2021	98	**4000 kW**		**1000 V DC, 3000 A**
Basto Electric	Passenger and car ferry	2019	143	**4000 kW**	30-minute crossings across Oslofjord between Moss and Horten at about 13.5 knots	

Table 1: Characteristics of All electric Ships

Name	Type	Built	LOA (m)	Battery - System	Operation Line	Charging
ISLAND DISCOVERY & ISLAND AURORA/ ROAD FERRY 8117	Passenger and car ferry (Diesel & battery)	2020	80	**Main gen. set power 2x 1500 kWe, 690V, 3ph / 60 Hz @ 1,200 rpm Energy storage system 800 kwh Li-Ion battery bank Emergency gen. set power 155 kWe, 690V, 3ph / 60 Hz @ 1,800 rpm**	Canada	-
MV Hallaig	Hybrid ferry	2012	44	**2 × 350 kWh**	Skye and Raasay,Scotland.	**50 kw Overnight**
MF Folgefonn	Hybrid ferry	2015	85	**1,000 kWh**	Jektevik–Nordhuglo–Hordnanes, Norway.	**1 MW 4 min at shortest stop, one longer charging period of 20–25 min**
Vision of the Fjords	Hybrid ferry	2016	40	**600 kWh**	Nærøyfjord, Norway.	**1.2 MW at 400 V**
MS Color Hybrid	Hybrid cruise	2019	160	**5,000 kWh**	Sandefjord, Norway,and Strömstad, Sweden.	**7 MW 25 min at lunch stop and overnight**

Table 2: Characteristics of Hybrid Ships

2.2 Historical Development

So far, the developments have been gradual and stepwise and each major new step has been dependent on the previous steps. The power-tool batteries brought the first power-optimized Li-ion battery designs and introduced new cathode materials. With the power-optimized designs, operation in sub-zero temperatures was possible and further materials development led to a longer battery lifetime than had previously been possible. These innovations were key enablers for the use of Li-ion battery systems in electric vehicles. The use of Li-ion batteries in electric vehicles was the key enabler for the maritime usage of such batteries since the reliability, cost, performance, lifetime and safety were brought to levels that were attractive for maritime usage. The maritime usage of large Li-ion battery systems will improve these systems in ways that will benefit other markets, such as off-grid energy systems, and lead to expanded usage for railways and commercial vehicles.

3. Environmental Aspect

There have been increasing concerns about the adverse impacts on the environment caused by cargo movement in international trade. Different stakeholders ranging from shippers and carriers to government bodies and international communities have expressed worries about the environmental impacts brought by shipping related activities. The pollution and waste created in the shipping processes have imposed environmental burdens and accelerated resource depletion. The air pollution places a heavy burden on the world's oceans, lakes and forests, and it is also considered to be responsible for lung cancer and asthma, among other things. The situation is set to worsen in the face of intensifying trade globalization, which has contributed to sustained growth in international shipping activities. To help protect the environment, many shipping firms have taken the initiative to find ways to lessen the environmental damage of their operations while enhancing their performance.

3.1 How Does the Shipping Industry Affect the Environment?

Approximately 80% of world trade by volume is carried by sea. In 2007 it is estimated that international shipping was responsible for approximately 870 million tons of CO_2 emissions, or 2.7% of global anthropogenic CO_2 emissions (IMO, 2009). Domestic shipping and fishing activity bring these totals to 1050 million tons of CO_2, or 3.3% of global anthropogenic CO_2 emissions. Despite the undoubted CO_2 efficiency of shipping in terms of grammes of CO_2 emitted per ton-km, it is recognized within the maritime sector that reductions in these totals must be made (IMO, 2009).

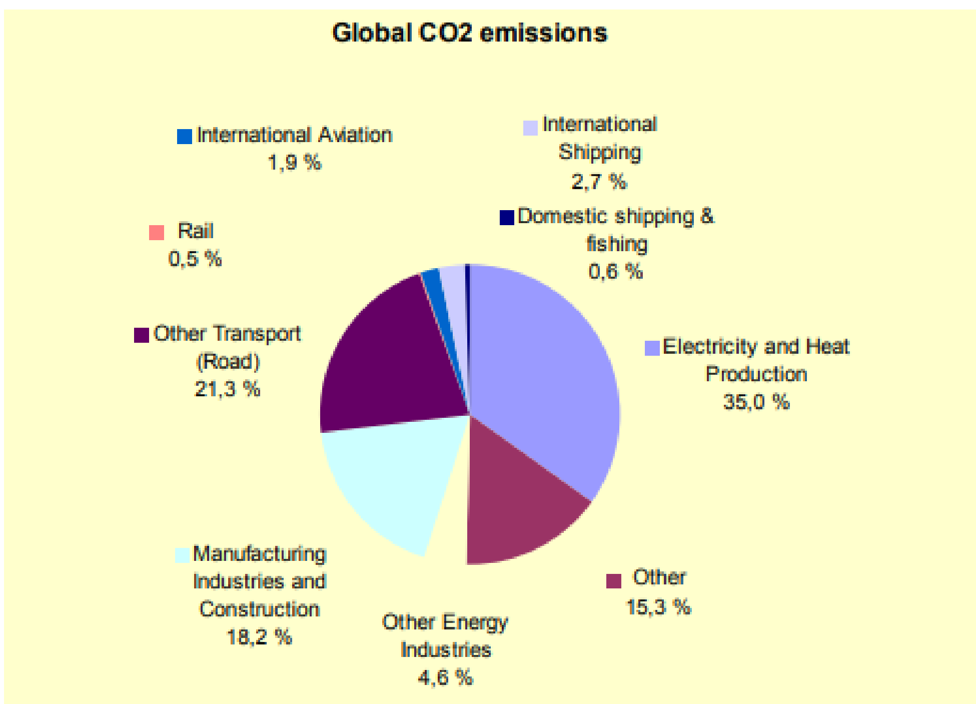


Figure 3.1 – 1: Emissions of CO_2 from shipping compared with global total emissions.

By 2050, the maritime transport segment needs to reduce its total annual GHG emissions by 50% compared to 2008 to be in line with the global GHG reduction target to limit the global temperature rise to no more than 2℃ above pre-industrial level.

CO_2 emissions from world shipping are directly related to the fuel consumption of the fleet. In 2007 approximately 277 million tons of fuel were consumed by international shipping. Three categories of ship account for almost two-thirds of this consumption. The liquid bulk sector accounts for ~65 million tons fuel/ year, container vessels for~55 million tons fuel/year and the dry bulk sector for ~53 million tons fuel/year (IMO, 2009, p. 42). Many of the present efforts to reduce CO2 emissions from global shipping are aimed at the container vessel sector since this contains relatively large vessels travelling at comparatively high speeds, leading to high fuel consumptions. Significant reductions in fuel consumption and hence emissions may be made through introducing slower operational speeds in a practice referred to as 'slow steaming'. Less attention has been paid to the dry and liquid bulk sectors, where operational speeds are much slower and vessel design optimized over many decades.

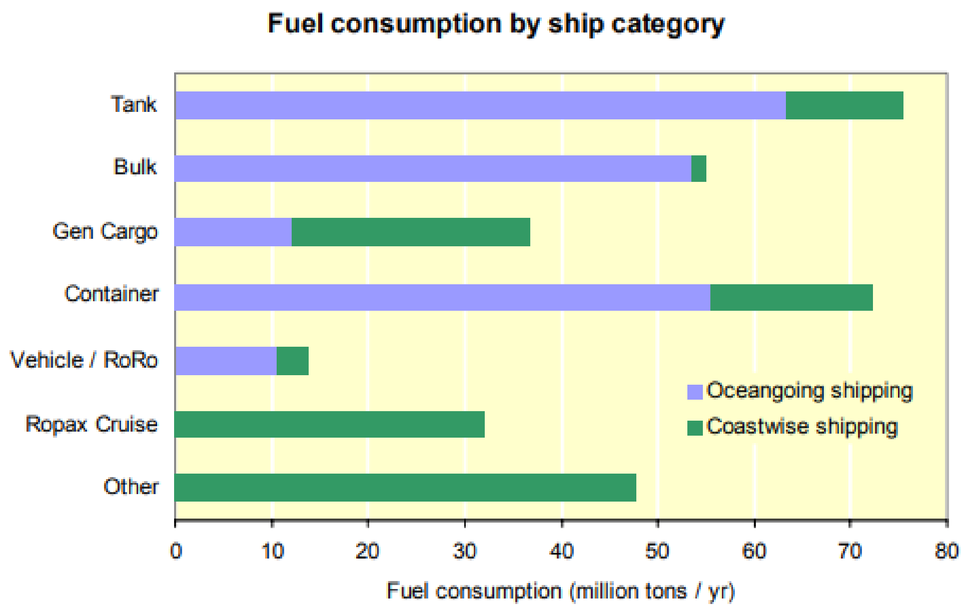


Figure 3.1 – 2: Fuel consumption, separated into consumption by main categories of vessel and assumed typical types of operation.

Shipping is responsible for a greater percentage share of NOx (~37%) and SOx (~28%) emissions and recent legislation is aimed at reducing these emissions through the introduction of emission control areas and requirements on newly built marine diesel engines (MARPOL,2005). With regards to pollutant emissions, in order to comply with MARPOL Annex VI limitations on nitrogen oxides (NOx), sulphur oxides (SOx) and particulate (PM), fuel choice and power generation system technology are of particular concern. Since 2016, all vessels sailing in Emission Controlled Areas (ECAs) must comply with the very low SOx and NOx limits set by the Tier III standards. The limit of fuel's sulphur content by weight is 0.10% (0.50% outside ECAs). Maximum allowed NOx emission, depending on the engine's rated speed, is 2.0 ÷ 3.4 g/kWh (7.7 ÷ 14.4 g/kWh outside ECAs). Moreover, all new ships sailing in Baltic Sea and North Sea after January 2021 will have to reduce NOx emissions by 80% with respect to actual levels, as new NOx ECAs will be established.

Marine diesel engines operating with heavy fuel oil or marine diesel oil are not a viable powering solution for the shipping industry in terms of the required reduction in GHG and pollutants. Various efforts have been made to improve the existing diesel engine based technologies, e.g. using Liquefied Natural Gas (LNG) in dual-fuel or gas engines. Though the NOx, SOx and particulate matter emissions can be reduced significantly with LNG, the GHG saving offered by LNG is limited to no more than 21%, and methane slips could potentially cancel out the benefit. Ships operating within Emissions Control Areas have adopted exhaust gas treatment devices which could potentially lead to the GHG emission performance being even worse as a consequence of the requirement for additional power and the negative impacts on engine efficiency.

3.2 Benefits of Implementing Batteries

The introduction of greener non-detrimental solutions at sea, such as, electrification, reveals the turning point to a new perspective of environmental saving applications and promotion of renewable resources. Batteries have been used in the automotive industry in the development of hybrid car applications and have a significant role in the overall efficiency of the power train. The success of the system is dependent on the development of the appropriate battery technologies. The weight and operational characteristics are considered to play a significant role in the selection of an appropriate storage system for use in the marine environment.

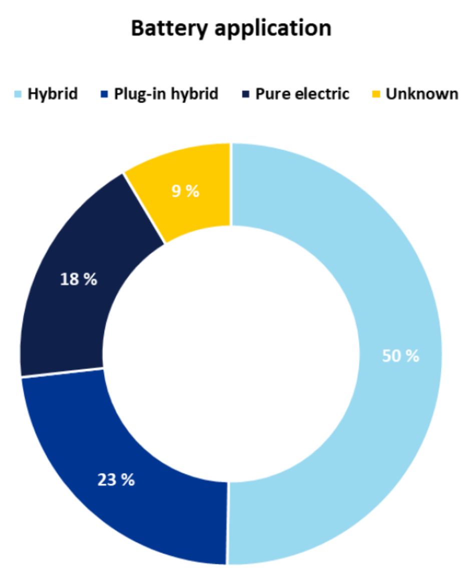


Figure 3.2 – 2: Battery application on maritime sector

A battery solution for electrical operation is viable for ferry routes with a high number of trips, because the savings in operating costs become so large that they can cover the investment costs and even exceed them. On long journeys, ferries have a need for batteries with higher capacity, which sets greater requirements for charging while they are in port. Hence for long routes, it is more financially and environmentally viable with a hybrid solution, i.e. a combination of batteries and diesel or gas electric propulsion, where it is made possible for internal combustion engines to always operate at their optimum operating point.

In order to calculate the full potential of environmental benefits offered by electrification, a study has been carried out by Siemens focusing on Denmark's ferry fleet. The study's main conclusion is that 7 out of 10 ferries will be more profitable if current ferries are replaced with green, electrical ferries. In fact, the green conversion will give companies a return of a total of DKK 35 million per year over a 10-year period. The reason is that the operational savings from e-ferries reach as high as DKK 81 million a year, which outweighs the costs of the required additional investment. If Denmark succeeds in electrifying these ferries, the environmental gains will be significant. The study shows that the potential for reducing the ferries' CO2 emissions amounts to 50,000 tons per year. By comparing the current diesel ferries with a corresponding number of electrical ferries, we have calculated the environmental potential.

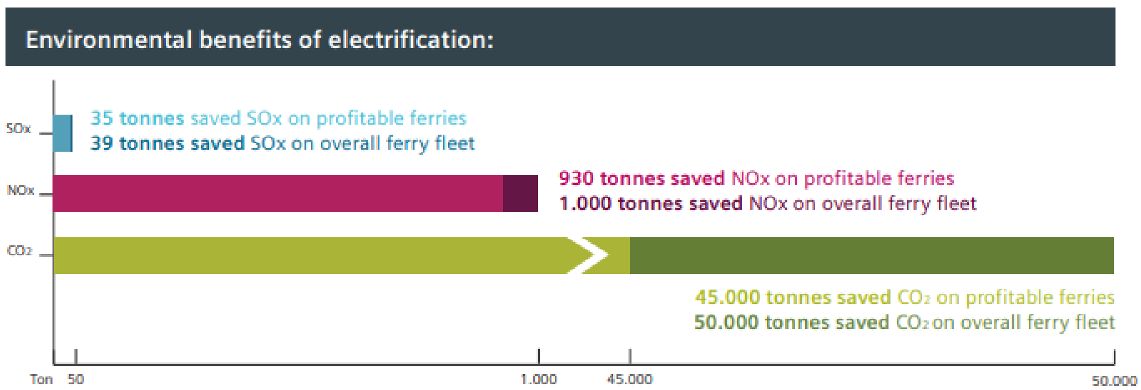


Figure 3.2 – 2: Environmental Benefits of Electrification

Conversion to fully electrical operation does not only achieve environmental benefits. Crew and passengers will also advantage from the electrical ferries. First and foremost, e-ferries result in a better environment on board, as it will no longer be necessary to have fuel as well as large quantities of various lubricating oils on board. The fumes from hot engine rooms will be entirely removed and the air on board will no longer be affected by dangerous substances and particles from the engines running. The demanding maintenance work needed for internal combustion engines and their auxiliary systems, such as fuel centrifuges and fuel pumps, can be entirely removed from the crew's tasks and the total quantity of maintenance significantly reduced.

As there will no longer be a need for fossil fuels, crew work in connection with refueling is reduced. An added benefit will be less disturbance from heavy truck traffic in port areas and remove the CO2 emissions from the fuel tankers that are no longer needed. Crew and passengers will experience an increased level of comfort when e-ferries quietly sail along the coast with far less noise and vibration on board.

3.3 Energy efficiency design index (EEDI)

The Energy Efficiency Design Index (EEDI) provides a newbuilding standard, assuring that ship designs achieve a certain level of efficiency and decrease carbon emissions. The EEDI was introduced by the IMO years ago and is well established today in the maritime community. The concept of EEDI is to quantify CO2 emissions per unit of transport work. It is proposed to instigate development of more efficient ships by establishing baselines for newly-built vessel design. Attained EEDI values of new ships and ships subjected to major conversion is required to be evaluated at design process and to be finally verified during official sea trials. Meanwhile, an EEDI reference line is defined as a curve representing an average EEDI value calculated from a set of individual index values. The attained EEDI, therefore, must always be equal or less than the reference line which is already established for various ship types.

As required by the IMO, the index is to be more stringent every five years in accordance with the implementation phases. The CO2 reduction level for the first phase starting from 2015 is set to 10%, while the final phase requires a 30% reduction from 2025 onwards. In this direction, development of more efficient vessels by implementing various technologies would be actively encouraged. The attained EEDI with the respective emission conditions and energy efficient factors can be calculated by the following formula:

$$\frac{(\prod_{j=1}^{M} f_j)\overbrace{(\sum_{i=1}^{nME} P_{ME(i)} \cdot C_{FME(i)} \cdot SFC_{ME(i)})}^{\text{Main engine}} + \overbrace{(P_{AE} \cdot C_{FAE} \cdot SFC^{*}_{AE})}^{\text{Aux. engine}} + ((\prod_{j=1}^{M} f_j \cdot \overbrace{\sum_{i=1}^{nPTI} P_{PTI(i)}}^{\text{Shaft motor}} - \overbrace{\sum_{i=1}^{neff} f_{eff(i)} \cdot P_{AEeff(i)})C_{FAE} \cdot SFC_{AE})}^{\text{Energy efficiency technology (electrical)}} - \overbrace{(\sum_{i=1}^{neff} f_{eff(i)} \cdot P_{eff(i)} \cdot C_{FME} \cdot SFC_{ME})}^{\text{Energy efficiency technology (mechanical)}}}{f_i \cdot Capacity \cdot V_{ref} \cdot f_w}$$

Figure 3.3 – 1: EEDI Formula

The symbols in this formula are described in detail in MEPC (2014), so here only parameters that have significant impact on passenger ships are described. For passenger ships, capacity in gross tonnage is used instead of deadweight.

According to the formula, the attained EEDI value is mainly influenced from five generic terms.

- Main engine emissions represent total energy demand for the main engines.
- Auxiliary engine emissions represent total ship service loads and electrical power requirements for the propulsion system.
- Shaft engine emissions represent shaft motor/generator power which can be reduced by energy saving technologies eventually present onboard for the auxiliary systems.
- Main engine power reduction represent energy saving technologies for the propulsion power.
- Transport work represents ship capacity and ship speed.

It should be noted that the current EEDI equation may not be applicable to a vessel comprising non-conventional propulsion (i.e. diesel-electric, turbine and hybrid propulsion) except for cruise passenger ships and LNG carriers. The limitation is due to undetermined key variables in the equation. However, based on continued improvement on EEDI calculation guidelines, the IMO intends to expand the standard to include further ships types and propulsion systems by modifying the formula or offering alternative formulations in the future.

A drawback of the EEDI analysis is that it only considers one operating condition at 75% of nominal installed propulsion power. A single operating point may not represent all operating efficiency as the ship performance greatly varies in the real operating conditions. The formulation of the EEDI reference line is another drawback as it is determined only by the ship capacity. However, ship energy efficiency can be influenced by various parameters. Ship speed, for example, proves to have a profound impact on fuel consumption and directly on CO2 emissions. These parameters thus should be considered to include into the definition of the prescribed baseline. Additionally, the index value only takes CO2 emissions into consideration and disregards other potential emissions. At present, some exhaust emissions such as methane have not yet been restricted by any regulations that means while the regulation is enforced to reduce CO2 emissions, it might end up increasing other unregulated exhaust gases.

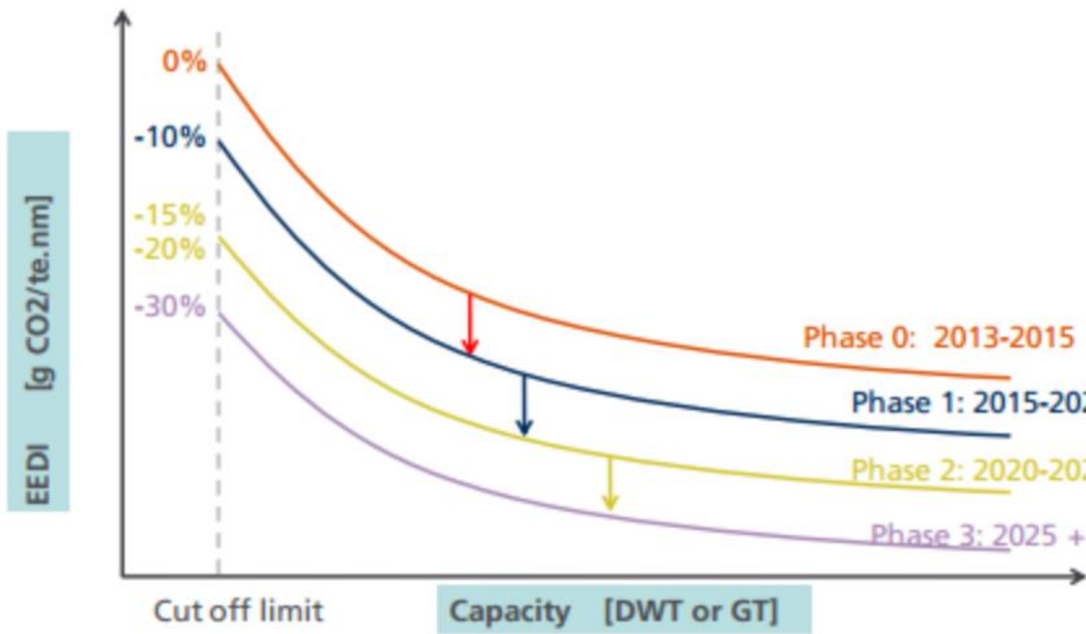


Figure 3.3 – 2: EEDI Reduction Factor

The EEDI is currently insufficient for vessels comprising non-conventional propulsion. Nevertheless, extension of the index or introduction of alternative formulations to cover more vessel types can be highly anticipated in the future. Intention to equip unregulated electric vessels with the technologies would be advantageous for not only the legislative provision but also the global environment.

Part B - E-ferry Design Project

4. Preliminary Design

4.1 Overview, sizing and operational profile

With full awareness of the huge environmental potential and keeping in mind the complexity and technical limitations a project like this may rise, a preliminary design will be conducted which will mainly include, but not limited to, the following:

1. General Arrangement drawing
2. Design of Propulsion System
3. Electric Load Analysis
4. Electrical configuration and Wiring Diagrams
5. Monitoring and Automation System

In Ro/PAX vessels, cargo (DWT) is considered the number of passengers and vehicles on board. Based on the general arrangement drawing, which is presented below, payload capacity in passengers and cars is estimated both in summer and winter conditions. Vessels details and main particulars are shown in the following table:

VESSEL MAIN PARTICULARS AND DETAILS	
Vessel Type	Ro-Pax
Specific Hull Design	Passenger Car Ferry
Displacement (m^3)	2100
Length Overall (m)	72
Beam Mld. (m)	20
Depth up to Freeboard Deck (m)	4.7
Draft Design Mld. (m)	2.9
Block Coefficient	0.5
Passengers (Summer)	250
Passengers (Winter)	125
Cars	40

The ship's electric battery system design is mainly addressed by the size of its propulsion requirements, corresponding to an explicit cruising speed V_S at specific loading conditions (DWT) and correlated draft. The most accurate and comprehensive way to begin with, is to import the morphology of the ship's hull into an appropriate 3D Design software and calculate its hydrostatic particulars and characteristics. Different loading conditions must be taken into consideration and stability criteria must be full complied with.   Afterwards, hulls and its' appendages resistance should be measured through CFD modeling in order to select a proper propulsion system able to overcome such resistance during sailing and maneuvering.

For the sake of good order and to avoid overextending beyond the main point of this study, such research will not be carried out. It is a given that many major elements are missing, like vessels' lines plan or a systematic series used for these vessels and familiarity with the relative programs is not granted. On the other hand, it was preferred for our calculation methodology to rely on existing all electric ferries and build an energy balance sheet based on ship's operational profile, electrical load balance and given principal dimensions.

Beginning, the wetted surface was estimated by using the following empirical formulas:

$$WSA = 1{,}7\ L \cdot T + \frac{V}{T} = 1079\ m^2 \qquad (Denny - Mumford)$$

$$WSA = (3{,}4\ \cdot V^{\frac{1}{3}} + 0{,}5 \cdot L) \cdot V^{\frac{1}{3}} = 1018\ m^2 \qquad (Schneekluss\ and\ Bertram)$$

$$WSA = \frac{V}{B} \cdot \left[\frac{1{,}7}{Cb - 0{,}2 \cdot (Cb - 0.65)} + \frac{B}{T}\right] = 1060\ m^2 \qquad (Danckwardt, 1969)$$

Taking into account a safety margin, Wetted surface of 1100 m^2 was considered. The nominal cruising speed of the vessel is selected at 9 knots. Basic variables used for the calculations are summarized in the following table:

Fr	0,174197821
μ	0,00122
ρ	1026
ν	1,19E-06
Re	2,80E+08
T (Draught)	2,9
S (Wetted Area)	1100
V (Displ)	2100

Based on the above, the resistance forces alongside with the effective power for propulsion were determined as shown in the following table:

Resistance Forces	
Cf (Friction coefficient) ITTC	0,0018041
Rf (Friction Resistance)	21823,3
1+k (Form Factor)	1,15
Rv (Viscous Resistance)	25096,8
Rv/Rt	65%
Rt (Total Resistance)	38610,5
Rw (Wave Resistance)	13513,7
Rr (Residuary Resistance)	16787,2
Effective Power (EHP)	178,8

A preliminary estimation of the necessary power for both the azipod thrusters and the electric driving motors was conducted, taking into consideration sea margin, coefficient and load factors. Results are presented below:

Pod Power	
Propulsive Coefficient PC	*55%*
Shaft Power (HP)	*325,0*
Sea Margin	*15%*
Pod Power at 9kn (Mechanical)	*373,8*
NCR	*85%*
Pod Nominal Power (Mechanical)	*439,7*

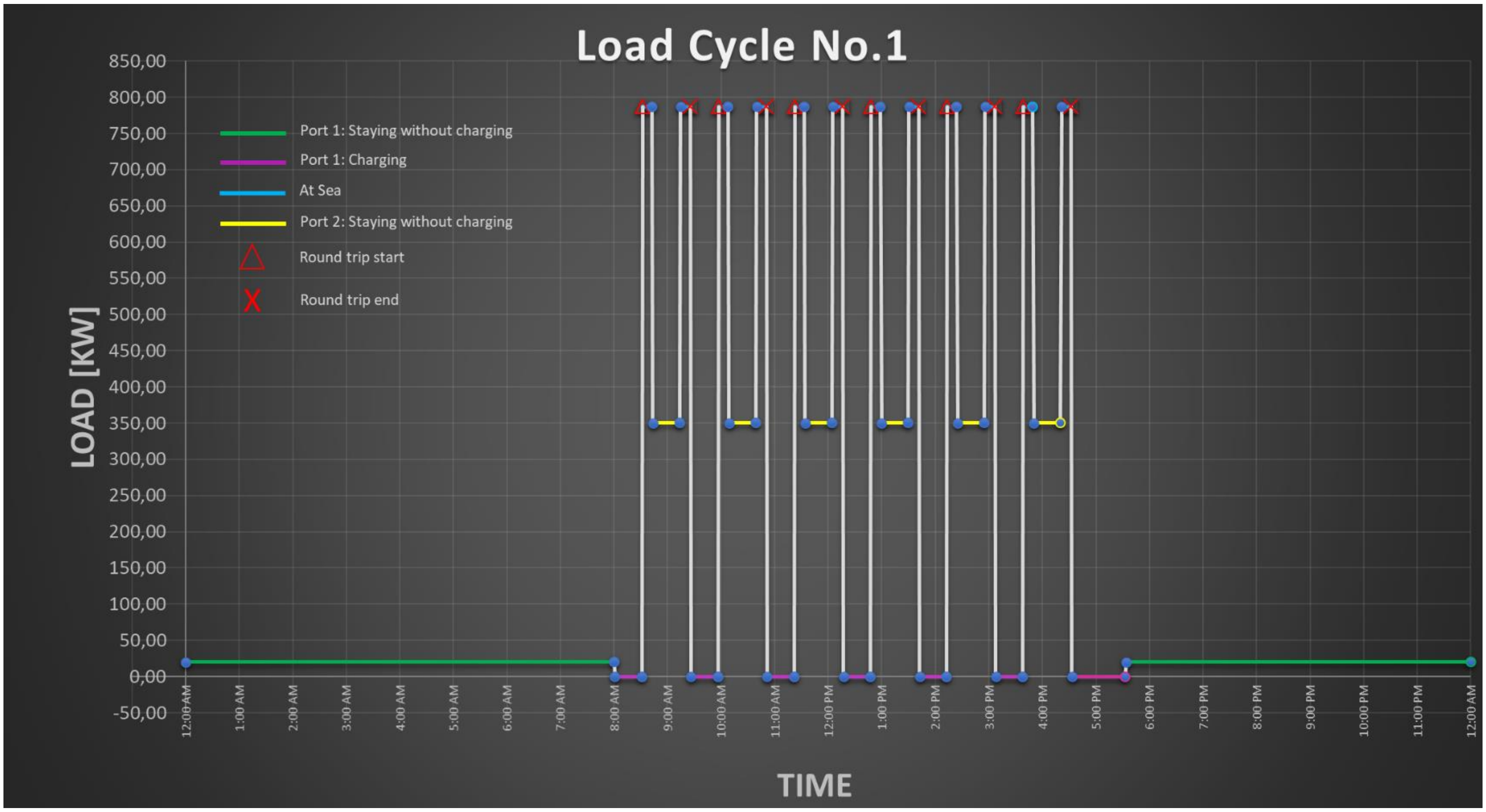
Motor Power	
nM (Motor efficiency factor)	*95%*
Motor Power at 9kn (Electrical)	*393,5*
Load Factor	*85%*
Motor Nominal Power (Electrical)	*462,9*

Electric Load	
Battery-Motor efficiency factor (converters)	*90%*
Propulsion Load at 9kn	*437,2*
Hotel - Auxiliary Loads	*350*
Total Power Load at 9kn (Propulsion& Auxiliary)	*787,2*

The main operation Design profile in terms of power consumption, for the route of Perama-Paloukia (1,6 nautical miles) is displayed below.

More specifically:

- The ship is expected to complete 6 round trips per day.
- Load at Port 350 kW
- Load at Sea 787,2 kW
- Load at night 20 kW
- Time at each port 30 minutes
- Time at sea 10.67 minutes
- Charging Load of 1197 kW while berthing
- Total Energy Loses of 454,88 kWh per trip



The onboard battery system is expected to support all required loads of vessel during operation providing reliability, adequate flexibility and ensuring safety of passengers, crew and craft at all costs. The battery bank should be sized accordingly by the greater expected load demand to ensure reliable and comfort trips. The number of battery modules needed and their arrangement in the vessel depends, as well, from market available battery solutions. When battery system is installed, it will power directly all hoteling loads and electric motors driving the azipod thrusters. The battery system will be capable to regenerate all of its energy while at berth through a convenient and automatic system on shore, while, also, quick redundancy could be achieved by battery swapping from available battery racks from the land. The most possible, initially, scenario is that vessels will charge only in one port.

4.2 Propulsion and Energy Demands

As implied from their hull's form, their propulsion system is based on 2 azipod thrusters installed in both ends of the vessel, coupled to corresponding motors. With reference to the above calculation, which is based on ships operational profile, the propulsion load at sea was roughly estimated. For redundancy purposes and to include the increased energy demands during acceleration, the nominal output of the azimuths is taken as 600kW.

Regarding the hotel load power estimation, the approach is based on details concentrated from similar Ro Pax vessels. In addition, in case of ferries and cruise ships following a well-known route, the hotel load power requirements are expected to behave in a typical manner, highly depended on water and air temperature.

The maximum power load is expected to be handled adequately by the onboard battery system and it is to be calculated by simply summing all possible electric loads on a more mature phase of this design. In this preliminary approach, a total 350 kW of Additional Electric Load (excluding Propulsion loads) was estimated. At the detailed phase, the selection of each individual consumer, as well as, the installation/sizing of the corresponding Switchboards will determine the meticulous load sharing among consumers

Propulsion Loads	2 x 600 kW
Hotel Loads	350 kW
Estimated Energy demand for propulsion	*190,9368421 kWh*
Estimated Energy demand for hoteling/electrical loads	*213,5175 kWh*
Estimated energy required for one trip	*808,9086842 kWh*
Estimated demanded energy of the vessel per day	*4853,452105 kWh*

A well-designed high-performance propulsion system should offer the required sustainability and reliability and integrate all safety features under all circumstances. The required propulsion demands will be adequately supplied from a pair of two (2) motors combined with the corresponding reduction gearbox equipment.

4.3 Azipod Electric propulsion and Electric Motor Technologies

A typical system for double ended ferries can be two azipod propulsion thrusters interfaced in a battery-electric system. Azipod propulsion is a gearless steerable propulsion system where the electric drive motor is housed within a pod outside the ship hull. An Azipod System is combination of propulsion and steering of ships, which replaces traditional propellers, lengthy drive shafts, stern tubes and rudders which were used on oceangoing vessels, passenger cruises. The main benefit of using Azipods is that they do not have engines inside. Instead they have a huge Variable Frequency Electric Motors (VFEM). It is also known as POD Drive (Propulsions with Outboard Electric Motor), in which the electric motor is used to turn the propeller.

The podded drive propulsion plant has been of interest to researchers since the 1990s and are currently popular in the marine industry. This plant offers many advantages over conventional propulsion systems, such as more uniform flow, improved maneuverability, enhanced sea keeping performance characteristics lower noise and vibration, less fuel consumption, space savings in ship architecture and arrangement, and rudder and shaft elimination.

The compact Azipod unit consists of four main modules:

a) Propeller

Propellers are divided into two groups. The first is Fixed Pitch Propellers (FP) and other is Controllable Pitch Propellers (CPP). Fixed pitch propellers are cast in one block and normally of a copper alloy. Compact Azipod can be provided with a duct as an option for vessels with high efficiency requirements.

b) Electric Motor

- The electric power is controlled by an onboard frequency converter, and transmitted to the electric motor via power slip rings at the power transmission and steering module. Frequency controller is used to change frequency of supplied power so that rotating motor speed can be controlled. The compact Azipod incorporates a **Permanent Magnet Synchronous Motor** with a Fixed Pitch Propeller (FPP) that is mounted directly onto the motor shaft. Permanent magnet technology has many benefits over the conventional one. The outer diameter of POD can be decreased, which improves hydrodynamic efficiency. The uniform frame design enables the motor to be directly cooled via convection to the surrounding seawater, thus eliminating the use of cooling system (and problems attached to it too). The Azipod are suspended beneath the water line at the aft end of the ship. Azipod is mounted on a shaft perpendicular to the center line of the ship's hull.

c) Strut

Strut module acts as a connective element in Compact Azipod structure. Control cables, piping and power supply bus bars for propulsion motor are located inside the one -piece cast called strut module.

d) Power Transmission and Steering Module

Azipod is a Podded propulsion system, azimuthing through 360 degrees. Power transmission and steering module consists of local control and equipment box, cable drum (slipping unit as an option), steering motors with gearboxes and assembly block. This model is located inside the hull of ship. The shaft can be rotated to any position in 360 degrees. The angular position of rotation can change the direction of the ship's movement or keep it sailing straight ahead. Thus, ships with Azipods are steered without a rudder.

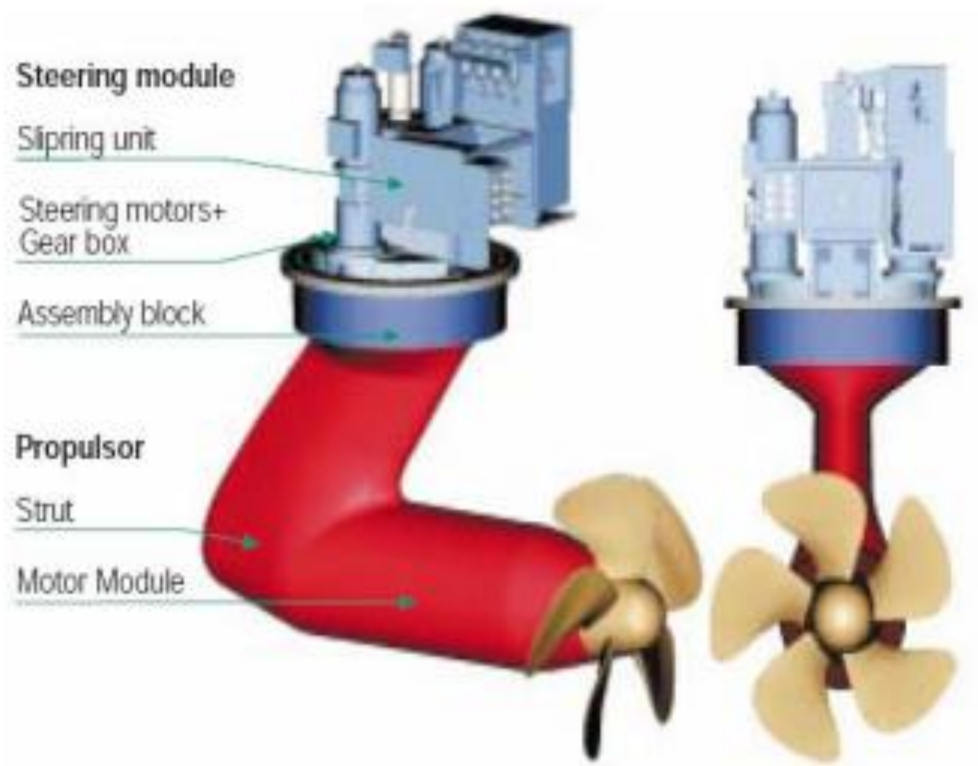


Figure 4.3 – 1: Azipod Module

In an AC drive, a frequency converter is used to control the speed and torque of electric motor housed in the azipod unit. The speed of the AC electric motor can be controlled by varying the voltage and frequency of its supply. A frequency converter works by changing the constant frequency mains electrical supply into a variable frequency output. The frequency converter drive provides step less control of three-phase AC currents from zero to maximum output frequency, corresponding to a desired shaft speed both ahead and astern directions.

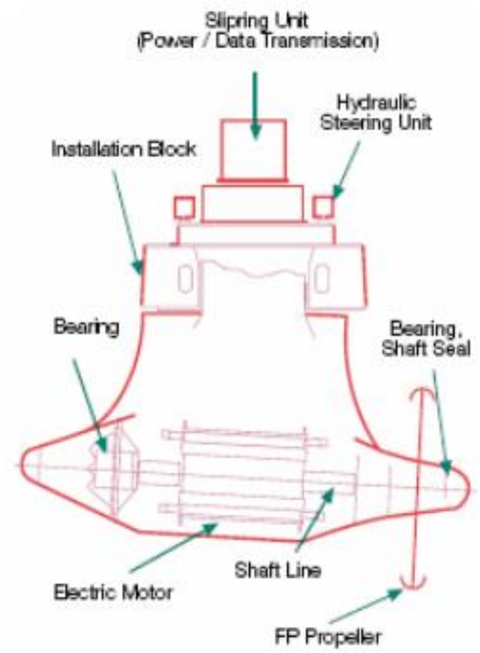


Figure 4.3 – 2: Azipod Cross sectional view

Using electric propulsion can avoid the prime mover's wide range speed regulation, and improve its efficiency. But, on the other hand, energy consumption increases significantly. Therefore, the propulsion motors must have high efficiency, and can meet the ship promoting conditions. With the development of the power electronics technology and magnetic materials, in the ship electric propulsion system, the permanent magnet synchronous motor was usually used. Major azipod vendors, such as ABB, use permanent magnet motor as their standard propulsion unit.

Figure 4.3 – 3: ABB Azipod with Permanent magnet motor

Compared with the conventional motor, it has high power density, high torque density, high efficiency, high power factor and so on. This is mainly due to the high energy density NdFeB and SmCo magnets, which are commercially available today. In other words, advancements in high-energy permanent magnet materials and magnet manufacturing technologies enabled the manufacturing of high power density and high efficiency permanent magnet motors at a reasonable cost. The propulsion system consisted by the permanent magnet synchronous motor, is low noise, high efficiency, maintenance and performance better.

There are two types of permanent magnet motors: brush and brushless. The brushless motors are becoming stronger candidates over traditional brush type motors for the following reasons: higher efficiency, higher power density, better heat dissipation, and increased motor life. In addition, brushless motors experience no losses due to brush friction and they deliver higher torque compared to a brushed type motor of equal size and weight.

The brushless motor construction combines the long life and low maintenance benefits of an AC induction motor, and the desirable speed-torque curve of a PMDC motor.

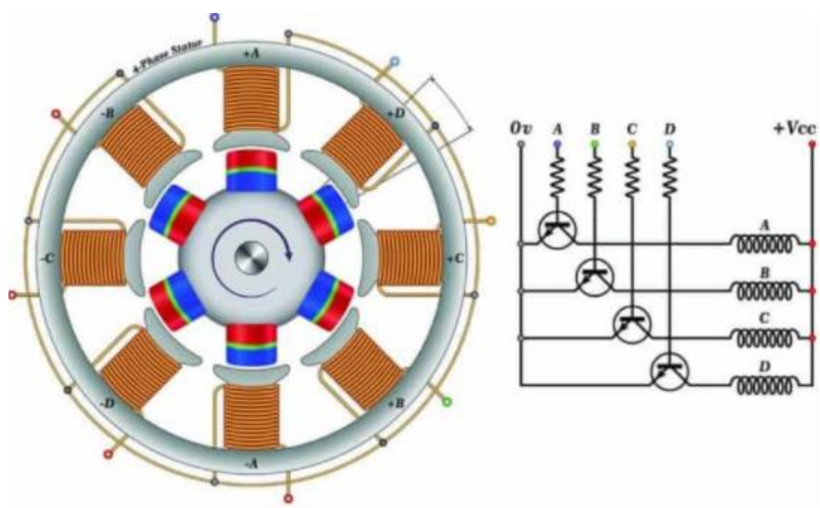


Figure 4.3 – 4: Brushless DC Motor

On the contrary, alternating current (AC) induction motors are the most common of all types of electric motors manufactured for the general use in household applications, industrial drives, and electric propulsion. These motors are rugged, relatively inexpensive, and require very little maintenance.

The stator is composed of laminations of highgrade steel with slotted inner surface to accommodate the current carrying wires. The rotor currents in an induction motor are induced by the stator’s changing, or rather, rotating magnetic field. This induction action is the central operating principle of AC induction motors.

An AC induction motor, when driven from a battery source by an appropriate inverter, has external characteristics that are well suited to vehicle propulsion and other applications. Induction motors have relatively low manufacturing cost and are mechanically rugged because they can be built without slip rings or brush and commutators. Consequently much attention has been given to induction motors for automotive applications in the areas of vehicle propulsion, engine starting, braking, electricity generating, speed reversal, speed change, etc.

The lack of brushes, combined with a relatively low speed, makes the AC motor a great choice for applications requiring quiet operation. On the other hand, they have a significantly lower starting torque than permanents magnet DC Motors, a factor that should be considered during the motor selection process. The induction motors have certain inherent disadvantages including speed which, is not easily controlled because a 3 phase induction motor is a constant speed motor and for the entire loading range, the change in speed of the motor is very low. Furthermore, it runs at low lagging power factors when lightly loaded. This is because during the start, the motor draws a large magnetising current to overcome the reluctance offered by the air gap between the stator and the rotor.

Apart from the above described induction and permanent magnet motors (Brushed and Brushless), the different types of electric motors are categorized in the below figure:

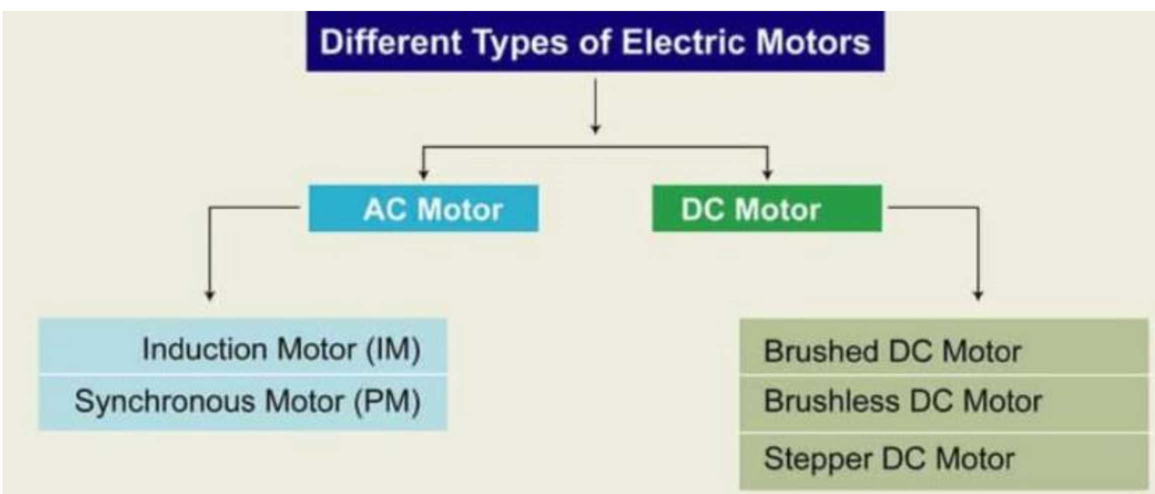


Figure 4.3 – 5: Types of electric motors

4.4 General Arrangement

The Vessel's tanks, compartments and superstructures to be arranged as shown in the accompanied GA drawing.

Two separate and completely independent engine rooms to be considered. The Vessel's propulsion power shall be provided by two (2) sets of battery packs. The electric distribution system shall be composed of two (2) main switchboards. Each asynchronous propulsion motor shall be started and stopped from its respective main switchboard (MSB) .Battery rooms shall have double hull protection. The battery space is the physical enclosure in which the batteries are located and it includes all functions and components which contribute to keep the battery system in the defined space at a specified set of environmental conditions.

Remote and automatic controls and instrumentation shall be provided in compliance with the requirements of the Classification Society for periodically unattended machinery space. Main switchboards and control and monitoring system for main and auxiliary equipment shall be arranged in ECR. The remote control and monitoring of the azipods shall be provided both in the wheelhouse and engine control room.

Wheelhouse equipped with nautical and communications equipment according to national Authorities and owner's requirements. Navigation and radio equipment shall comply with the appropriate IMO performance standards (IMO publication 978). At least the following equipment should be included:

- ECDIS, conning display system, radar equipment, DGPS navigator, gyro compass, magnetic compass, autopilot, e-logbook, echosounder, speed log, internal communication system, intercom, public address, internal telephone, CCTV, emergency communication, GMDSS-1, GSM telephone, VDR

Accommodation spaces shall be grouped into living spaces, public spaces, control spaces, passage spaces, catering spaces, and sanitary spaces as listed below:

- Public spaces: Cafeteria, Lounge and open deck passenger area
- Control Spaces: Wheelhouse and ECR
- Catering spaces: Galley
- Sanitary Spaces: Public Toilets
- Crew Accommodation: Crew Pantry, Ships Office, Crew Changing Rooms and lockers.
- Sundry Spaces: Electric equipment room, Deck Store, Provision Store and Garbage Store

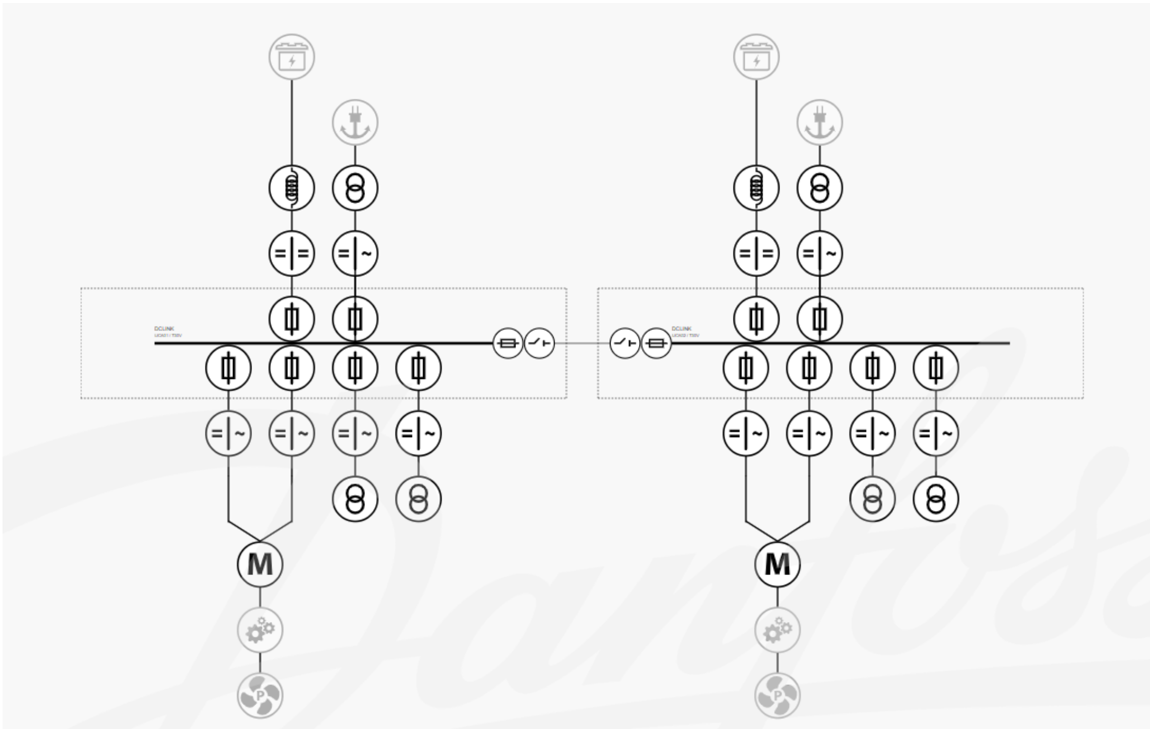
Totally, 80 internal seats and 232 outside seats are provided alongside 2 passenger toilets. First aid equipment shall be arranged in deck store. Air-conditioning system shall be designed for enclosed area. The sewage discharge system shall be designed based on vacuum toilet system with a sewage treatment plant and a gray water holding tank.

Two (2) main access ladders, one (1) at each side of ER, shall be provided. The ventilation system shall be designed and provided in compliance with the Rules and Regulations.

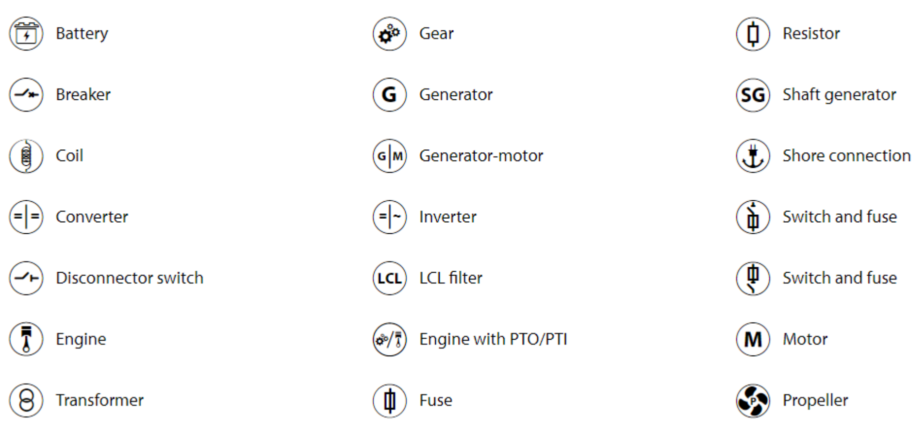
One (1) electrician workshop and one (1) ER store shall be arranged in ER. ER store shall be fitted with lockable cabinets and shelves for the stowage of spare parts and tools.

4.5 Electric Configuration

The preliminary electrical configuration is reflected in the herewith figure.



The used symbols are listed below:



Battery power plant shall be comprised of converters, inverters, transformers and shore connections. Power from battery systems shall be fed to main switchboards through suitable converters and afterwards through inverters to propulsion and hoteling loads. Two separate systems are considered, ensuring redundancy and flexibility.

The main components of each configuration are:

- One converter with coil for the supply of main switchboard
- Two inverters (DC/ AC) for the control of the induction propulsion motors
- Two inverters for the supply of the hotel and auxiliary loads (lighting, air condition etc.)
- Two transformers for serving the hotel and auxiliary loads
- Six fuses in each connection of main switchboard
- One shore connection with inverter and transformer for the charging of the batteries while at berth
- One connection switch for the interconnection of the battery rooms

Main switchboards shall be arranged to be accessible from front and rear side for maintenance in accordance with the manufacturer's standards and the maintenance space shall be prepared according to the requirement of the Classification Society.

Switchboards and internal components shall be capable of withstanding shipboard vibration without damage or faulty operation.

Switchboard shall be properly illuminated and part of these lighting shall be fed from the emergency supply system.

Transformers shall be located in dry, clean and well ventilated space free from dripping water and moisture.

5. Battery System

5.1 Rules and Regulations

The Vessel, including materials, hull, machinery, equipment, appliances and outfits, shall be designed, constructed and equipped in accordance with the requirements of the Classification Society, makers standards, flag state, related Regulatory Bodies and Port Authorities**.** For its recent developments in battery technology and ship electrification, DNV GL will be considered., appointed and authorized as the Classification society of the constructed vessel.

DNV GL has established a full range of tools and services to assist and develop both newbuild and retrofit hybrid and battery solutions. DNV GL published tentative rules for using lithium-ion batteries on-board vessels in 2012. These rules were updated and published in October 2015 under the common rule set of DNV GL. The latest edition of the DNV GL rules is from January 2018, with amendments from July 2018 (DNV GL, 2018). The requirements in the DNV GL Class Rules are function based and applicable for all DNV GL classed vessels. The primary focus of the rules are the safety of the complete battery installation and the specific test requirements for such a system.

Additionally, DNV offers Battery Ready services, type approval certification, technical/economic analyses, risk analyses, battery service life and optimization analyses, ship performance instrumentation, measurements and analyses, technology qualification and hardware-in-the-loop testing of Battery Management Systems.

Battery installations in ships today operate within a complex regulatory context and development. Apart from class rules, which focus primarily on safety of battery installations onboard ships and are increasingly obtaining the necessary regulatory certainty for practical implementation of battery technology, environmental and international regulations must also be considered and fully complied with.

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

- Belong to class D, for passenger ships engaged only on domestic voyages in sea areas where the probability of significant wave heights exceeding 1.5 meters is less than 10% over a one year period for all year round operation.
- Serve routes of categories: VI. Regional routes (▯ 6 nm)
VII. Protected zones
- Vessels serving routes VI and VII are allowed to be of "open-type"

In the following chapters, the technical design of the battery system and its arrangement in the vessel will be described, based on the following Rules, Regulations and Standards:

I. DNV-GL : Rules for classification, Part 6, Additional Class Notations (Oct.2015)
II. DNV GL Rules for classification of ships Oct-2015, Battery Power
III. DNV GL Rules for classification of ships Oct-2015, Dynamic positioning
IV. DNV GL Rules for classification of ships Oct-2015, Electrical installations
V. DNV GL Rules for classification of ships Oct-2015, control and monitoring systems
VI. DNV GL CP-0418, Type Approval of lithium batteries
VII. IEC 62620 Secondary cells and batteries containing alkaline or other non-acid electrolytes - Secondary lithium cells and batteries for use in industrial applications
VIII. UN Manual of Tests and Criteria, UN38.36
IX. IEC 62281 Safety of primary and secondary lithium cells and batteries during transport
X. UL1642 Standard for Lithium Batteries, edition 5 (2012-03-13)
XI. UL1973 Standard for Batteries for Use in Light Electric Rail (LER) Applications and Stationary Applications
XII. International Convention for the Safety of Life at Sea (SOLAS),1974
XIII. MARPOL Annex VI
XIV. MSC 1002-Guidelines for Alternative design and Arrangements for Fire Safety
XV. MSC 1212-Guidelines on Alternative Design and Arrangements for SOLAS Chapters II-1&III
XVI. MSC 1455- Guidelines for the approval of alternatives and equivalents as provided in various IMO instruments
XVII. IEC/ISO/IEEE 80005-1 Utility connections in port - Part 1: High Voltage Shore Connection (HVSC) Systems - General requirements
XVIII. IEC/IEEE 80005-2 Utility connections in port - Part 2: High and low voltage shore connection
XIX. IEC PAS 80005-3 Utility connections in port: Low Voltage Shore Connection (LVSC) Systems - General requirements.

5.2 DNV Class Notation

The Classification concept consists of the development and application of Rules with regard to design, construction and Survey of Vessels. Class notation is an abbreviation or keyword expressing a specific feature relating to a Vessel or its machinery, systems and equipment, or service area while referring to specific requirements in the Rules.

The Class Notations are based on the following structure:

1. Main Class Notation.
2. Ship type notations
   - 2.1. Mandatory ship type notations
   - 2.2. Optional ship type notations.
3. Additional Class Notations
   - 3.1. Mandatory additional notations
   - 3.2. Optional additional notations.
4. Service area restriction.

Main Class Notation and mandatory Class Notation stipulates requirements for:

- availability of Main Functions and the safety of installations supporting the Main Functions
- structural strength and integrity of essential parts of the Vessel's hull and its appendages
- the safety of machinery, systems and equipment supporting non- Main Functions that constitute possible hazards to personnel and Vessel.

Vessel's notation shall be distinguished in the Classification Society's register by the symbol of:

DNV +1A, FERRY B, BATTERY (POWER), E0, R4

The Class rules for the Main and Battery notations are found in the following:

- ➢ DNV GL rules for classification: High speed and light craft (RU-HSLC), Part 1, Chapter 2, Section 2-4
- ➢ DNV GL Rules for Classification of Ships (DNV GL, 2018), Part 6, Chapter 2, Section 1-2

Main class notation (1A)

The main class notation **1A** is assigned to vessels with hull, machinery, systems and equipment found to be in compliance with applicable rule requirements.

FERRY B

Ship type Mandatory notation is assigned to vessels for carriage of passengers and vehicles. Applies to ferries which carry more than 12 passengers and vehicles on decks that are ventilating freely. Requires operating restriction R2 or stricter.

Battery Power

Additional Class notation which is mandatory where battery power is used as propulsion power during normal operations. The rules put requirements for redundancy and location. In addition, the time or range that the battery can supply energy shall be calculated when taking the planned operation/voyage into account.

E0

Additional Class notation which is optional and signifies that ship is designed for UMS (Unattended machinery space) operation, where machinery, alarm and automation arrangements provide for the safety of the ship in all sailing conditions, including manoeuvring, and when alongside, which are equivalent to that of a ship having machinery spaces attended.

Additionally, class notation **E0** is considered to meet the regulations of SOLAS regulation II-1/E, for periodically unattended machinery spaces, when alarms, required for **E0** in this section, are relayed to the bridge and the engineers' accommodation. Additionally, a bridge control system for the main propulsion machinery, arranged as specified in Pt.4 Ch.1, and a watch responsibility transfer system are also required to be installed.

R4

The service area notation **R** followed by a number or a letter will be assigned to all high speed, light craft.

The service area restrictions, given in nautical miles and representing the maximum distance from nearest port or safe anchorage, are given in the below table.

Service area notations	*Seasonal zones (nautical miles)*		
	Winter	*Summer*	*Tropical*
R0	250	No restrictions	No restrictions
R1	100	200	300
R2	50	100	200
R3	20	50	100
R4	5	10	20
R5	1	2	5
R6	0.2	0.3	0.5

R4 notation is considered and signifies that ship nautical miles range is 5 nm for Winter conditions, 10 nm for summer conditions and 20 nm for Tropical conditions.

5.3 Battery System Installation, Capacity and Features

As already described in Par. 1.1, main components of the generic battery system are the cells, modules and packs together with the required components for thermal management and safety features (fuses, contactors and busbars).

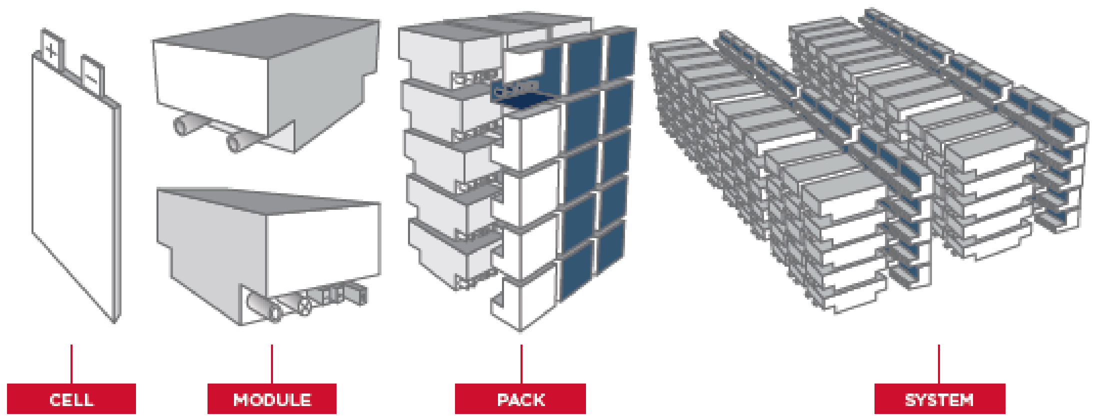


Figure 5.3-1: Battery System Components and Layout

Safety assurance, risk management and operational performance of lithium ion battery systems must be designed in at the most basic level, starting from the constituent elements from which the cell is built including all the ancillary components upon which the system is constructed.

Installation of the battery system should be checked and found in full compliance with maker's requirements and recommendations, as same are described in Maker's installation manual. All interfaces including the Battery Management System connections and features must be tested during commissioning and found in full compliance with Classification societys' rules. Functional testing of the safety features of the battery space (ventilation, gas detection, fire detection) must also be performed.

To begin with, the following instructions should be considered and followed up:

- 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.
- The battery module enclosures are to have a degree of protection not lower than IP44
- Battery cells of different physical characteristics, chemistries, and electrical parameters are not to be used in the same electrical circuit.
- 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.
- 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.

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

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. For 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. This provides galvanic isolation and a steady voltage to the main switchboard. Power electronics components can be substantial, both in terms of cost and size, relative to the battery. At least two completely independent battery packs/systems shall be installed as shown in Genera Arrangement drawing, to provide propulsion power in case one system fails.

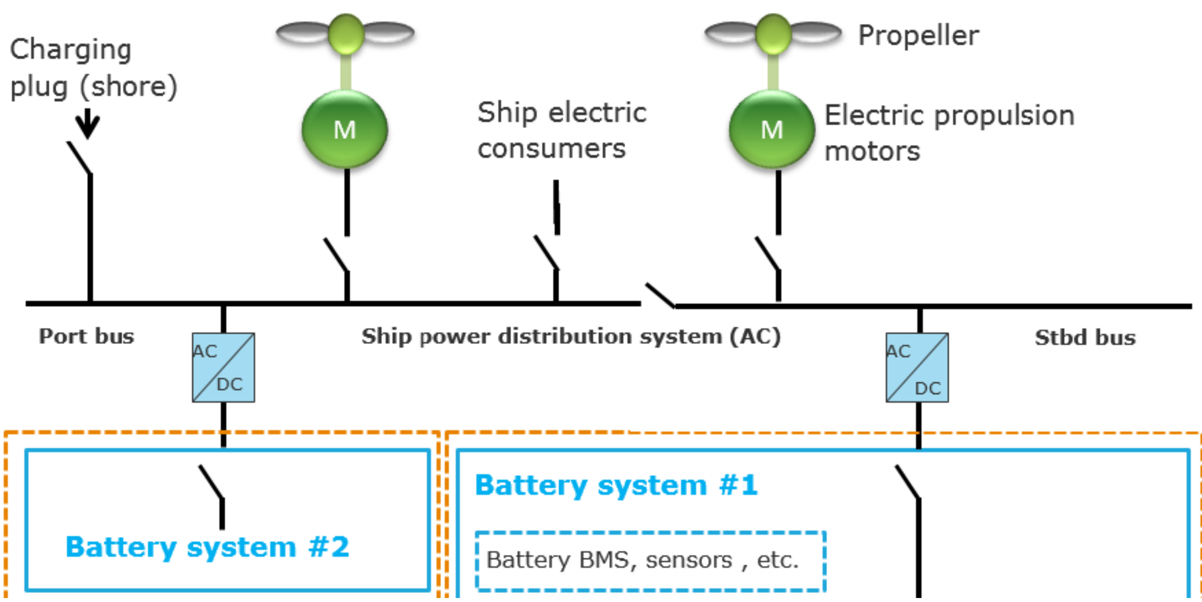


Figure 5.3-2: Ship Power Distribution System

When it comes to determining the required size of battery for a given application, many complex factors come into play. Because a battery will unavoidably experience degradation during its lifetime, and because operation at the extremes (top and bottom) of its State of Charge (SOC) range will accelerate degradation, batteries must be oversized for a given application. A smaller battery is more cost effective, while a larger battery is better able to maximize benefit or power a ship a longer period of time.

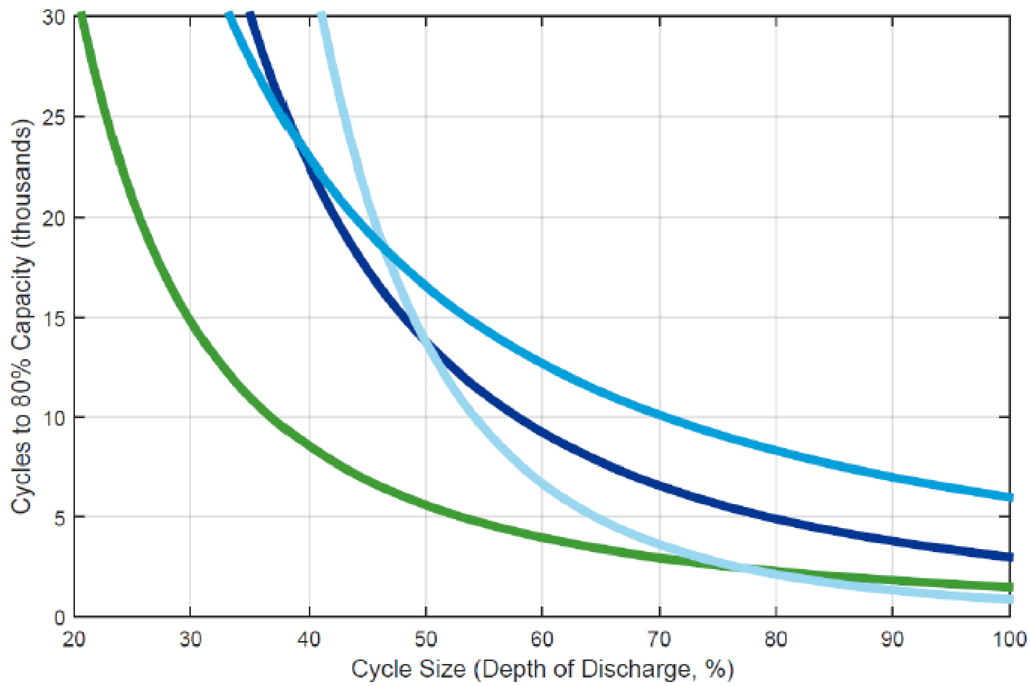


Figure 5.3-3: Batteries are able to perform more cycles when only a small portion of the total energy is used in each cycle

Capacity of the battery system shall be sufficient for the intended operation of the vessel, covering both propulsion and auxiliary/hotel loads. A safety margin of at least 10 % for weather adjustments to propulsion energy consumption shall be considered. Estimated demanded energy of the vessel per day was calculated as 4853,452105 kWh. Only a detailed electric load analysis, in a more mature phase of the design, assuming all the required consumers proposed to be installed and their utility factors to be in hand, is expected to indicate the exact power requirements of vessel's operational modes.

To sum up, battery system shall be designed taking into consideration the following:

- Demonstrate robustness for long term exposure in a marine environment (temperature, moisture, list, trim, roll, etc.).
- Be maintainable such that defect parts can be substituted safely and effectively.
- Battery lifetime should be such that the business case is economically reasonable.
- Battery system shall have sufficient useable energy for safe return to port also if one battery system fails.
- Enough charging shall be possible during port stay to keep an acceptable state of charge.
- Remaining range or time shall be displayed on the bridge as well as engine control room.
- Alarms and shutdown functions shall be provided.
- Important battery parameters shall be logged and stored in a non-volatile memory.
- Earthing of batteries: isolated system is recommended (isolated positive and negative terminals).
- A maintenance and operational plan including emergency operation shall be established.

5.4 Battery Management System

The operational performance and safety of a lithium-ion battery as a whole is accomplished by a control device commonly called the Battery Management System (BMS). A typical BMS is divided between components installed in individual battery modules and other components installed in battery packs.

A battery system typically has a BMS that works with a battery charger/converter to provide operational control and monitoring as well as safety functions. Operational control includes control of charging, discharging, cell balancing, etc. Safety functions will disconnect either portions of or the entire battery system in the event of over/under temperature, voltage, current, etc.

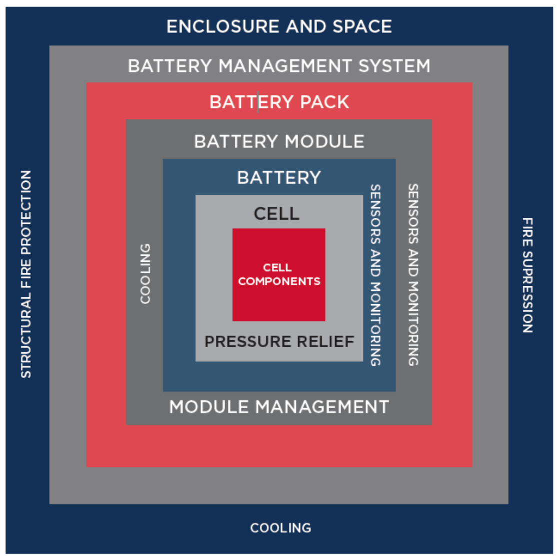


Figure 5.4-1: Layers of Protection

Primarily, BMS shall include the thermal management system to regulate the temperature of the battery modules. Control of the cell temperature maximizes the performance of energy storage/delivery, cycle and calendar life. The BMS and the thermal management system may operate at the module level, supplying liquid media or air to individual battery modules.

Voltage and temperature sensors are the most vital pieces of equipment for monitoring the battery and ensuring safe and optimal operation. The system shall monitor voltage of every cell (or lowest parallel grouping), which enables the highest level of detection of safety risks or unexpected performance. Temperature sensing requirements depend heavily on module design, but a higher degree of instrumentation can be regarded as advantageous.

The key objective is for the system to be able to remove heat from the cells, and in the case that excessive temperature is generated or focused at a location that it can quickly be detected. The need for redundancy for these fundamental measurements depends on design of the safety criticality of the system. A key principle when selecting sensor location is also to ensure that malfunctioning sensors may be detected.

Another key feature of the BMS, is its ability to monitor cells and ensure balanced operation. If a single cell's voltage differs substantially from those of the rest of the pack it is at a much higher risk of getting overcharged or overdischarged as the system is cycled up and down. In the case that this type of scenario is detected – as is greatly enabled with a high level of voltage instrumentation – it is highly advantageous for the BMS to have some capability to actively correct voltage and rebalance the cell(s). One approach is for some active control of resistive circuits which may interconnect the cells within a module specifically for this task. Typically each assembly of battery modules (eg. pack or rack) will have an additional layer of BMS control. This will likely include control of contactors to isolate the whole battery pack in case a fault is detected as well as other electrical controls and monitoring capabilities.

In addition, the BMS is responsible for calculating the State of Charge (SOC) and State of Health (SOH). SOC is analogous to the fuel gauge on a car or the percentage remaining on a mobile phone. Users may notice this indication often seems inaccurate, particularly as the battery ages; however, this is vital for a large maritime installation. Accurate SOC is required to give a clear indication of how far a vessel may go on its remaining battery power and also for ensuring that a hybrid system gets its maximum potential fuel consumption benefits. Likewise, SOH is a calculation of how much a battery has degraded over time. This calculation requires a BMS that is highly developed through experience and specifically calibrated to the battery cell being used.

Figure 5.4-2: BMS is the connection between the battery system and the operator

The BMS is responsible for monitoring voltage, current and temperature limits inside the battery system and evaluating signals to provide indication of when the system operations need to be curtailed. Voltage and current limits are dependent on each other as well as temperature – thus these represent calculations that are both complex and crucial, and are a key responsibility of the BMS.

In conclusion, battery management system shall:

- ✓ Communicate critical battery parameters like SOC,SOH, voltage and temperature
- ✓ Ensure that the battery operates in the safe operating window of the cells.
- ✓ Provide cell and module balancing
- ✓ Measure SOC and SOH
- ✓ Protect against over-current, over-voltage and under-voltage
- ✓ Include a thermal management system
- ✓ Provide alarms and shutdown functions to inform the operator when parameter limits are violated
- ✓ Include a data management system for data storage and tranfer.

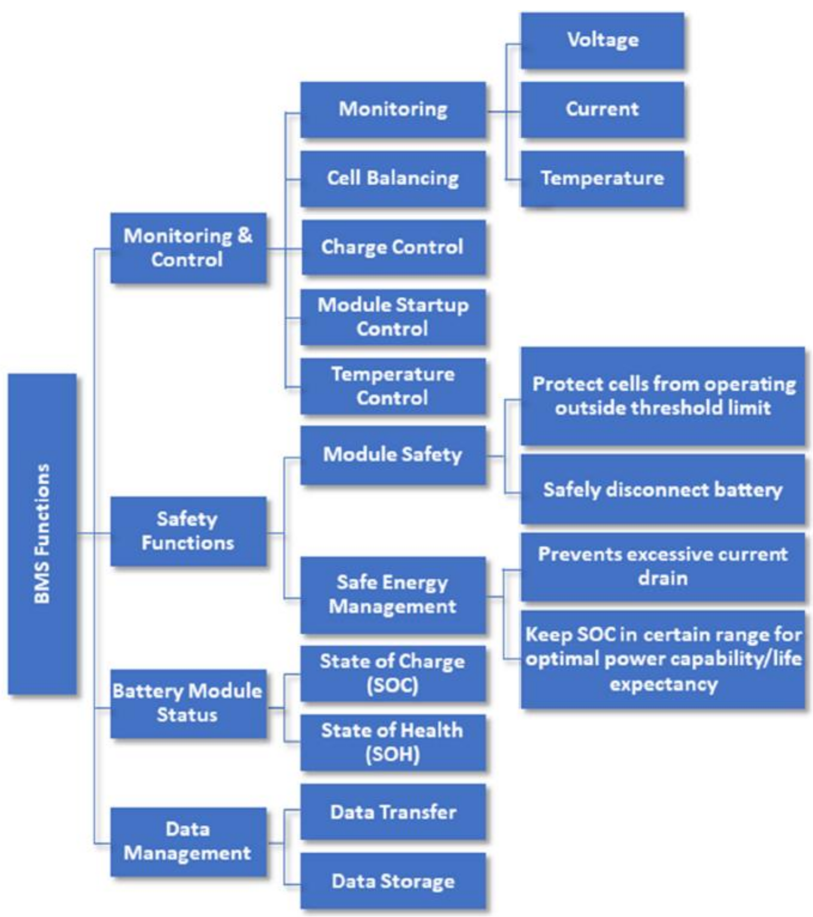


Figure 5.4-3: Battery management system functions.

Special attention shall be obtained on Battery Thermal Management System (BTMS) which is critical to the battery performance. In general, the heat generation of the Lithium-ion battery is caused by reaction heat, electrode overpotentials heat, and Joule heat of internal electrical resistance during charging and discharging processes. Higher charging and discharging rate produce more heat due to internal resistance. Heat generations and excessive accumulations during normal operations of Lithium-ion batteries would cause temperature elevations, leading to extensive degradation and shorten battery service life. An effective air-cooling BTMS could dissipate excessive heat within the battery pack and control the maximum operation temperature below a certain value as well as maintain the maximum temperature differences within a required range.

The advantage of air cooling is simple in structure without the requirement of cooling loops, easier to pack, low maintenance cost, no risk of liquid leaking into electronics or cabin, less weight and energy consumption. The air cooling method is widely used in the consumer electronics industry.

Below figure shows a typical air-cooling BTMS in which a typical Lithium-ion battery is passively or actively air cooled. Cells are regularly aligned inside the battery pack. Outside air flows into inlets on one side of the battery pack, passes through gaps between cells, and finally exits through outlets on the other side of the pack. The generated heat was carried away by air flow. Since the passive air cooling BTMS might not be sufficient, the active auxiliary method by adding fans or blowers to increase air flow rate is the necessary upgrade to ensure minimum cooling requirement.

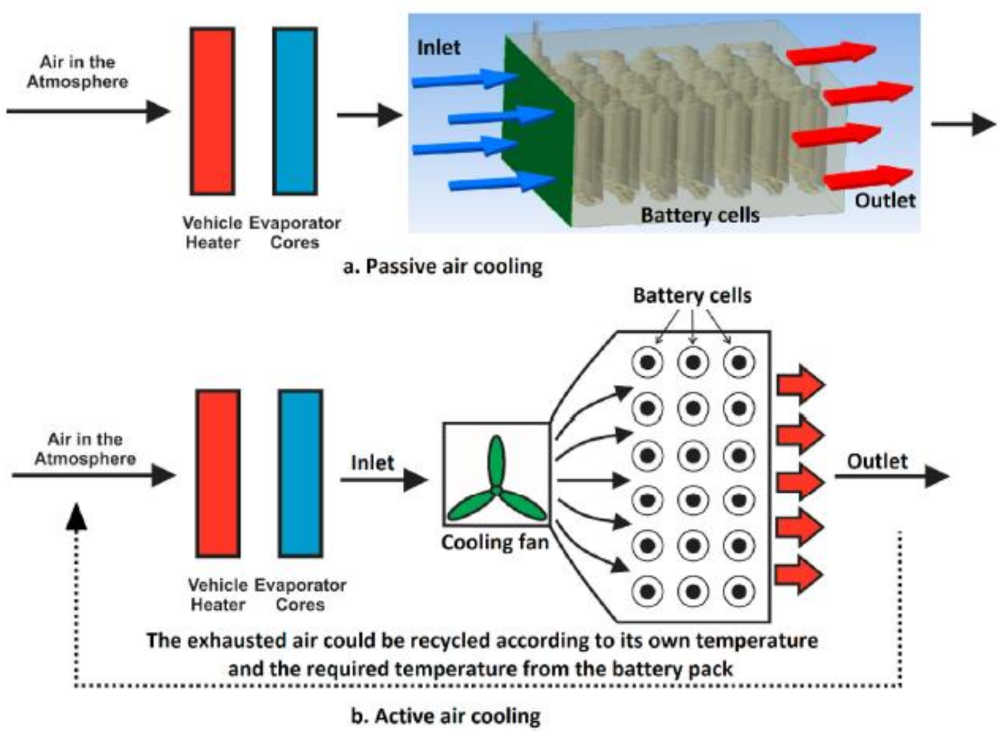


Figure 5.4-1: A schematic diagram of the air-cooling BTMS.

6. Charging System

6.1 Port Infrastructure

The connection to the electrical grid is a key component of battery energy storage systems. Utility-scale systems comprise of several power electronics units. Various grid connection topologies may be used, depending on the conversion stages within each unit, the load distribution between the power electronics and additionally the grid level to which the system is connected.

The selection of circuit topology is a key part of the shore network design which must be matched to the expected power demands of the berthed ship. Significant investment is required on the shoreside in order to provide the necessary infrastructure for shore connection. Fundamentally, the shore supply is expected to provide a suitable power supply able to meet the ship onboard requirements. Additionally, the supply must be able to provide the necessary extra power demand, possibly involving installation or upgrading of port area substations. One of the main challenges is the need for power to be provided at 50 or 60 Hz as demanded by the berthed vessel, requiring a frequency converter if the shore and onboard frequencies do not match.

The grid connection of battery system enables batteries to charge and discharge from the electrical grid. To connect the direct current (DC) of batteries to the electrical grid, which is based on alternating current (AC), power electronics components are required for the conversion of electricity and the control of the power flow. If the grid voltage differs from the AC voltage range of the power electronics, a transformer is often used to convert the voltage to the non-matching and typically higher voltage levels of the electrical grid.

As shown in the below figure, the main system elements are the following:

- transformer in the main switch board, matching land distributive grid voltage to the system installation (shore to ship)
- frequency converter matching land grid frequency to the vessel system,
- cable reel system enabling the supply of low voltage to the ship,
- transformer (on the ship) matching low voltage to ship voltage.

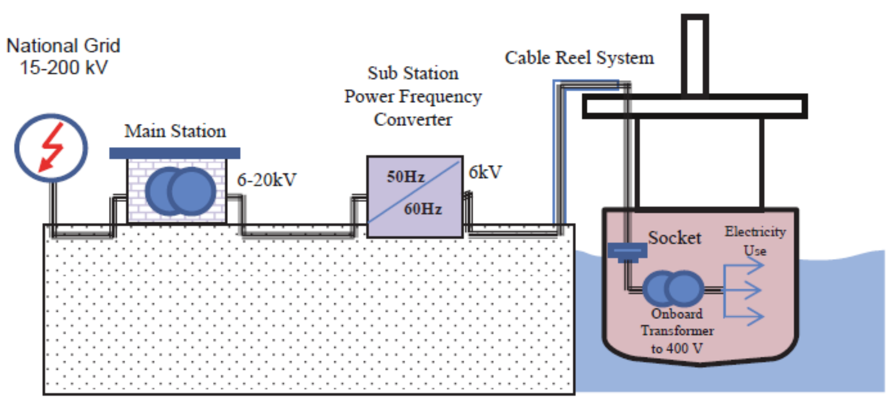


Figure 6.1-1: Main Components of the Grid & Distribution Network

It should also be mentioned that technology for long-term power supply from shore to other types of vessels has been developed and studied for several decades. For instance, supplying the auxiliary loads of ships at berth from the onshore grid (usually referred to as “cold ironing”) has been considered for a long time as an alternative to the use of auxiliary onboard (diesel) generators. Indeed, stopping all fossil-fuel-based onboard power generation helps to make the harbor area cleaner and reduces noise of diesel generators. Therefore, facilitation of power supply at ports for cold ironing and charging is turning into a requirement for future harbors. Consequently, further research is necessary for investigating loading strategies under constrained harbor environments, stability control methods, and renewable energy integration issues at future smart ports.

In general, the main battery charger can be installed onboard or can be located offboard, in a dedicated charging station. Although onboard chargers make it easy to charge using a regular AC plug everywhere, there would be several limitations for the size, weight, and cost of the onboard equipment, resulting in a constraint on charging power. In contrast, dedicated offboard charging stations can provide high power for charging since the weight and the size of the charger are not limited, enabling fast charging and reduced charging time. In marine vessels, there can be size and weight restrictions in the design, such as weight- and volume-sensitive ships. For instance, this would be the case of high-speed ferries where the weight of onboard equipment can highly affect the operation range and the performance of the vessel. Hence, eliminating an onboard transformer or minimizing onboard power conversion stages can be important when moving to more efficient zero-emission sea transportation.

A typical port charging facility is reflected in the herewith figure:

Figure 6.1-2: Charging Device

6.2 Charging System

The shore-to-ship interface is the part that enables the electric connection between the onshore and onboard power systems to transfer the electric power. This interface may include several main elements, such as electric connection, mechanical structures (e.g., robotic arms, pantograph, and towers), and monitoring systems. The electric connection should be established through a connection cubicle from the external electrical power supply connection point(s) to vessel ship-side reception arrangement. Earth connection is also to be considered with appropriate flexibility and reliability. Galvanic separation between the shore and on-board systems shall be provided on shore.

For ferries with short stays at berth, automatic connection systems will not only improve the safety of the system but can also maximize the time available for charging during the docking time, for instance by using a robotic arm capable of dynamic movement. Thus, automatic connection systems are needed, although they may add complexity and cost to the shore infrastructure. For long-stay vessels, the time required for connection is less critical since the connection and disconnection time will always be a small portion of the docking time. However, it can still be beneficial to utilize automatic plug systems because they provide greater safety and can operate with heavy high-voltage cables. For our case, the batteries will be charged overnight with low power and between ferry dockings with higher power.

Figure 6.2-1: The Cavotec Automated Plug-in System Counterweight allows automatic connection with the charging point on ferry bow.

The charging system shall be designed to comply with the following features and capabilities:

- The charger shall be designed with the needed capacity specified by the battery application.
- The charger should be designed in such a way that too high charge currents and voltages are avoided.
- The charger shall be designed to prevent exceedance of the specified current level (C-rates) and voltage level.
- The charging system and shore connection shall include temperature sensors in order to detect high impedance and heating in an early stage.
- Charging failure shall give alarm at a manned control station.

Thus, in the charging station, an EMS and a power management system (PMS) are needed for generating the references for the total charging power and the power from the grid. The power and energy management system shall generate the power and voltage set points for stable and efficient operation of the power system during the charging process. The monitoring and control system should communicate with the onshore and onboard battery management systems, which are responsible for estimation of the state of charge (SoC) and the state of health, thermal management, and cell balancing. When a ferry will be at berth, onboard charging control would send the amount of required charging power, so the onshore EMS should decide the share of the grid power. A typical example of a shore-to-ship charging system is presented below:

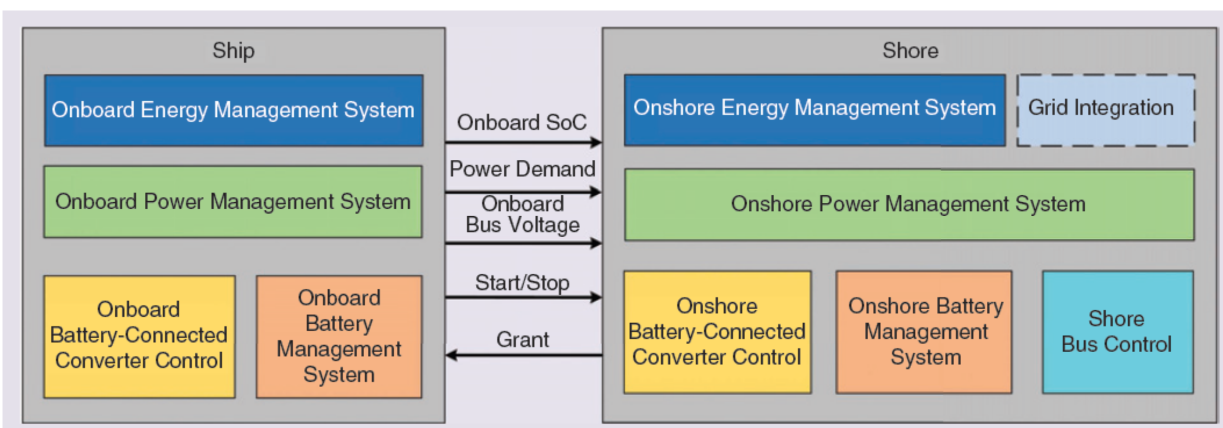


Figure 6.2-2: Shore-to-ship charging system

7. Safety Assessment

7.1 Thermal Runaway and Prevention Measures

The main concern of a battery system is that the temperature will rise to such level that it will go into thermal runaway. Thermal runaway is the exothermic reaction that occurs when a lithium ion battery starts to burn. The thermal event often starts from an abuse mechanism that causes sufficient internal temperature rise to the electrolyte within a given cell, causing high pressure and often release, and then ignition. This fire then poses significant risk of igniting the electrodes that are contained within the battery cell, thus producing a high temperature fires involving both liquids and gases. These fires are hard to extinguish and to cool down. Additionally, the electrodes may contain oxygen, which is released as it burns. Not all lithium-ion batteries contain oxygen within the electrodes but all lithium-ion batteries on the market today contain electrolyte that can ignite and cause this thermal runaway scenario.

Below figure summarizes the causes and consequences of thermal runaway.

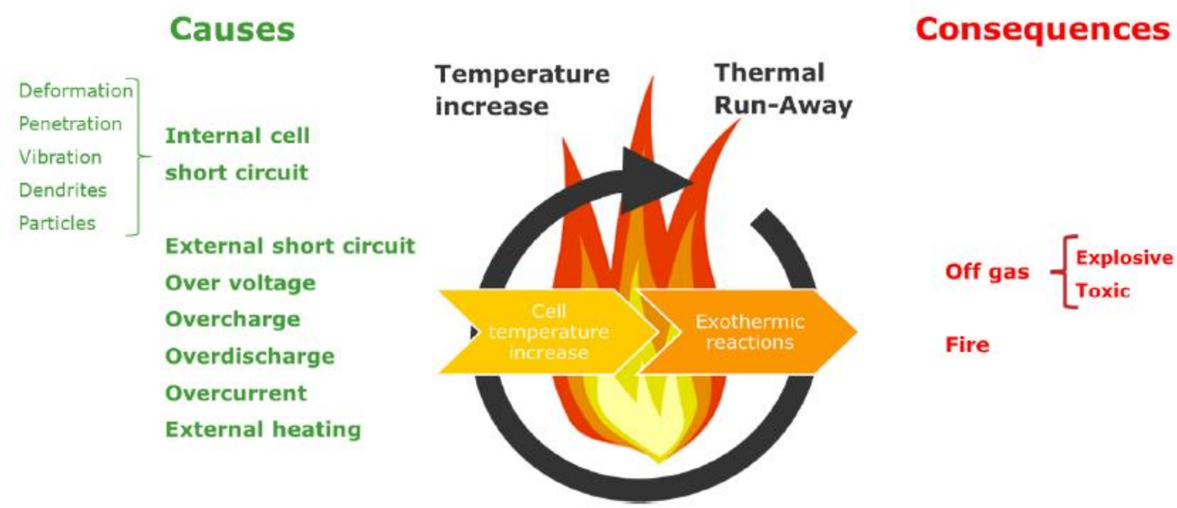


Figure 7.1-1: Causes and consequences of a thermal runaway in a battery system.

A maritime battery system is typically made up of hundreds or thousands of cells. The failure and total heat release of a single cell is a relatively minor threat. The greater threat comes from that thermal event producing sufficient heat that it propagates to other cells, causing them to go into thermal runaway. Numerous findings have reported that the thermal runaway mechanism in Li-ion batteries is the chain reaction of an uncontrollable temperature increase. Heat generation is inevitable due to the electrochemical reaction inside the battery. During normal operation, the generated heat can be dissipated over time, and the battery temperature can still be under control. However, the heat generation significantly increases if the battery is operating in abnormal modes, such as overcharging, external heating, and penetration. The natural heat dissipation cannot release all the generated heat in time, the battery temperature then increases significantly.

To minimize the risk of thermal runaway, the mechanical and thermal stability of the battery must be guaranteed. This is ensured by appropriate monitoring mechanisms of the battery cells and the battery pack. For example, positive temperature coefficient (PTC) thermistors, current interrupt devices (CIDs) and safety vents are playing leading roles in protecting commercial cells from thermal runaway.

- PTC thermistors are built into Li-ion batteries to protect the single cell from excessive current by its resistance increases with temperature
- CID is a protection device built into cells to remove the hazards of high internal pressure or temperature. It disrupts the electrical connection in a battery when the cell pressure or battery temperature exceeds a predetermined level.
- Safety vents relieve the internal pressure of the battery by exhausting generated gases

Some other components in Li-ion batteries can also improve battery safety. For example, the separator can shut down the battery under elevated temperature, and electrolyte with additives can protect the battery from overcharging and catching fire.

- The separator is an important component in Li-ion batteries that can determine the battery performance and safety. The separator is placed between two electrodes to keep them apart and avoid electrical short circuits. Meanwhile, the separator is moistened with electrolyte, which allows the transportation of ions between two electrodes during charge and discharge. Separator shutdown is the ability to stop the electrochemical reactions between two electrodes at a temperature slightly lower than the trigger temperature of thermal runaway, while maintaining the physical barrier between two electrodes.
- The electrolytes in Li-ion batteries provide the transportation circumstance for ions between two electrodes during charge and discharge. They consist of one or several conducting lithium salts (e.g., $LiClO_4$, $LiAsF_6$, $LiBF_4$, $LiPF_6$) dissolved in non-aqueous solvents. Additives are substances added into the electrolytes at a low concentration to modify their properties. Ideally, they should have no effect on the battery's cycling performance. Various electrolyte additives, such as overcharge protection additives and flame-retardant (FR) additives, have been investigated to enhance the safety of Li-ion batteries.

Taking a closer look at the below presented four stage mechanism of thermal runaway, it becomes clear that the ideal moment to prevent thermal runaway is at an early stage. Reaction should ideally occur in the prevention region, but this requires a means of detection in stages one or two. If off-gases can be detected and batteries shut down before thermal runaway can begin, it is possible that fire danger can be averted.

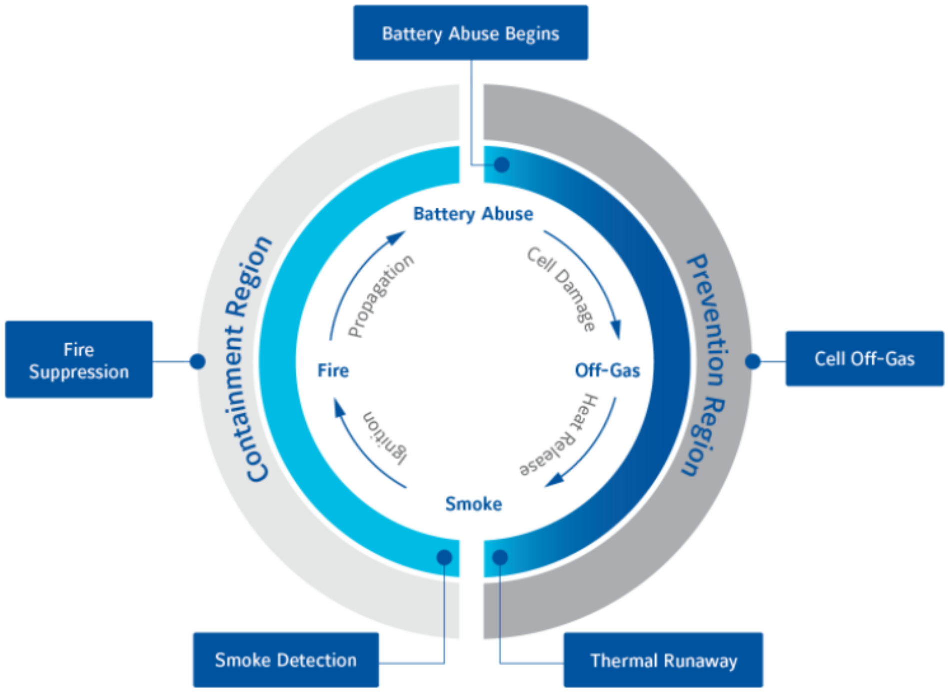


Figure 7.1-2: Thermal Runaway Stages

- ✓ **Stage 1: Battery Abuse**

During this first stage, thermal, electrical or mechanical abuse results in cell damage, causing battery cell temperatures and pressures to increase.

- ✓ **Stage 2: Off-Gas Generation**

As cell temperatures and pressures rise, flammable gases vent from the cells. This is the critical point at which action must be taken to avoid thermal runaway and a fire event.

- ✓ **Stage 3: Thermal Runaway**

Thermal runaway marks the very end of the prevention region and the start of the containment region. Temperatures rapidly rise several hundred degrees and smoke is produced. It is at this point that catastrophic failure is imminent.

- ✓ **Stage 4: Fire Generation**

After thermal runaway, fire ignites. While lithium-ion battery racks are structured to maximise energy storage density, this also allows for fast fire spread. Once ignited, fire can easily move to adjacent cells and construction materials and become uncontrollable.

7.2 Gas Development, toxicity and explosion risk

The battery space is to be fitted with flammable gas detection, appropriate to the battery chemistry being used. The amount(s) and composition(s) of gases provide the basis for properly addressing important aspects such as emergency ventilation, explosion vent panels or weak walls, emergency operating procedures and physical size and outline of the battery space. Other aspects to be considered include, but are not limited to, placement of ventilation openings due to the gas being lighter/heavier than air, placement of sensors, possible gas pockets in the space where gas accumulates and special considerations such as the need for a breathing apparatus to enter the room.

The gasses identified in similar projects are carbon monoxide, nitrogen dioxide, hydrogen chloride, hydrogen fluoride, hydrogen cyanide, benzene, toluene. CO is the main component present for the longest period of time and is considered especially important for early stage detection. Off-gas in the early stages of thermal runaway events will be colder than off-gas release in the later stages. The early off-gas can therefore become heavier than the air, collecting at floor level. It should therefore be considered if gas-detection related to room explosion risks should be applied at both levels, close to the floor and close to the ceiling.

Gas	Max % observed from cell level	L of specific gas per Ah (assuming 2.6 total L/Ah)	Immediately dangerous to life or health (IDLH) [ppm]	Relative Vapor density (air = 1)
CO	38.1%	0.9906 L/Ah	1200	0.97
NO2	9.7%	0.2522 L/Ah	20	2.62
HCL	9.7%	0.2522 L/Ah	50	1.3
HF	3.7%	0.0962 L/Ah	30	0.92
HCN	0.7%	0.0182 L/Ah	50	0.94
C6H6 (benzene)	13.6%	0.3536 L/Ah	500	2.7
C7H8 (toluene)	4.1%	0.1066 L/Ah	500	3.1

Figure 7.2-1: Volumes of primary gasses of concern with regard to toxicity

The off-gases in a lithium-ion battery is known to be flammable as well as toxic. This presents an explosion risk in enclosed spaces. Although, lithium-ion batteries are not more significantly toxic than a comparable plastics fire, there absolutely is the potential for low concentrations of more harmful gasses to be produced. Very small gas concentrations will make the atmosphere toxic, and the gas will dilute fast. Hence the sensor detecting the toxic gases can be placed in the normal breathing zone for people. The primary recommendation is that, following a lithium-ion battery fire, there should be no re-entry without sufficient Personal Protective Equipment.

The risk of an explosion needs to be assessed based on the gases that might be emitted. This includes analysis of the generated quantities and resulting gas concentrations as these gives the design basis for battery space. From a safety perspective, key issues are to determine how likely it is that flammable gases will be detected and the expected effectiveness of ventilation with regard to keeping the gas concentrations below the respective limits.

7.3 Fire Suppression and Protection Measures

The battery space is to be considered a Machinery Space of category A as defined in SOLAS Regulation II-2 and is subject to the structural fire protection requirements listed therein.. DNV GL Class rules require that the battery space has to meet a general fire integrity level of A-0 and A-60 towards any muster stations or evacuation routes. In case the battery power is used for propulsion under normal operation, dynamic positioning or other relevant operations, it shall also meet a fire integrity level of A-60 towards any machinery space of category A as defined in SOLAS Reg. II-2/3. Thus, fire resistant rated A-60 insulation walls, floor and ceilings protecting the Battery Racks, as wells as, several fire doors opening to outdoors are to be provided.

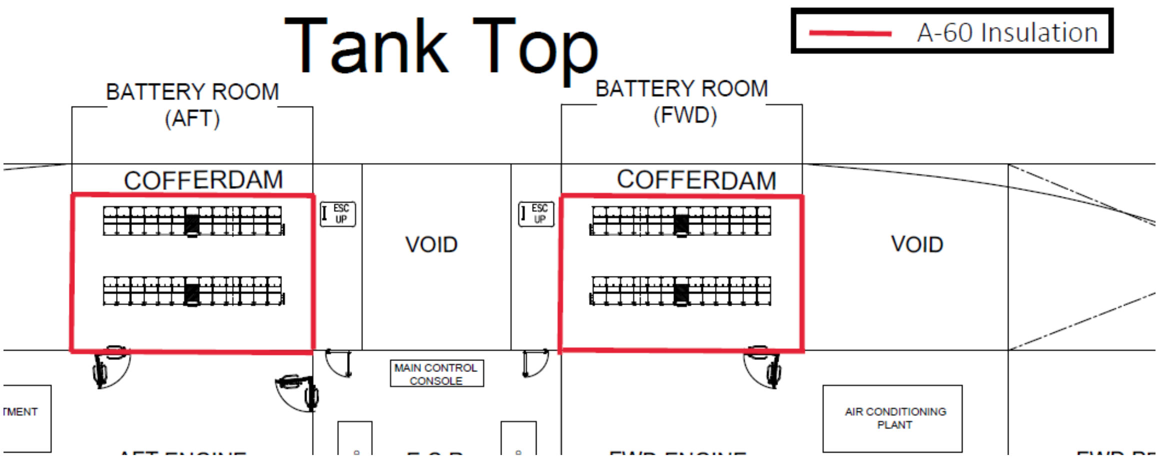


Figure 7.3-1: Structural Fire Protection of battery spaces

A fire external to the battery itself presents a significant danger. The battery system normally has no way of protecting itself in such an event, and an external fire is likely to heat up multiple cells and modules simultaneously. A designated battery room thus provides significant protection from such an event – particularly with the requirements for no fire-risk objects to be installed in the room and with fire rated boundaries. Portable fire extinguishers are to be provided as required by SOLAS and LSA code.

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. The key role of fire suppression systems is to absorb heat and reduce the degree of propagation, or the number of batteries which will be involved in the fire. A single cell fire is typically not of significant concern with regard to safety or survival of the ship. The prime concern is that a battery is made up of tens of thousands of cells, and this fire will tend to propagate to additional cells.

Based on this arrangement, several principles become evident. First, detection and early release of suppression medium greatly increase its effectiveness. The more a fire has propagated, the more heat is being produced and the more difficult it is to put out. It is recommended that fire suppression, detection and release systems still are fully functional after a single failure in any other subsystem, such as the BMS.

The fire suppression system shall be able to swiftly extinguish a fire in the space of origin, and in order to fulfill the functional requirements as stipulated in SOLAS Chapter II-2 Regulation 2.2, the following objectives should be met in particular:

- Preventing module-to-module propagation
- Multiple battery module fire suppression

The fire suppression media or systems evaluated were:

- Sprinklers: Offer a common method for fire extinguishment that is in line with lithium-ion expected requirements – large amounts of volume can be supplied to provide for maximal heat absorption.
- Hi-Fog: Is a high-pressure water mist system that produce a fine mist which increases surface area for heat absorption. A typical water mist system would have capacity for a minimum of 30 min freshwater release, followed by back-up access to seawater from the vessel fire main providing cooling properties over time.
- NOVEC 1230: Is an equivalent gas-based fire suppression system. The primary function of NOVEC is to put out flames by physically cooling below the ignition temperature of what is burning and chemically inhibiting the fuel source.
- Direct injection of water: For the purpose of combating heat generation, direct injection of water is considered as the most efficient alternative. In the stationary industry today, this method is generally included as a last resort back-up since the affected module(s) will be considered lost after deployment.
- FIFI4Marine CAFS: Is a foam-based system, that can be installed to deploy directly in to the battery modules, their surroundings in the racks or in the room. The concept evaluated in this report is only direct injection into the modules. The FIFI4Marine CAFS system is designed to re-deploy several times during an incident as the foam will degrade over time as it participates in combating the battery fire

	Primary objective			Secondary objective		Suppression method properties	
	Flame extinction	Long Term Heat Absorption	Short Term Heat Absorption	Reduce Gas Temp in room	Gas Absorption in room	Can be Used with Ventilation	Suppression method
Sprinkler						YES	Total-flooding
Hi-Fog						YES	Total-flooding
NOVEC 1230						NO	Total-flooding
FIFI4Marine				Not evaluated	Not evaluated	YES	Direct injection
Direct Water injection *)				Not evaluated	Not evaluated	YES	Direct injection

*) Not expected or recommended to be used in practice for high voltage applications, due to the risks of short circuit and hydrogen production. The method is presented as a flame extinction and heat absorption capability reference.

High capability — Low capability — Medium capability — No or very low capability

Figure 7.3-2: Fire suppression systems' capability assessment

7.4 Ventilation and other design parameters

As discussed in the previous subsection, battery off-gas constitute both an explosive and a toxic hazard. In order to avoid high concentrations collecting in the battery space a well-designed ventilation system is required. Mitigation of explosion risk due to off-gassing in a battery room can be done by ventilation. The purpose of the ventilation is then to dilute and air out the combustible gasses before they can accumulate and cause an explosion.

Assessment of the needed ventilation rates requires knowledge of how many liters of gas that are expected to be released from a cell and how many cells and modules will be involved in the event. In this way the total volume of gas to be released is found and used for an assessment. The total volume of gas released is hence used as the decisive design parameter for the ventilation system. Propagation rate is the next crucial factor to determine. Fast propagation between cells significantly increases the rate of gas accumulation in the room.

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

The ventilation is supposed to be maintained through the Battery Ventilation exhaust ducts, dedicated to lead any unwanted residual gases by the forced cooling air system, to open air. The fan is to be of the non-sparking type and shall provide approximately six (6) air changes per hour. The ventilation ducting for the battery space is to be separate from the HVAC systems used to ventilate other spaces on the vessel. Air recirculation in the battery room is prohibited.

Figure 7.4-1: Battery Rooms Overview

Additional design criteria re summarized below:

Walls

a) Walls shall be continuous from floor to ceiling and be securely anchored.
b) Windows shall not be provided in battery rooms.

Ceilings

a) The ceilings should be flat to ensure that the release of hydrogen gas cannot be trapped in pockets.
b) Skylights and false ceilings shall not be used.
c) Ceilings shall be given the same paint treatment as walls.

Doors

a) The battery room door shall have the applicable fire and security rating and shall be not less than 800 mm wide and 2000 mm high. The door shall have one leaf that opens outwards.
b) The inside surfaces of the door shall be protected by an approved light-colored, acid resistant paint.

Battery Mounting

a) The battery mounting rack or cubicle should be of robust construction to withstand the battery loading. It should also be suitably treated for resistance to the corrosive electrolyte.
b) Foundation of each battery rack is to be equipped with appropriate vibration damping system. Battery racks are expected to have passed vibration test according to classification requirements.

Fire Resistance Ratings

a) Individual battery rooms should be treated as separate zones for fire detection and suppression purposes.
b) Any duct, pipe, conduit, cable or other equipment that penetrate a wall, floor or ceiling, having a fire resistance rating, shall be fire stopped with a fire resistant material, such that the fire resistance of the wall, floor or ceiling will not be negatively affected.

Electrical

a) All electrical equipment or fittings installed in a battery room must be intrinsically safe to reduce the risk of arcing, flashing or ignition.
b) Illuminance levels in the battery room shall be designed to meet a minimum illumination level of 300 lux (30 fc). The lighting design shall consider the type of battery rack and the physical battery configuration to ensure that all points of connection, maintenance and testing are adequately illuminated.
c) Battery room lighting fixtures shall be pendant or wall mounted and shall not provide a collection point for explosive gases
d) Receptacles and lighting switches should be located outside of the battery area.

7.5 Safety Plan and instrumentation

Classification guidelines underline that the escape routing arrangements in case of casualty such as stairways, ladders and corridors as crew spaces and in case of other spaces to which the crew normally have access are to be arranged in such a way, so as to provide ready means of escape to a deck from which disembarkation may be accomplished. At least two means of escape, as widely separated as possible, are to be provided from each section of accommodation spaces, service spaces and control stations.

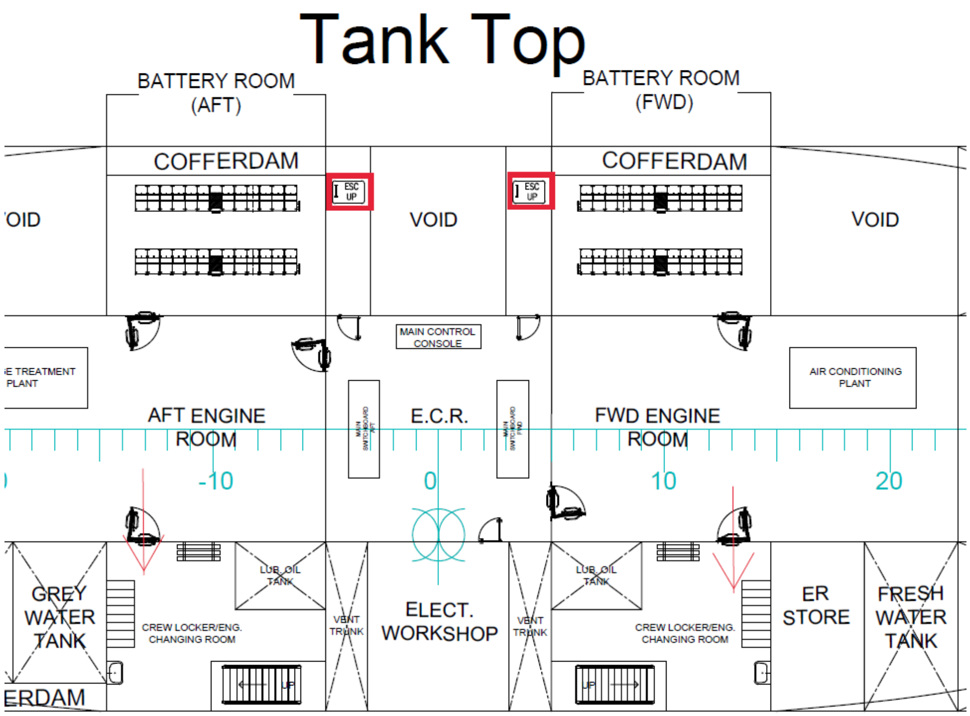


Figure 7.5-1: Emergency Escape Routes

Areas on the open deck within 3 meters (10 ft) of the battery space intake(s) and exhaust ventilation outlet(s) are to be considered as hazardous areas.

Regarding the motoring and instrumentation, the following should be considered:

a) 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.
b) Sensors for safety functions are to be independent from sensors used for other purposes.
c) 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.
d) Ventilation system shall include sensors (differential pressure switch) for initiating alarm signals to the central control room in the event of ventilation system failure.
e) The ventilation system is to be interlocked with the battery chargers to prevent battery charging when the ventilation is not operating.

8. Techno-Economic Analysis

The economic analysis will further determine the economic reliability and feasibility of the e-ferry concept. The financial efficiency will be checked by using the net present value (NPV), which is one of the most used tools for financial assessment of projects. The NPV uses the cash flow as input, which is the sum of the incomes and outgoings of a project in its entire lifetime. In real-life projects, financial efficiency is greatly affected by adjusting certain variables. Using a sensitivity analysis approach and taking into explicit account possible fluctuation will provide a deeper insight in projects risks and limitations.

To begin with, a CAPEX estimation is summarized in the below table:

Catergory	Item	Cost in Euro
Structural	Steel Material (in tonnes)	282.000
	Shipyard Engineering & Services	1.000.000
Outfitting	Accomodation/Furniture	125.000
	Navigation Equipment	100.000
	Piping	50.000
	Cables	50.000
	Other Outfitting (Ramp, mooring, Insulation, Doors, ladders, etc.)	100.000
	Other (e.g. paint, auxilliary equipment)	50.000
Machinery	Batteries	2.250.000
	DC/DC Converters (Batteries->SWBD)	150.000
	AC/DC Inverters	300.000
	Azimuth Pods	480.000
	Propulsion Motors	130.000
	Transformer	120.000
	Auxiliary Machinery	100.000
	Power Management /Automation System	100.000
	Sum	5.387.000,00
	SUC	269.350,00
	Final Sum	5.656.350,00

Shipyards' erections cost, along with outfitting and machinery were calculated based on simila retrofit studies and New Building projects. A SUC (Start-Up-Cost) calculated as 5% of estimated CAPEX was added for certification purposes and various studies.

In order to estimate the steel weight in the ship hull structure, the empirical equation, developed by Garbatov's research team (Garbatov et al., 2017) is represented below:

$$W_1 = 0.00072 \cdot Cb^{\frac{1}{3}} \cdot L^{2.5} \cdot T/D \cdot B$$

$$W_2 = 0.011 \cdot L \cdot B \cdot D$$

$$W_3 = 0.0198 \cdot L \cdot B \cdot D$$

$$W_4 = 0.0388 \cdot L \cdot B \cdot NJ$$

$$W_5 = 0.00275 \cdot L \cdot B \cdot D$$

$$W_s = W_1 + W_2 + W_3 + W_4 + W_5$$

Where.

W_s is the steel weight of case ship, [tonne]; W_1 is the weight of main hull, [tonne]
W_2 is the weight of bulkheads in the main hull, [tonne]
W_3 is the weight of decks and platforms, [tonne]
W_4 is the weight of the superstructure, [tonne]
W_5 is the weight of the foundation and other, [tonne]
L is the length of the case ship, [m]
B is the breadth of the case ship, [m]
D is the depth of the case ship, [m]
T is the draft of the case ship, [m]
NJ is the deck number of the case ship superstructure;
C_b is the block coefficient of the case ship

Steel weight was calculated as 705 tonnes and a reference price of 400Euro per ton was considered.

To calculate the capital cost of battery system including the BMS, various makers have been approached to quote for the initial phase of the design process. A reference value of 450€ per kWh was granted, thus the total cost for the 5000 kWh Battery System (2x2500kWh Battery Systems), as calculated in par. 4.2, is given in the below equation:

$$Battery\ Cost = 450€/kWh \cdot 5.000kWh = 2.250.000€$$

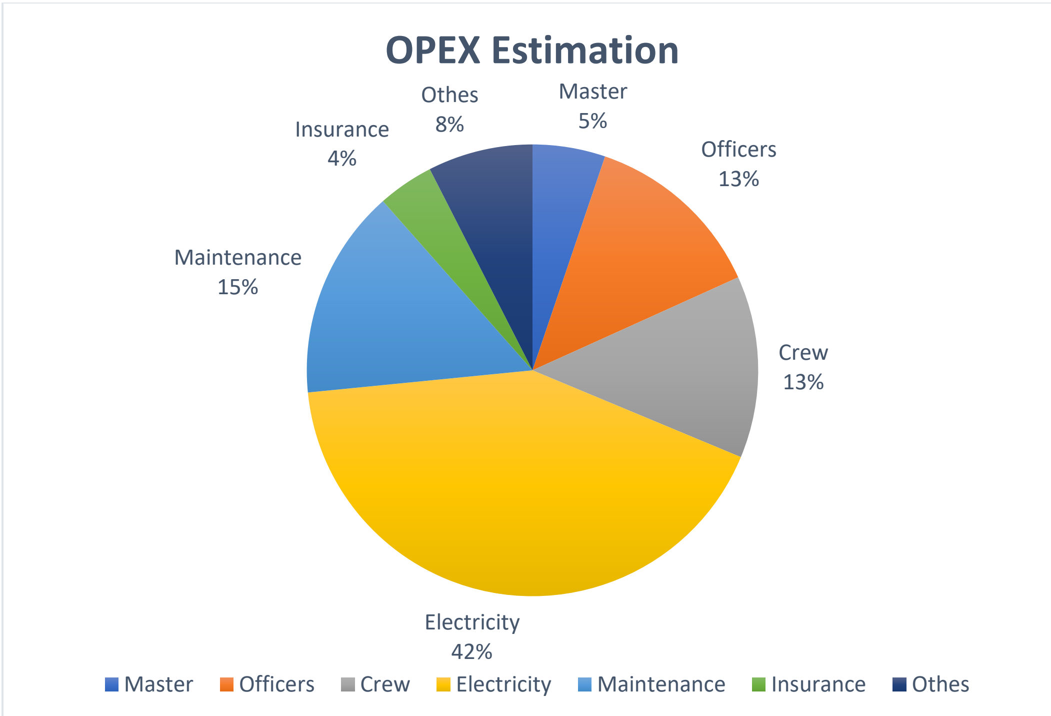
Operating expenditures (OPEX) will also be estimated. OPEX is the operating cost of the project. It includes items such as utilities, operating labor, maintenance, overheads (administrative, accounting, among others), taxes, and depreciation. OPEX calculation is summarized in the below table:

Crew Cost				
Item	*Cost/Unit*	*Units*	*Cost in Euro*	*Remark*
Master	8.000,00	13,00	104.000,00	*€ / Month for 13 Months*
Officers	5.000,00	52,00	260.000,00	
Crew	2.000,00	130,00	260.000,00	
Sum			624.000,00	

Energy Cost				
Item	*Cost/Unit*	*Units*	*Cost in Euro*	*Remarks*
Electricity	0,32	2.628.000,00	840.960,00	€ / kWh
Sum			840.960,00	

General Cost				
Item	*Cost/Unit*	*Units*	*Cost in Euro*	*Remark*
Maintenance	300.000,00	1,00	300.000,00	
Insurance	80.000,00	1,00	80.000,00	
Othes	150.000,00	1,00	150.000,00	
Sum			150.000,00	

Total OPEX was estimated as 1.614.960,00 € from which the largest amount is the electricity cost as expected. Costs per kWh are based on the Greek spot prices for electricity, and includes the fee for green electricity. Charging load of 1200kWh per trip was calculated. Thus, for 6 trips per day and 365 days of service, a grant total of 2.628.000 kWh was estimated. General costs, including maintenance costs, repairs, dockings and surveys have been calculated for a ten-year period, and then distributed over the same ten years. Other general costs that apply are: insurance (ship and shore), “other expenses”, which includes items such as VAT and taxes (except VAT and other fees on electricity, already included in the electricity costs.



Annual income calculations I summarized in the below table:

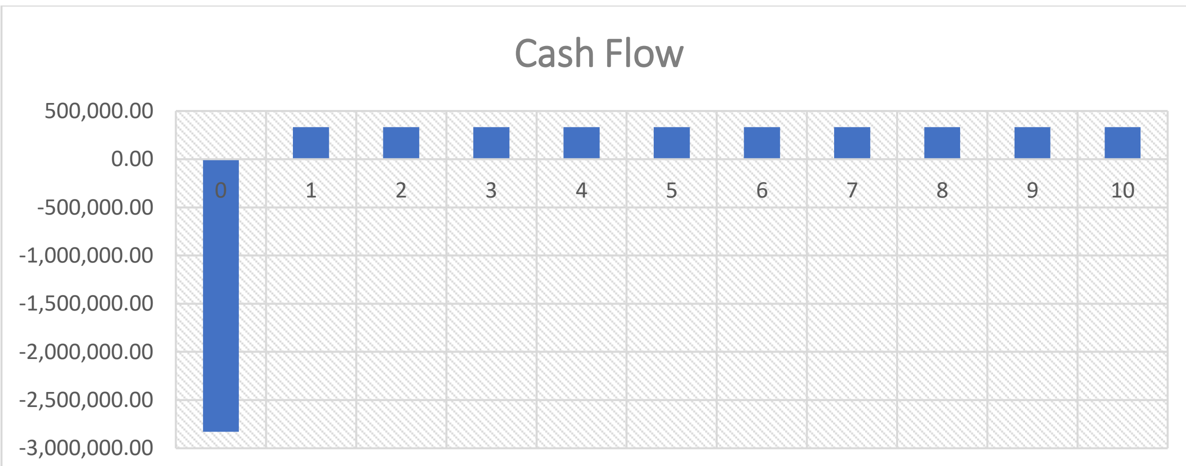
Winter	*Ticket*	*Cost/ticket*	*Income*
Passengers	100	2	480.000,00
Cars	30	5	360.000,00
Sum			840.000,00
Summer	*Ticket*	*Cost/ticket*	*Income*
Passengers	250	2	990.000,00
Cars	40	5	396.000,00
Sum			1.386.000,00
		Total	2.226.000,00

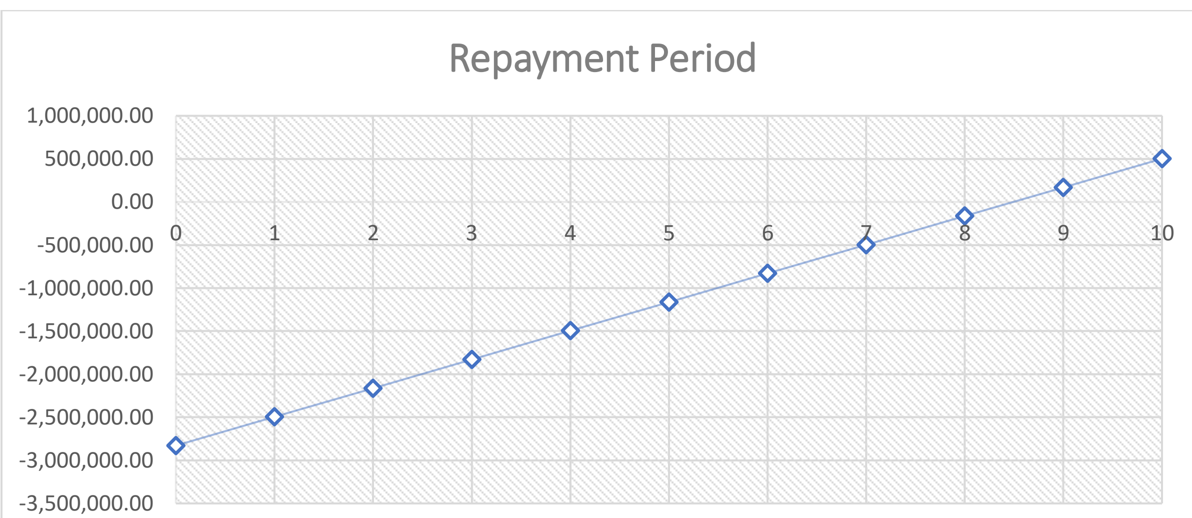
For the present economic analysis the cash flow must be defined first considering the following conditions:

- The total lifetime of the vessel is considered 10 years
- Half CAPEX will be taken as bank loan with 5% interest. Annual repayment of 366.261,60 euro was calculated
- Discount rate will be considered 4& and 6% respectively
- No environmental taxation will be considered
- The cost for the replacement of the battery has not been included in the operational costs, e.g. as part of the maintenance and repair costs. Replacement of the batteries will be necessary when their performance is no longer suited for commercial ferry operation. End-of-life for this has, for the E-ferry prototype been determined to be when the overall available SoC capacity is at 80%.

Year	Income	Expenses	CashFlow	Discount Rate	NPV
0	2.828.175,00	5.656.350,00	-2.828.175,00	4%	-3.670.977,92
1	2.226.000,00	1.981.221,60	244.778,40	6%	-3.854.759,68
2	2.226.000,00	1.981.221,60	244.778,40		
3	2.226.000,00	1.981.221,60	244.778,40		
4	2.226.000,00	1.981.221,60	244.778,40		
5	2.226.000,00	1.981.221,60	244.778,40		
6	2.226.000,00	1.981.221,60	244.778,40		
7	2.226.000,00	1.981.221,60	244.778,40		
8	2.226.000,00	1.981.221,60	244.778,40		
9	2.226.000,00	1.981.221,60	244.778,40		
10	2.226.000,00	1.981.221,60	244.778,40		

For both cases, a negative NPV is obtained which demonstrates that the investment is not considered profitable. On the contrary, such low NPV value proves that the e-ferry concept is not feasible at the moment, considering the excessive capital expenses with special attention to the high battery cost along with the non-negligible operational expenses.





Summary and Conclusions

Within this diploma thesis, the preliminary design of an all electric battery double end ferry was investigated. Particularly, details of the following elements of the innovative e-ferry design were analyzed:

- *Battery Technologies*: Lithium-ion Battery technology distinguished in terms of shot-trip coastal routes due to its enhanced incomparable power density
- *Environmental Benefits:* A significant reduction of CO2 emissions along with an increased level of comfort due to e-ferry's quiet operation.
- *E-ferry Arrangement & Composition*: Based on existing all electric vessels characteristics and taking into account ships operational profile, the energy demands were estimated, and the propulsion system selected. General arrangement drawing and electrical configuration drawing were also conducted.
- *Battery System*: Systems features and automation functions were extensively described. To ensure safe operation and control, an advanced Battery management system is required to cover the high demands of the regulatory framework.
- *Charging System*: Connection to electrical grid and charging station were briefly examined
- *Safety Considerations:* Failure mechanisms and potential dangers of the battery system were presented. Thermal runaway is considered the primary concern regarding battery systems. Precaution measures along with design recommendations were introduced.
- *Economic analysis:* The economic analysis highlighted the challenges involved in the e-ferry concept. Although not economically reliable at this time, the environmental gains will be significant. In the future while further battery cost reduction is expected and with government support, the e-ferry project may flourish. The economic benefits over time of going fully electric does not take into consideration any future requirements for low-emission vessels, including potential fees or quotas for e.g. the emission of CO2. Thus, the environmental evaluation of the E-ferry prototype is based exclusively on the value for the environment.

Increasing environmental concerns necessitate advancements towards a cleaner maritime industry. As hybrid and all-electric vessels become more common as a means of reducing emissions, improved battery technology will be a requirement to ensure efficient and effective operation of environmentally safe systems. Current lithium-ion batteries are sufficient for maritime applications, but their limited energy capacity and safety concerns indicate the need for next generation batteries to allow for advancements in maritime battery systems. Higher capacity batteries would allow for more efficient hybrid vessels and could potentially make all-electric vessels more viable. Improved battery systems also allow for renewable energy sources to better have their energy captured and stored, especially for discontinuous energy like wind and solar that are not always available. With so many developing technologies relying on a high power, high energy source of electricity, it is imperative that new battery technologies are developed and implemented.

There are several energy storage technologies currently available. Battery powered propulsion systems are the most popular ones, and they are already being engineered for smaller ships. For larger vessels, engine manufacturers are focusing on hybrid battery solutions. Challenges related to safety, availability of materials used and lifetime must be addressed to ensure that battery driven vessels are competitive with conventional ones, but the pace of technology is advancing rapidly. Other energy storage technologies that could find application in shipping in the future include flywheels, supercapacitors, fuels cells, and thermal energy storage devices. It is very likely that in the future there will be a more diverse fuel mix where LNG, biofuels, renewable electricity and maybe hydrogen all play important roles. Electrification and energy storage enable a broader range of energy sources to be used. Renewable energy such as wind and solar can be produced and stored for use on ships either in batteries or as hydrogen.

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