National Technical University of Athens

School of Naval Architecture and Marine Engineering

Division of Marine Engineering

Diploma Thesis

Techno-economical Feasibility Study on The Retrofit Of Mid-size Ro-Pax into Hybrid Ones / Battery Thermal and Energy Behavior Prediction

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Abstract

Emissions from ships exhausts into the atmosphere can potentially be harmful to human health ,cause acid rain and may also contribute to global warming. The marine industry takes action on this matter by implementing strict regulations. IMO's Marine Environment Protection Committee (MEPC) has given extensive consideration to control of GHG emissions from ships and finalized in July 2009 a package of specific technical and operational reduction measures. In March 2010 MEPC started the consideration of making the technical and operational measures mandatory for all ships irrespective of flag and ownership.

MEPC 67 approved the Third IMO GHG Study, providing updated emission estimates for greenhouse gases from ships. According to estimates presented in this study, international shipping emitted 796 million tonnes of CO_2 in 2012, that is, about 2.2% of the total global CO_2 emissions for that year. By contrast, in 2007, before the global economic downturn, international shipping is estimated to have emitted 885 million tonnes of CO_2, that is, 2.8% of the total global CO_2 emissions for that year.

By moving to hybrid or electric propulsion, marine vessels ensure in-built flexibility that can not only reduce emissions and optimize fuel consumption, but they are lighter and take up less space, with lower noise and vibration levels and reduced maintenance costs. The industry is moving towards this path we ought to contribute in achieving this.

The abovementioned is what motivated this thesis, whose structure is discussed in the following sentences. Chapter 2 presents the hybrid propulsion technologies that are available, some concepts and case studies of marine vessels that comprise mechanical and electrical elements. This chapter also analyzes the hybrid configuration under study and in details the basic elements that is consisted of. The third chapter describes battery's functions and how to evaluate each battery's technology characteristics. In addition, the most important lithium ion battery technologies alongside with their specifications and applications are presented in order to help us evaluate the appropriate battery chemistry for the hybrid ship. Conceptual design of electrical topologies on board, on shore and cost calculation method is described on chapter 4. Possible electrical diagrams and infrastructures either on shore or on the boat depending to different scenarios/energy demands (existing electrical grid, high voltage/low voltage etc.) are explained as well. Chapter 5 is consisted of three parts. The first part describes the physics and available mathematical models, derived through experimentation, which define the thermal/electrochemical analysis. The second part describes the methodology we followed with the help of ANSYS to simulate the battery cell's operational behavior, and the third the analysis of the results acquired. Chapter 6 analyses our retrofit design philosophy and the methodology developed for the estimation of the required battery capacity and PTO output power installed on board. Its inputs and equations are described in detail and the most important guidelines generated from the methodology are outlined. Chapter 7 discusses the results from the implementation of the

methodology in the case study of: medium size passenger vessel. Topology designs, number of batteries installed according to operational profile and overall hybrid configurations are also included along with some diagrammatic predictions for the discharge behavior of the battery cells. Chapter 8 contains the criteria we considered, for evaluating the investment required for this project and some very important coefficients describing the dynamic relationship of capital and products through time. In addition this chapter entails an annual cash flow analysis followed by a sensitivity analysis, regarding the discount rate, and feasibility determination. The final chapter contains the conclusions for both the case study and the simulation analysis and recommendations for future work.

Keywords: emissions, IMO, hybrid propulsion, battery technology, regulations, battery management system, shore side/ship side topologies, ANSYS, thermal/electrochemical simulation, CFD analysis, retrofit methodology, mid-size passenger ship, PTO, energy prediction, investment analysis, annual cash flow

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Chapter 1: Introduction

1.1 Background of study

Different kinds of propulsion systems are used on ships and choosing which the best is for a particular type of vessel is strongly dependent on the requirements set early in the design stage. Within these requirements, a suitable propulsion concept can be selected according to its operational profile, serving route and technical characteristics. Hybridization of marine vessels is essential in some cases, but presents certain engineering challenges that require deep understanding of the topologies and machinery installed in the engine room. One of the main reasons hybridization has been drastically developed, is the fluctuating and unpredictable bunker prices in combination with new environmental regulations and increased awareness for shipping contribution to global greenhouse gas emissions, which are putting a lot of pressure on the shipping industry and the passenger vessels are not any exception. As a result of the growing concern for fuel prices and environmental awareness, there has been a growing interest by the ship owners to investigate the application of new technologies and solutions regarding propulsion and power plants. One solution, that is widely used in different types of industries and is experiencing a huge development, is the concept of hybrid propulsion. In the shipping industry, hybrid propulsion is often referred to a mechanical/electrical retrofit with or without batteries. It has been shown today that hybrid propulsion on ships can save up to 20-30% in fuel consumption (DNV GL, 2014a). This is achieved by storing the energy when the power demand is low and using it when the power demand is higher, or turn off the engines if the batteries can provide the required power. The battery technology is developing very fast, both when considering the storage of energy compared to weight but also considering price per unit. For example the unit price of 1 kWh has decreased from 900 USD to 700 USD in 2011-2014 and market specialists within the area claim that the price will decline to 500 USD before 2020. Today the batteries on the market are up to 200 Wh/kg but manufacturers are already testing prototypes up to 400 Wh/kg, which implies large potential since the weight and operational criteria is of great importance, regarding applications on ships **[1]**.

But back to our main concern, if no measures are taken, CO_2 emissions are projected to increase 50–250% by 2050, while the Paris convention requires a significant reduction to achieve the 2 °C global warming target. Moreover, shipping already contributes to 15% of the global NO_x emissions, which is also projected to increase if no measures are taken. Advances in propulsion systems and energy management improvements, however, can significantly contribute to reducing SOx, CO_2 and NO_x emissions.

In order these advances to be enforced, the International Maritime Organization (IMO) Marpol regulations impose increasingly stringent restrictions on ship's emissions. First, IMO Marpol annex VI sets limitations on the weighted cycle nitrogen oxide (NO_x)

emissions for diesel engines with an output of more than 130 kW. For example, diesel engines on ships constructed after January 2011, referred to as Tier 2, are limited to 7.7 g/kWh for high speed engines and 14.4 g/kWh for very low speed engines. In emission control areas, from January 2016, referred to as Tier 3, these limits reduce to 2.0 g/kWh and 3.4 g/kWh. These limits currently address the NO_x production of engines and not of the ship propulsion and power generation as a whole. However, developments to address NO_x production per mile for cars and the public outcry to determine standards in realistic driving conditions, might lead to future shipping regulations limiting the production of NO_x per mile **[2]**. Nevertheless, the most important research area to reduce NO_x emission from propulsion and power generation of diesel engines are NO_x abatement technologies such as Exhaust Gas Recirculation (EGR) and Selective Catalytic Reduction aftertreatment (SCR). Additionally, IMO and Marpol regulations have set targets for reducing the Energy Efficiency Design Index (EEDI) for new ships by altering the hydronamic behavior and design of the hull and propeller. EEDI is a measure of the amount of CO2 emissions that a cargo ship produces per tonne of goods and per mile, which is referred as cargo work. New cargo ships have to reduce their EEDI from 10%, compared to benchmark cargo ships at the introduction in 2013, to 30%, in 2030. Similar measures are being prepared for other ship types. Therefore, the propulsion and power generation plants for future marine vessels have to significantly reduce fuel consumption and emissions over the coming years. Finally SOx emissions are the last environment threat produced by shipping and the fuels that are used for marine transportation. For Emission Control Areas (ECAs) the threshold has been set to 0.1 % and worldwide to 1.5 %, forcing ship owners to solution like scrubbers , dual fuel engines and energy storage systems. That leads us to believe that the industry is turning electric for newbuildings and hybrid for retrofit projects, or at least is investigating some alternatives.

1.2 Literature review

At this point we have to mention some important research in the field of marine hybrid propulsion, which was a source of knowledge in order to investigate the performance of a hybrid configuration and find our scope of work. The feasibility of using a hybrid power system for different vessel types was studied by Dedes et al. (2012), Volker (2013), Diaz-de Baldasano et al. (2014), Andersson and Logason (2015), NSBA (2015) and Yum et al. (2016). The service life of the battery, availability of shore power, vessel size and chartering commands and use of generated heat were found to influence the feasibility of the hybridization depending on the vessel type. Baldi et al. (2016) used the mixed integer non-linear programming method (MINLP) to optimize the load-sharing in a hybrid power system without batteries. Combining sequential quadratic programming (SQP) for the continuous variables and using the branch and bound method for the integer variables, the problem was solved with Matlab. A cruise ship was used for the case study. The shaft generator/motor was sized for the hybrid power system by trying out different unit sizes. The integrating element of a rechargeable energy storage with capacity limits brings a time aspect to the problem. Vu et al. (2014a), Vu et al. (2014b) and Vu et al. (2015) presented variations of a power management optimization method using a series hybrid tugboat. Zahedi et al. (2014) studied the fuel savings in a series hybrid o_-shore support vessel (OSV) with a DC grid. The proposed power management strategy charges and discharges the battery between the minimum and maximum capacity in a repetitive cycle. If the pulsed cycle of this square wave -like usage becomes infeasible, a so-called continuous mode is engaged, where the battery state of charge (SOC) oscillates in a smaller range to even the load oscillation at the active diesel generators. Using a simulation model from Zahedi and Norum (2013), they showed that with the proposed algorithm, the DC grid series hybrid leads to 15% fuel savings compared with a conventional DE configuration with an AC grid and 7% fuel savings compared with a DC grid configuration without a battery. Bassam et al. (2017) compared different energy management strategies for a hybrid passenger vessel powered by fuel cells and a battery. The authors' multi-scheme strategy was a combination of the other strategies reviewed in the comparison. A Simscape and Matlab environment was used for system modeling and optimization. The duty cycle of the studied passenger vessel was fairly at excluding the docking phase with higher load peaks and the acceleration phase with a higher and wider power peak. The size of the battery and the energy management strategies that were used, led to a small variation in the battery SOC during the operation excluding the charge-depleting|charge-sustaining (CDCS) strategy. The battery was charged to the initial SOC using shore power after the daily shift **[3]**. But none of these works have attempted to predict the thermal behavior of the batteries implemented in hybrid configurations and how the ambient temperature affects it due to the various machineries installed in the engine room. Another missing link is the stage after designing the system: the optimal sizing considering the electromechanical elements of a hybrid propulsion/energy system, in order to keep the cost at low levels and ''prolong its life''.

1.3 Problem Statement and Objectives

In the last 5 years a trend is rising in the shipping industry regarding the electrification of small distance passenger vessels, usually double ended, because of the unpredictable bunker prices in combination with new environmental regulations leading to numerous projects especially in Europe. But from this movement a challenge has presented itself upon us:

- Is full electrification possible for a passenger ship that covers a larger distance and of substantially bigger power and energy needs?
- Which is more feasible technically and economically, full electrification or hybridization?
- Is the operational profile of a passenger vessel compatible with ship types suitable for the application of hybrid-propulsion technologies?
- How will the operational and investment cost change with hybrid and diesel electric propulsion system?

An attempt of answering these questions is the main purpose of this thesis. This is achieved by creating a system that will be fully electrical, when maneuvering and at port, using battery packs and shaft generators. While it will be also responsible for the transiting of the vessel, by employing the main diesel engines, which will additionally feed the shaft generators for covering the energy needs of the vessel when at sea.

The definition of a hybrid system is the combination of mechanical and electrical components, in order to achieve higher efficiency according to the operational profile of a vessel. Energy Storage Systems (ESS) are the cornerstone of hybrid concepts, in order to storage energy when the power demand is low and using it when the power demand is higher. The most reliable and frequently used ESS are batteries and specifically Lithium-Ion batteries.

A question arises regarding which is the most appropriate Lithium-Ion electrochemistry for every application. But this is a problem that is controlled by many variables like power density, energy density, thermal behavior, cost etc. So, in this paper, there will be an investigation of Li Polymer battery cells that present some interesting features, compared to the LiFeMgPO4 that are a safe and reliable choice, like lower cost, less weight and higher power density. That is very important when there is a need for high release rate of energy, in cases such as a black ship or during the transition into electrical propulsion, through a synchronous or induction motor.

Another concern when implementing the batteries in the engine room is the battery management system which is responsible for their safe operation. The prediction of the cooling system of the battery packs requires knowledge of the thermal and electrochemical behavior of the battery cells when they are discharging, in order to power the vessel's hotel loads or the electrical machines onboard purposed for main propulsion. So we are going to simulate the operational behavior of the battery cells, in order to have a more clear view of the cooling requirements and their dependency from factors such as the discharge current, the cut-off voltage value and the ambient temperature in the engine room.

1.4 Structure of Study

Chapter 2

Chapter 2 presents the hybrid propulsion technologies that are available, some concepts and case studies of marine vessels that comprise mechanical and electrical elements. This chapter also analyzes the hybrid configuration under study and breaks down the basic elements that is consisted of.

Chapter 3

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

Chapter 4

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

Chapter 5

Chapter 5 is consisted of three parts. The first part describes the physics and available mathematical models, derived through experimentation, which define the thermal/electrochemical analysis. The second part describes the methodology we followed with the help of ANSYS to simulate the battery cell's operational behavior, and the third the analysis of the results acquired.

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Chapter 7

Chapter 7 presents the results from the implementation of the methodology in the case study of: medium size passenger vessel. Topology designs, no of batteries installed according to operational profile and overall hybrid configurations are also included along with some diagrammatic predictions for the discharge behavior of the battery cells.

Chapter 8

This chapter contains the criteria we considered, for evaluating the investment required for this project and some very important coefficients describing the dynamic relationship of capital and products through time. In addition this chapter entails an annual cash flow analysis followed by a sensitivity analysis, regarding the discount rate and feasibility determination.

Chapter 9

It is the chapter that contains the final conclusions for both the case study and the simulation analysis and recommendations for future work.

Chapter 2: Hybrid Propulsion Technology

The hybrid drive technology shows great potential for propulsive systems in the shipping industry, in which there are several activities to replace the proven diesel engines by new drive concepts. The triggers are first and foremost the ever increasing price of fossil fuels and the emission standards in so-called Sulphur Emission Control Areas (SECA) from 1 January 2015. After that, only fuels with a sulfur content of 0.1% may be used in many coastal regions, which leads to additional costs for running on ultra-low sulphur fuel.
For ships that their operational speed is constant most of the time, such as container ships, it would not be efficient to replace a diesel-mechanical drive by hybrid concepts, because these drives are optimized for this operation by achieving a lower consumption than a diesel-electric or hybrid system. This is a reason why most hybrid systems are applied on vessels such as double-ended ferries, tug boats and small/medium sized passenger ships.

2.1 Hybrid Propulsion Configurations

In a hybrid vessel propulsion can be achieved using a combination of fuelled power source like a diesel or petrol engine and a stored energy source, in other words a battery bank and electric motor.

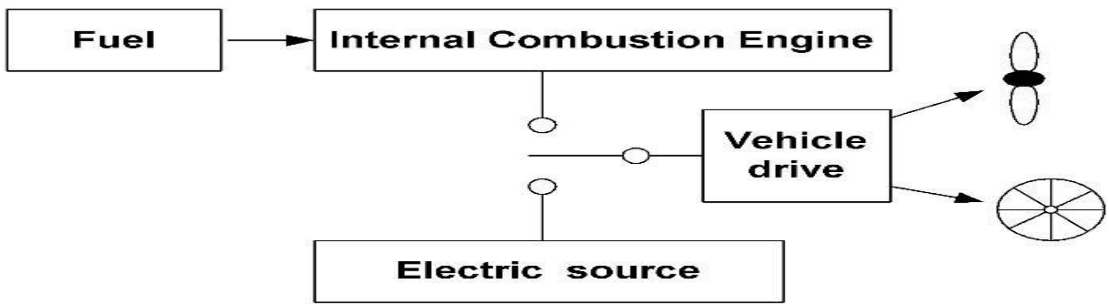


Figure 2.1 Hybrid topology basic elements

There are four basic Hybrid configurations (with many variations), Diesel/Electric, Serial hybrid, Parallel Hybrid and combination of both.

Diesel/Electric

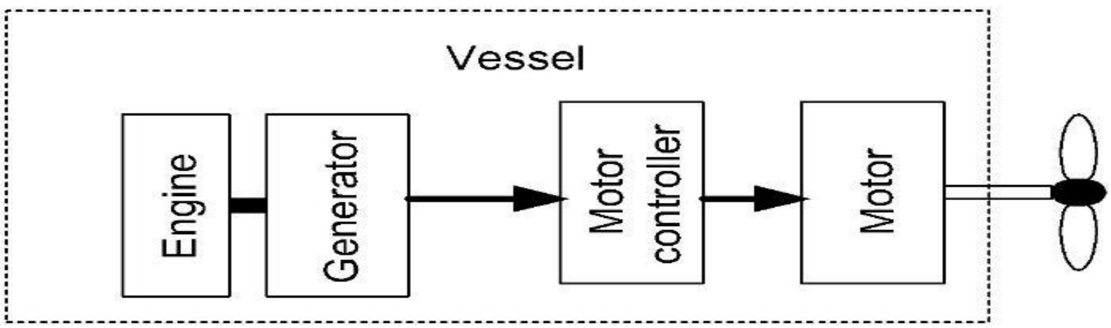


Figure 2.2 Diesel /Electric

The engine is connected directly to an electrical generator which feeds the motor. A motor controller is often installed to regulate the frequency of the motor, hence the speed of the propeller. The propeller is moved by the electric motor. The system usually has multiple generators and motors connected to a common electrical bus. This technology is used in diesel/electric trains and many large ships such as the Queen Mary 2. Although there is no electric storage of energy this might be considered a hybrid system.

Serial Hybrid

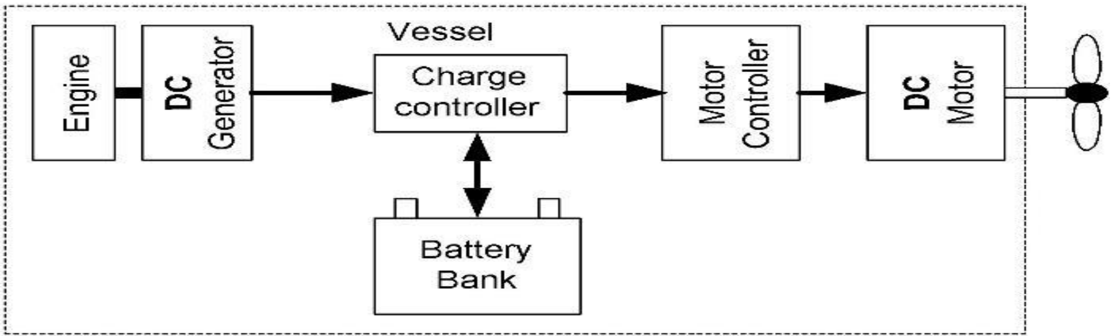


Figure 2.3 Serial Hybrid

The serial hybrid is similar to the Diesel/Electric in that it breaks the mechanical connection between the engine and propeller shaft. However, some kind of energy storage system like batteries is connected to the main bus, which can be AC or DC depending on whether there is an inverter installed or not. In this configuration there is the option of decoupling the engine and use the stored energy for the motor feeding. This can might as well be very good substitute for generators onboard **[4].**

Parallel Hybrid

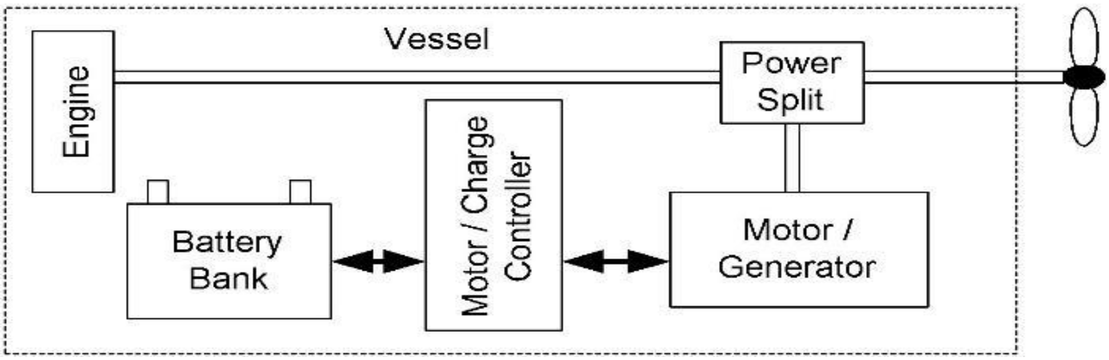


Figure 2.4 Parallel Hybrid

A parallel hybrid system is very flexible in a way that it can move the propeller by employing simultaneously a diesel engine and an electric motor usually for running the main engine with optimal load and consequently low fuel oil consumption. The Power split is a mechanical device that allows the parallel running of the diesel engine and the motor. Of course there is the option of running the propeller only with one of the aforementioned drives. Lastly there is even the possibility of ''regenerative braking'' by disengaging the propeller (stopping the main engine) and by operating the motor as generator in case of synchronous machine that can feed the batteries or the hotel loads during port stay.

From a design point, the main difference is that the electric machines (EM) in a series topology need to be able to cover the maximum power demand, while in parallel topologies the EM can be sized for lower power levels. In parallel topology, the engine can feed the propulsion loads without additional electric conversion losses, which is beneficial under high propulsion loads.

Series/Parallel

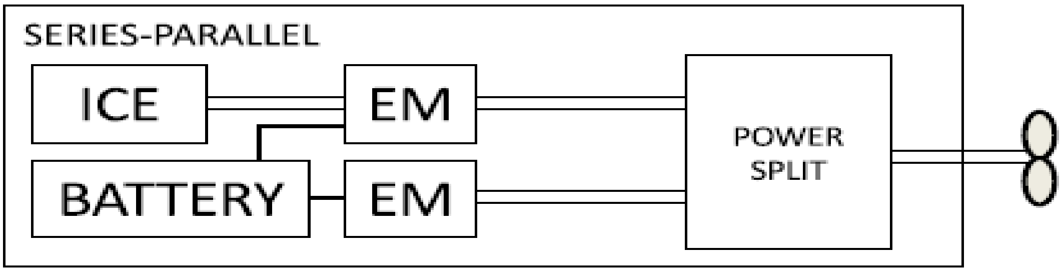


Figure 2.5 Series/Parallel

The series/parallel topology combines the features of both configurations mentioned before, while enabling an asymmetric sizing of the electric machines and having an electric motor with adequate propulsive power. Of course the increased number of components leads to cost effective topologies with high level of complexity.

2.2 Case studies and Concepts of hybrid marine vessels

In the following pages we are going to mention some hybrid propulsion cases that are currently operational, as well as some concepts that are under investigation.

MF NORDENHAM

The motor ferry NORDENHAM is a double-ended ferry which performs daily routes on Weser River.

Figure 2.6 Motor Ferry Nordenham

It is driven by two Voith-Schneider propellers, which are connected directly to two gas engines. The MF NORDENHAM operates between the city of Bremerhaven and the district of the city Blexen Nordenham. The trip, which includes time at port, lasts for about 20 minutes and the distance covered is approximately 3 km.

In Table 2.1, is presented the power requirement for the ferry under study. The two Voith- Schneider propellers each need propulsive power of 470 kW and for consumers in the electrical system, the power needs are approximately 50 kW.

Consumer	Power Consumption
Propulsion drives	2 x 470 kW
Secondary consumers	50 kW
Total	990 kW

Table 2.1 Power requirement for the motor ferry

The following figure shows the different drive concepts that are considered.

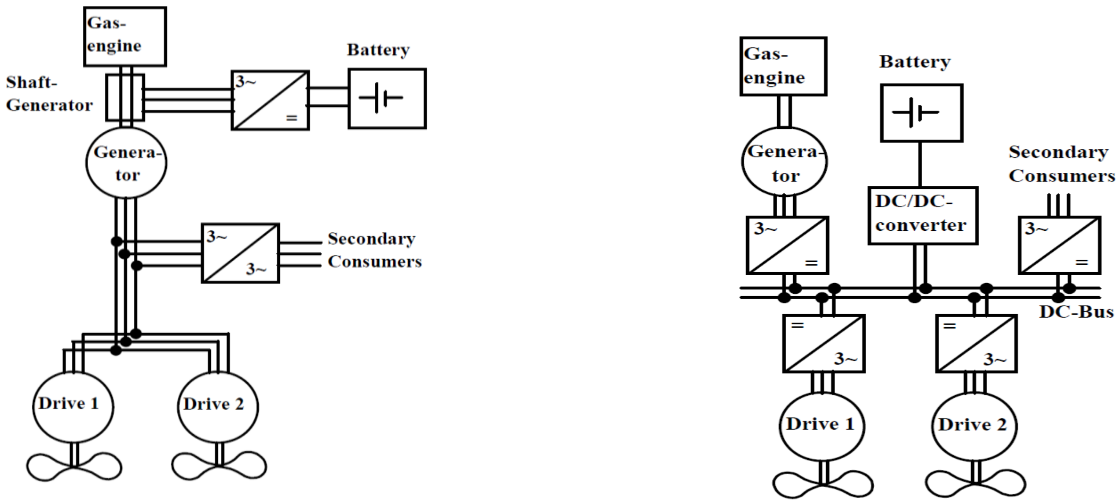


Figure 2.7 Hybrid concept topologies

All concepts include a gas engine with a synchronous generator and extra batteries as energy storage. The concepts differ in that the Concept 1 and 2 present a three-phase system as a distribution network on board and in type 3 and 4 there is a DC power supply. Moreover, the coupling of the battery is different in that in concepts 1 and 2, the coupling takes place with an additional drive, which is coupled to the mechanical shaft between the gas engine and the synchronous generator. In the concepts 3 and 4, the coupling of the battery is via a DC/DC-converter directly to the DC bus **[5]**. The following table shows the performance of gas engine and battery system and the capacity of batteries for the different concepts.

	Concept 1	Concept 2	Concept 3	Concept 4
$P_{Gasengine}$	850 kW	1200 kW	850 kW	1200 kW
$P_{Battery}$	83 kW	1040 kW	97 kW	981 kW
$E_{Battery}$	35 kWh	420 kWh	40 kWh	400 kWh

Table 2.2 Different drive concepts for MF NORDENHAM

MF PRINSESSE BENEDIKTE

Figure 2.8 MF PRINSESSE BENEDIKTE

The Prinsesse Benedikte is a hybrid electric ferry powered by an Energy Storage System (ESS) provided by Corvus that was commissioned for retrofit in Copenhagen, Denmark. The Prinsesse Benedikte ferry refit represents a successful conversion of a former diesel-electric ferry to a battery hybrid vessel and a major advance in green ferry transportation. The ESS onboard Prinsessse Benedicte has been installed and successfully operating for over 10,000 hours.

The AT6500 modules fitted to the Prinsesse Benedikte, can recharge in 30 minutes from onboard generator power, and can propel the 14,822 ton ship for about 30 minutes on battery power alone **[6]**. This commissioning is a significant milestone because it represents the world's largest hybrid propulsion marine energy storage system (ESS) ever installed at 2.6MWh and an important early success in the operational implementation of marine battery hybrid technology.

Energy Storage System (ESS) specifications:
Pack: 399 x 6.5kWh
Capacity: 2.6MWh
Bus Voltage: 932VDC
Partners: Scandlines, Siemens

TRACTOR TUG

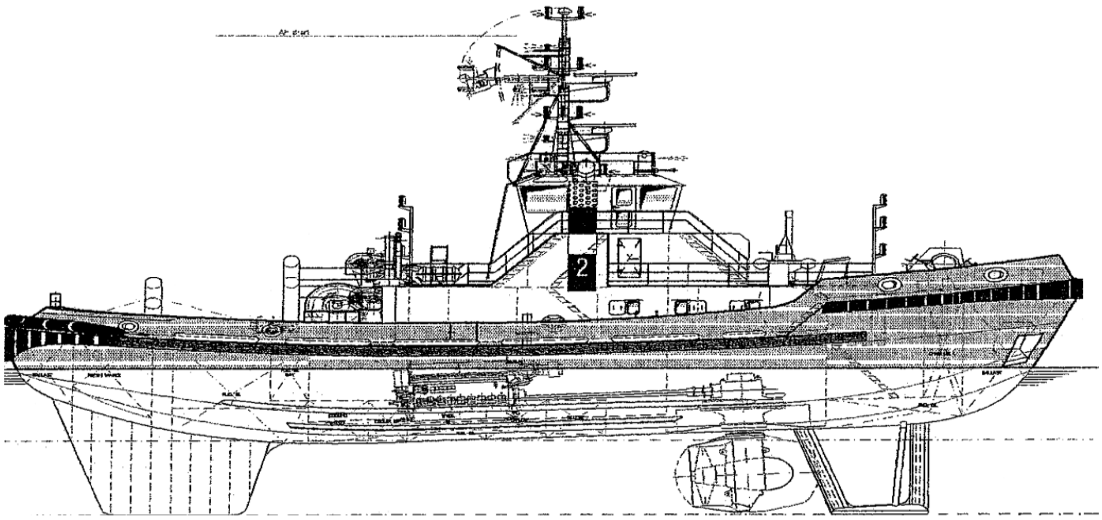


Figure 2.9 Tractor Tug

The investigated harbor tug is a tractor tug, which means that it has two thrusters in the forward part of the vessel (see figure 2.9). The main task of a harbor tug is towing of large ships in the harbor area. An exemplary load profile of a typical harbor tug use is shown in the following figure.

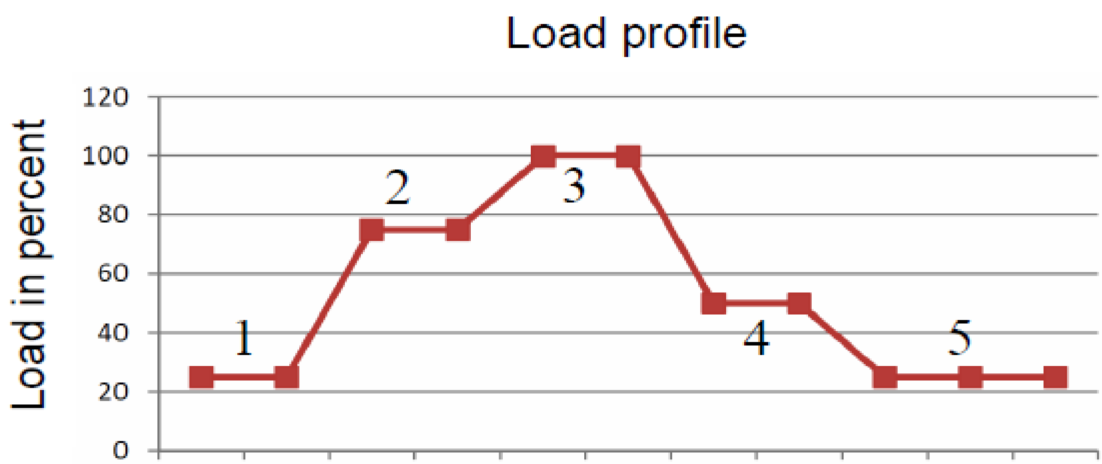


Figure 2.10 Harbor tug load profile

The percentage load times are shown in the diagram in figure 2.10. As the load profile suggests harbor tug operates mainly in part-load. This high proportion of part load allows savings of fuel by the use of a hybrid drive system. When using more than one combustion engine, one drive can optionally be turned off or the combustion engines can run in the improved efficiency in the partial load operation.

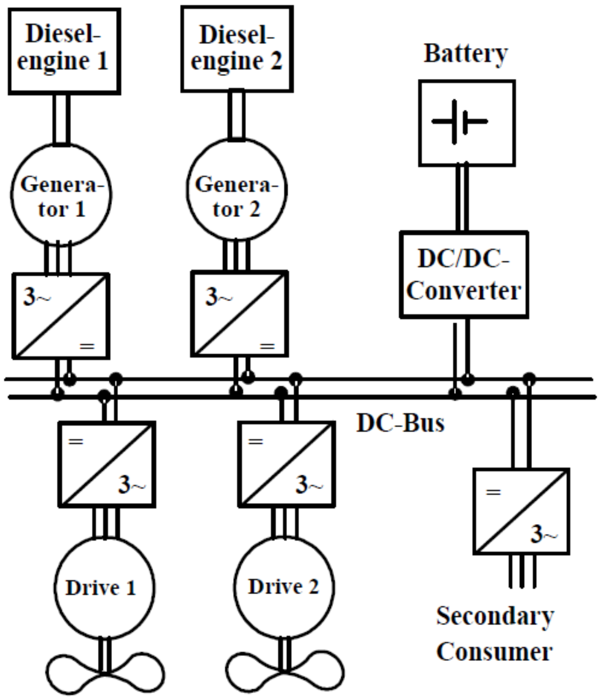


Figure 2.11 Hybrid concept topology

Figure 2.11 shows the examined hybrid drive concept for the harbor tug. Here, the electric power is generated by two synchronous generators, which are driven by diesel engines, and fed into a DC bus by a rectifier. On this DC bus, the drive machines are now connected by an inverter. Moreover, battery modules are connected to the DC bus. Via a DC/DC-converter the power can be stored in the batteries, or be powered from the battery to the DC bus.
The savings potential of a hybrid drive system on ships is in the fact that this engine is used in operating areas, in which the specific fuel consumption is lower.

Viking Lady

Figure 2.12 Viking Lady

The Viking Lady Platform supply vessel comprises many innovative, regarding efficiency and fuel savings, technologies.

The 92 m vessel combines four Wärtsilä 32DF dual-fuel engines which employ advanced vessel automation resulting in a configuration with minimimal electrical losses. The vessel runs on liquefied natural gas (LNG), a fuel that significantly reduces NOX and CO2 emissions and when combined with an oil recovery capacity of 2500 m3, this means that it complies with a number of classification notations, including Clean Design, Nautical OSV and Comfort Class. The element that makes it a true hybrid energy system is an impressive battery pack for energy storage is installed.

Energy Storage System (ESS) specifications:

Pack: 68 x 6.5kWh Corvus AT6500 Battery Modules

Capacity: 442kWh

Bus Voltage: 856VDC

The three-year-old LNG-fuelled vessel, which is owned by Eidesvik Offshore, was the very first merchant ship to use a fuel cell as part of its propulsion system. The fuel cell, which generates an electric output of 330 kW, was installed in the autumn of 2009 and has successfully run for more than 18,500 hours. Based on this, the Viking Lady is already one of the world’s most environmentally friendly ships.

The primary potential benefits of the hybrid energy system for a ship like the Viking Lady are a 20/30% reduction in fuel consumption and CO2 emissions through smoother and more efficient operation of the engines and fuel cell. The reductions of other exhaust components are even higher.

2.3 Analysis of the propulsive configuration elements

This part is dedicated for the investigation of the possible components that can be implemented in the hybrid configuration except from the batteries, which are explained in detail in chapter 3 and 4 regarding their types, operation/installation and regulatory network.

2.3.1 PTO/PTI gearbox systems

Basic Operational modes

The possibility to operate the alternator in generator or motor mode gives the hybrid configurations a vast array of possible operational scenarios.

Power Take Off

In normal Power Take Off mode, the main engine drives the propeller through a gearbox. An alternator is connected at the gearbox that provides the electric power for the hotel and auxiliary loads. In this configuration the main engine is the only prime mover, which runs on a high load, therefore efficiently. In case the main engine is running on HFO, fuel costs for electric power generation will often be lower than an auxiliary engine running on MDO or MGO. Because the alternator's rotor needs torque in order to create a periodical magnetic field (it is fed with direct current) this mode can be implemented during a vessel's transiting.

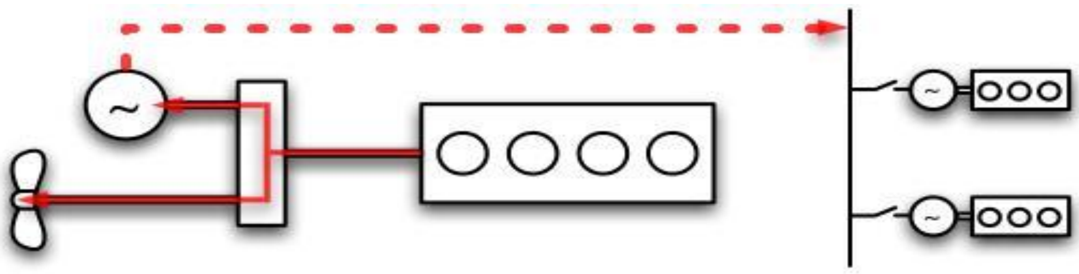


Figure 2.13 Energy flow in PTO mode

Boost Power Take In

In the power take in mode the electric machine delivers extra power through the gearbox to the propeller. It is driving the propeller in parallel with the diesel engine, so extra power is transferred to the propeller. The diesel generators provide this power in the form of electrical power, see Figure 2.14. It has the advantage that power in electrical form can easily be transported throughout the ship through cables. Some vessels require high power for only short amounts of their total operational profile. Instead of installing a larger engine, the PTI can provide this extra power. This does require more or larger auxiliary engines.

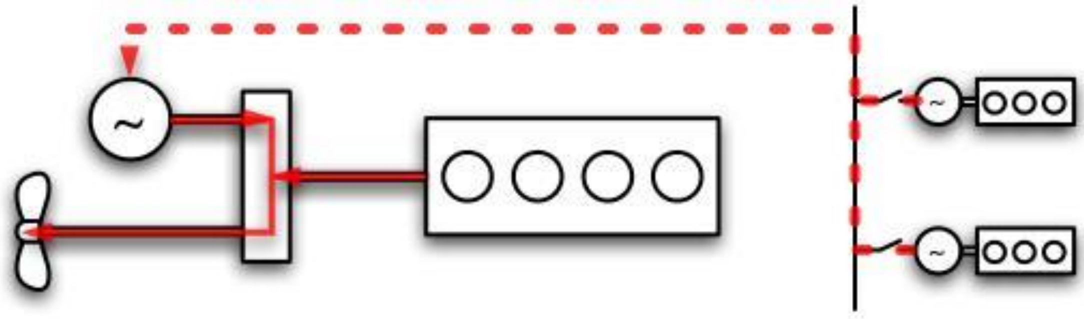


Figure 2.14: Energy flow in PTI boost mode

Slow Power Take In/Power Take Home

When the main diesel engine is not running, a clutch can disconnect it from the gearbox. Propulsion power can still be provided by the electric motor, which uses the electric power delivered by the diesel generators or in other cases by an energy storage system. (Figure 2.15). This could have two applications.

One is for vessels that often sail at low speeds. At low load the diesel engine becomes less efficient and fouling starts to become an issue. The PTI motor will run on electric power that is provided by a flexible amount of diesel generators. Generally speaking, more power is generated by the diesel generators, so larger or more auxiliary engines are required as opposed to a conventional diesel mechanical system.

The other application is an alternative propulsion capability. When the main engines fail for whatever reason, the ship is still capable of sailing on a slower speed using the electric motor. Class societies have set regulations regarding minimum speed, distance and/or power available.

The IMO has issued new SOLAS regulations that came into force in 2009 regarding safety on board passenger vessels. For given casualty scenarios, it sets requirements for safe evacuation of the passengers. One of these requirements is a redundant propulsion system or Power Take Home (PTH) function. This ensures the vessel will be able to return to port at limited speed after a defined amount of fire damage. At the moment there is no requirement regarding the speed, distance or available power. There is also no explicit requirement for the ship to be able to return to port in the case of flooding [Lloyds, 2010]. The regulations are applicable to passenger vessels constructed after July 1, 2010, with a length of over 120 meters or with three or more vertical fire zones1.

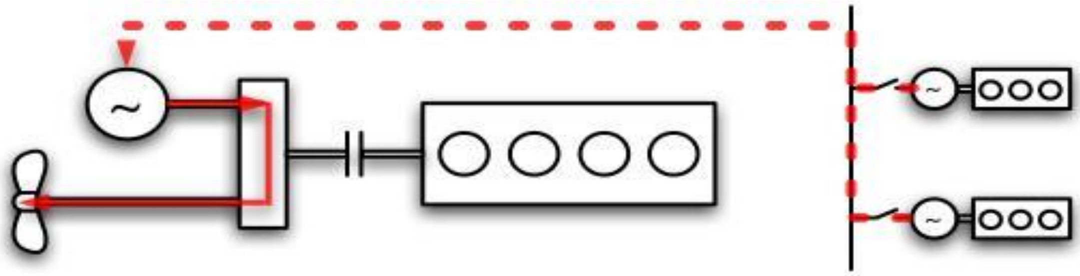


Figure 2.15: Energy flow in PTH mode

Any combinations between these three operating modes are possible. Of course, all these configurations are also possible on two or even more shaft applications. A two-shaft hybrid configuration could have an extra operating mode. If for any reason the port main engine fails, the starboard main engine can still drive the starboard propeller and a PTO. This electric power can then be transferred to the portside electric motor to drive the propeller. This so called cross-connection or electric-shaft between the two sides has the important advantage that the ship can still drive both sides to maintain maneuverability, without the need of using the auxiliary engines.

The electric motor can also be directly coupled onto the propeller shaft. This means that the motor has to run with the same relatively low speed as the propeller. To maintain the same power output, the torque produced by the motor has to be much higher. Because the torque of an electric motor is related to the current, the currents will increase. In order to withstand these higher currents the motor needs a higher number of poles and therefore a larger construction in comparison to the high-speed / low-torque motors. The costs of such a motor will also be higher, as the purchase costs of an electric machine are largely dependent on the amount of copper used in the windings. For 4-stroke applications an electric motor on the propeller shaft is therefore not often used **[7].**

2.3.1.1 Electrical Machines

In this chapter we are going to analyze the working principle, advantages and disadvantages of the electrical machines that are implemented in the retrofit.

Synchronous Motor Working Principle

Electric motor in general is an electro-mechanical device that converts energy from electrical mechanical form. Based on the type of input, there are two ''classifications'': single phase and 3 phase motors. Among 3 phase motors, induction motors and **synchronous motors** are more widely used. When 3 phase electric conductors are placed in certain geometrical positions (In certain angle from one another) then an electrical field is generated. Now the rotating magnetic field rotates at a certain speed, that speed is called synchronous speed. Now if an electromagnet is present in this rotating magnetic field, the electromagnet is magnetically locked with this rotating magnetic field and rotates with same speed of rotating field.

Synchronous motor is called so because the speed of the rotor of this motor is same as the rotating magnetic field. It is basically a fixed speed motor because it has only one speed, which is synchronous speed, and therefore no intermediate speed is there or in other words it's in synchronism with the supply frequency. Synchronous speed is given by $N_s = \frac{120f}{p}$

Where, **f = supply frequency** and **p = no. of poles**

Construction of Synchronous Motor

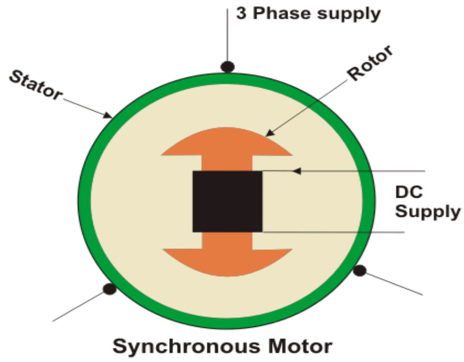


Figure 2.16 Construction of Synchronous Motor

Normally its construction is almost similar to that of a 3 phase induction motor, except the fact that the rotor is given DC supply, the reason of which is explained later. The basic construction of this type of motor is presented in Figure 2.16.

The stator is given is given three phase supply and the rotor is given DC supply.

Main Features of Synchronous Motors

Synchronous motors are inherently not self-starting. They require some external means to bring their speed close to synchronous speed to before they are synchronized.

The speed of operation of is in synchronism with the supply frequency and hence for constant supply frequency they behave as constant speed motor irrespective of load condition.

This motor has the unique characteristics of operating under any electrical power factor. This makes it being used in the improvement of the power factor.

Principle of Operation Synchronous Motor

Synchronous motor is a doubly excited machine i.e two electrical inputs are provided to it. It's stator winding which consists of a 3 phase winding is provided with 3 phase supply and rotor is provided with DC supply. The 3 phase stator winding carrying 3 phase currents produces 3 phase rotating magnetic flux. The rotor carrying DC supply also produces a constant flux. Considering the frequency to be 50 Hz, from the above relation we can see that the 3 phase rotating flux rotates about 3000 revolution in 1 min or 50 revolutions in 1 sec. At a particular instant rotor and stator poles might be of same polarity (N-N or S-S) causing repulsive force on rotor and the very next second it will be N-S causing attractive force. But due to inertia of the rotor, it is unable to rotate in any direction due to attractive or repulsive force and remain in standstill condition. Hence it is not self-starting. To overcome this inertia, rotor is initially fed some mechanical input which rotates it in same direction as magnetic field to a speed very close to synchronous speed. After some time magnetic locking occurs and the synchronous motor rotates in synchronism with the frequency. So at the start, in a way it behaves as an induction motor.

Methods of Starting a Synchronous Motor

Motor starting with an external prime Mover: Synchronous motors are mechanically coupled with another motor. It could be either 3 phase induction motor or DC shunt motor. DC excitation is not fed initially. It is rotated at speed very close to its synchronous speed and after that DC excitation is given. After some time when magnetic locking takes place supply to the external motor is cut off.

Damper winding: In case, synchronous motor is of salient pole type, additional winding is placed in rotor pole face. Initially when rotor is standstill, relative speed between damper winding and rotating air gap flux in large and an emf is induced in it which produces the required starting torque. As speed approaches synchronous speed, emf and torque is reduced and finally when magnetic locking takes place, torque also reduces to zero. Hence in this case synchronous is first run as three phase induction motor using additional winding and finally it is synchronized with the frequency.

Alternator Synchronous Generator

The definition of alternator is hidden in the name of this machine itself. An alternator is a machine that converts mechanical energy from a prime mover to AC electric power at specific voltage and current. It is also known as synchronous generator.

Use of Alternator

The power for electrical system of modern vehicles is produced from alternators. In previous days, DC generators or dynamos were used for this purpose but after development of alternator, the DC dynamos are replaced by more robust and light weight alternator. Although the electrical system of motor vehicles generally requires direct current, still an alternator along with diode rectifier instead of a DC generator is better choice as the complicated commutation is absent here. This special type of generator which is used in vehicle is known as automotive alternator. Another **use of alternator** is in diesel electric locomotive. Actually the engine of this locomotive is nothing but an alternator driven by diesel engine. The alternating current produced by this generator is converted to DC by integrated silicon diode rectifiers to feed all the DC traction motors. And these dc traction motors drive the wheel of the locomotive.

This machine is also used in marine similar to diesel electric locomotive. The synchronous generator used in marine is specially designed with appropriate adaptations to the salt-water environment. The typical output level of marine alternator is about 12 or 24 volt. In large marine applications, more than one units are used to provide large power. In those marine systems the power produced by the alternator is first rectified then used for charging the engine starter battery and auxiliary supply battery of marine purposes.

Types of Alternator

Alternators or synchronous generators can be classified in many ways depending upon their application and design.

According to application these machines are classified as:

- Automotive type - used in modern automobile.
- Diesel electric locomotive type - used in diesel electric multiple unit.
- Marine type - used in marine.
- Brush less type - used in electrical power generation plant as main source of power.
- Radio alternators - used for low brand radio frequency transmission.

These ac generators can be divided in many ways but we will discuss now two main **types of alternator** categorized according to their design.

a)Salient pole type

It is used as low and medium speed alternator. It has a large number of projecting poles having their cores bolted or dovetailed onto a heavy magnetic wheel of cast iron or steel of good magnetic quality. Such generators are characterized by their large diameters and short axial lengths. These generators look like a big wheel. These are mainly used for low speed turbine such as in hydel power plant.

b)Smooth cylindrical type

It is used for steam turbine driven alternator. The rotor of this generator rotates in very high speed. The rotor consists of a smooth solid forged steel cylinder having a number of slots milled out at intervals along the outer periphery for accommodation of field coils.

These rotors are designed mostly for 2 pole or 4 pole turbo generator running at 36000 rpm or 1800 rpm respectively **[8].**

2.3.1.2 Operational Comparison of available topologies

In order to achieve a hybrid propulsion configuration it is necessary to implement transmission systems that can transform a part of the mechanical energy of the main engine into electrical energy for charging purposes (battery packs sustainability) or supplying with energy the hotel loads of the vessel during its operation. In order to choose the right PTO configuration a literature review explaining the different operational principles was employed with the assistance of MAN B&W technical reports and catalogs.

There are 3 types of transmission systems that we are considering:

- PTO/GCR (power take off/gear constant ratio)
- PTO/RCF (power take off/RENK constant frequency)
- PTO/CFE (power take-off/constant frequency electrical)

- The PTO/GCR (power take off/gear constant ratio) Layout for operating at constant propeller speed The PTO/GCR system is the most simple and cheapest of the shaft generators, and it comprises a standard synchronous alternator and a simple step-up gear. Since the frequency produced by the alternator is proportional to the engine speed, the operation of this type of shaft generator normally takes place at constant propeller speed. The GCR shaft generator system is therefore normally utilized in connection with a controllable pitch propeller, with which constant propeller speed and relatively constant frequency are available over a wide engine power range. Due to the fact that the GCR experiences small engine speed and frequency instabilities it is not possible to run it parallel for long periods of time with other generating sets. This leads to the conclusion that this configuration can be implemented during the voyage of the vessel, hence all the electric power is supplied by it. The total efficiency of the above mentioned system is between 89-95 %.

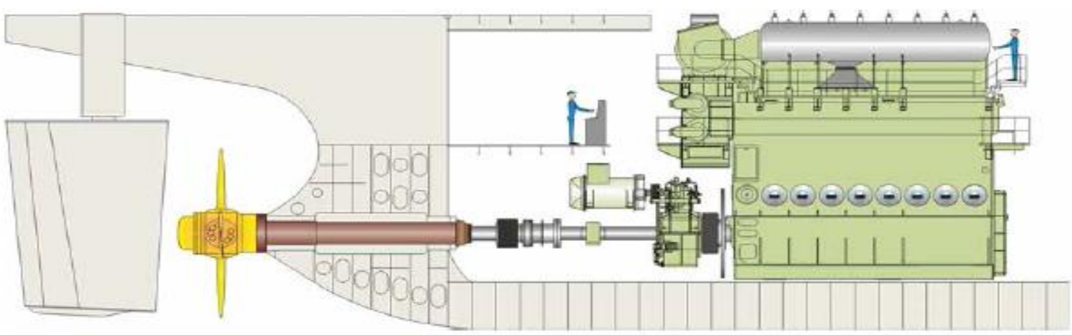


Figure 2.17 PTO/GCR (power take off/gear constant ratio) configuration

- The PTO/RCF system produces electricity with a constant electrical frequency over a wide propeller speed range, and the shaft generator type can be utilized in combination with a fixed pitch propeller and continuous operation in parallel with generating sets. The constant electrical frequency over a wide propeller speed range is achieved through a controlled planetary gearbox. Based on the detected output speed from the crankshaft gear, the RCF gear transmission can serve a constant speed to the alternator over an engine speed range of 35%. It consists of an epicyclic gear with a hydrostatic superposition drive. The hydrostatic motor is controlled by an electronic control unit and is driven by the built-on hydrostatic pump. The hydrostatic system drives the annulus of the epicyclical gear in either direction of rotation and continuously varies the gear ratio according to the engine speed. In the standard PTO/RCF layout, the output speed range of the gearbox is set between 70% to 105% of the engine's specified MCR speed, but this could be selected otherwise. The speed range from 70% to 105% equals an engine power of between 34% to 105% and the total efficiency of the RCF shaft generator system varies between 88% and 91%.

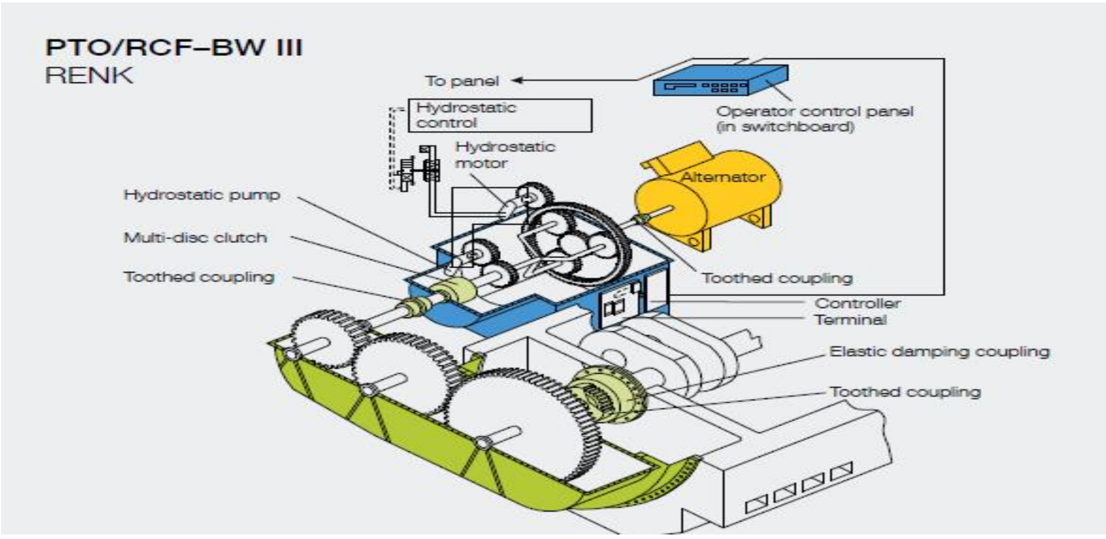


Figure 2.18 PTO/RCF (power take off/RENK constant frequency) configuration

- The PTO/CFE generates electric power with constant electrical frequency over a wide engine speed range. The shaft generator can be used in combination with fixed pitch propellers and continuous operation in parallel with generating sets. The most commonly used PTO/CFE is as a slow-running alternator type operating at the same speed as the propeller shaft. Alternative and faster step-up gear systems with a low-cost synchronous alternator are possible, but only a limited number of step-up-gear-based PTO/CFE systems have been introduced. The PTO/CFE slow-running alternator is available as an engine-mounted front end DMG/CFE solution, or installed as a tank-top-mounted aft end SMG/CFE solution with the rotor integrated on the intermediate propeller shaft. More poles are necessary for a low speed operated synchronous alternator. This means that the alternator type becomes bigger than for the step-up gear based alternative. The slow-running alternator type does not need any kind of flexible coupling, necessary for the faster-running step-up gear shaft generator types. Both the DMG/CFE and the SMG/ CFE are able to operate in parallel with the gensets and serve full rated electric power output when the speed of the main engine is between 75% and 105%, which equals an engine power range of 40% to 105%. The CFE system also has the capacity for a reduced electric output that is proportional to the engine speed of between 40% to 75% of the SMCR speed, a traditional PTO/CFE shaft generator is installed with a thyristor converter and synchronous condenser. The alternator generates a three-phase alternating current with a varying frequency that corresponds to the propeller speed **[9].** This is then rectified and conducted to the thyristor converter system in the engine room, which produces alternating current with constant frequency. The synchronous condenser is necessary because the DC intermediate link used by the thyrister converter system has the effect that there will be no reactive power served to the main switchboard. A synchronous condenser is therefore necessary to generate the reactive power needed. A novel marine shaft-driven generator system with two PWM-pulse width modulated converters has been introduced. With this system, one of the PWM converters is used to convert the varying current into the DC energy. Afterwards, the other PWM converter converts the DC energy into AC energy with the fixed frequency and voltage. Thanks to the space vector control used with this converter system, the generator can maintain a constant voltage and frequency. The PWM pulse width modulated converter system is able to supply effective power and reactive power to load on ships without a synchronous condenser and, thereby, simplifies the installation and later on maintenance processes. The traditional thyrister converter running with a synchronous condenser is illustrated by the control principle for a DMG/CFE unit, Fig. 8. However, the tank-top-mounted aft end SMG/CFE solution with integrated rotor on the intermediate propeller shaft is much more frequently used than the DMG/CFE, because it is not subjected to any limitations from the installation on the main engine and the limited space between the bulkhead and PTO.

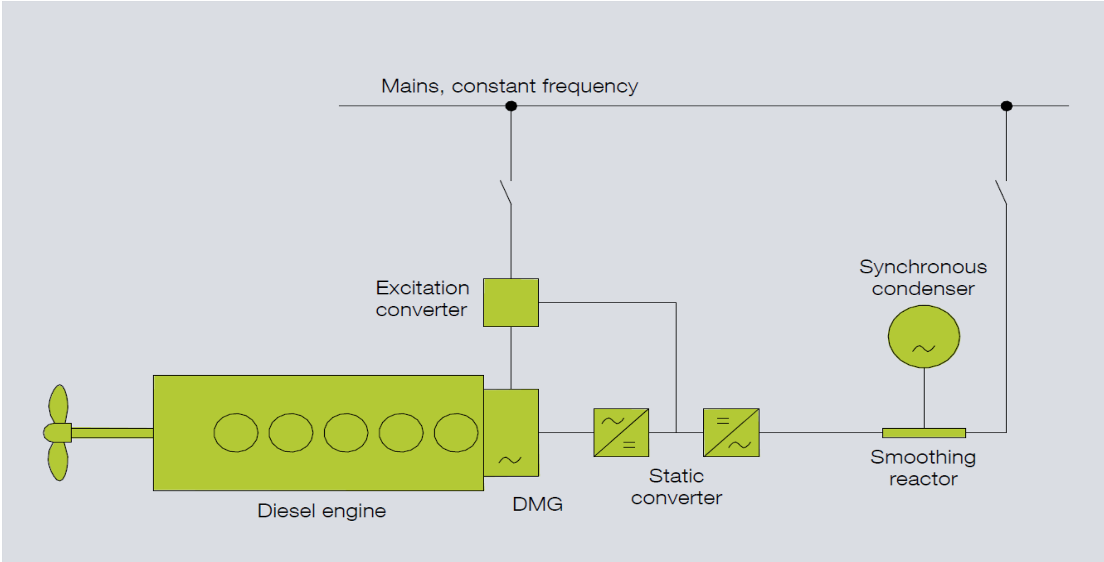


Figure 2.19 PTO/CFE (power take-off/constant frequency electrical) configuration

The range of electric power available from a shaft generator system depends on the shaft generator type selected. To illustrate the variation, the electric power diagrams are shown for the CFE, RCF and GCR principles. The diagrams are shown for basic layouts, but it is important to note that other shaft generator layout ranges based on a particular engine load profile could be selected to ensure that the electric power from the shaft generator is available for most preferred main engine load conditions. Normally, the most inexpensive GCR solution is operated with the controllable pitch propeller running at constant speed. This means that electric power is available throughout the main engine's power range. If the variable frequency is acceptable for the ship, the GCR gear system could be matched according to a suitable speed range for the fixed pitch propeller layout. The RENK RCF solution offers constant frequency at parallel running with gensets and has a full electric power capacity available within a wide range of engine power and propeller speed. The CFE constant frequency application is offered by several suppliers and can be selected for constant frequency, parallel running with gensets and for generating electric power for an even wider engine power and propeller speed range**.**

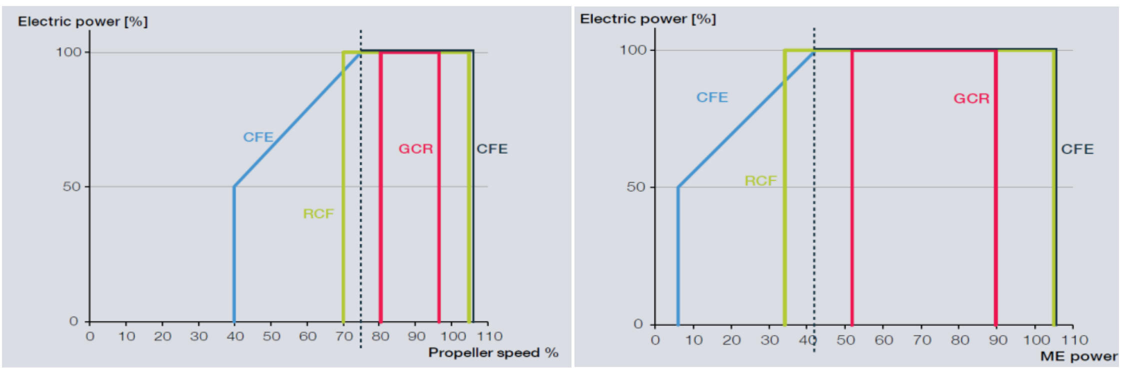


Figure 2.20 operational range of the electric power generated by the various PTO transmission systems discussed in accordance with the main engine power and propeller speed

2.3.2 Frequency converters

Frequency converters are employed when there is a need for a drive which can provide a vast range of frequencies intended for different operating speeds of an electric motor. This can be achieved with a modulation technique called Pulse Width Modulation (PWM). A fixed pitch propeller depending on the sea state and desired voyage time will need a range of power from the main engine that can be between 75-90% of MCR. This means that when a system's shaft generator operates in generator mode, the power transmitted by the main engine will be variable, thus the output frequency will be variable as well. That creates a problem for frequency sensitive devices on board, thus a frequency converter might be needed to keep the output frequency in generator mode constant, even with variable shaft speed. A frequency converter in combination with a CPP introduces the use of the combinator curve. According to a case study done by Rolls-Royce [2010] on a platform supply vessel, a hybrid system running on a combinator curve saves about 5% of fuel compared to a fixed speed system. Even though the efficiency of a converter lies in the region of 97%-98%, there still remains a significant improvement in overall efficiency. A fixed input frequency of 50 or 60 Hz will be converted to a variable frequency that determines the motor speed. Two commonly used converters in the power range of medium converters are the Pulse width modulated and the Current Source Inverter (CSI) converter, which both have the same principle diagram as in Figure 2.21. A 3-phase AC will be converted to a DC. This DC link acts as an energy buffer. Then through switching elements the DC is converted to a varying AC that drives the motor. Theses conversions are possible through a rectifier and an inverter. The principles of operation are presented below.

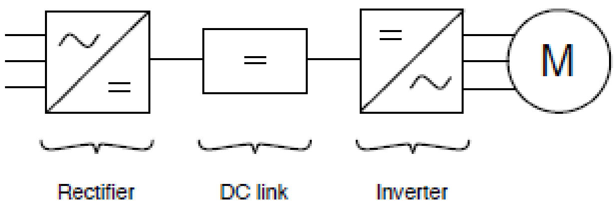


Figure 2.21: Principle of frequency converter with DC link

Frequency converter types

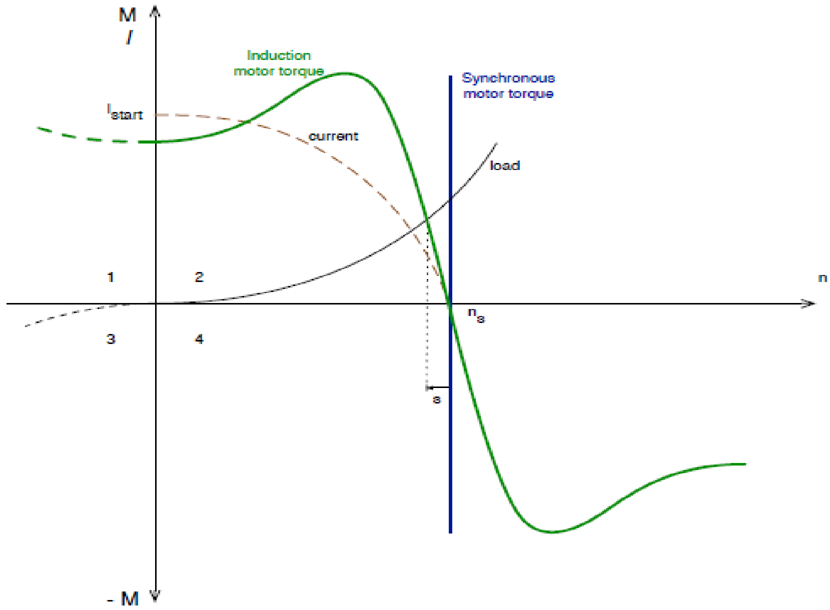


Figure 2.22: Principle of frequency converter with DC link

The different configurations the rectifier and inverter are put in together and controlled determine the type of frequency converter.

Pulse width modulated converter

A PWM converter consists of an uncontrolled rectifier with capacitor and a PWM inverter. The rectifier is usually a full bridge rectifier where 4 diodes are put in a way that the current after the rectifier flows in the same direction independent of the periodical change in flow direction due to AC power. In this converter the voltage is held constant. The capacitor in the DC link smoothens the voltage by storing energy during the charging and releasing during discharging in order to eliminate the ripple. Therefore this type of converter is often called a voltage source inverter (VSI). With an uncontrolled rectifying bridge, the converter cannot generate negative voltage. This means that it can only operate in the motoring quadrants as seen in Figure 2.22. If needed, the converter can be provided with a so called active frond end, which has switching transistors instead of passive diodes. This makes it possible to deliver power back to the grid, for example in PTO operation.

CSI converter

A CSI converter consists of a controllable rectifier and an inverter. By controlling the switching rate of the thyristors in the controlled rectifier, any DC voltage and current can be produced. This wave is not so smooth, so some energy buffer is required in the form of an inductor that smoothens the current. In the DC link the current is kept constant, hence the name current source inverter (CSI). The varying DC makes it possible to create a varying output voltage and frequency by the inverter bridge. The input AC commutates the thyristors on the rectifier side. Therefore this converter is referred to as a load-commutated inverter (LCI). This natural commutation is only possible with a leading power factor (i.e. current phase leads the voltage phase). With a synchronous motor this is possible, because the excitation can be controlled. With an induction motor, this cannot be done, so CSI converter can only be applied with synchronous motors. Therefore the default converter is a PWM converter. Because the rectifier bridge is controlled, it has a varying power factor that varies with the desired frequency. Also, it enables delivery of power back to the grid, in a 4-quadrant operation which translates in both generator and motor mode in a hybrid energy/propulsion system.

Chapter 3: Battery Technology

This chapter describes battery's functions and how to evaluate each battery's technology characteristics. In addition, the most important lithium ion battery technologies alongside with their specifications and applications are presented in order to help us evaluate the appropriate battery chemistry for the hybrid ship scenario.

3.1 Battery Technology Basics

In the pages below are described some of the most important characteristics that define the operation of batteries provided by a technical guide generated by MIT (2008).

• **Cell, modules, and packs** – Hybrid and electric vehicles have a high voltage battery pack that consists of individual modules and cells organized in series and parallel. A cell is the smallest, packaged form a battery can take and is generally on the order of one to six volts. A module consists of several cells generally connected in either series or parallel. A battery pack is then assembled by connecting modules together, again either in series or parallel.

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

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

• **Secondary and Primary Cells** – Although it may not sound like it, batteries for hybrid, plug-in, and electric vehicles are all secondary batteries. A primary battery is one that cannot be recharged. A secondary battery is one that is rechargeable. Battery Condition This section describes some of the variables used to describe the present condition of a battery.

• **State of Charge (SOC)(%)** – An expression of the present battery capacity as a percentage of maximum capacity. SOC is generally calculated using current integration to determine the change in battery capacity over time.

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

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

• **Open-circuit voltage (V)** – The voltage between the battery terminals with no load applied. The open-circuit voltage depends on the battery state of charge, increasing with state of charge.

• **Internal Resistance** – The resistance within the battery, generally different for charging and discharging, also dependent on the battery state of charge. As internal resistance increases, the battery efficiency decreases and thermal stability is reduced as more of the charging energy is converted into heat. Battery Technical Specifications This section explains the specifications you may see on battery technical specification sheets used to describe battery cells, modules, and packs.

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

• **Cut-off Voltage –** The minimum allowable voltage. It is this voltage that generally defines the "empty" state of the battery.

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

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

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

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

• **Energy or Nominal Energy (Wh (for a specific C-rate)) –** The "energy capacity" of the battery, the total Watt-hours available when the battery is discharged at a certain discharge current (specified as a C-rate) from 100 percent state-of-charge to the cut-off voltage. Energy is calculated by multiplying the discharge power (in Watts) by the discharge time (in hours). Like capacity, energy decreases with increasing C-rate. • Cycle Life (number for a specific DOD) – The number of discharge-charge cycles the battery can experience before it fails to meet specific performance criteria. Cycle life is estimated for specific charge and discharge conditions. The actual operating life of the battery is affected by the rate and depth of cycles and by other conditions such as temperature and humidity. The higher the DOD, the lower the cycle life.

• **Specific Energy (Wh/kg)** – The nominal battery energy per unit mass, sometimes referred to as the gravimetric energy density. Specific energy is a characteristic of the battery chemistry and packaging. Along with the energy consumption of the vehicle, it determines the battery weight required to achieve a given electric range.

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

• **Energy Density (Wh/L)** – The nominal battery energy per unit volume, sometimes referred to as the volumetric energy density. Specific energy is a characteristic of the battery chemistry and packaging. Along with the energy consumption of the vehicle, it determines the battery size required to achieve a given electric range.

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

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

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

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

- **Float Voltage** – The voltage at which the battery is maintained after being charge to 100 percent SOC to maintain that capacity by compensating for self-discharge of the battery.

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

- **(Maximum) Internal Resistance** – The resistance within the battery, generally different for charging and discharging **[10].**

The following information about battery cell types and the different Lithium Ion battery types were gathered from various sources like Wikipedia, scientific articles, and websites with technical information about battery technology and applications.

3.2 Battery cell types

The following information about battery cell types and the different Lithium Ion battery types were gathered from various sources like Wikipedia, scientific articles, and websites with technical information about battery technology and applications.

Cylindrical Cell

Cylindrical cells are one of the most widely used packaging modes for primary and secondary batteries. It comprises a great solution due to ease of construction and mechanical stability. High internal pressures can be developed because of the tubular shape which prevents pressure concentration.

Most lithium and nickel-based cylindrical cells include a positive thermal coefficient (PTC) switch, thus if exposed to excessive current, the normally conductive polymer heats up and become resistive, stopping current flow and acting as short circuit protection. Once the short is removed, the PTC cools down and returns to the conductive state.

Most cylindrical cells also feature a pressure relief mechanism, and the simplest design utilizes a membrane seal that ruptures under high pressure. Leakage and dry-out may occur after the membrane breaks. Re-sealable vents with a spring-loaded valve are the preferred design. Some Li-ion cells connect the pressure relief valve to an electrical fuse that permanently opens the cell if an unsafe pressure builds up. Figure 3.1 shows a cross section of a cylindrical cell.

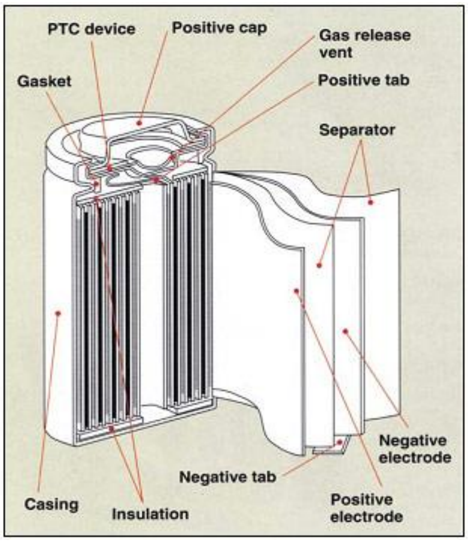


Figure 3.1: Cross section of a lithium-ion cylindrical cell.

The cylindrical cell design has good cycling ability, offers a long calendar life and is economical, but is heavy and has low packaging density due to space cavities.

Typical applications for the cylindrical cell are power tools, medical instruments, laptops and e-bikes. To allow variations within a given size, manufacturers use partial cell lengths, such as half and three-quarter formats, and nickel-cadmium provides the largest variety of cell choices. Some spilled over to nickel-metal-hydride, but not to lithium-ion as this chemistry established its own formats. The 18650 illustrated in Figure 3.2 remains one of the most popular cell packages. Typical applications for the 18650 Li-ion are power tools, medical devices, laptops and e-bikes.

Figure 3.2 Popular 18650 lithium-ion cell.

The metallic cylinder measure 18mm in diameter and 65mm the length. The larger 26650 cell measures 26mm in diameter.

The 18650 could well be the most optimized cell; it offers one of the lowest costs per Wh and has good reliability records. As consumers move to the flat designs in smart phones and tablets, the demand for the 18650 is fading and Figure 3.3 shows the over-supply that is being corrected thanks to the demand of the Tesla electric vehicles that also uses this cell format for now. As of end of 2016, the battery industry fears battery shortages to meet the growing demand for electric vehicles.

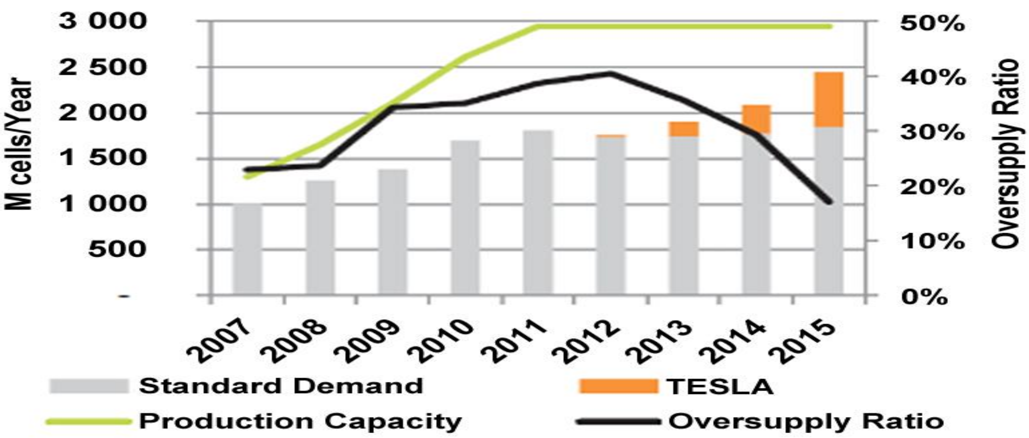


Figure 3.3: Demand and supply of the 18650.

The demand for the 18650 would have peaked in 2011 had it not been for new demands in military, medical and drones, including the Tesla electric car. The switch to a flat-design in consumer products and larger format for the electric powertrain will eventually saturate the 18650. A new entry is the 21700.

There are other cylindrical Li-ion formats with dimensions of 20700, 21700 and 22700. Meanwhile, Tesla, Panasonic and Samsung have decided on the 21700 for easy of manufacturing, optimal capacity and other benefits. While the 18650 has a volume of $66cm^3$ with a capacity of around 3000mAh, the $97cm^3$ volume of the 21700 is said to produce a capacity of up to 6000mAh, essentially doubling the capacity with a 50% increase in volume. Tesla Motor refers to their company's new 21700 as the "highest energy density cell that is also the cheapest." (The 2170 nomenclature Tesla advocates is not totally correct; the last zero of the 21700 model describes a cylindrical cell harmonizing with the IEC standard.)

The larger 26650 cell with a diameter of 26mm does not enjoy the same popularity as the 18650. The 26650 is commonly used in load-leveling systems. A thicker cell is said to be harder to build than a thinner one. Making the cell longer is preferred. There is also a 26700 made by E-OneMoliEnergy.

Some lead acid systems also borrow the cylindrical design. Known as the Hawker Cyclone, this cell offers improved cell stability, higher discharge currents and better temperature stability compared to the conventional prismatic design. The Hawker Cyclone has its own format.

Even though the cylindrical cell does not fully utilize the space by creating air cavities on side-by-side placement, the 18650 has a higher energy density than a prismatic/pouch Li-ion cell. The 3Ah 18650 delivers 248Ah/kg, whereas a modern pouch cell has about 140Ah/kg. The higher energy density of the cylindrical cell compensates for its less ideal stacking abilities and the empty space can always be used for cooling to improve thermal management.

Cell disintegration cannot always be prevented but propagation can. Cylindrical cells are often spaced apart to stop propagation should one cell take off. Spacing also helps in the thermal management. In addition, a cylindrical design does not change size. In comparison, a 5mm prismatic cell can expand to 8mm with use and allowances must be made.

The most common used battery cell configurations in hybrid electric marine vessels are the prismatic and pouch cells which are described below.

Prismatic Cell

Introduced in the early 1990s, the modern prismatic cell satisfies the demand for thinner sizes. Wrapped in elegant packages resembling a box of chewing gum or a small chocolate bar, prismatic cells make optimal use of space by using the layered approach. Other designs are wound and flattened into a pseudo-prismatic jelly roll. These cells are predominantly found in mobile phones, tablets and low-profile laptops ranging from 800mAh to 4,000mAh. No universal format exists and each manufacturer designs its own.

Prismatic cells are also available in large formats. Packaged in welded aluminum housings, the cells deliver capacities of 20–50Ah and are primarily used for electric powertrains in hybrid and electric vehicles. Figure 3.4 shows the prismatic cell.

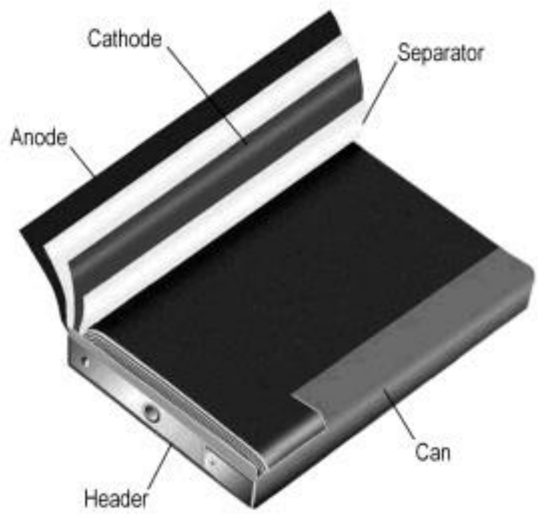


Figure 3.4 Cross section of a prismatic cell.

The prismatic cell improves space utilization and allows flexible design but it can be more expensive to manufacture, less efficient in thermal management and have a shorter cycle life than the cylindrical design. Allow for some swelling.

The prismatic cell requires a firm enclosure to achieve compression. Some swelling due to gas buildup is normal, and growth allowance must be made; a 5mm cell can grow to 8mm after 500 cycles. Discontinue using the battery if the distortion presses against the battery compartment. Bulging batteries can damage equipment and compromise safety.

Pouch Cell

In 1995, the pouch cell surprised the battery world with a radical new design. Rather than using a metallic cylinder and glass-to-metal electrical feed-through, conductive foil-tabs were welded to the electrodes and brought to the outside in a fully sealed way. Figure 3.5 illustrates a pouch cell.

Figure 3.5 The pouch cell.

The pouch cell offers a simple, flexible and lightweight solution to battery design. Some stack pressure is recommended but allowance for swelling must be made. The pouch cells can deliver high load currents but it performs best under light loading conditions and with moderate charging.

The pouch cell makes most efficient use of space and achieves 90–95 percent packaging efficiency, the highest among battery packs. Eliminating the metal enclosure reduces weight, but the cell needs support and allowance to expand in the battery compartment. The pouch packs are used in consumer, military and automotive applications. No standardized pouch cells exist; each manufacturer designs its own.

Pouch packs are commonly Li-polymer. Small cells are popular for portable applications requiring high load currents, such as drones and hobby gadgets. The larger cells in the 40Ah range serve in energy storage systems (ESS) because fewer cells simplify the battery design.

Although easily stackable, provision must be made for swelling. While smaller pouch packs can grow 8–10 percent over 500 cycles, large cells may expand to that size in 5,000 cycles. It is best not to stack pouch cells on top of each other but to lay them flat, side by side or allow extra space in between them. Avoid sharp edges that can stress the pouch cells as they expand.

Extreme swelling is a concern. Users of pouch packs have reported up to 3 percent swelling incidents on a poor batch run. The pressure created can crack the battery cover, and in some cases, break the display and electronic circuit boards. Discontinue using an inflated battery and do not puncture the bloating cell in close proximity to heat or fire. The escaping gases can ignite. Figure 3.6 shows a swollen pouch cell.

Figure 3.6 Swollen pouch cell.

Swelling can occur due to gassing. Improvements are being made with newer designs. Large pouch cells designs experience less swelling. The gases contain mainly CO_2 (carbon dioxide) and CO (carbon monoxide).

Pouch cells are manufactured by adding a temporary "gasbag" on the side. Gases escape into the gasbag while forming the solid electrolyte interface (SEI) during the first charge. The gasbag is cut off and the pack is resealed as part of the finishing process. Forming a solid SEI is key to good formatting practices. Subsequent charges should produce minimal gases, however, gas generation, also known as gassing, cannot be fully avoided. It is caused by electrolyte decomposition as part of usage and aging. Stresses, such as overcharging and overheating promote gassing. Ballooning with normal use often hints to a flawed batch.

The technology has matured and prismatic and pouch cells have the potential for greater capacity than the cylindrical format. Large flat packs serve electric powertrains and Energy Storage System (ESS) with good results. The cost per kWh in the prismatic/pouch cell is still higher than with the 18650 cell but this is changing. Figure 3.7 compares the price of the cylindrical, prismatic and pouch cells, also known as laminated. Flat-cell designs are getting price competitive and battery experts predict a shift towards these cell formats, especially if the same performance criteria of the cylindrical cell can be met.

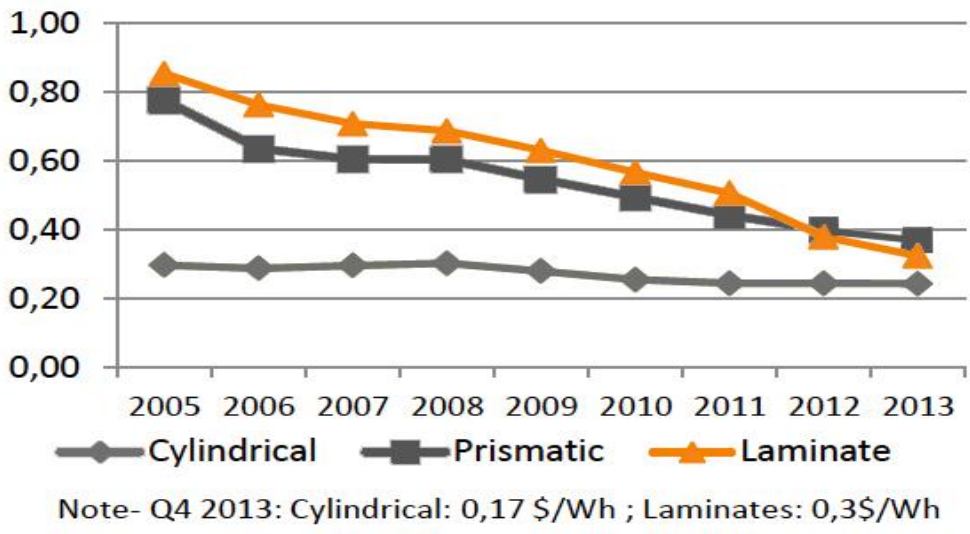


Figure 3.7 Price of Li-ion ($US/Wh).

Historically, manufacturing costs of prismatic and pouch formats (laminate) were higher, but they are converging with cellular design. Pricing involves the manufacturing of the bare cells only.

Summary

With the pouch cell, the manufacturer is attempting to simplify cell manufacturing by replicating the packaging of food. Each format has pros and cons as summarized below.

Cylindrical cell has high specific energy, good mechanical stability and lends itself to automated manufacturing. Cell design allows added safety features that are not possible with other formats; it cycles well, offers a long calendar life and is low cost, but it has less than ideal packaging density. The cylindrical cell is commonly used for portable applications.

Prismatic cell are encased in aluminum or steel for stability. Jelly-rolled or stacked, the cell is space-efficient but can be costlier to manufacture than the cylindrical cell. Modern prismatic cells are used in the electric powertrain and energy storage systems.

Pouch cell uses laminated architecture in a bag. It is light and cost-effective but exposure to humidity and high temperature can shorten life. Adding a light stack pressure prolongs longevity by preventing delamination. Swelling of 8–10 percent over 500 cycles must be considered with some cell designs. Large cells work best with light loading and moderate charge times. The pouch cell is growing in popularity and serves similar applications to the prismatic cell **[11].**

3.3 Types of Lithium-ion Batteries

Lithium-ion is named for its active materials and the words are either written in full or shortened by their chemical symbols. A series of letters and numbers strung together can be hard to remember and even harder to pronounce, and battery chemistries are also identified in abbreviated letters.

For example, lithium cobalt oxide, one of the most common Li-ions, has the chemical symbols $LiCoO_2$ and the abbreviation LCO. For reasons of simplicity, the short form Li-cobalt can also be used for this battery. Cobalt is the main active material that gives this battery character. Other Li-ion chemistries are given similar short-form names.

Bellow six types of Li-ion batteries are presented.

Lithium Cobalt Oxide ($LiCoO_2$)

Its high specific energy makes Li-cobalt the popular choice for mobile phones, laptops and digital cameras. The battery consists of a cobalt oxide cathode and a graphite carbon anode. The cathode has a layered structure and during discharge, lithium ions move from the anode to the cathode. The flow reverses on charge. The drawback of Li-cobalt is a relatively short life span, low thermal stability and limited load capabilities (specific power). Figure 3.8 illustrates the structure.

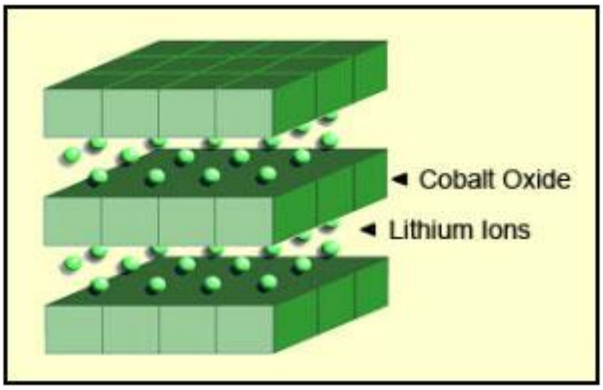


Figure 3.8: Li-cobalt structure.

The cathode has a layered structure. During discharge the lithium ions move from the anode to the cathode; on charge the flow is from cathode to anode.

The drawback of Li-cobalt is a relatively short life span, low thermal stability and limited load capabilities (specific power). Li-cobalt is maturing and newer systems include nickel, manganese and/or aluminum to improve longevity, loading capabilities and cost.

Li-cobalt should not be charged and discharged at a current higher than its C-rating. This means that an 18650 cell with 2,400mAh can only be charged and discharged at 2,400mA. Forcing a fast charge or applying a load higher than 2,400mA causes overheating and undue stress. For optimal fast charge, the manufacturer recommends a C-rate of 0.8C or about 2,000mA. The mandatory battery protection circuit limits the charge and discharge rate to a safe level of about 1C for the Energy Cell.

The hexagonal spider graphic (Figure 3.9) summarizes the performance of Li-cobalt in terms of *specific energy* or capacity that relates to runtime; *specific power* or the ability to deliver high current; *safety; performance* at hot and cold temperatures; *life span* reflecting cycle life and longevity; and *cost*. Other characteristics of interest not shown in the spider webs are toxicity, fast-charge capabilities, self-discharge and shelf life.

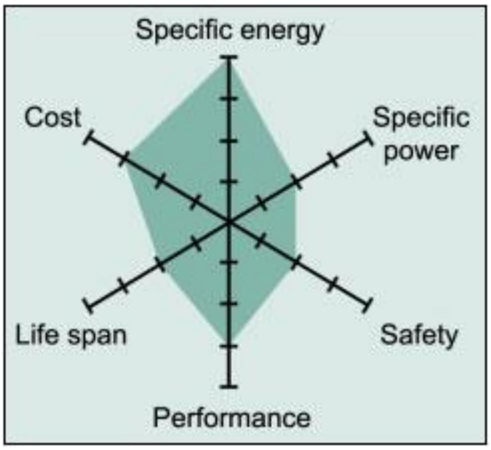


Figure 3.9: Snapshot of an average Li-cobalt battery.

Li-cobalt excels on high specific energy but offers only moderate performance specific power, safety and life span.

Summary Table

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

Table 3.1 Characteristics of lithium cobalt oxide.

Lithium Manganese Oxide ($LiMn_2O_4$)

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

Low internal cell resistance enables fast charging and high-current discharging. In an 18650 package, Li-manganese can be discharged at currents of 20–30A with moderate heat buildup. It is also possible to apply one-second load pulses of up to 50A. A continuous high load at this current would cause heat buildup and the cell temperature cannot exceed 80°C (176°F). Li-manganese is used for power tools, medical instruments, as well as hybrid and electric vehicles.

Figure 3.10 illustrates the formation of a three-dimensional crystalline framework on the cathode of a Li-manganese battery. This spinel structure, which is usually composed of diamond shapes connected into a lattice, appears after initial formation.

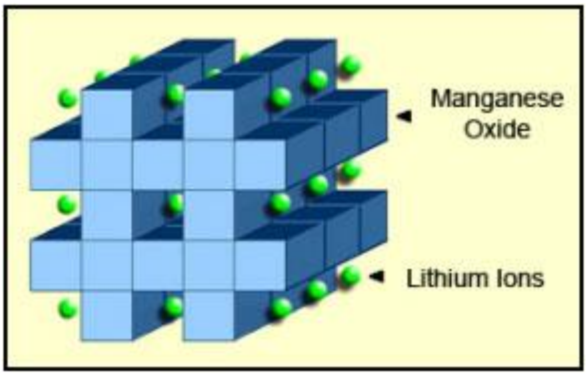


Figure 3.10 Li-manganese structure.

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

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

Figure 3.11 shows the spider web of a typical Li-manganese battery. The characteristics appear marginal but newer designs have improved in terms of specific power, safety and life span. Pure Li-manganese batteries are no longer common today; they may only be used for special applications.

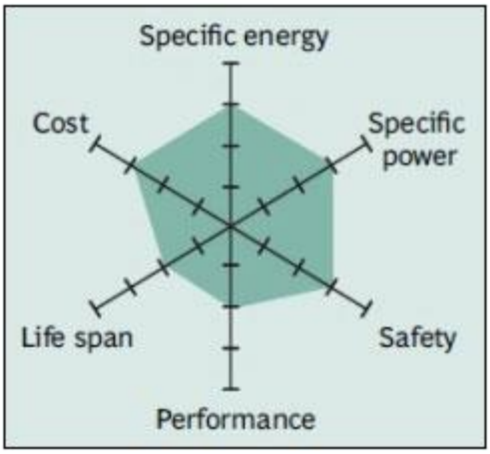


Figure 3.11 Snapshot of a pure Li-manganese battery.

Although moderate in overall performance, newer designs of Li-manganese offer improvements in specific power, safety and life span.

Most Li-manganese batteries blend with lithium nickel manganese cobalt oxide (NMC) to improve the specific energy and prolong the life span. This combination brings out the best in each system, and the LMO (NMC) is chosen for most electric vehicles, such as the Nissan Leaf, Chevy Volt and BMW i3. The LMO part of the battery, which can be about 30 percent, provides high current boost on acceleration; the NMC part gives the long driving range.

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

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

Summary Table

Lithium Manganese Oxide: $LiMn_2O_4$ cathode. Graphite anode Short form: LMO or Li-manganese Commercially available Since 1996	
Voltages	3.70V (3.80V) nominal; typical operating range 3.0–4.2V/cell
Specific energy (capacity)	100–150Wh/kg
Charge (C-rate)	0.7–1C typical, 3C maximum, charges to 4.20V (most cells)
Discharge (C-rate)	1C; 10C possible with some cells, 30C pulse (5s), 2.50V cut-off
Cycle life	300–700 (related to depth of discharge, temperature)

Thermal runaway	250°C (482°F) typical. High charge promotes thermal runaway
Applications	Power tools, medical devices, electric powertrains
Comments	High power but less capacity; safer than Li-cobalt; commonly mixed with NMC to improve performance.

Table 3.2: Characteristics of Lithium Manganese Oxide.

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

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

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

NMC is the battery of choice for power tools, e-bikes and other electric powertrains. The cathode combination is typically one-third nickel, one-third manganese and one-third cobalt, also known as 1-1-1. This offers a unique blend that also lowers the raw material cost due to reduced cobalt content. Another successful combination is NCM with 5 parts nickel, 3 parts cobalt and 2 parts manganese. Further combinations using various amounts of cathode materials are possible. New electrolytes and additives enable charging to 4.4V/cell and higher to boost capacity. Figure 3.12 demonstrates the characteristics of the NMC.

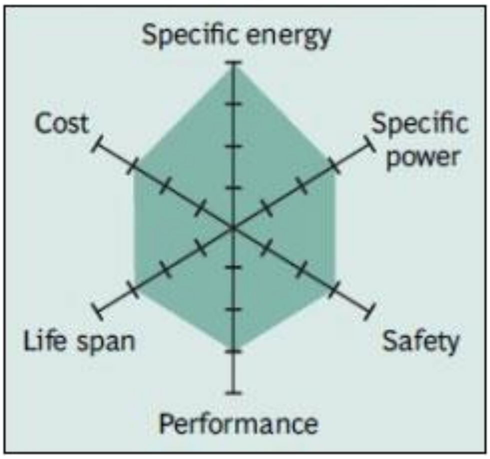


Figure 3.12 Snapshot of NMC.

NMC has good overall performance and excels on specific energy. This battery is the preferred candidate for the electric vehicle and has the lowest self-heating rate.

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

Summary Table

Lithium Nickel Manganese Cobalt Oxide: $LiNiMnCoO_2$ cathode, graphite anode Short form: NMC (NCM, CMN, CNM, MNC, MCN similar with different metal combinations) Since 2008	
Voltages	3.60V, 3.70V nominal; typical operating range 3.0–4.2V/cell, or higher
Specific energy (capacity)	150–220Wh/kg

Charge (C-rate)	0.7–1C, charges to 4.20V, some go to 4.30V; 3h charge typical. Charge current above 1C shortens battery life.
Discharge (C-rate)	1C; 2C possible on some cells; 2.50V cut-off
Cycle life	1000–2000 (related to depth of discharge, temperature)
Thermal runaway	210°C (410°F) typical. High charge promotes thermal runaway
Applications	E-bikes, medical devices, EVs, industrial
Comments	Provides high capacity and high power. Serves as Hybrid Cell. Favorite chemistry for many uses; market share is increasing.

Table 3.3 Characteristics of lithium nickel manganese cobalt oxide (NMC).

Lithium Iron Phosphate ($LiFePO_4$)

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

Li-phosphate is more tolerant to full charge conditions and is less stressed than other lithium-ion systems if kept at high voltage for a prolonged time. As a trade-off, its lower nominal voltage of 3.2V/cell reduces the specific energy below that of cobalt-blended lithium-ion. With most batteries, cold temperature reduces performance and elevated storage temperature shortens the service life, and Li-phosphate is no exception. Li-phosphate has a higher self-discharge than other Li-ion batteries, which can cause balancing issues with aging. Cleanliness in manufacturing is of importance for longevity. There is no tolerance for moisture, lest the battery will only deliver 50 cycles. Figure 3.13 summarizes the attributes of Li-phosphate.

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

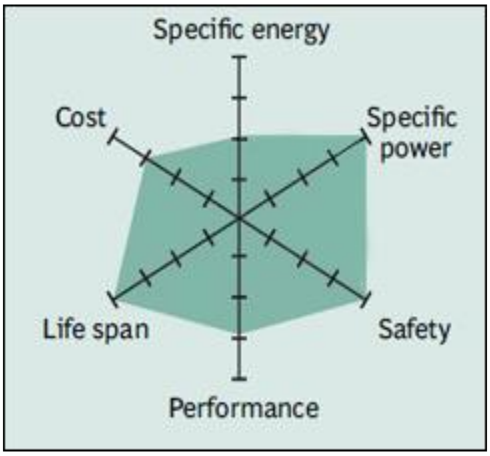


Figure 3.13 Snapshot of a typical Li-phosphate battery.

Li-phosphate has excellent safety and long life span but moderate specific energy and elevated self-discharge.

Summary Table

Lithium Iron Phosphate: $LiFePO_4$ cathode, graphite anode Short form: LFP Commercially available Since 1996	
Voltages	3.20, 3.30V nominal; typical operating range 2.5–3.65V/cell

Specific energy (capacity)	90–120Wh/kg
Charge (C-rate)	1C typical, charges to 3.65V; 3h charge time typical
Discharge (C-rate)	1C, 25C on some cells; 40A pulse (2s); 2.50V cut-off (lower that 2V causes damage)
Cycle life	1000–2000 (related to depth of discharge, temperature)
Thermal runaway	270°C (518°F) Very safe battery even if fully charged
Applications	Portable and stationary needing high load currents and endurance
Comments	Very flat voltage discharge curve but low capacity. One of safest Li-ions. Used for special markets. Elevated self-discharge.

Table 3.4 Characteristics of lithium iron phosphate.

Lithium Nickel Cobalt Aluminum Oxide ($LiNiCoAlO_2$)

Lithium nickel cobalt aluminum oxide battery, or NCA, has been around since 1999 for special applications. It shares similarities with NMC by offering high specific energy, reasonably good specific power and a long life span. Less flattering are safety and cost. Figure 3.14 summarizes the six key characteristics. NCA is a further development of lithium nickel oxide; adding aluminum gives the chemistry greater stability.

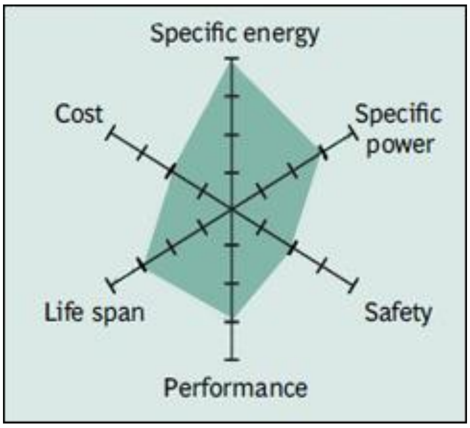


Figure 3.14 Snapshot of NCA.

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

Summary Table

Lithium Nickel Cobalt Aluminum Oxide: $LiNiCoAlO_2$ cathode (~9% Co), graphite anode Short form: NCA Commercially available Since 1999	
Voltages	3.60V nominal; typical operating range 3.0–4.2V/cell
Specific energy (capacity)	200-260Wh/kg; 300Wh/kg predictable
Charge (C-rate)	0.7C, charges to 4.20V (most cells), 3h charge typical, fast charge possible with some cells
Discharge (C-rate)	1C typical; 3.00V cut-off; high discharge rate shortens battery life

Cycle life	500 (related to depth of discharge, temperature)
Thermal runaway	150°C (302°F) typical, High charge promotes thermal runaway
Applications	Medical devices, industrial, electric powertrain (Tesla)
Comments	Shares similarities with Li-cobalt. Serves as Energy Cell.

Table 3.5 Characteristics of Lithium Nickel Cobalt Aluminum Oxide.

Lithium Titanate ($Li_4Ti_5O_{12}$)

Batteries with lithium titanate anodes have been known since the 1980s. Li-titanate replaces the graphite in the anode of a typical lithium-ion battery and the material forms into a spinel structure. The cathode can be lithium manganese oxide or NMC. Li-titanate has a nominal cell voltage of 2.40V, can be fast charged and delivers a high discharge current of 10C, or 10 times the rated capacity. The cycle count is said to be higher than that of a regular Li-ion. Li-titanate is safe, has excellent low-temperature discharge characteristics and obtains a capacity of 80 percent at –30°C (–22°F). However, the battery is expensive and at 65Wh/kg the specific energy is low, rivalling that of NiCd. Li-titanate charges to 2.80V/cell, and the end of discharge is 1.80V/cell. Figure 3.15 illustrates the characteristics of the Li-titanate battery. Typical uses are electric powertrains, UPS and solar-powered street lighting.

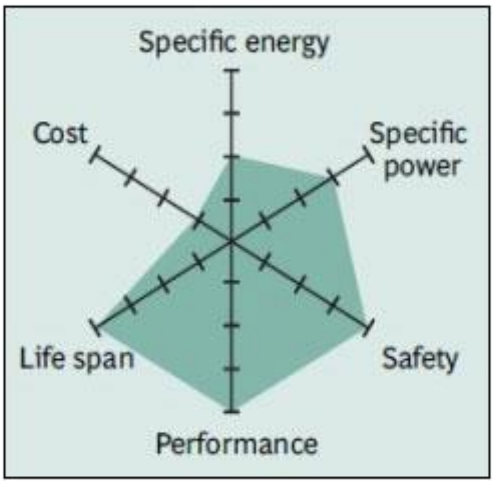


Figure 3.15 Snapshot of Li-titanate.

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

Summary Table

Lithium Titanate: Can be lithium manganese oxide or NMC; $Li_4Ti_5O_{12}$ (titanate) anode Short form: LTO or Li-titanate Commercially available since about 2008.	
Voltages	2.40V nominal; typical operating range 1.8–2.85V/cell
Specific energy (capacity)	70–80Wh/kg
Charge (C-rate)	1C typical; 5C maximum, charges to 2.85V
Discharge(C-rate)	10 possible, 30C 5s pulse; 1.80V cut-off on LCO/LTO
Cycle life	3,000–7,000
Thermal runaway	One of safest Li-ion batteries
Applications	UPS, electric powertrain (Mitsubishi i-MiEV, Honda Fit EV), solar-powered street lighting
Comments	Long life, fast charge, wide temperature range but low specific energy and expensive. Among safest Li-ion batteries.

Table 3.6 Characteristics of lithium titanate.

Figure 3.16 compares the specific energy of lead-, nickel- and lithium-based systems. While Li-aluminum (NCA) is the clear winner by storing more capacity than other systems, this only applies to specific energy. In terms of specific power and thermal stability, Li-manganese (LMO) and Li-phosphate (LFP) are superior. Li-titanate (LTO) may have low capacity but this chemistry outlives most other batteries in terms of life span and also has the best cold temperature performance. Moving towards the electric powertrain, safety and cycle life will gain dominance over capacity. (LCO stands for Li-cobalt, the original Li-ion.)

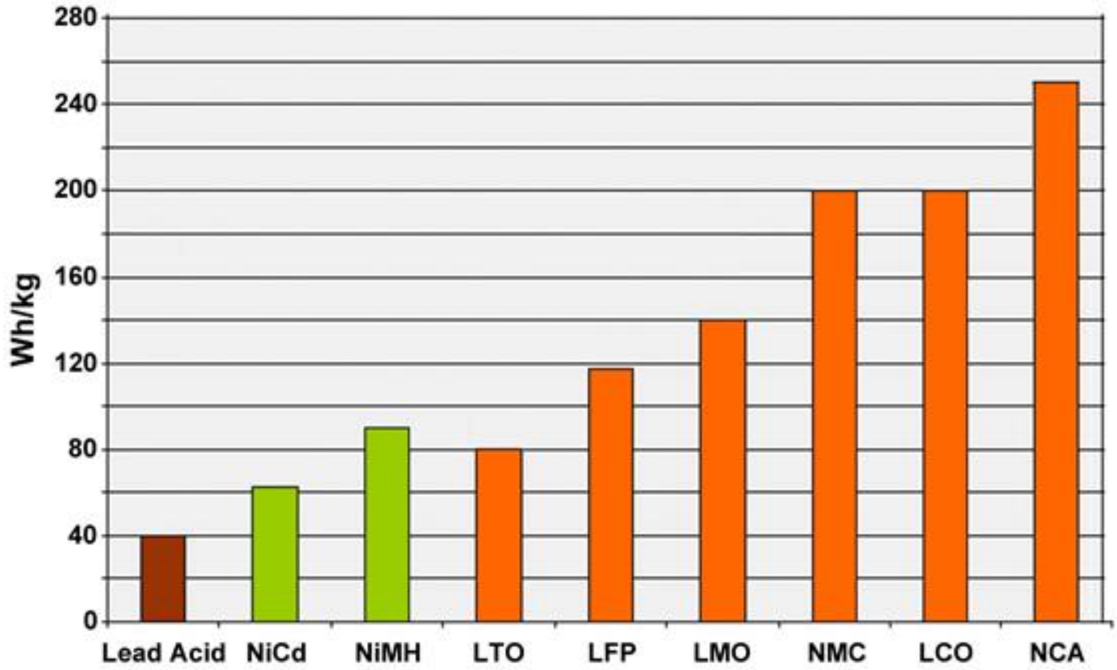


Figure 3.16 Typical specific energy of lead-, nickel- and lithium-based batteries.

NCA enjoys the highest specific energy; however, manganese and phosphate are superior in terms of specific power and thermal stability. Li-titanate has the best life span **[11].**

Chapter 4: Methodology's delimitation

Scope of this study is the development of a generic formula assessing the technical feasibility of the retrofit of medium distance Ro/Pax ferries into hybrid ones. In order to reach to an optimal solution an investment analysis was employed as well. An electrification design methodology was also developed in order to compare the different configurations and choose the best solution possible. Eco-benefit and impact on human health has also been taken into account.

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

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

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

- Installation of appropriate number of battery modules forming battery packs in the place of existing fuel tanks
- Suitable arrangement of battery packs into arrays in order to ensure the required voltage and capacity(Ah) based on the desired operational profile and regulatory framework
- Location of the battery system shall be according to national and international legislation
- Installation of Battery Management System
- Suitable transformation of ship's electrical distribution network
- Uninstallation of electric generators, since the required electrical power will be provided directly from the battery system and the shaft generators
- Installation of a connection point with shore-side for recharging
- Emergency Generator should not be omitted in every case but investigated according to class rules.

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

- Underground Cables
- At least one substation including :
    - Frequency converters and/or rectifiers

    - Power transformers
    - All the necessary protection equipment
- Interconnection equipment including
    - Plugs and sockets
    - Cables and cable reels
    - Cranks
    - Mooring system

The task of finding the optimal layout, sizing and setup of modifications both on shore and on board is a multivariate problem. Many parameters need to be taken into consideration both from the technical side/design, operational requirements of the route in question and safety criteria, for the optimization of this task. Main priorities of a battery system for maritime applications are safety and reliability of the passengers and the vessel, and sufficient life for the system to be economically feasible. Part of the structure and compartmentation of this chapter is based on *Techno-economical feasibility study on the retrofit of double- ended Ro/Pax ferries into battery-powered ones* (C. Bakirtzoglou, 2017) and modified for the hybrid scenario we are investigating, by adding specific guidelines regarding the battery system operation inside a hybrid power plant.

4.1 Legal & Regulatory framework

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

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

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

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

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

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

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

The guidelines and regulations presented in the next pages are combination of the following publications :

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

Figure 4.1: New fuel tanks (CORVUS, 2016)

4.2 Battery system

The Battery system provides the energy for propulsion and hotel loads in conjunction with the shaft generator, but in this chapter we are focusing on the battery system elements. Some of the most important are listed below:

- Cells, sub packs, packs
- the hardware needed for making battery modules
- The required components for thermal management
- Safety features as contactors and fuses
- Bus-bars and high voltage cabling
- Voltage and temperature sensors
- Low voltage cabling and connectors.

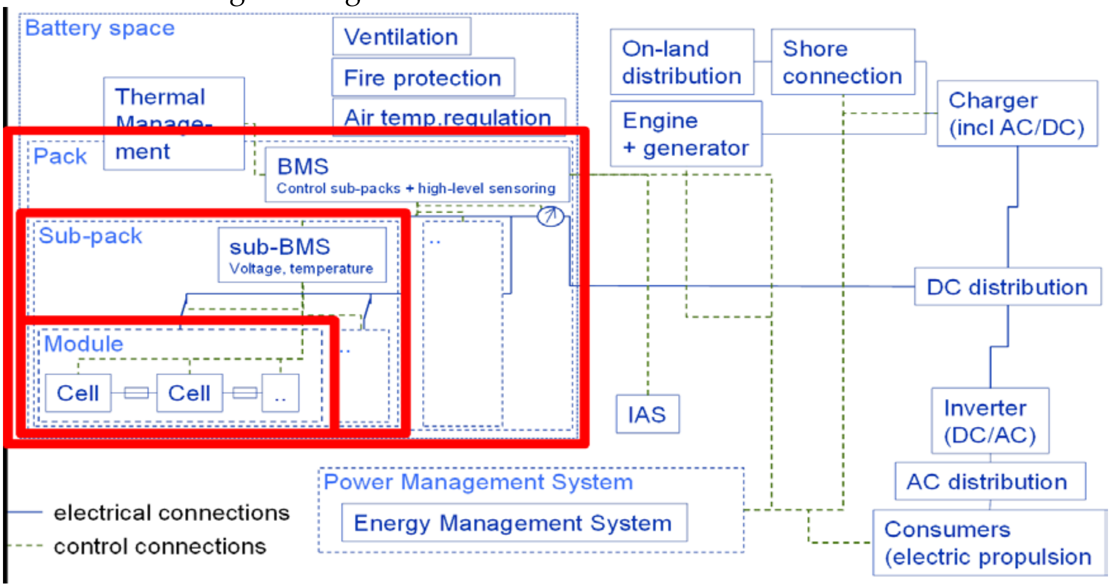


Figure 4.2:Battery system and related sub-systems (DNV, 2014)

A cell is the smallest electro chemical unit. An assembly of cells including some level of electronic control forms the module. The modules are connected into series and parallel to form a sub-pack. Sub-Pack is the smallest unit that can be electrically isolated. Depending on the system architecture, each sub-pack can have internal relays/contactors which can interrupt main power connection. A battery pack usually can be consisted of parallel sub-packs. The battery system may consist of several battery packs. The electrical connections between the different aggregate levels of the battery system may be connected using cables, bus bars or a combination of these.

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

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

CELL’S DANGERS:

- High Impedance
- Internal short circuit
- Insulation fault
- Electrolyte leakage

MODULE’S DANGERS:

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

SUBPACKS’ DANGERS:

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

PACKS’ DANGERS:

- High level sensor failure
- Voltage and temperature imbalance
- Battery life too short
- Contactor does not open/close when required
- Reverse polarity protection
- Emergency shutdown

In case the internal electrical configuration of a sub-pack contains independently controllable parallel strings, each string shall include independent current measurement.

Low contact impedance for the electrical connections is crucial to avoid over-heating and control the fire risk, as well as maximum efficiency. In order to avoid overheating and lower the chances of fire, low contact impedance is employed for the electrical installations. Another good practice to avoid overheating and achieve generally better thermal management is to divide the batteries in as many as possible parallel battery strings, which can also ease the detection of elevated levels of contact impedance in the electrical connections resulting in increased safety of the system.

The battery casing, covering modules and cells, shall be made of a flame-retardant material to prevent self-ignition of substances like fuel (considering the installation is in the engine room).

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

The outgoing circuits on a battery system must include a disconnector switch for isolating purposes. This measure is important in order to make maintenance a safe practice. In addition to the disconnector switch, a short circuit and overcurrent switch must be provided.

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

4.3 Battery system capacity

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

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

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

Capacity of the battery system shall be sufficient for the intended operation of the vessel. Charging will be possible during port stay to keep acceptable state of charge and it must be verified sufficient for the planned voyage before leaving the port. In case of a hybrid system the batteries could be charged during voyage as well, a factor that can be considered in the sizing procedure and voyage planning.

Battery capacity installed shall be designed for a safety margin of at least 10 % or higher for weather adjustments to propulsion energy consumption. Battery capacity installed is not designed to cope with extreme operational situations encountered only one or two times per year, for example the relocation to ship yard for maintenance. Instead mobile power packs should be an option for such planned deviations. Because our system is used for propulsion only during maneuvering the weather adjustment is not such a concern but fouling might be. So 10-15% margin is appropriate even if it is more than enough for just maneuvering considering the time the it lasts.

Emergency generator can be omitted if national flag authorities agree.

Single failure of critical modules shall not compromise the integrity of the vessel, for non-propulsion cases loss of battery power shall not affect critical vessel functions. So there must be enough energy for hotel loads during maneuvering even if there is a critical failure in some of the modules. In emergency cases the main engine can be employed as well.

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

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

The total battery capacity installed must be sufficient to absorb charging and discharging powers according to the electrical balance sheet, including hotel power, without exceeding recommended temperatures generated within batteries from battery loads as deviations would lead to lower life-span of batteries. The battery capacity installed must be reasonably balanced in relation to the chosen maximal charging powers in port thus higher charging powers will save battery weight but vice versa also result in high investment cost of the shore charging connection station as its price depends mostly on maximum power capacity. So in the sizing process the port shore substation power is a major factor in order to assess the energy requirements.

The battery pack installed should be increased to exploit the lower night rates of electricity (at certain times spot rates are negative). The reason behind this is to achieve the least port charges during the day, when the electricity cost is higher. Of course this leads to bigger investment and an analysis should be employed considering the difference in electricity price during day and night.

4.4 Battery system

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

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

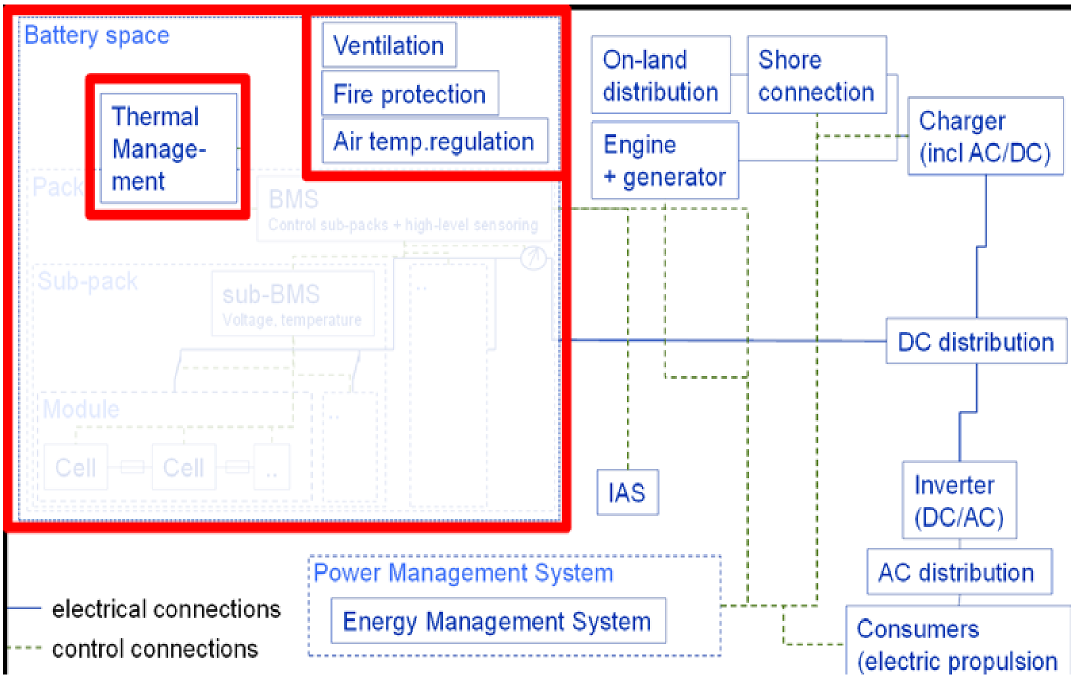


Figure 4.3: Illustration of battery system (DNV, 2014)

4.4.1 Arrangement

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

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

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

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

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

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

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

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

Battery systems within the battery space shall be arranged with sufficient protection (partition plates or sufficient distance in accordance with maker recommendation) to prevent escalation between battery modules in case of a thermal runaway. The battery configuration shall not contain other systems supporting essential vessel services, including pipes and cables serving such systems, in order to prevent loss of propulsion or steering upon possible incidents (e.g. thermal runaway) in the battery system. Additionally it should not contain heat sources or high fire risk objects. High fire risk objects are objects similar to those listed in SOLAS Reg. II – 2/3.31 (Heat sources are sources with temperature higher than 220 ºC as used in SOLAS Reg. II-2/4.2.2.6.1) . The battery space shall be adequately arranged so that access for repairs and substitution of defected parts is facilitated and should demonstrate robustness for long term exposure in a marine environment (temperature, moisture, list, trim, roll, etc.) and shall provide protection against external hazards (e.g. fire, mechanical impact, water ingress, pipes leakage).

4.4.2 Operational Environment

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

The battery system shall not be located without adequate protection from heat and a cooling system based on the operational behavior of the batteries must be employed. Ignition sources, dust, oil pollution or other potential harmful environmental influence to the system and its components must be taken into consideration when choosing the appropriate ingress protection index according to the operational environment (i.e. engine room). Therefore, specified procedures should be followed, and relevant controls or alarms must be installed.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

As a general fire extinguishing medium (heavy) foam could be, also, be considered. It's advantages are:
1. Longer lasting cooling effect since heavy foam might form a "wall" around and between battery sub-packs with a good cooling effect (depending on layout).
2. Potential off-gas which is warmer than air can be ventilated from a high position in the battery space while foam can be injected from the top and spreading slowly downwards.
3. Surrounding foam can bind potentially flammable solid or fluid off-gas products while gases can be ventilated out.

Battery spaces shall be monitored by conventional smoke detection within the spaces. Smoke detection shall comply with the international code for Fire Safety Systems (FSS Code) and battery space fire alarm shall be given at the bridge

Emergency disconnection of the battery system shall be arranged at the following locations:

- adjacent to (outside of) the battery space
- navigation bridge

4.5 Battery management system, Controls and Alarms

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

More specifically,

The Battery Management System (BMS) shall:

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

The following parameters shall be measured:

- cell voltage
- cell temperature
- battery string current.

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

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

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

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

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

4.6 Connection System

In principal there are two possible interconnection systems

- AC interconnection system
- DC interconnection system

IEC 80005-1 covers AC high-voltage shore connection systems while IEC 80005-3 covers AC low voltage shore connection system.

Currently there is no standard or recommendation covering DC shore connection systems, therefore AC charging system is selected although the DC connection system may have some significant advantages.

4.6.1 Shore Side

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

The standard provides a simple connection configuration in order to eliminate the modifications on the ship side for different shore side systems. Although simple and straightforward, the standard makes it impossible for vessels that do not comply with it to connect to compliant shore supplies.

The standards cover:

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

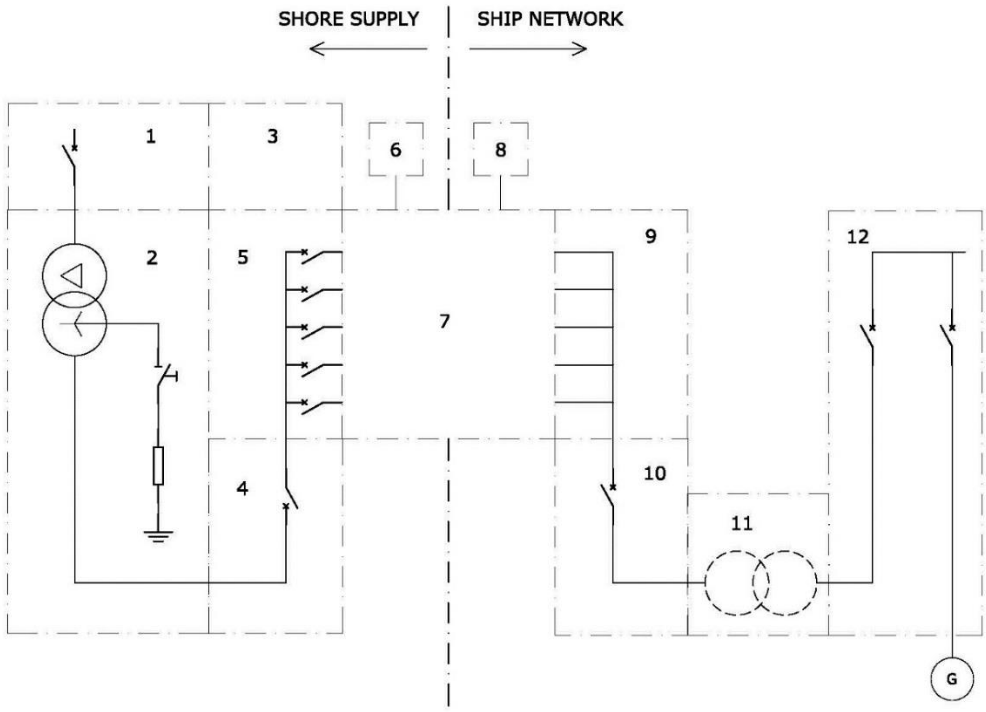


Figure 4.4: port side configuration for a LVSC system presented in IEC/ISO/IEEE 80005-3

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

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

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

A port includes many facilities that require power, thus many power system grounding problems and stray currents associated with these facilities can affect the ship power-supply ground fault protection, unless the shore power system has an integrated grounding zone provided by a dedicated transformer with a neutral grounding resistor. The isolation transformer should be of Dyn configuration, with the star winding connected to the ship-side due to the higher main bus bar voltage in comparison with the shore substation voltage.

The neutral point of the isolation transformer feeding the shore-to-ship power receptacles shall be earthed through a neutral earthing resistor. The neutral earthing resistor may be omitted when shore LVSC utilizes IT system. Of course a better solution would be a coil because the resistor due to ohms phenomenon consumes a small fraction of power.

When frequency conversion of the shore supply is required a secondary delta winding of the transformer, in combination with an earthing transformer with resistor on the primary side, suitable to compensate for possible circulating currents, are permitted provided that the other requirements of the standard are fulfilled.

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

Equipment earthing conductors terminated at the shore power outlet box receptacles shall be connected to the ship and continued to the ship to create an equipotential bond between the shore and ship. This may require bonding to the ship switchgear earthing bus and or bonding to ship hull.

Another important topic that the IEC/ISO/IEEE 80005-3 standard covers is the number of cables that should be incorporated in a LVSC system. Table 2 shows the number of feeding cables as a function of the maximum power demand and the voltage of the connection, while table 3 presents the maximum corresponding current per cable.

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

Table 4.1: Number of feeding cables as a function of the maximum power demand and the voltage of the connection.

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

Table 4.2: maximum corresponding current per cable

4.6.2 Ship Side

CHARGING SYSTEM

For an AC connection with shore side the vessel's system shall have its own battery charger(S) system which shall communicate with and operate within the limits given by the battery management system depended on the DOD that is decided by the class rules. The charger shall be designed with the needed capacity specified by the battery application. The charging system and shore connection shall include temperature sensors in order to detect high impedance and heating in an early stage.

The mating process of the shore connection should be preferably automatic, but in case of involved personnel a risk assessment analysis must be performed. The charger should be designed in such a way that too high charge currents and voltages are avoided (to prevent exceedance of the specified current level (C-rates) and voltage level).

Charging failure shall give alarm at a manned control station.

The charging system and other relevant systems shall detect the connection to shore power and activation of propulsion shall be inhibited in this case. Note that some applications will need propulsion power even when connected to shore power, in those cases safety measures must be taken to avoid unintended un-plugging of the charging interface. An example of that would be the time the vessel is prepared to leave the port when it starts the main engines, there should be very high caution not to clutch the propeller axis before the charger are unplugged from the shore side.

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

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

An onboard shore connection switchboard shall be provided at a suitable location, as close as possible to the receiving point and its distance from the supply point shall be as short as possible. The shore connection switchboard shall be in accordance with IEC 61439.

The switchboard shall include a circuit-breaker to protect the ship electrical equipment downstream. In no case shall the protection at the shore connection switchboard be omitted.

CIRCUIT-BREAKER

In order to have the installation isolated before it is connected, a circuit-breaker with built in disconnection function shall be provided and shall be in conformity with IEC 60947-2. The rated making capacity of the circuit-breaker shall not be less than the prospective peak value of the short-circuit current (*I*P) calculated in compliance with IEC 61363-1. Calculations must be employed as well for the rated short-circuit breaking capacity and of the circuit-breaker shall not be less than the maximum prospective symmetrical short-circuit current (*I*AC (0.5T)) as it is stated in IEC 61363-1.

A motor-operated circuit-breaker shall be provided.

The shore connection switchboard shall be equipped with:

a) Voltmeter: all three phases
b) Short-circuit devices: tripping and alarm
c) Overcurrent devices: tripping and alarm
d) earth-fault indicator: alarm; and
e) Unbalanced protection for systems with more than one cable.

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

Alarms and indications shall be provided at an appropriate location for safety and effective operation (i.e. engine room and control panel).

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

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

Galvanic separation between the shore and on-board systems shall be provided on shore in order to eliminate stray currents such as difference in ground potential or currents induced by AC power, which need to be blocked.

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

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

Additionally, there shall be no flammable materials close to shore power connector in order to prevent fire propagation from connector to environment and vessel **[10].**

Note: Galvanic isolation (separation) is a design technique that separates electrical circuits to eliminate stray currents. Signals can pass between **galvanically isolated** circuits, but stray currents, such as differences in ground potential or currents induced by AC power, are blocked.

Chapter 5: Thermal-electrochemical Behavior of the battery cell

The purpose of this chapter is to investigate the thermal and electrochemical behavior of a LiMn2O4 battery cell. The reason behind this is that LiMn2O4 have bigger specific energy than the LiFeMgPO4 battery cells, less cost and are lighter.

We are going to analyze why those three factors are worth looking into LiMn2O4 battery cells thermal and electrochemical behavior.

- Although the battery cells used in this case study have bigger power density, one of the most important parameter when we are dealing with batteries is the energy density. A really nice example to differentiate those two is described below.
  The energy density of a battery is comparable to how many people a room can hold (i.e. the size of the room), while the power density is comparable to how quickly the people in that room are able to escape/leave the room (i.e. the number/size of exit doors). A high energy-density battery with a low power-density would then be equivalent to a large room full of people, but with only a single small exit door. Typically, the electrical equivalent of the small door would be a high internal (current-limiting) resistance. So batteries with higher power density should be used for applications that we need energy in short amount of time (instead backup generators or during changes from mechanical to electrical propulsion). On the other hand batteries with higher energy density should be used for storing purposes. Example of that are big vessels with demanding hotel loads when at sea, or combination of many consumers during ''heavy'' operations, like maneuvering, and bow thrusters.

- The weight is a very important parameter when we are attempting a retrofit because the vessel is designed to fulfill certain criteria of stability, service speed etc. For example a large volume of batteries can induce trim on the vessel that is not desirable because they are installed in the engine room that is aft of amidships. Another result of increasing the displacement of the vessel is increased resistance therefore more power needed to create adequate thrust to propel the vessel. Especially in cases that the power margin is not enough and the resistance rises further more due to hull fouling/deterioration the problem is even bigger. Although the aforementioned examples might be exaggerated the designer has to consider them.

- Of course the cost is probably the most influential factor when we are designing or studying a project and the most important parameter for a ship owner.

The simulation we are about to discuss was achieved with the simulation environment of ANSYS.

The principle of the simulation we are attempting to achieve is described below:

5.1 Theoretical background

In a lithium-ion battery, the anode and cathode are made of active materials coated on the surface of metal foils. A polymer separator is placed between the foils of opposite polarity to prevent electrons from passing between them. To predict the chemical, thermal, and electrical behavior of a battery, ANSYS Fluent offers the following models:

- *Single-Potential Empirical Battery Model*
- *Dual-Potential MSMD Battery Model*

The Single-Potential Empirical Battery Model is useful if the geometries of the current collector, electrodes, and separator can be fully resolved and only one potential equation is solved in the computational domain.

The model, however, has a limited ability to study the full range of electrochemical phenomena in battery systems, especially systems having complex geometry. When constructing a battery cell, the anode-separator-cathode sandwich layer is usually wound or stacked up into a 'jelly roll' or a prismatic shape, hence it would be very expensive to resolve all the layers explicitly, even for a single battery cell. Furthermore, many industrial applications use a battery pack consisting of a large number of cells connected in series or in parallel.

The ANSYS Fluent Dual Potential Multi-Scale Multi-Dimensional (MSMD) Battery model overcomes these limitations by using a homogeneous model based on a multi-scale multi-dimensional approach. In this approach, the whole battery is treated as an orthotropic material.

The difficulty with modeling a lithium-ion (Li-ion) battery is due to its multi-domain, multi-physics nature. Vastly different length scales associated with different physics complicates the problem. When performing a thermal analysis, the goal is to determine the temperature distribution at the battery length scale.
The physics governing the Li-ion transport occurs in the anode-separator-cathode sandwich layers (the electrode pair length scale). Li-ion transport in an active material occurs at the atomic length scale. The Multi-Scale Multi-Domain (MSMD) approach deals with different physics in different solution domains **[14]**.

Battery thermal and electrical fields are solved in the CFD domain at the battery cell's scale using the following differential equations:

(3.1)
$$\frac{\partial \rho C_p T}{\partial t} - \nabla \cdot (k \nabla T) = \sigma_+ \left| \nabla \phi_+ \right|^2 + \sigma_- \left| \nabla \phi_- \right|^2 + \dot{q}_{ECh} + \dot{q}_{short}$$

(3.2-3.3)
$$\nabla \cdot \left(\sigma_+ \nabla \varphi_+ \right) = -\left(j_{ECh} - j_{short} \right)$$
$$\nabla \cdot \left(\sigma_- \nabla \varphi_- \right) = j_{ECh} - j_{short}$$

where σ_+ and σ_- are the effective electric conductivities for the positive and negative electrodes, φ_+ and φ_- are phase potentials for the positive and negative electrodes, j

and $\dot{q}_{ECh}$ are the volumetric current transfer rate and the electrochemical reaction heat due to electrochemical reactions, respectively. The source terms, j_{ECh} and $\dot{q}_{ECh}$ are computed using an electrochemical sub model.

If there is no internal short-circuit, j_{short} and $\dot{q}_{short}$ are equal to zero.

A Wide range of electrochemical models, from simple empirically-based to fundamental physics-based, is available in the open literature. In ANSYS Fluent, the following electrochemical sub models are implemented:

- Newman, Tiedemann, Gu and Kim (NTGK) model
- Equivalent Circuit Model (ECM) model
- Newman Pseudo-2D (P2D) model

The semi empirical model we are using to simulate the thermal and operational behavior of the battery cells under study is the Newman, Tiedemann, Gu, and Kim (NTGK) model.

NTGK Model

The Newman, Tiedemann, Gu, and Kim (NTGK) model is a simple semi-empirical electrochemical model. It was proposed by Kwon and has been used by others. In the model formulation, the volumetric current transfer rate in Equation 3.2 is related to the potential field by the following algebraic equation:

(3.3) $$j_{ECh} = aY\left[U - \left(\varphi_{+} - \varphi_{-}\right)\right]$$

Where a the specific area of the electrode sandwich is sheet in the battery, Y and U are the model parameters which are functions of the battery depth of discharge (DoD):

(3.4) $$DoD = \frac{Vol}{3600Q_{Ah}}\left(\int_0^t j\,dt\right)$$

Where Vol denotes the battery volume, and Q is the battery total electric capacity in Ampere hours.

The equation (3.3) was first proved by Gu who in order to define the current-voltage characteristics of a battery worked on an experiment discharging a cell periodically (current was ramped periodically to a specific value with steady intervals and when it reached that value the discharge started again from the base value) until the voltage reached the cutoff voltage that he defined, relied on the electrochemistry and the capacity of the cell.

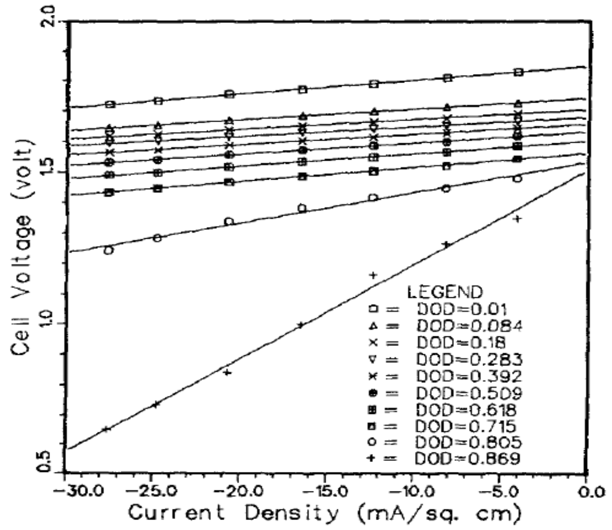


Figure 5.1 experimental process V=f (I/A) introduced by Gu

The Y and U coefficients proved to be functions of the DOD. The U is the curve created by the points of the intercept voltage in each periodical discharge and Y is the inverse slop of the current-voltage curves.

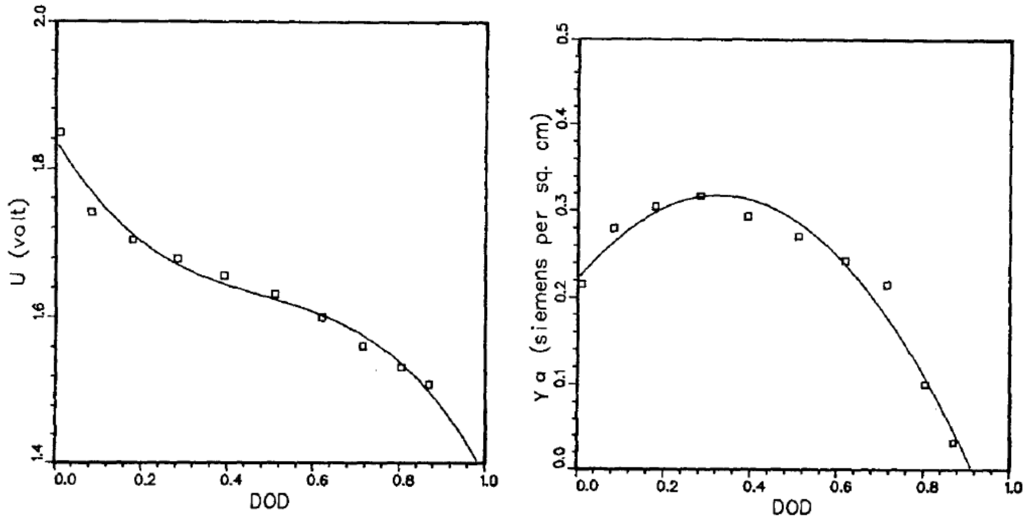


Figure 5.2 experimental U and Y factors in relation to the DOD derived from the experiment conducted by Gu

For a given battery, the voltage-current response curve can be obtained through experimentation. Y and U can then be determined by curve fitting the data **[16].**
Kim in his paper introduced a formula for calculating the Y and U coefficients experimenting on Li-Polymer cells. The formulas created are presented below:

(3.5) $$U = a_0 + a_1(DOD) + a_2(DOD)^2 + a_3(DOD)^3$$

(3.6) $$Y = a_4 + a_5(DOD) + a_6(DOD)^2 + a_7(DOD)^3 + a_8(DOD)^4 + a_9(DOD)^5$$

Where a_0 ~ a_9 are the constants to be determined by experiments.

Theses constants were taken from Kim's paper because there were not any available cells for experimentation.

For a given battery, the voltage-current response curve can be obtained through experimentation. Y and U can then be determined by curve fitting the data. In order to model the discharge behaviors at the different environmental temperatures other than 25_C, Y and U should be modified as follows

(3.7) $$Y = \left(\sum_{n=0}^{5} a_n (DoD)^n \right) \exp\left[-C_1 \left(\frac{1}{T} - \frac{1}{T_{ref}} \right) \right]$$

(3.8) $$U = \left(\sum_{n=0}^{3} b_n (DoD)^n \right) - C_2 (T - T_{ref})$$

Where Y0 and U0 are the values of Y and U at an environmental temperature of 25_C, T and Tref are the absolute temperatures (K) of the environment and 25_C, respectively, and C1 and C2 are constants to be determined to fit the temperature dependence of Y and U.

The electrochemical reaction heat $\dot{q}_{ECh}$ in Equation 3.1 is calculated as

(3.9) $$\dot{q}_{ECh} = j_{ECh}\left[U - (\varphi_+ - \varphi_-) - T\frac{dU}{dT}\right]$$

Where the first term is heat due to over potential and the second term is heat due to entropic heating **[15].**

5.2 Methodology breakdown

The methodology followed to perform the simulation was achieved by studying the ANSYS battery fluent manual and various scientific articles in order to understand the variables and equations that define our problem.

Simulation Process

1. First of all a three-dimensional model of a prismatic cell was created in Rhinoceros-3d for input in the simulation software ANSYS FLUENT.

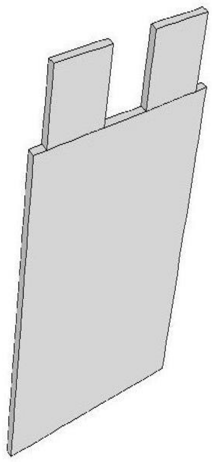


Figure 5.2 14.6 Ah Battery cell model as created in Rhino 3d

The battery geometry is considered as 3 zones, 1 active and 2 passive

- Cell (active)
- Negative tab (passive)
- Positive tab (passive)

2. The geometry mesh was created in order to specify the vital zones for the simulation :

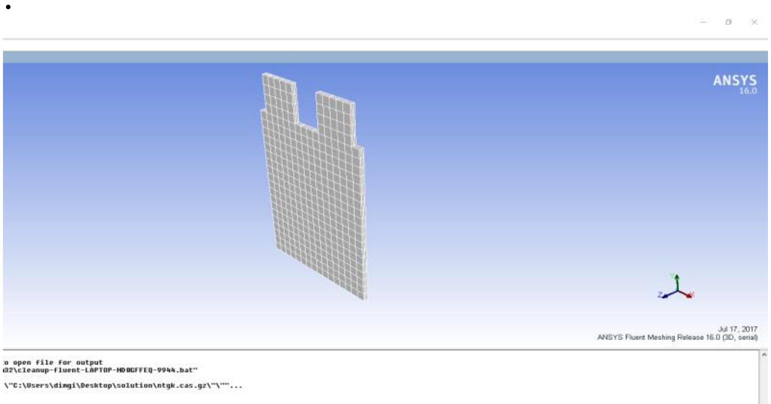


Figure 5.3 Mesh creation of the battery cell for implementation in ANSYS fluent

3. Electro-chemical reactions occur only in the active zone (cell). Battery tabs are modeled as passive zones, in which the potential field is also solved.

   The battery cell cross-section is shown in the figure below.

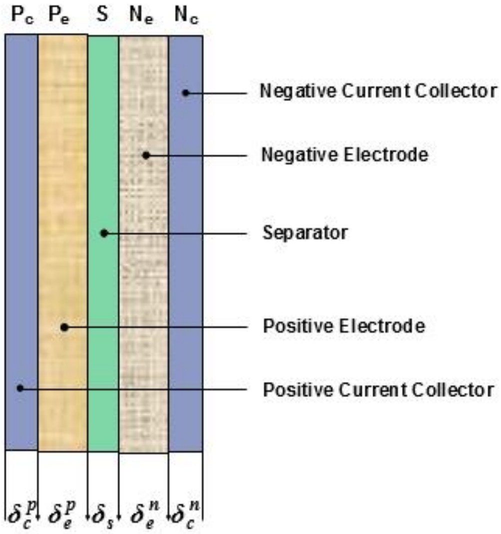


Figure 5.4 Breakdown of the cell geometry in zones for calculating the properties of the equivalent material

The next step was to import the cell geometry in the program and run the simulation using the NTGK semi-empirical model. The battery we are simulating is a 14.6 Ah LiMn2O4 cathode/graphite anode battery and its dimensions are 5.4x145x192 (lxwxh) mm. The experimental data were taken from Kim's paper.

The estimation of the material properties for the battery cell is accomplished using the following correlations:

- For density ρ, heat capacity C_p, and thermal conductivity K:

(3.8) $$x_{eff}=\frac{0.5x_c^p\delta_c^p+x_e^p\delta_e^p+x_s\delta_s+x_e^n\delta_e^n+0.5x_c^n\delta_c^n}{\delta_{total}}$$

(3.9) $$\delta_{total}=0.5\delta_c^p+\delta_e^p+\delta_s+\delta_e^n+0.5\delta_c^n$$

Where $x\ ff$ is the effective property value of a material property (such as density, heat capacity, or thermal conductivity), is the thickness. The subscripts c, e, and s

refer to current collector, electrode, and separator, respectively. The superscripts p and n refer to positive and negative, respectively.

- For electric conductivity σ:

(3.10) $$\sigma_p = \frac{0.5\sigma_c^p\delta_c^p + \sigma_e^p\delta_e^p}{\delta_{total}}, \quad \sigma_n = \frac{0.5\sigma_c^n\delta_c^n + \sigma_e^n\delta_e^n}{\delta_{total}}$$

The results are shown in the table below:

Zone	P_c	P_e	S	N_e	N_c	**TOTAL**
δ [um]	20	150	12	145	10	322
ρ [kg/m]^3	2700	1500	1200	2500	8960	2092
C_p [J/kg-K]	900	700	700	700	385	678
K [W/m-K]	238	5	1	5	398	18.2
σ [s/m]	3.83e7	13.9		100	6.33e7	σ_p = 1.19e6 σ_n = 9.83e5

Table 5.1 Calculation of properties for the equivalent material

The material of the tab zones is a modification of copper.

Our solution convergence is approached using residuals. The definition is presented below.

The residual is one of the most fundamental measures of an iterative solution's convergence, as it directly quantifies the error in the solution of the system of equations. In a CFD analysis, the residual measures the local imbalance of a conserved variable in each control volume. Therefore, every cell in our model will have its own residual value for each of the equations being solved.
In an iterative numerical solution, the residual will never be exactly zero. However, the lower the residual value is, the more numerically accurate the solution. Basically it is the difference between two consecutive solutions of the equations that define you problem. The most accurate solution is when the residual value becomes minimum.

5.3 Simulation Data analysis

Data from the last step are presented below:

Flow time = 1620s, time step = 54

1 more time step

Updating solution at time level N... done.

iter	energy	uds-0	uds-1	time/iter	
1080	7.0270e-17	1.8150e-14	2.2875e-11	0:00:00	20
1081	5.6242e-07	2.0634e-08	2.3590e-05	0:00:00	19
1082	2.4128e-09	2.9113e-08	4.2894e-05	0:00:00	18
1083	7.8418e-11	4.2053e-09	4.5382e-06	0:00:00	17
1084	4.2307e-12	5.2784e-09	5.5056e-06	0:00:00	16
1085	2.3283e-13	3.2798e-09	3.6707e-06	0:00:00	15
1086	1.2826e-14	9.1968e-10	1.0843e-06	0:00:00	14
1087	7.3882e-16	1.7096e-10	1.9725e-07	0:00:00	13
1088	2.0643e-16	2.4469e-10	2.8186e-07	0:00:00	12
1089	1.0087e-16	1.2515e-10	1.4648e-07	0:00:00	11
1090	7.8270e-17	2.6606e-11	3.1871e-08	0:00:00	10

iter	energy	uds-0	uds-1	time/iter	
1091	8.3341e-17	9.5094e-12	1.0592e-08	0:00:00	9
1092	8.2053e-17	1.0693e-11	1.2326e-08	0:00:00	8
1093	8.1915e-17	4.5947e-12	5.3647e-09	0:00:00	7
1094	8.0381e-17	8.1196e-13	9.5921e-10	0:00:00	6
1095	8.6472e-17	5.5028e-13	6.2344e-10	0:00:01	5
1096	7.4967e-17	4.4522e-13	5.1586e-10	0:00:01	4
1097	7.9097e-17	1.5937e-13	1.8712e-10	0:00:00	3
1098	8.2191e-17	2.4149e-14	2.8712e-11	0:00:00	2
1099	7.5627e-17	2.7640e-14	3.1633e-11	0:00:00	1
1100	7.4139e-17	1.7308e-14	2.0681e-11	0:00:00	0

step	flow-time	voltage_vp	max_temp
55	1.6500e+03	3.2904e+00	3.0757e+02

Flow time = 1650s, time step = 55

As we can clearly see the simulation runs for 55 time steps, each time step is calculated every 30 seconds and the maximum number of iterations/step is 20.

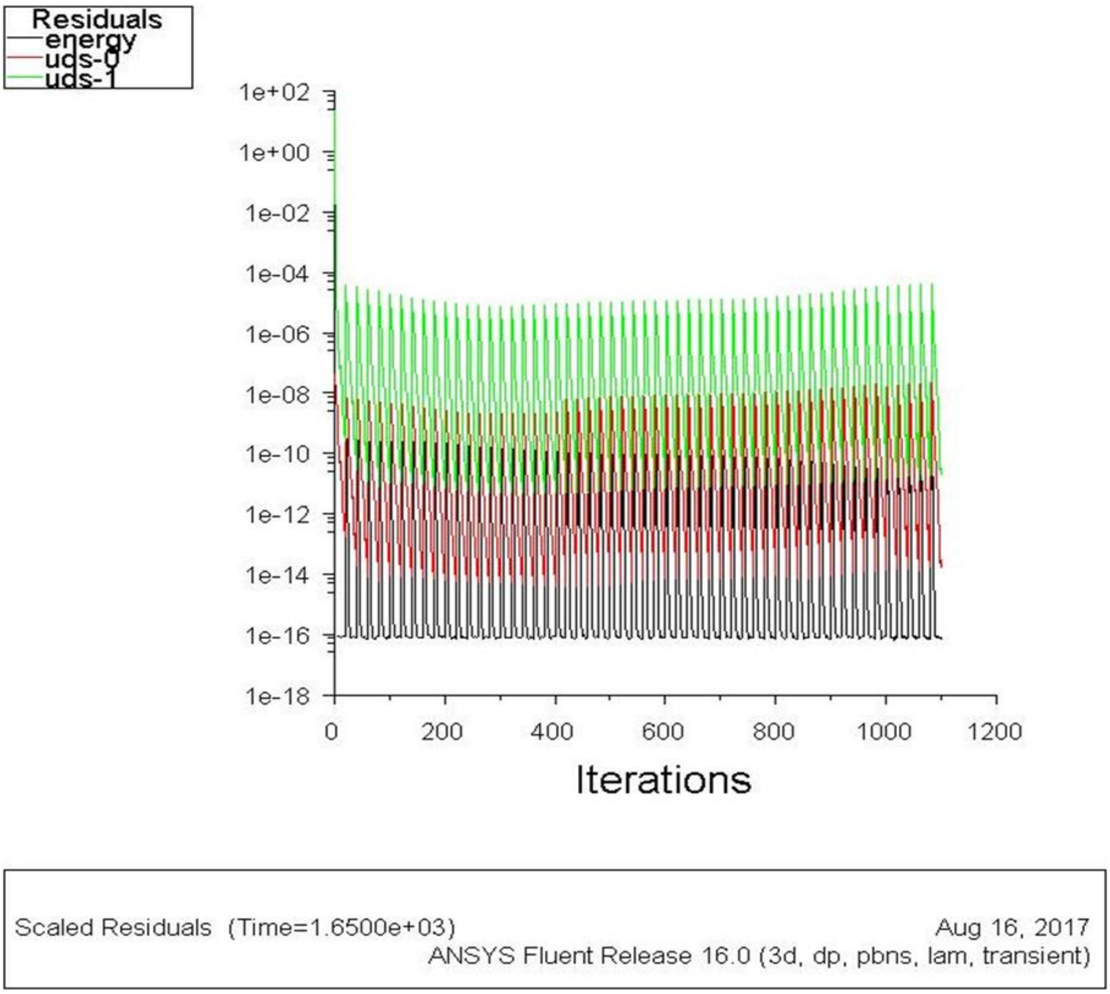


Figure 5.5 Residual History of the Simulation

This graph shows the difference between two consecutive solutions for the voltage values and the thermal energy inside the battery cell. The solution converges adequately in every iteration as we can clearly see for each and every one of the three equations that define our problem. For every periodic discharge there is a time step in which the equations defining our problem are solved.

Note:

The solutions of the equations (3.1)-(3.3) are the thermal energy and the User defined Scalars that ANSYS uses for the simulation. So UDS0 and UDS1 represent the voltage values for the positive and negative electrodes of the battery cell.

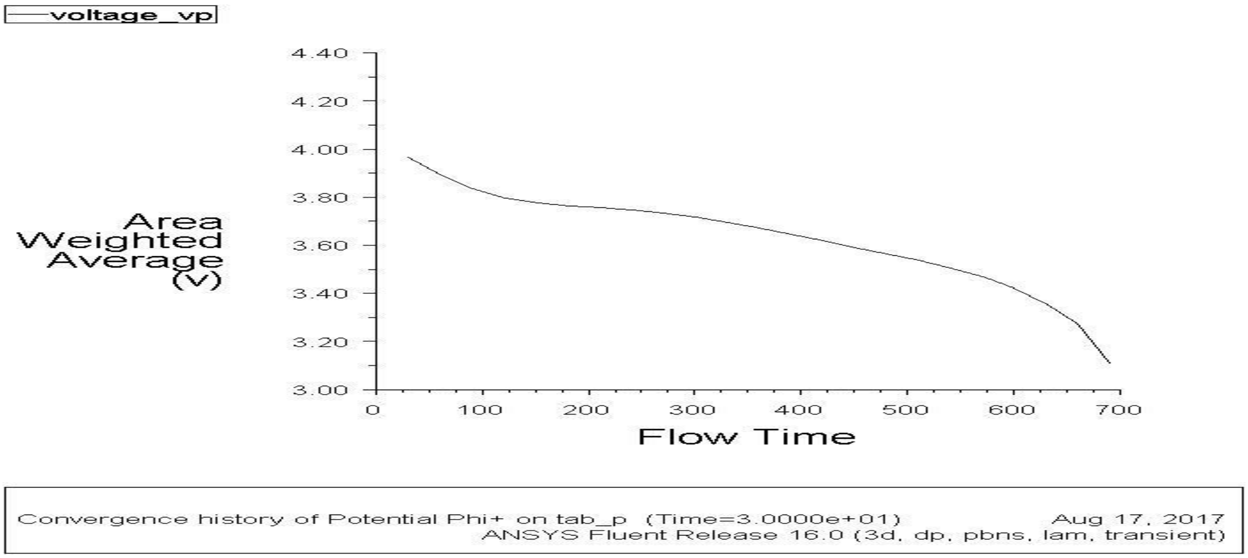


Figure 5.6: Surface Monitor Plot of Discharge Curve at 2 C

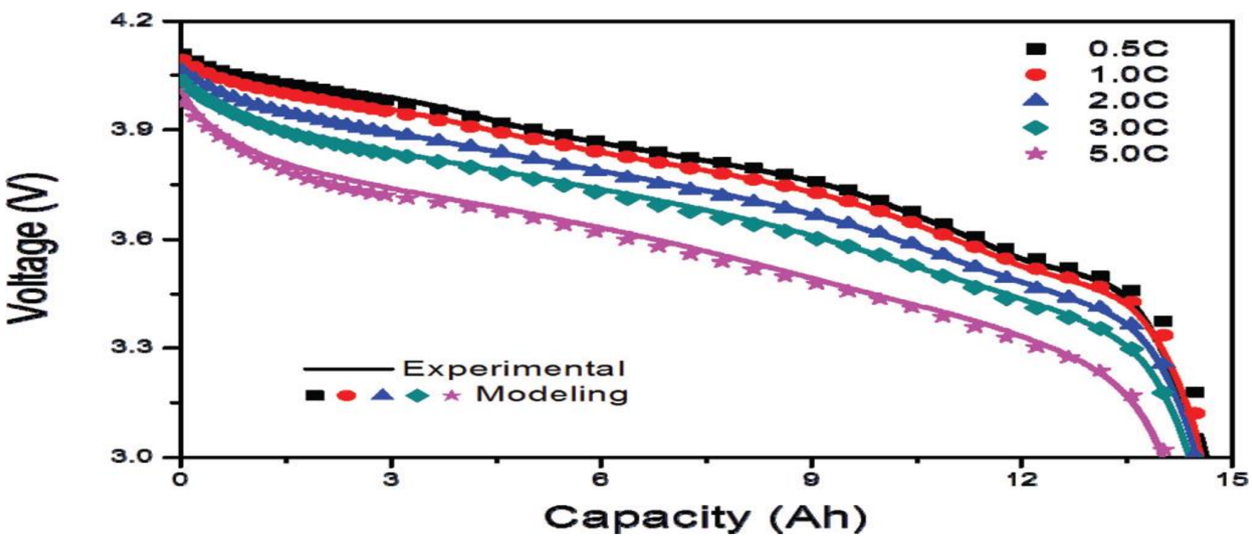


Figure 5.7: Surface Monitor Plot of Discharge Curve for various discharge currents derived from Kim's paper

The voltage plot of the positive tab against the time shows the discharge of the battery at 2C current that follows a decreasing path from the nominal voltage of the cell until the voltage value becomes the cut-off. As we are going to notice in further diagrams with different discharge currents the time the battery cell needs to degrade its voltage to the cut-off value is shorter as the discharge current rises. We have to highlight that the experimental data from Kim's paper are in harmony with the formula that Gu predicted in his paper. This shows the dependence of this semi-empirical method with the DOD. The second picture shows the results from Kim's paper and the 2C curve that is almost the same with the one derived from the simulation we performed. We can understand that the implementation of the equations that define our problem, in the simulation software is correct.

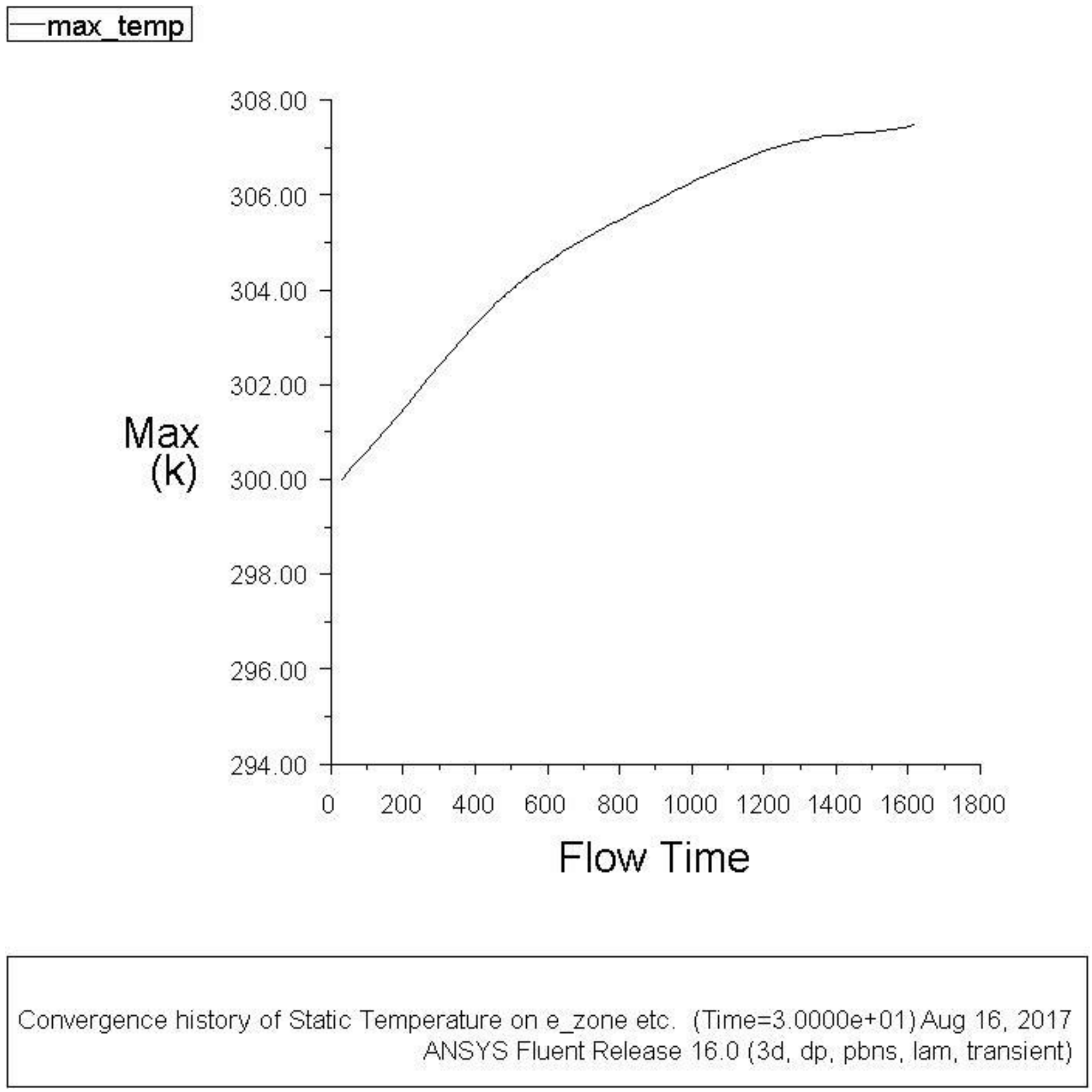


Figure 5.8: Volume Monitor Plot of Maximum Temperature in the Domain

The static temperature of the cell zone in which the electrochemical reactions of the battery take place rises for about 7 K throughout the simulation for 2 C discharge current. Of course this plot is depended on the discharge current of the battery cell and in every case it is different as we are going to see later.

The contours presented in the next pages depict the battery cell's condition in the end of the simulation

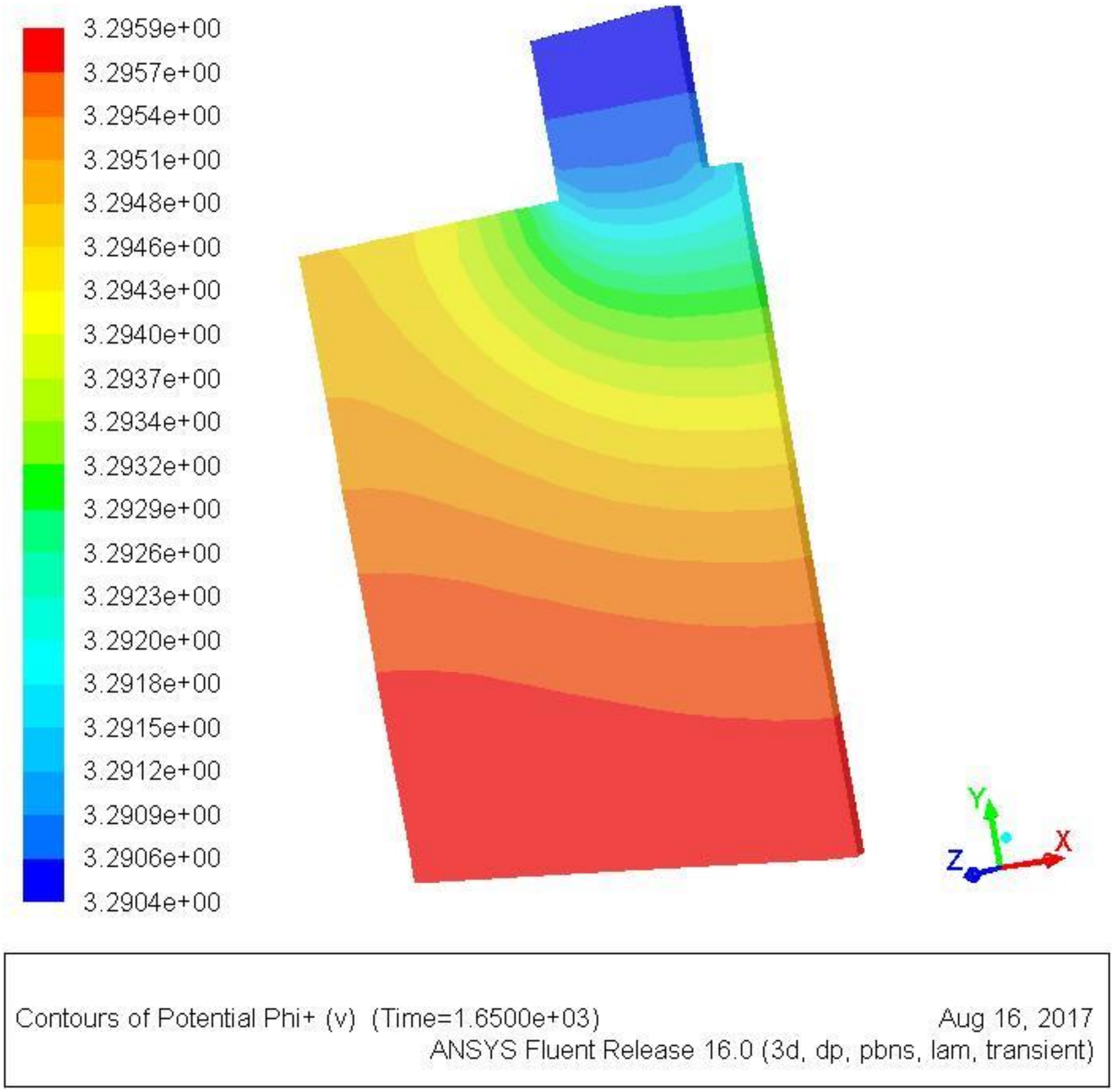


Figure 5.9: Contour Plot of Phase Potential for the Positive Electrode

The contour of the phase potential $\varphi+$ for the positive electrode depicts the behavior of the positive electrode regarding the voltage inside the cell and tab zone in the end of the simulation. It is clear that the voltage in the battery cell domain is almost constant in any numerical node.

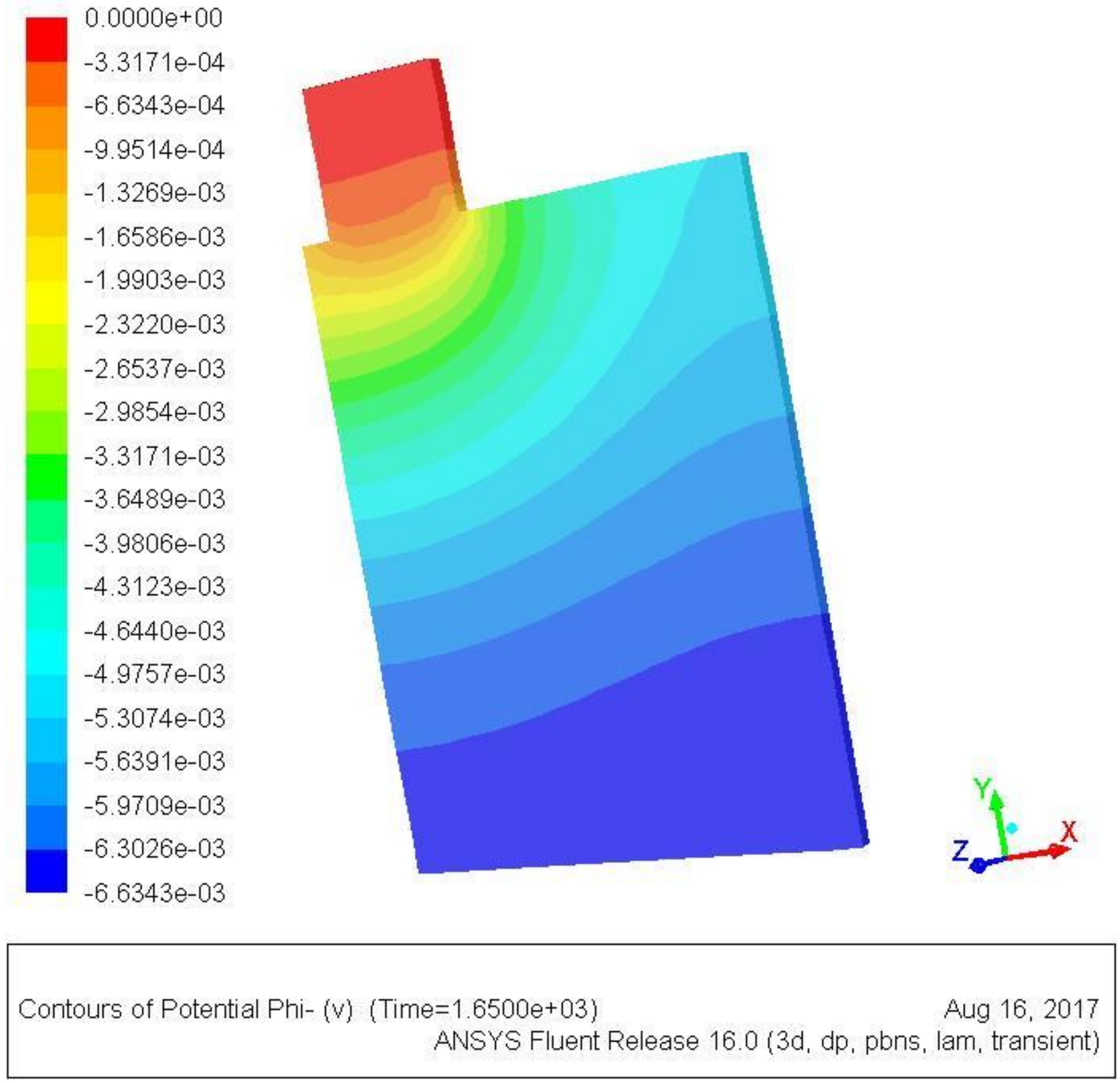


Figure 5.10: Contour Plot of Phase Potential for the Negative Electrode

The contour of the phase potential φ- for the negative electrode depicts the behavior of the negative electrode regarding the voltage inside the cell and tab zone in the end of the simulation. As stated before the voltage in the battery cell domain is almost constant in any numerical node.

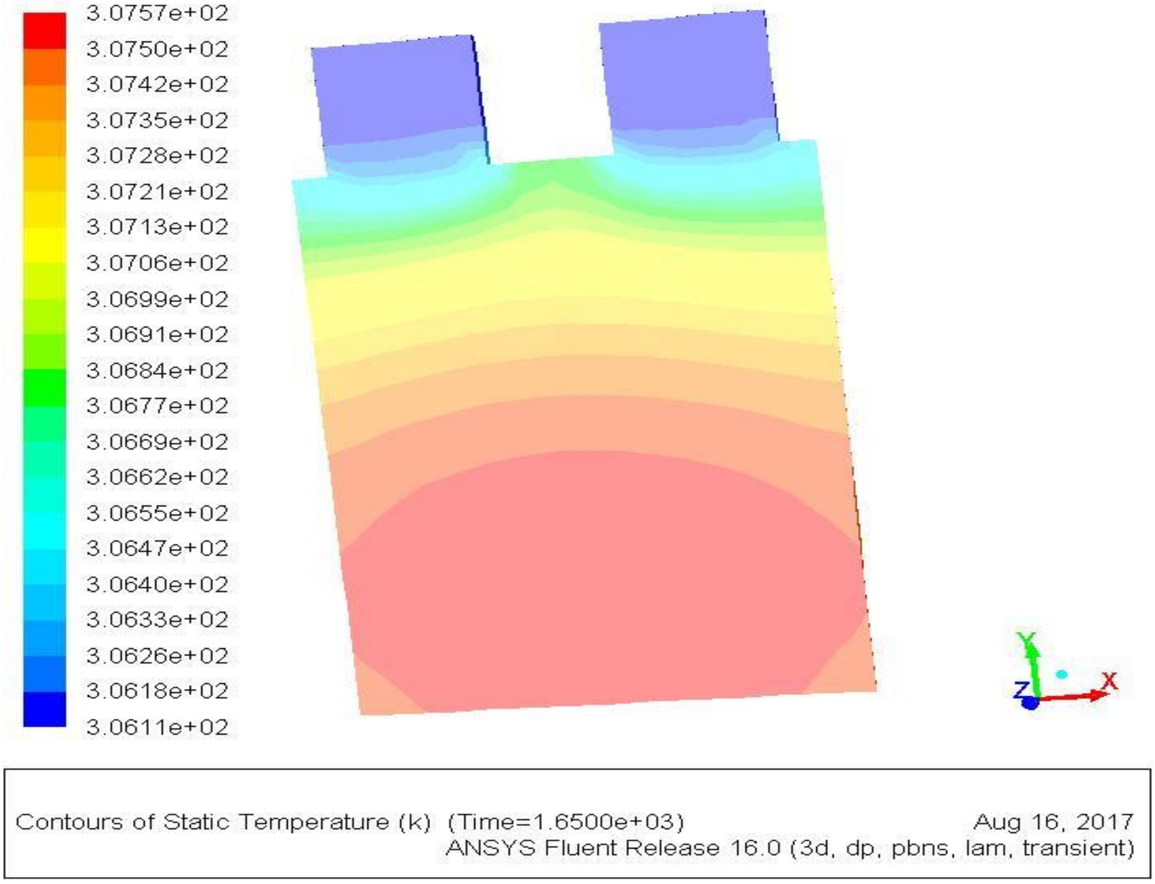


Figure 5.10: Contour Plot of Temperature

The contour of the static temperature of the battery cell in the end of the simulation shows us the temperature difference between the active and passive zones. The contour shows that the thermal activity is bigger in the active cell zone between the separator and the positive and negative electrodes than that in the tab zones. An explanation, someone would give, is due to the internal resistance of the battery and the electrochemical reaction that take place inside the cell. Contacting the same simulation for 5C discharge current the contour depicts the same thermal pattern, with different minimum and maximum temperatures. Although the internal resistance would be a viable explanation, experimental results derived from Kim's paper indicate that the areas with maximum temperature are higher and close to the current collecting tabs (Figure 5.20). This can be explained by the fact that the current density is bigger near those regions as we will show in the pages below (Figure 5.11) and considering, that the simulation time is not more than 30 minutes the heat due to the internal resistance might not have taken full effect yet, compared to the heat due to electrochemical reaction near the tabs. It has to be mentioned that the high temperature zone moves downwards as the operational time passes (Figure 5.20). The different high temperature zones between simulation and experimental data can be explained by the fact that the active zone of the battery cell is constructed from a material that correlates the positive/negative electrode, the separator and the current collectors. So, the contour plots of temperature showcase deviations, due to the methodology suggested by ANSYS fluent software manual.

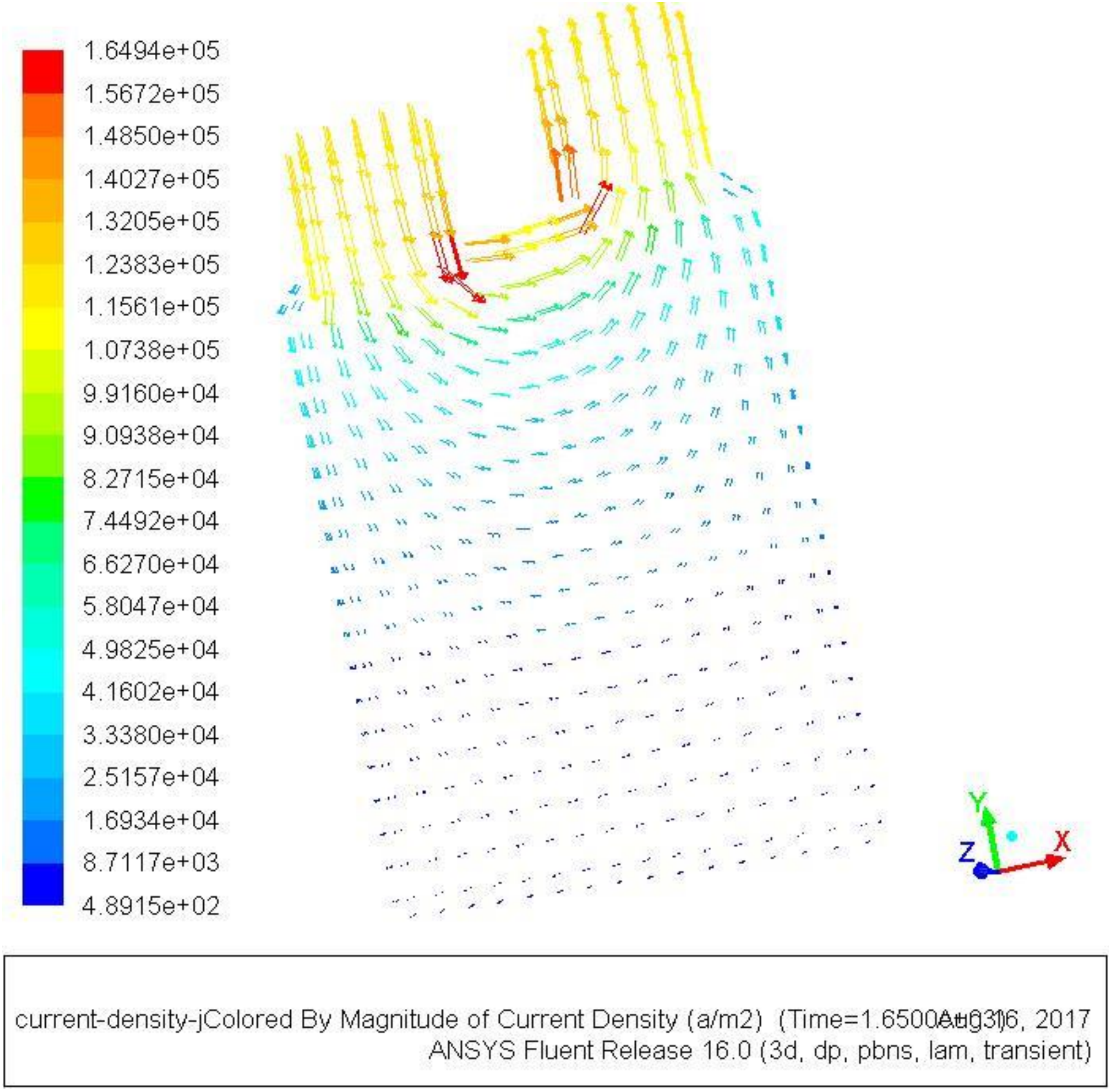


Figure 5.11: Vector Plot of Current

The current density is bigger near the positive and negative tabs and the flow, is as expected coming from the negative tab to the negative electrode inside the cell through the separator and following the same path for the positive electrode and tab. The reason behind the different magnitude inside the cell and near the tab zones of the current density can be explained with two facts. The electrical conductivity of the active material is 1.19e6 and 9.83 e5 for the positive and negative electrode respectively meanwhile the one of the tabs (modified copper) is 10^7. So the current is bigger near the tabs. But it is obvious as well that because the contour shows current density the values are bigger in the upper part of the battery domain because the area the current passes through is less.

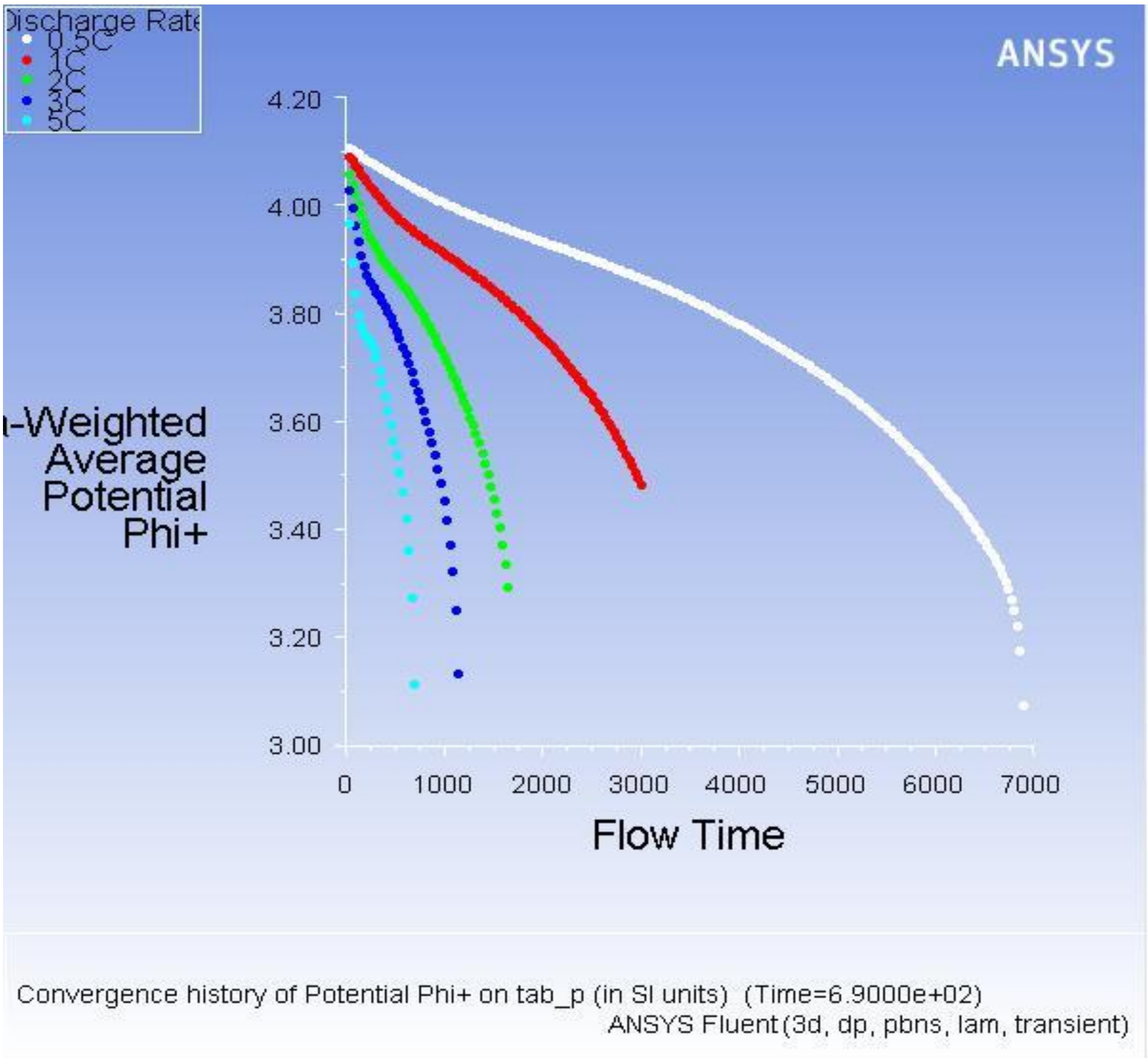


Figure 5.12: NTGK Model: Discharge Curves

As expected the voltage cut-off value will reach its value sooner when the discharge current rises. In other words the battery will discharge in a shorter amount of time. The curves agree with the results predicted in Gu's paper.

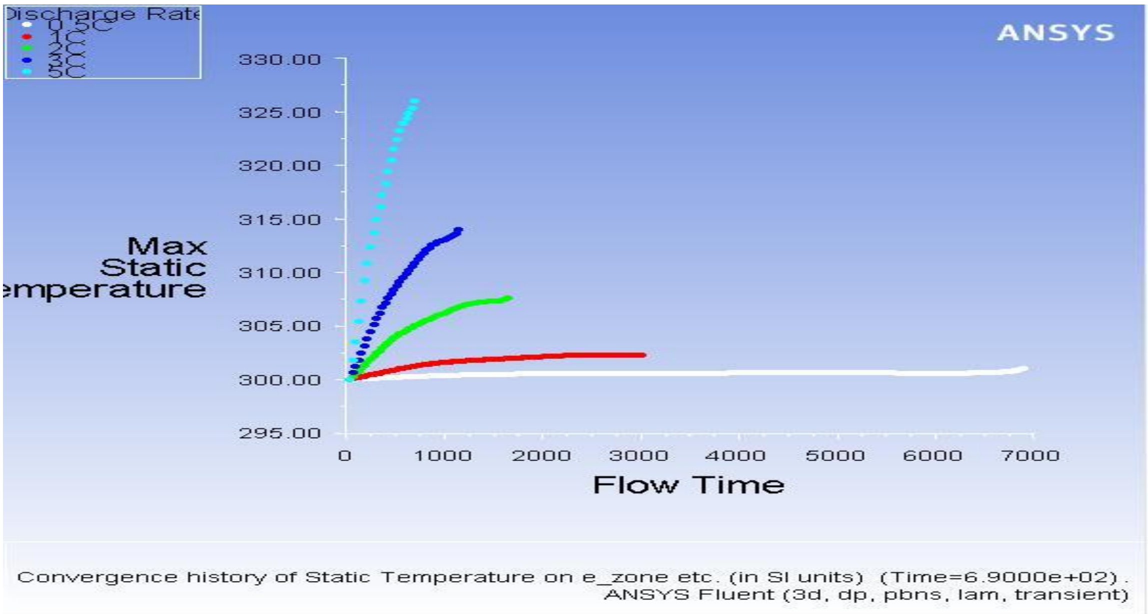


Figure 5.13: NTGK Model: Maximum Temperature in the Domain

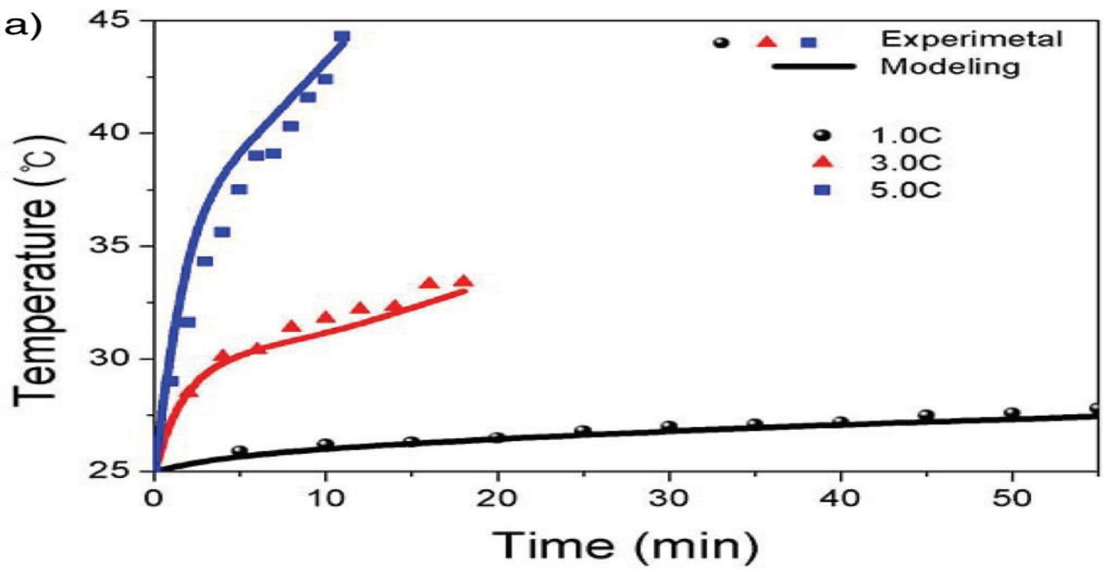


Figure 5.14 NTGK Model: Maximum Temperature in the Domain for different discharge currents derived from Kim's paper

As expected the plot of the static temperature throughout the simulation is dependent on the discharge current. The bigger the current the hotter the battery cell gets in less time due to its electrochemical reactions and internal resistivity. The simulation for the additional discharge currents was conducted for shorter periods in order to be comparable with each other. The second image is taken from Kim's paper to check the validity of our simulation. It is clear that the results are very close in small discharge currents but up to 5 Celsius in larger than 3C. We believe that this can be attributed to the fact that this methodology creates a material that correlates all the different parts inside the battery cell. Of course every part has different properties because it is consisted of a material with different properties, thus a deviation is expected.

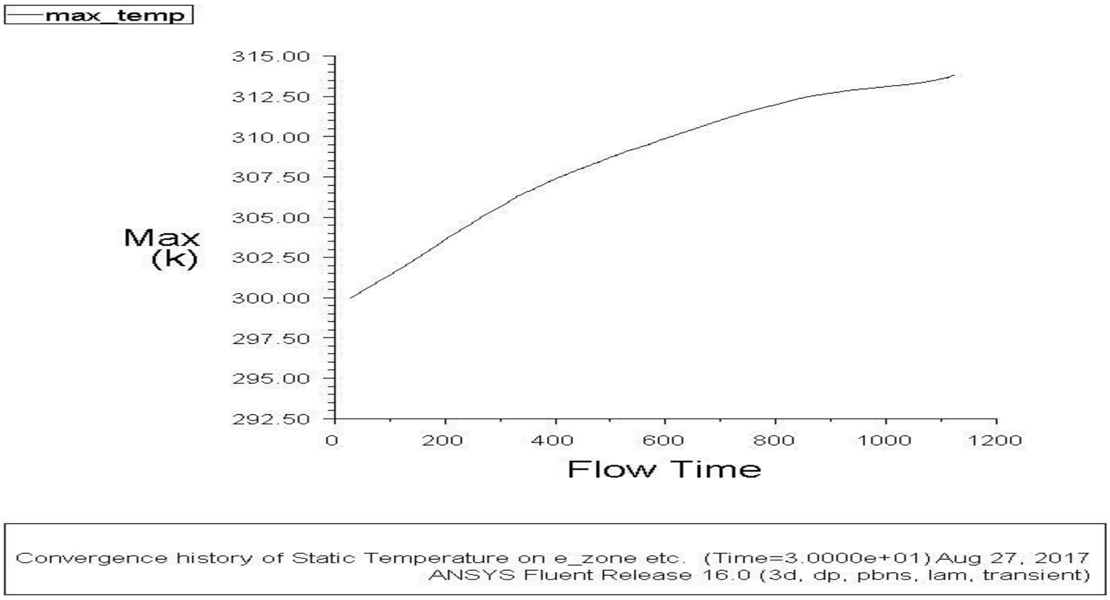


Figure 5.15 Temperature diagram for 3C discharge current with 300 K (25 C) ambient temperature

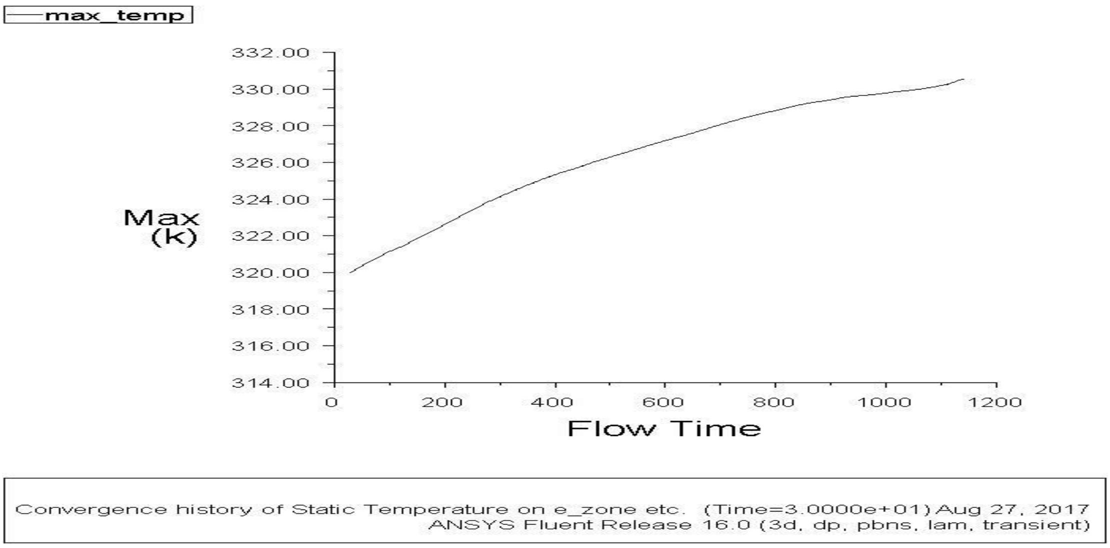


Figure 5.16 Temperature diagram for 3C discharge current with 320 K (45 C) ambient temperature

Another concern that we have to investigate is the rise in temperature with different ambient temperatures. This is important when we are implementing battery modules in an engine room that experiences temperatures up to 45 Celcius.

The two figures above depict the temperature behavior of the battery cell for 3C discharge current and the same simulation time as in Kim's paper. Generally Li-ion batteries behave well when charged from 0-45 Celsius and discharge from -20-60 Celsius. Exceeding these values can lead to capacity fade after several cycles. Engine room temperature lies within the aforementioned limits so battery cells can easily be implemented in it. It is clear that when the ambient temperature rises, the augmentation of the internal temperature in the cell is **less, even though the regions of high temperature are bigger. This fact can be verified by Kim's paper as well and this is the reason we present figures for 3C discharge current as well as 5C in the following**

pages. We believe that this can be attributed to the fact that when the ambient temperature is high there is not much heat transfer (convection) between the surface of the battery and the internal region of it due to the low temperature difference. The reverse situation is observed when the temperature is lower and the heat transfer due to convection is larger.

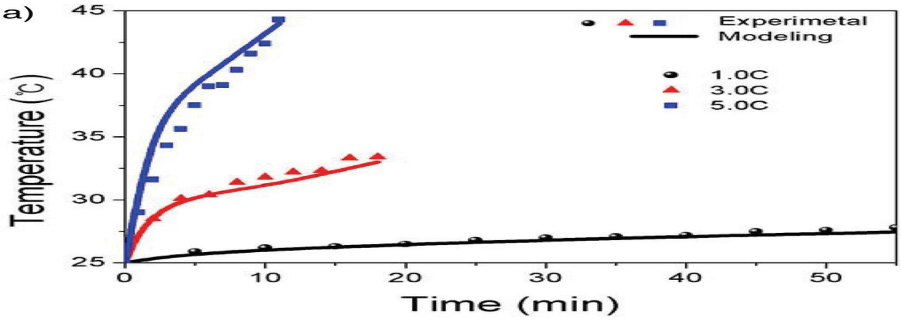


Figure 5.17 Temperature diagram for 3C discharge current with 300 K (25 Celcius) ambient temperature by Kim

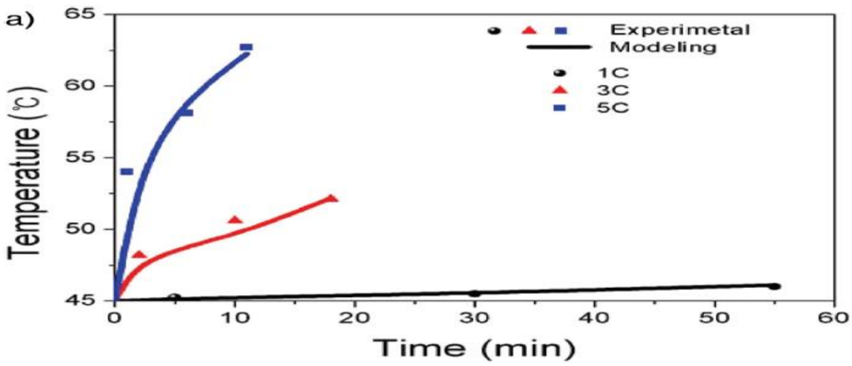


Figure 5.18 Temperature diagram for 3C discharge current with 320 K (45 Celsius) ambient temperature by Kim

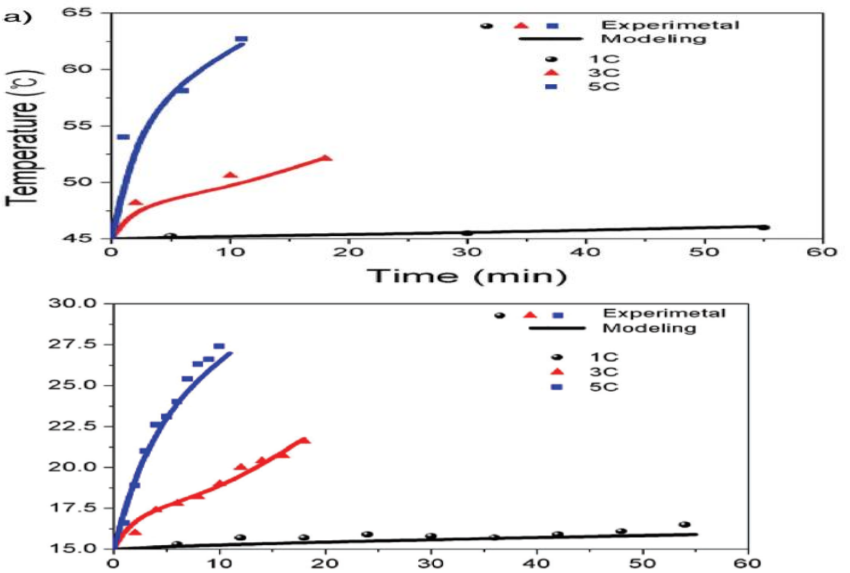


Figure 5.19 Comparison between rise in temperature for discharge current of 5C for 45 and 15 Celsius ambient temperature respectively

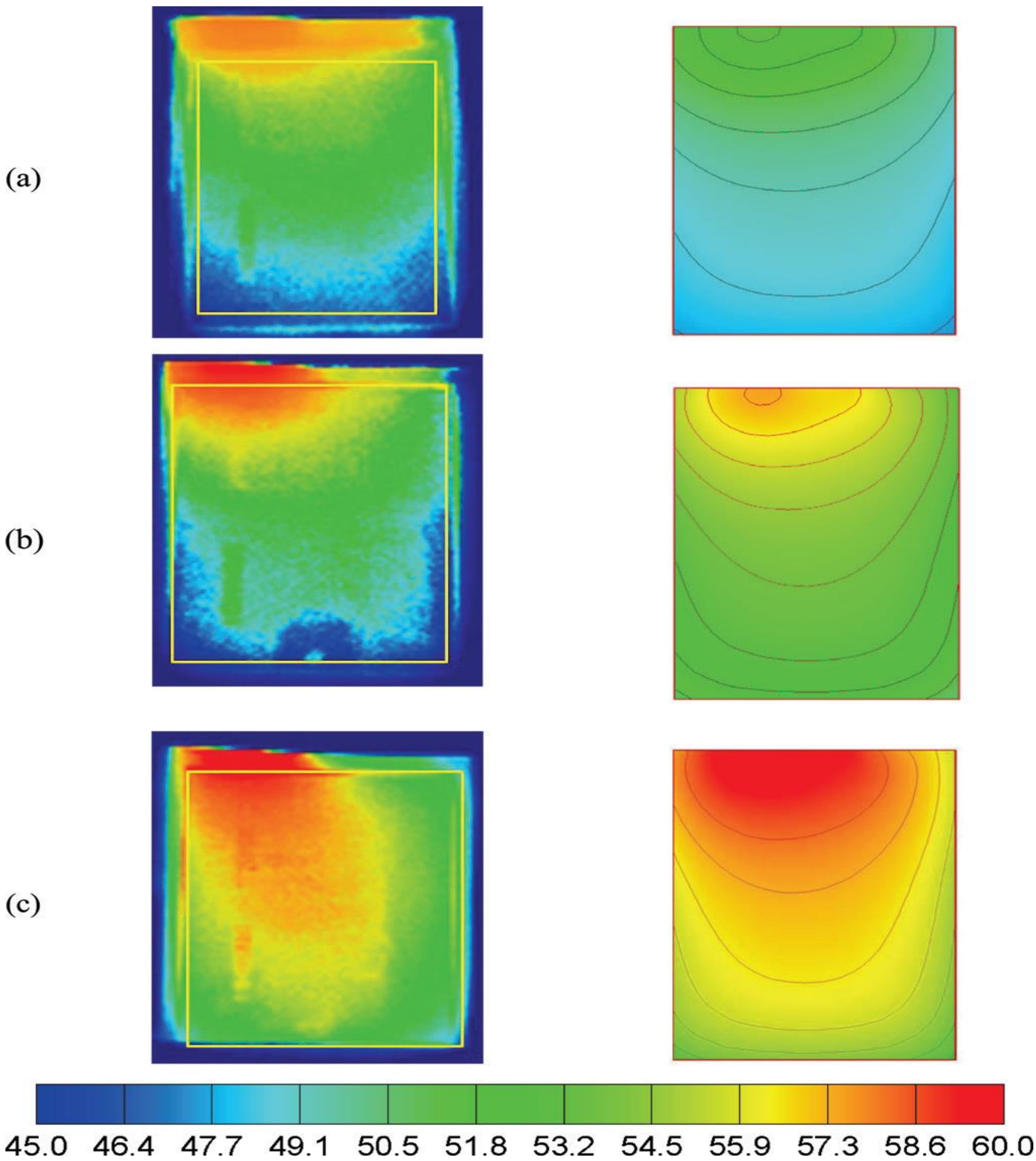


Figure 5.20 Temperature distributions based on the experimental IR image and the modeling for the LIB at discharge times of (a) 1, (b) 6, and (c) 11 min

The figure above depicts the high temperature zone movement during the simulation for different discarge times and constant discharge current.

It has to be noted as well that the bigger the current, the bigger the high temperature zones get.

Chapter 6: Design methodology

This chapter presents our retrofit design philosophy and the methodology developed for the estimation of the required battery capacity and PTO output power installed on board. Its inputs and equations are described in detail and the most important guidelines generated from the methodology are outlined.

6.1 Retrofit philosophy

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

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

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

The number of battery modules needed and their arrangement in the vessel depends, as well, from market available battery solutions. When battery system is installed, it will power directly all hoteling loads in conjecture with the shaft generator, while at berth, it will be recharged. There is also the possibility of charging the modules through the alternator.

The replacement or uninstallation of emergency generator will not be considered because it may be possible from a technical point of view but lack of advanced legislation concerning modern system emergency topologies, its position above the weather deck held us off.

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

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

Another approach to determine required power output would be to calculate ship's main machineries' consumptions and translate these measurements into required installed energy (kWh). Imprecise and sloppy data of fuel consumptions kept us away from this path, in fear of over/under estimating ship's power demands.
As explained above, it was preferred for our calculation methodology to build an energy balance sheet based on ship's operational profile in accordance with the existing diesel engines' nominal output and electrical load balance.

Vessel's main dimensions are variables that will not affect final outcome. As explained above, vessel's resistance won't be possible to be calculated. Current machinery has been designed to be adequate for ship's operational profile and V_{DESIGN}.

So, considering the above mentioned, we are going to explain the philosophy behind this project.
The main philosophy of this work was to create an algorithm that will be capable to determine the number of batteries in conjunction with shaft generators that need to be installed on a vessel. Our goal was safe operation and implementation of criteria that maximize the efficiency and the operational duration of the system. Finally the reason we created an algorithm in Matlab is that any excel worksheet has its limitation when there are many variables and criteria that use matrices in order to store values.

6.2 Model inputs and equations

In order to assess the energy requirements the batteries we have to take under consideration various parameters such as:

- DOD of the batteries
- Distance covered by the vessel (time at sea)
- Power of the charging substation (shore side)

In order to solve and modify a multivariable problem such as the battery sizing of a marine vessel, for different case studies, a MATLAB code was created to ensure reliability of the calculations.

The ship side calculations methodology is described below:

So for a trip from one port to another the required energy for batteries considering that we charge the batteries at every port is

Eq. (6.1) $E_{trip}=(t_{port} \times P_{port} + t_{man} \times P_{man})/60.$

tman=the time for the maneuvering of the vessel at port (min)

tport=the time the vessel stays at port (min)*

Pport=the power needed for the vessels operation at port (kW)

Pman= the power needed for the vessels operation during maneuvering (kW)

**The energy for the hotel loads during the vessel's stay at port must be provided exclusively from the batteries because the shaft generators can only be operated when the main engine is running.*

As we mentioned before two shaft generators are going to be implemented and replace the preinstalled generators.

So the energy the alternators are going to provide to the batteries and the hotel loads of the vessel during its time at sea are respectively:

Eq. (6.2) $E_{sg}=load_{gen}*(P_{sg}-P_{sea})*t_{sea}/60$ *(The energy the alternator provides for the charging of the batteries)*

Eq. (6.3) $E_{sghl}=P_{sea}*t_{sea}/60$ *(The energy the alternator provides for the hotel loads)**
**value taken from the electrical load balance*

Where

Psg =Power output of the shaft generator (kW)

Psea=Power required for the vessel's operation at sea (kW)

loadgen =the percentage of the maximum power of the alternator that is used

tsea= the time the vessel is travelling from one port to another (min)

A really important parameter that has to be taken into consideration is that the main engine is bound to deliver more power each time the vessel is at sea, in order to operate the shaft generator. The additional power the main engines have to deliver is:

Eq. (6.4) $AddP=P+P_{sg}$

P=the power of the main engine when at sea

Considering the above mentioned, the energy that has to be provided by the batteries is deducted by the energy provided by the alternator to the batteries.

Eq. (6.5) *Ereq=Etrip-Esg*

But we have to consider ***a)** that the manufacturer proposes a certain D.O.D in order to have a longer life cycle* and ***b)** that in case of battery failure or failing to charge properly at port the number of batteries installed must be multiplied by a redundancy factor*. So the minimum energy installed on board should be:

Eq. (6.6) *Emin= (Ereq/D.O.D)*redundancy*

The batteries are arranged in series and parallel in order to fulfill two criteria:

The voltage of the main bus that indicates the number of modules in series as described below:

Eq. (6.7) $N_{series} = {}^{V_{SYST}}/_{V_{Bt}}$

Where, V_{SYST} = System's main bus bar's voltage (V) (440 V AC)
V_{Bt} = Battery module's nominal voltage (V)

The energy that is required in order to satisfy the vessel's safe operation indicating the number of parallel battery strings as described below:

Eq. (6.8) $\mathrm{N_{paral}} = {}^{\mathrm{E_{min}}}/_{(\mathrm{N_{Bt.SERIES}} \times \mathrm{Emodule})}$

Where, Emodule is the nominal energy of the module.

The installed energy on board will be:

Eq. (6.9) *Einst=Nbatt*BattE*

Nbatt=the total number of batteries installed on board

BattE=the energy of the installed battery modules (kWh)

Of course during maneuvering the ideal situation will be to disengage the main engine from the propeller axis and the small amount of power will be provided by the alternator. This time the alternator is going to work a synchronous motor and the energy the batteries have to give is:

Eq. (6.10) *Emotor=load-man*MCR*(tman/60)* *load-man=the percentage of the load of the main engine's MCR the synchronous motor has to provide during maneuvering*

The number of trips that the vessel is going to be performing each working day is calculated as shown below:

Eq. (6.11) $Ntrip=roundown((tday*60)/(tport+tsea+tman))$

tday=the total time in hours the vessels is operating per day (min)

The battery system life will be approached considering the basic principle of how many times during the day the battery modules are charged and discharged.

Eq. (6.12) $Ndisch= (Ereq*Ntrip-Eport+(Ntrip*Emotor))/Einst$

Eq. (6.13) $Nchrg= (Echrg*(Ntrip-1)+Ntrip*Esg)/Einst$

Eq. (6.14) $Ncycl=Nchrg+|Ndisch-Nchrg|/2$

Ndisch= the number of times the modules are discharged until 0% SOC
Nchrg= the number of times the modules are charged until 100% SOC
Ncycl= the number of times the modules are charged/discharged during the day

The estimation of the battery system life can be achieved by the formula below:

Eq. (6.15) $Syslife=(Ncyclman/Ncycl)/365$

Ncyclman=the life cycle performance for the decided DOD of the battery modules

<u>The shore side calculations methodology is described below:</u>

The shore substations have to provide certain kW of power each. The transformer that has to be implemented is going to be a delta-star isolation transformer. The voltage of the secondary coil of the transformer is:

Eq. (6.16) $Vsec=Vchrg*Nser$

Eq. (6.17) *Vchrg=the charge voltage of the battery module (V)*

Considering that, and the power of the shore substation, we can now calculate the charge current of the modules. This is very important because the time it takes to charge or discharge a battery is in a great factor dependent with the current it encounters:

*Ichrg=(Psub*1000)/(Vsec*Npar)*

This current feeds every parallel string of battery modules.

The current is calculated as DC because there will be a rectifier to transform the AC current of the substation.
The energy the batteries are charged with every time the vessels stays at port is:

Eq. (6.18) *Echrg =(Psub*tchrg)/60*

Eq. (6.19) *tchrg=tport-tplug(the time the vessel is at port minus the time it takes to connect the battery modules with the substations in order to charge (min)*

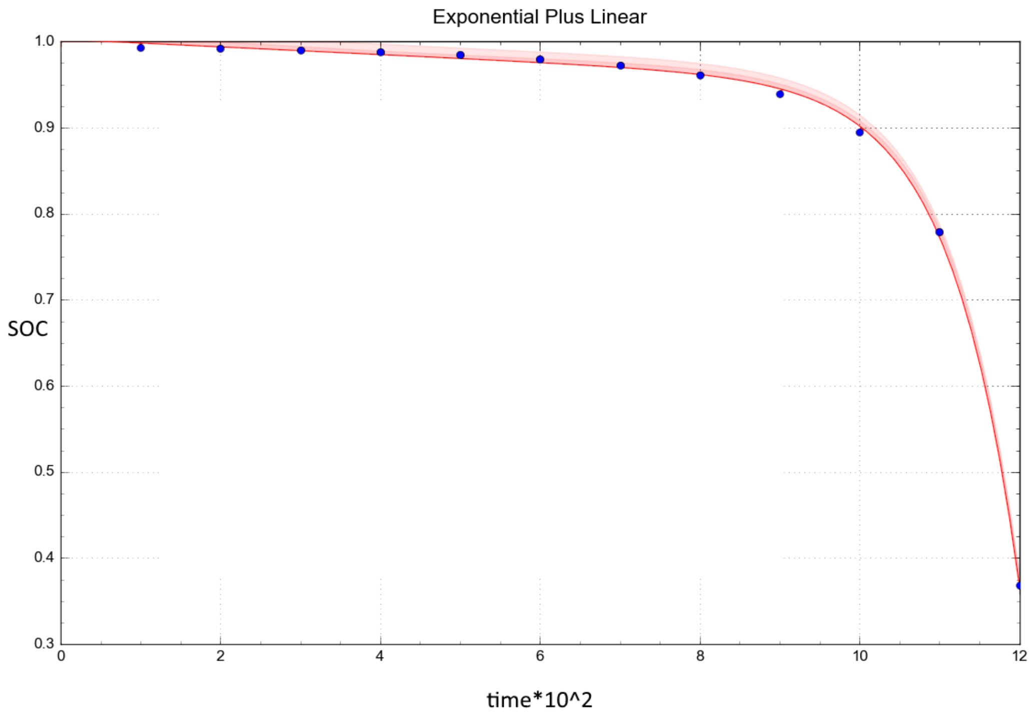
To ensure safety, we have to set some criteria that indicate that the energy of the batteries during the vessel's daily operation, are adequate in order to fulfill the energy requirements this scenario needs. This feasibility criterion is described below:

*cri_feas=(0.8*Einst)-((Ntrip*Ereq)-Eport)-(Ntrip*Emotor)+(Ntrip-1)*Echrg+(Ntrip*Esg)>0*
Eq. (6.20)

To simulate the battery performance using the code that was created in MATLAB a matrix was created. The matrix contains the values of the SOC (a percentage of the capacity of the battery modules) for every minute during the vessel's daily operation. The purpose of this is to simulate the interface in an engine room where in any time the crew members need to know the battery packs' capacity to take decisions depending on the various conditions. To achieve this we recreated the curves of charging and discharging of the battery modules (found at Valence web page) using a specific mathematical software that enabled us to define the equations of these curves. Predicting the energy behavior of a battery is really important and can lead more efficient sizing of the propulsive configuration as well as
The discharge curve for C/2 current that is presented below was approached by an exponential plus linear equation:

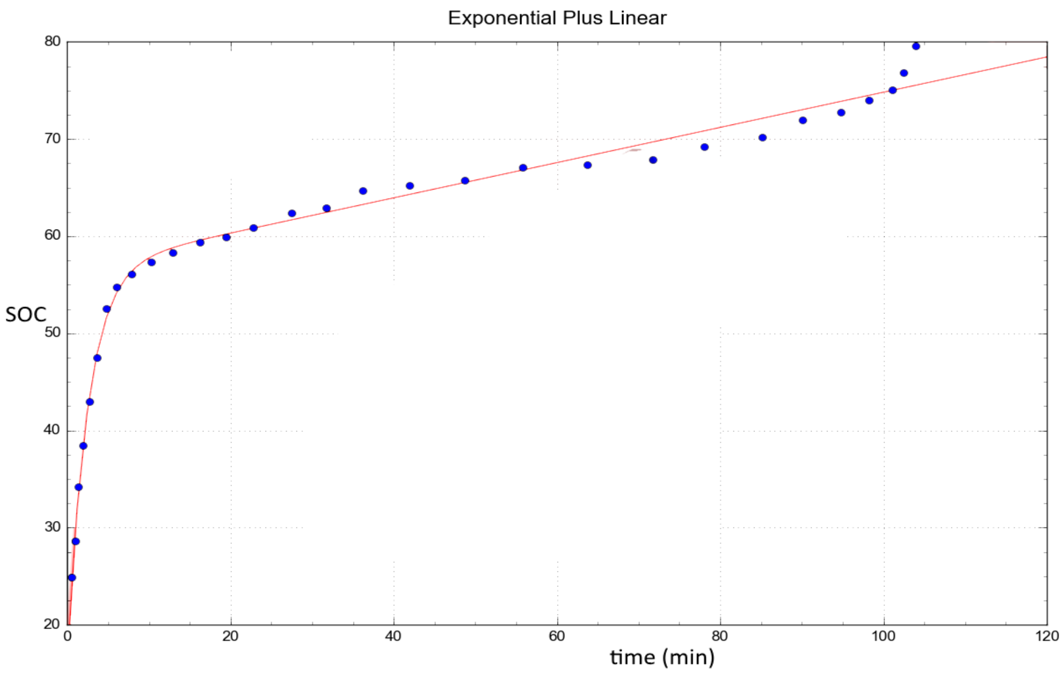
Eq. (6.21) *y=1.002589-(4.8079*10^ (-7))*(3.2122^x)-(4.451*10^ (-3))*x*

It has to be noted that this curve can be approached very well with a cubic spline as well. The y axis presents the capacity and the x axis the time in minutes. The capacity as the battery discharged divided by the nominal capacity of the cell gives us the SOC.



The curve of the charge performance of the battery is presented below , where the y axis represents the SOC of the battery module and x axis the time in minutes.
The equation of this curve is:

Eq. (6.22) $y=56.6947-40.3966*(0.6708^x)+0.1813*x$



Having those ''base'' equations we can then modify their parameters in order to predict the battery energy behavior , although combining experimental results would lead us to better understand this subject.

Chapter 7: Case study of medium size Passenger vessel

This chapter presents the results from the implementation of the methodology in case study of: medium distance passenger vessel. Topology designs, no of batteries installed according to operational profile and overall hybrid configurations are also included along with some diagrammatic predictions for the discharge behavior of the battery cells.

7.1 Study area

In this part of the case study we are going to investigate possible routes for implementation of hybrid propulsion in order to choose a vessel for our case study. In order to do that we have to consider some restrains that can filter our search such as:

- **Distance between ports under consideration**: a factor that can show us the energy needs that have to be met for safe transiting when at sea and maneuvering when in port considering the fuel consumption and regulations as well.

- **Marine traffic** because the time that is required to enter or leave the port plays a crucial role on fuel consumption. Busy ports like Piraeus, Igoumenitsa, Iraklion, Zakinthos and Patra, are preferred.

- **Particulars of the vessel serving the route under consideration** for an approximate estimation of the difficulty in maneuvering and berth allocation when in port.

- **The vessel type**: we choose it to be RO/PAX because it offers a better implementation potential of the hybrid propulsion configurations due to the frequent use of marine transportation in Greece, hence a promising economic relief for ship-owners. In addition such retrofits are more realistic when we are dealing with smaller vessels that are less complicate and need smaller capital investment.

- **and the vessels age** : we are going to choose vessels that are not recently built because fouling and machinery deterioration are not as big of a problem as opposed to an older ship that needs to cut corners in savings in order to stay "alive". But on the other hand we will not study a very old (20+ years) vessel because an investment such as retrofitting into hybrid is redundant in this particular case.

In the first stage of our search we gathered information from vessels that are built after 1998 and before 2011 (after their first 2 dry-docks which is generally after 2-3 years at sea for passenger ships) and the routes that are serving vary from 17 to 299 nautical miles in order to have a wider variety of choices.

The results after applying the above mentioned filters are presented in the table below:

No	SEA ROUTES	VESSEL NAME	DISTANCE(NM)	VESSEL PARTICULARS(L*B*T)	YEAR BUILT
1	EGINA-PIRAEUS	ACHAEOS	17	87,7*16*3,5	2006
2	CORFU-IGOUMENITSA	NIREAS	18	60,08*14,2*2,9	2002
3	ZAKINTHOS-KYLINI	FIOR DI LEVANTE	19	118,65*20*4,6	1998
4	IGOUMENITSA-PATRA	SUPERFAST I	55	198,99*26*6,3	2008
5	PIRAEUS-SYROS-PATMOS	SUPERFAST XII	95	188*25*6,5	2002
6	IRAKLIO-THIRA-IOS-PAROS-MYKONOS	HIGHSPEED 7	151	85*21*3,5	2005
7	PIRAEUS-PAROS-NAXOS-DONOUSA-AIGIALI-ASTYPALAIA	BLUE STAR PAROS	175	124,2*18,9*5	2002
8	PIRAEUS-HERAKLION	KNOSSOS PALACE	177	214*26,4*6,7	2000
9	IGOUMENITSA-BARI	SUPERFAST II	192	198,99*26*5,6	2009
10	PIRAEUS-CHIOS-MYTILENE	BLUE STAR 1	205	176*26*6,5	2000
11	PIRAEUS-KARLOVASI-KOS-RHODES	BLUE STAR 2	299	171,4*26,2*6,5	2000

Table 7.1 Possible vessels for retrofit

After considering all the factors that contribute for a feasible and realistic case study we will choose a vessel that serves the route Kylini- Zakynthos because the duration of its voyage is average and requires a lot of time at ports hence more challenging maneuvering (very good prospect for optimizing these operations with hybrid configurations).This vessel combines all the above mentioned parameters/restrains (acceptable route distance for considering a full battery case, busy ports, appropriate age for optimizing it's operation) that define our case study. In the end another contributing factor is that this particular route presents a major economic interest for the Greek maritime transportation due to its touristic destinations.

7.2 Assessing the current energy system of the vessel under study

The existing machinery intended for propulsion and hotel loads of the vessel, is consisted of:

- 2 main engines
- 4 auxiliary engines(diesel generators)
- 1 emergency generator
- 1 bow thruster

The engine room arrangement is shown bellow

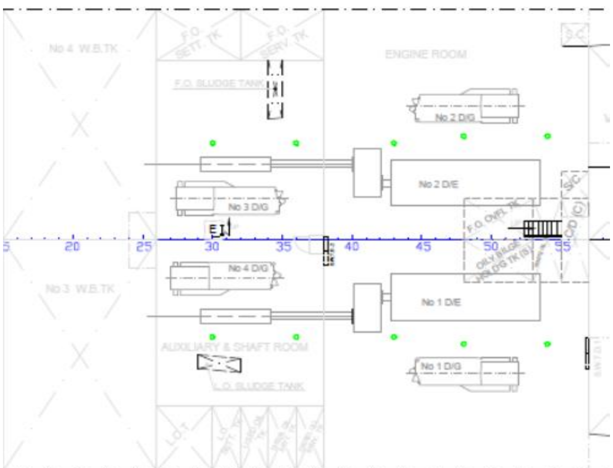


Figure 7.1 Engine room arrangement of the vessel under study before the retrofit

Some calculations were necessary at first in order to check the sizing of the cables that the generators use in order to compare them with the ones that our battery configuration is going to require. In that way we can determine if some of the cables can be kept for use.

The calculations are presented in the table below:

Data	GENERATOR 1	GENERATOR 2	GENERATOR 3	GENERATOR 4
POWER (KVA)	700	700	700	768
VOLTS (Vac)	450	450	450	450
f (Hz)	60	60	60	60
cosϕ	0,8	0,8	0,8	0,8
current (A)	898,1004187	898,1004187	898,1004187	985,3444594
cables used	6*(3*80)	6*(3*80)	6*(3*80)	6*(3*95)
maximum current cables used can toleratote (A)	1026	1026	1026	1170
difference	127,8995813	127,8995813	127,8995813	184,6555406

Table 7.2 Cable compliance check according to DNV rules

The cables are properly sized for the load intended to withstand.

7.3 Hybrid configuration analysis of the vessel under study

The topology of this scenario is presented below:

- 2 Main Engines
- 2 Shaft Generator
- 1 emergency generator
- 2 4-quadrant AC/DC converter providing P &Q power where necessary
- Batteries with battery management system

A CAD design was created in order to showcase the above mentioned configuration

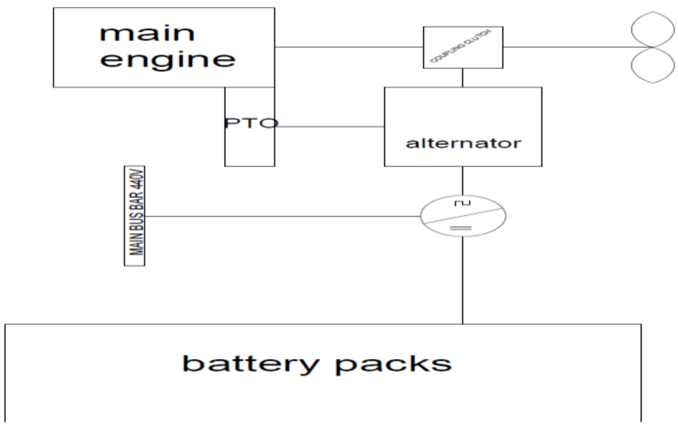


Figure 7.2 Hybrid system configuration

*It is important to mention that the emergency generator is going to remain in the vessel as stated in the regulations.

The working principle of this scenario is that the main engine is responsible for the propulsion of the vessel when at sea, but when arriving at port and specifically during maneuvering the alternator works as a motor and the main engine is decoupled from the propeller.

The hotel loads during the voyage of the vessel is covered by the shaft generator and during maneuvering and the time at port by the battery packs installed onboard

The battery packs are charged as the main engine runs, by implementing the gearbox (PTO/PTI) [through which the alternator will work as a synchronous generator.

The charging/discharging of the batteries and the feeding of the hotel loads from the shaft generator is achieved through a converter. The connection from AC to DC and vice versa will be achieved by a 4-quadrant AC/DC converter, that will provide the main bus bar(440V) with Alternative Current for hotel loads and the batteries with direct current when charging them.

<u>Breakdown of the elements implemented in the configuration are presented below</u>

<u>4-quadrant AC/DC converter</u>

Regenerative DC drives are also known as four-quadrant drives and they are capable of controlling not only the speed and direction of motor rotation, but also the direction of motor torque. The term regenerative describes the ability of the drive under braking conditions to convert the mechanical energy of the motor and connected load into electrical energy which is returned (or regenerated) to the AC power source. When the drive is operating in the first and third quadrants, both motor rotation and torque are in the same direction and it functions as a conventional non-regenerative unit. The unique characteristics of a regenerative drive are apparent only in the second and fourth quadrants. In these quadrants, the motor torque opposes the direction of motor rotation which provides a controlled braking or retarding force. A high performance regenerative drive is able to switch rapidly from motoring to braking modes while simultaneously controlling the direction of motor rotation. A regenerative DC drive is essentially two coordinated DC drives integrated within a common package. One drive operates in the first and fourth quadrants and the other operates in the second and third quadrants **[17].** The reason we are choosing this converter is the bidirectional flow of electricity that enables to activate the ''regenerative braking'' properties of the shaft generator. This is achieved by exciting the magnetic field of the alternator in order to induce an electromagnetic force according to Lenz's law that is called back EMF that resists the flow of electricity in the rotor winding of the alternator. By achieving this Back EMF becomes larger that the supplied voltage of the alternator and the flow of electricity is reversed, making the synchronous motor work as a generator.

Renk constant frequency (RCF) PTO

In case of a fixed pitch propeller, in order to keep the frequency relatively steady for sensitive machineries around 60Hz, adaptable variable frequency drives must be employed to achieve that if the PTO transmission is a GCR. So the cost of the configuration rises beyond our budget. Another solution is the PTO/RCF. The Renk constant frequency configuration keeps the frequency steady by utilizing a hydrostatic motor moved by a hydrostatic pump and a regulator and mechanical movement through a clutch from the main engine.

It has to be noted that the RCF gear transmission can serve a constant speed to the alternator over an engine speed range of 35%.

The RCF PTO transmission system is the most suitable for our case study because

- The vessel under study is equipped with fixed pitch propellers that when operating , depending on the different sea states the vessel comes upon when transiting , require variable power and speed from the main engine in contradiction to the controllable pitch propellers that fit better with GCR PTO gear. This creates a huge problem for frequency sensitive equipment like the windlash, etc.
- The main engines of the vessel under study equip piston bores of diameter under 40 cm because they deliver a maximum continuous rating power of 7630 Kw with 16 cylinders in V configuration. It is easy to understand, that the bigger the bore of the piston, the bigger the torque and consequently the power each piston delivers. So a small rise in the main engine load dedicated to move the alternator can yield more power if the piston bores are bigger because it is dependent on the square of the diameter. On the contrary the number of pistons does not play such a big role when compared to the diameter of the bore (I mention this because a good argument to oppose the aforementioned would be that the bigger the bore the fewer the number of pistons). That leads us to the conclusion that smaller bore main engines can be matched with alternators of smaller output and in our case 250-700 Kw.
- It comprises the perfect solution for the given vessel because it does not cost so much as the CFE configuration and of course the modified GCR with the multiple small dedicated VFDs for every frequency sensitive machinery.

Battery configuration

After studying carefully the above mentioned requirements for marine battery installations by DNV (chapter 4) we must highlight some factors that affect the place of the battery space.

Its longitudinal position, should be as close as possible to the center of floatation of the vessel's design waterline, in order to experience smaller deviations when the weather induces trim upon the vessel and avoid large trim.(something that can however be easily treated with filling the appropriate ballast tanks fore of the midship)

Its transverse position should be symmetrical to the center line of the ship in order to avoid rolling motions.

Its vertical position should be as high in the engine room as possible in order to have lower transverse deviations when rolling angles are experienced due to the sea forces.

The battery modules that we are going to use in our retrofit are manufactured by VALENCE and the specific model is **U27-24XP** and its characteristics are presented below:

	U27-24XP	24V	69Ah	18.6 kg/ 40.9 lbs	12.0" x 6.77" x 8.86" 306mm x 172mm x 225 mm	Group 27	140A	29.2V	1766 Wh

Table 7.3 Battery modulw specifications

The U-Charge® U27-24XP is a high-performance, 24-volt battery, built on Lithium Iron Magnesium Phosphate chemistry platform **[18].**

Figure 7.3 Valence battery modules

The reason why we chose the specific module is because of its high energy density (kwh/kg) and low voltage that contributes to a smoother electrical configuration overall.

A Computer Aided Design was created in order to place the batteries according to the rules of the vessels flag and make sure there is adequate space for our batteries in the engine room. Between battery string modules there must be enough space for inspection (700mm at least). The engine room is adequately ventilated and the battery space distance from structural bulkheads is enough to ensure safety of the configuration. Of course a fire pump has to be installed nearby if there is not one already.

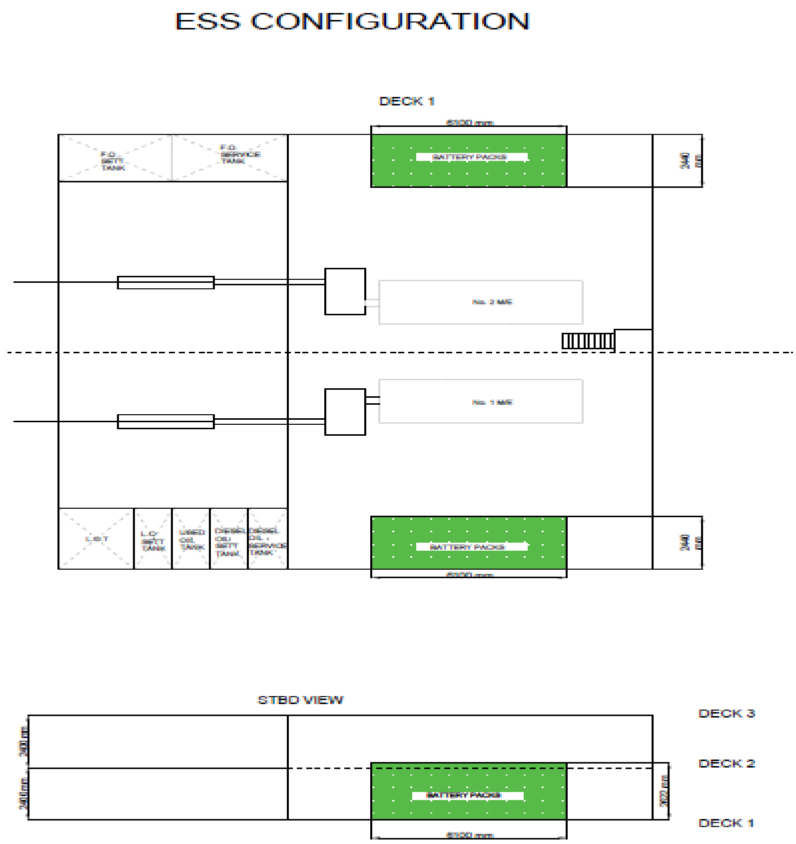


Figure 7.4 Engine room layout with batteries

One solution for the battery space is to be containerized, and this particular option is implemented by many ESS providers.

7.4 System calculations

First of all we need to calculate the electrical energy the vessel requires in order to function properly.

After examining in great detail the one line diagram of the vessel we created its electrical load balance based on the values and the machinery that are used in each condition.

The conditions we are examining are presented below:

- **24 hours at sea**
- **Maneuvering**
- **At port**
  The results are summarized in the table below and the values refer to kW

24 HRS AT SEA	MANOUEVERING	AT PORT
603.88	1037.05	534.17

Table 7.4 Electric balance energy needs

The full electrical load balance is provided in APPENDIX

In order to assess the energy requirements the batteries we have to take under consideration various parameters such as:

- DOD of the batteries
- Distance covered by the vessel (time at sea)
- Power of the charging substation (shore side)

In order to solve and modify a multivariable problem such as the battery sizing of a marine vessel, for different case studies, a MATLAB code was created to ensure reliability of the calculations.

Scenario 1 Charging in both ports

The ship-side calculations are described below:

From the electrical load balance, we understand that we need 1037.05 kW in maneuvering and 534.17 at port. The fs values, that are related with machineries that contribute to the work of the diesel generators, are to be considered as zero in this scenario because the electrical energy on board is provided solely by the installed batteries and the shaft generators.

From data that we found on Marine Traffic, we can see that the vessel stays at port for one hour approximately and is maneuvering for about **10-15** minutes in each port.

So for a trip from one port to another the required energy for batteries considering that we charge the batteries at every port is

Etrip=(tport x Pport + tman x Pman)/60= ***793.43 kwh****.*

tman=the time for the maneuvering of the vessel at port (min)

tport=the time the vessel stays at port (min)*

Pport=the power needed for the vessels operation at port (kW)

Pman= the power needed for the vessels operation during maneuvering (kW)

**The energy for the hotel loads during the vessel's stay at port must be provided exclusively from the batteries because the shaft generators can only be operated when the main engine is running.*

As we mentioned before two shaft generators are going to be implemented and replace the preinstalled generators. The power output of the alternators must be **500 kW** each.

So the energy the alternators are going to provide to the batteries and the hotel loads of the vessel during its time at sea are respectively:

Esg=loadgen(Psg-Psea)*tsea/60=0.85*400*1=***336.6 kwh** *(The energy the alternator provides for the charging of the batteries)*

*Esghl=Psea*tsea/60=* ***604 kwh*** *(The energy the alternator provides for the hotel loads)**

**value taken from the electrical load balance*

Where

Psg =Power output of the shaft generators (kW)

Psea=Power required for the vessel's operation at sea (kW)

loadgen =the percentage of the maximum power of the alternator that is used for charging the batteries besides feeding the hotel loads

tsea= the time the vessel is travelling from one port to another (min)

A really important parameter that has to be taken into consideration is that the main engine is bound to deliver more power each time the vessel is at sea, in order to operate the shaft generator. The additional power the main engines have to deliver is:

AddP=P+Psg

P=the power of the main engine when at sea

Considering the above mentioned, the energy that has to be provided by the batteries is deducted by the energy provided by the alternator to the batteries.

*Ereq=Etrip-Esg=793.43-336.6=**456.83 kWh***

But we have to consider ***a)** that the manufacturer proposes 80% D.O.D in order to have a longer life cycle* and ***b)** that in case of battery failure or failing to charge properly at port the number of batteries installed must be multiplied by a redundancy factor*. So the minimum energy installed on board should be:

*Emin= (Ereq/D.O.D)*redundancy=**913.6 kWh***

*Where **DOD=0.8** and **redundancy=1.6***

The batteries are arranged in series and parallel in order to fulfill two criteria:

- the voltage of the main bus that indicates the number of modules in series as described below:

$$\boldsymbol{N_{series}} = \boldsymbol{V_{SYST}} / \boldsymbol{V_{Bt}}$$

Where, V_{SYST} = System's main bus bar's voltage (V) (440 V AC)
V_{Bt} = Battery module's nominal voltage (V)

- the energy that is required in order to satisfy the vessel's safe operation indicating the number of parallel battery strings as described below:

$$\mathrm{N_{paral}} = \mathrm{E_{min}} / (\mathrm{N_{Bt.SERIES}} \times \mathrm{Emodule})$$

Where, Emodule is the nominal energy of the module.

<u>After applying the above mentioned formulas we need 18 batteries in series in every string and 30 strings.</u>

The installed energy on board will be:

*Einst=Nbatt*BattE=(18*30)*1.766=**953.64 kwh***

Nbatt=the total number of batteries installed on board
BattE=the energy of the installed battery modules (kWh)

Of course during maneuvering the ideal situation will be to disengage the main engine from the propeller axis and the small amount of power will be provided by the alternator. This time the alternator is going to work a synchronous motor and the energy the batteries have to give is:

*Emotor=load-man*MCR*(tman/60)=2*0.05*7630*(15/60)=**190.75 kwh***

load-man=the percentage of the load of the main engine's MCR the synchronous motor has to provide during maneuvering

The number of trips that the vessel is going to be performing each working day is calculated as shown below:

*Ntrip=roundown((tday*60)/(tport+tsea+tman))+1=**8***

tday=the total time in hours the vessels is operating per day (min)

The battery system life will be approached considering the basic principle of how many times during the day the battery modules are charged and discharged.

*Ndisch= (Ereq*Ntrip-Eport+(Ntrip*Emotor))/Einst=5.4325*

Nchrg= (Echrg(Ntrip-1)+Ntrip*Esg)/Einst=4.6588*

*Ncycl=Nchrg+|Ndisch-Nchrg|/2=**5.0456***

Ndisch= the number of times the modules are discharged until 0% SOC
Nchrg= the number of times the modules are charged until 100% SOC
Ncycl= the number of times the modules are charged/discharged during the day

The estimation of the battery system life can be achieved by the formula below:

*Syslife=(Ncyclman/Ncycl)/365=(5000/5.4)/365=**2.71 years***

Ncyclman=the life cycle performance for 80% DOD of the battery modules

The shore side calculations are described below:

The shore substations have to provide 300kw of power each (Psub=2*300=600kw).
The transformer that has to be implemented is going to be a delta-star isolation transformer. The voltage of the secondary coil of the transformer is:

*Vsec=Vchrg*Nser=29.2*18=**525.6 V***

Vchrg=the charge voltage of the battery module (V)

Considering that, and the power of the shore substation, we can now calculate the charge current of the modules. This is very important because the time it takes to charge or discharge a battery is in a great factor dependent with the current it encounters:

*Ichrg=(Psub*1000)/(Vsec*Npar)=(600*1000)/(525.6*30)=**38.05 A***

This current feeds every parallel string of battery modules.
The current is calculated as DC because there will be a rectifier to transform the AC current of the substation.
The energy the batteries are charged with every time the vessels stays at port is:

*Echrg =(Psub*tchrg)/60=(600*25)/60=**250 kwh***

tchrg=tport-tplug(the time the vessel is at port minus the time it takes to connect the battery modules with the substations in order to charge (min)

To ensure safety, we have to set some criteria that indicate that the energy of the batteries during the vessel's daily operation, are adequate in order to fulfill the energy requirements this scenario needs. This feasibility criterion is described below:

*cri_feas=(0.8*Einst)-((Ntrip*Ereq)-Eport)-(Ntrip*Emotor)+(Ntrip-1)*Echrg+(Ntrip*Esg)>0*
*cri_feas=**447.392 kWh***

Shaft generator output	**500**	**kW**
batteries parallel	**30**	
batteries series	**18**	
required battery energy/trip	**456,83**	**kW**
Energy installed onboard	**953,64**	**kWh**
battery system life	**2,71**	**years**
Remaining energy	**559,24**	**kWh**

Table 7.5 Scenario 1 sizing parameters

Scenario 2: Charging in one port

In case the route of the vessel entails only one port with power substations for recharging the batteries we have to modify some criteria in our code in order to assess the situation.

The modified criterion is presented below:

*cri_feas= (0.8*Einst)-((Ntrip*Ereq)-Eport)-(Ntrip*Emotor) + (Ntrip/2-1)*Echrg+ (Ntrip*Esg)>0*
Also there will be a change in the number of charge cycles the batteries experience during the vessel's operation

Nchrg= (Echrg(Ntrip/2-1) +Ntrip*Esg)/Einst*

In order to ensure the safe operation of the vessel, the batteries installed onboard have to be more, or the output of the shaft generators has to rise. We are considering that the power of the substation cannot be modified because it is not depended on the owner of the vessel.

Both options entail appendages, like bigger investment for the inverters, rectifiers and the 4 quadrant converters if we follow the battery option, and of course even bigger investment for a bigger (in power output) PTO configuration.

The first option gives us a **redundancy of 3** which is **87.5%** more from the required energy installed on board in the previous scenario. In this option we didn't modify anything else but 87.5 % more batteries need to be installed.

The initial investment for the battery option costs 700 K $ more.

The second option is achieved by implementing shaft generators of 550 Kw nominal power unlike the previous scenario that was achieved with 500 Kw. The price difference is going to be about 100 K $ with a rough estimation. The remaining energy in the system after a full day of operation with the second is 420 kWh meanwhile in the battery option is 170 kwh.

Therefore the prevailing choice is the second

In table 7.6 below some of the most important sizing parameters of the second scenario are summarized.

Shaft generator output	**550**	**kW**
batteries parallel	**26**	
batteries series	**18**	
required battery energy/trip	**396,63**	**kW**
Energy installed onboard	**826,488**	**kWh**
battery system life	**3,15**	**years**
Remaining energy	**420,72**	**kWh**

Table 7.6 Scenario 2 sizing parameters

The next page depicts the charge/discharge behavior of the battery modules installed on board during a daily operation of the vessel unser study.

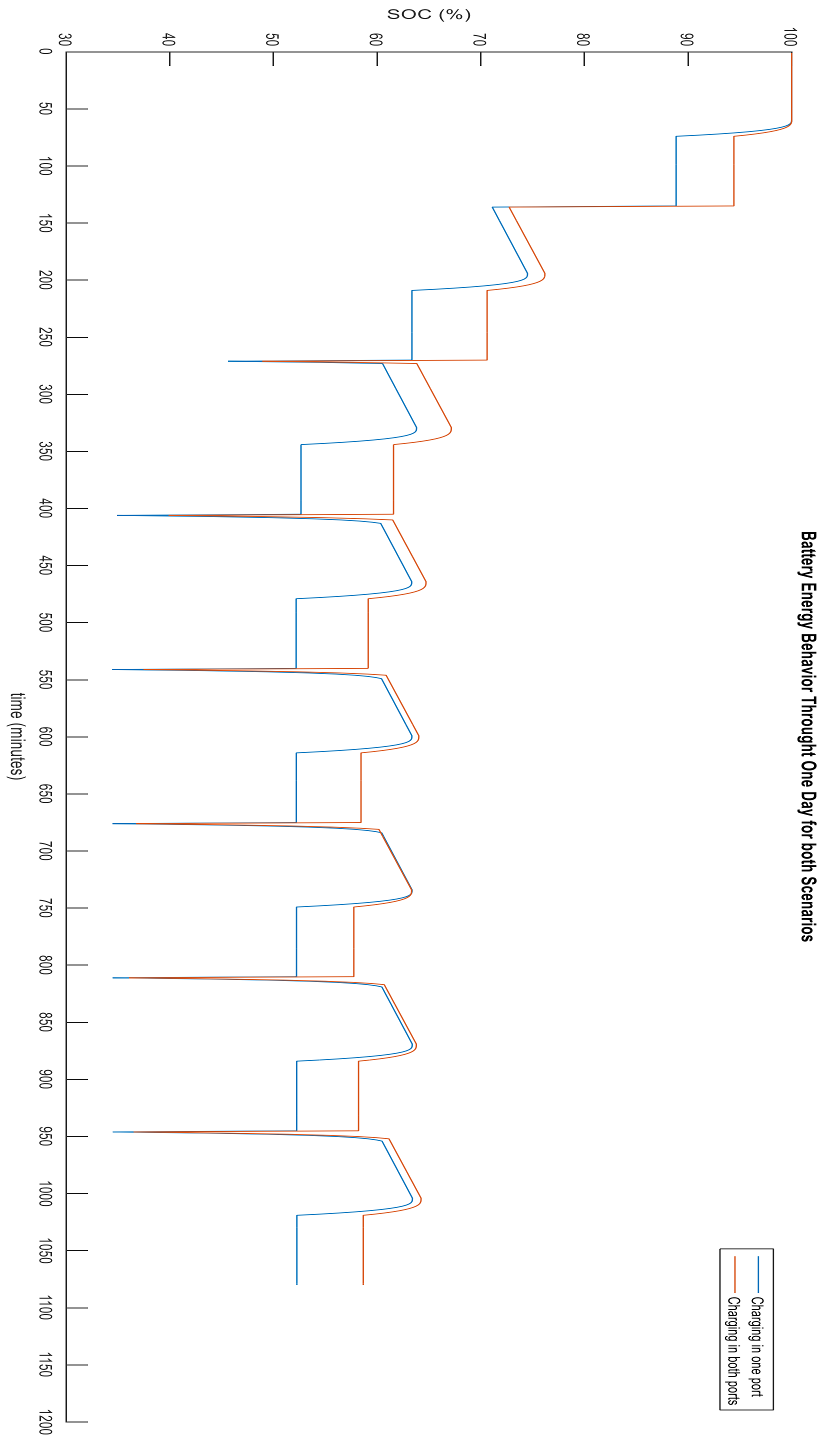


Figure 7.5 Battery energy performance throughout the day

Chapter 8: Techno-economical Analysis

The techno-economic analysis that we performed includes the scenario of battery charging, in one port, because it is the most. The analysis will be held for a nine year period time according to battery manufacturers' guidelines concerning the degradation of batteries' nominal capacity to 80%$Ah_{NOMINAL}$.

The methodology for this analysis was developed combining knowledge from:

- Dimitrios V. Lyridis (Proff. At NTUA)
- Various articles regarding investment analysis
- C. Bakirtzoglou diploma thesis
- O. Kritikos diploma thesis

8.1 Investment evaluation Criteria

The dictionary meaning of investment can be explained as follows:

"the act of putting money, effort, time, etc. into something to make a profit or get an advantage, or the money, effort, time, etc. used to do Stocks are regarded as good long-term investments."(Cambridge Dictionary, 2013)

Gareth D. Myles has made a fundamental definition of the investment analysis in his book as below;

"Investment analysis is the study of financial securities for the purpose of successful investing." (Myles, 2003)

According to above definition, some important points come into prominence such as financial securities which mean how to trade and what assets there are for trading, and analytical issues which represent the calculation of risks and returns, and their relationship with each other. In addition to that, successful investing is to lead investors how to succeed in trade, and which investment strategies have to be chosen in order to be successful.

As a result, investment analysis depends on financial theories. These theories are expressed by calculation methods and techniques. Most commonly used techniques and methods for investment analysis are), Internal Rate of Return (IRR) and Net Present Value (NPV), which are also known as traditional techniques and developed to make investment decision for the investors by considering the value of money within the years and evaluating the time for return of the capital assets. This is because investors do not only put large amounts of money as capital to make profit in the long-term, but also they have crucial financial risk on loss of money.

Internal Rate of Return

The Internal Rate of Return (IRR) has been defined as the discount rate that forces the project's net present value to equal zero (Brigham & Houston, 2007). In this technique the present value of the capital assets in-flows are equal to the present value of the money out-flows (Milis et al, 2006).

Differently from the previous techniques mentioned above, with IRR the time value of money is taken into consideration by performing a discount factor. This is an essential progression and a reason why IRR is a more useful technique today.

Nevertheless, IRR has some negative sides (Milis et al, 2006):

- IRR calculation is resulted as a percentage. Therefore it is hard to compare services regarding size and outcome.
- If the IRR differs substantially from the cost of capital, it will become difficult to compare investments with a different time pattern.
- When this technique is used as a selection tool for mutual exclusive services, risks are not accounted for. It lacks the possibility of entering risk-levels into the selection. This is a major disadvantage when used in a service where levels of future use are often highly uncertain.

Since IRR is defined as a variable wherein NPV formula when NPV is equal to zero, the IRR formula can be shown as follows:

(Eq. 8.1)

$$NPV = \sum_{i=1}^{n} \frac{A_i}{(1 + IRR)^i} = 0$$

Where

n is project life,

A_i is net cash flow at the end of the year *i*.

Net Present Value

The Net Present Value (NPV) is another technique to analyse investments by using a discount rate. This technique, in principle, calculates the present value of the capital assets and money flows. Unlike IRR, different rates could be applied to show the risk-levels of mutual exclusive investments. The NPV technique is considered as being theoretically superior to the IRR technique, and NPV can be found as follows (Milis et al, 2006):

- Find the present value of each cash flow, including the cost, discounted at the project's cost of capital.
- The sum of these discounted cash flows is defined as the project's NPV.

(Eq. 8.2)

$$NPV = \sum_{i=1}^{n} \frac{A_i}{(1+r)^i} - C$$

Where

n is project life,
A_i is net cash flow at the end of the year i.
r is discount rate,
C is initial capital expenditure.

In principle, in order to create a NPV model, there must be estimated some variables, such as inflation rates for discount rates and future price of specific commodities according to investment type. Therefore, to make an investment analysis of the CI system on account of port management, future price of electricity will be used as an alternative energy to MGO. For this reason the future price of MGO should be estimated in order to find comparable annual values. So, the NPV model will contain future prices of MGO and electricity.

- **Future price of MGO**

Marine gas oil consumed by ships is limited in the world within the long term perspective. This makes it one of the most expensive products in comparison with other fuel oils. In the literature review, the best future assumption model of energy sources can be found in a study accomplished by the US Energy Information Administration (EIA). Every year EIA regularly publishes the report of "Annual Energy Outlook". The final report consists of energy sources data for 2016 with projections to 2040. In this time period, the report examines three different scenarios; one is if the market price is low, how many barrels will be produced; the other one depends on if the market price is high, and the last one, namely reference, is a mix of the two other scenarios.

According to this report, the amount of oil production will continue to rise, even if the market price is low. The annual growth rate of diesel oil distillate prices are estimated 1.5%.

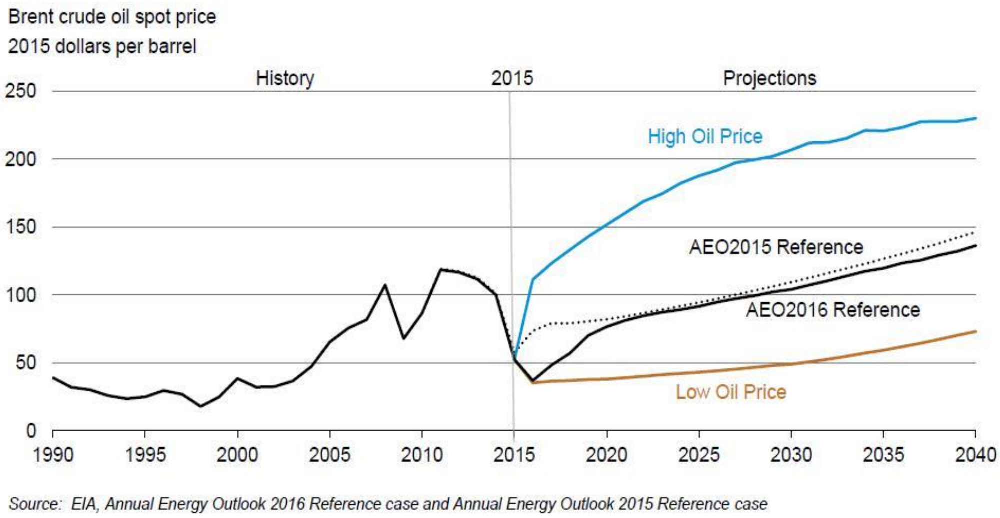


Figure 8.1 Average spot price for Brent crude oil in three scenarios, source: EIA, 201

*Since no other data were available we are using this report to apply the annual growth of ULSFO price that fits our case study.

- **Future price of electricity**

Estimating the future electricity price is a very difficult task as well. There have been conducted many studies on how to calculate a safe projection. Most of them depend on algorithms taking under consideration parameters such as GDP growth, impact of energy efficiency investments and privatizations on investments, new power plants, carbon market developments, as well as petrol, coal and natural gas prices etc.

Ozan Korkmaz published a paper in 2013 namely, «Long Term electricity Price Predictions for Turkey Between 2013 and 2030". The main purpose of this paper is to explain how the simulation model for the long term electricity price assumption was built and worked. He used a simulation model with a unique algorithm which is based on most of the major parameters.

Considering the similar geographic and climatic conditions between Greece and Turkey, the results of his study could be considered valid. These are presented in the following figure. However, the recent events in Greece of opening the electricity market and at the same time the bidding competition in renewable energy sources result in a higher competition in the energy supply market. Therefore, the annual growth of electricity price will be considered 1.5% instead of 2% proposed by Ozan Korkmaz **[19].**

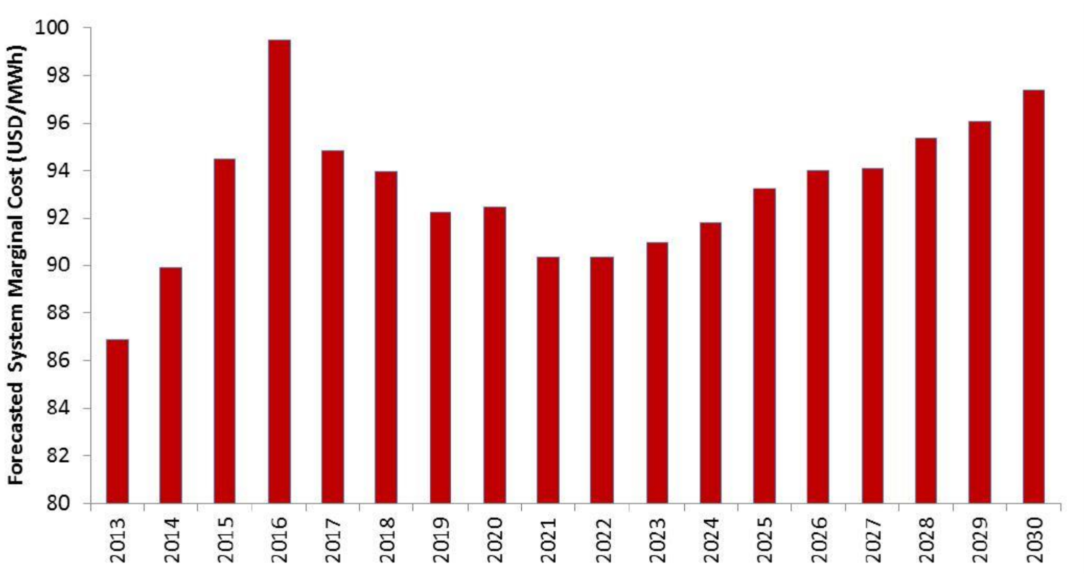


Figure 8.3 Forecast on electricity price in Turkey by years, source: Korkmaz, 2013

8.2 Annual cash flow analysis

MACHINERY	price/unit	number	price
pto	**400000**	**2**	**800000**
batteries	**580320**		**580320**
transformer	**30000**	**2**	**60000**
4quadrant converter	**120000**	**2**	**240000**
rectifier	**50000**	**2**	**100000**
used generators	**32480**	**3**	**134560**
cables	**5000**		**5000**
initial investment			**1650760**

Table 8.1 Investment cost

Initial investment=1.650.760$

Benefit from fuel and O&M costs may be considered as one of the most important revenues in the analysis (in order to have a clear picture on the comparison of running the vessel on batteries)

The residual value of equipment bought is estimated as described below:

- 20% of batterie's initial cost
- 60% for the rest of equipment
- ULSFO growing price 1.5%
- 50% of the shaft generators initial cost

MACHINERY	RV
pto	**400000**
batteries	**116064**
transformer	**36000**
4quadrant converter	**144000**
rectifier	**60000**
used generators	
cables	
initial investment	**756064**

Table 8.3 Residual value of investment

Residual value of investments=756.064 $

NPV rate is estimated 6% although in the end of this chapter we will perform a sensitivity analysis regarding its value in order to calculate the IRR.

The capital that would be essential for operation if the generators were in use is calculated below

Data for the specific fuel oil consumption provided by the owner are given in the table below. The data refer to a single stay at the port for one hour.

PORT DATA		
PORT POWER NEEDS	600	KW
PORT ENERGY NEEDS	600	KWh
fueol oil consumption	59,5	kg
sfoc at port	99,16666667	gr/kwh

Table 8.3 Port energy/fuel data

For the hotel loads the vessel depends on 4 generators and one emergency generator.

The daily consumption of ulsfo the generators would use for their operation is presented in the table below

tones of ulsfo per day at sea	0,623
tones of ulsfo per day at port	0,476
tones of ulsfo per day maneuvering	0,266112
tones of ulsfo per day	1,365112

Table 8.3 Daily consumption of ULSFO

The **cost of the fuel is 196794 $/year** taken into account the price per tone of the ULSFO 420.5 $/ton. This is considered as profit because the vessel no longer employs generators.

The electricity cost can be approximately taken equal to 0.05$/Kwh.

ENERGY/DAY	2000
operational cost of M/E due to shaft generator	36000

Table 8.4 Daily electricity cost

The cost is calculated using only the daily charging energy, required for the battery packs from the shore substations.

The quantification of the volume of emissions saved in the atmosphere because of vessel's retrofit is based on guidelines of TIER-III protocol which requires as input the individual consumptions of main and auxiliary engines and estimates their emissions during each phase of the trip.

For a single trip the emissions can be expressed as:

(Eq. 8.3)

$$EM_{TRIP} = EM_{AT\ SEA} + EMman + EM_{AT\ PORT}, (tn)$$

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

(Eq. 8.4)

$$EM_{TRIP,i,j,m} \sum_{P} \left(FC_{j,m,p} \times EF_{i,j,m,p}\right)$$

Where:

EM_{TRIP} = emission over a complete trip (tn)

FC = fuel consumption (tn)

EF = emission factor (kg/tn) i = pollutant (NOx, NMVOC, $PM_{2,5}$, PM_{10}, CO, SO_X)

m = fuel type (HFO, MDO/MGO, LNG)

j = engine type (slow-, medium-, gas-turbine etc.)

The pollutants will be calculated only for the gensets that are going to be replaced because we want to consider them as profit in our analysis.

Engine	Phase	Engine Type	Fuel Type	NO_X EF (g/kWh)	NMVOC EF (g/kWh)	TSP PM_{10} $PM_{2.5}$ EF (g/kWh)	CO* (kg/tn)	SO_X* (kg/tn)
	Cruise	Medium	MDO/MGO	12.3	0.5	0.3	7,4	2
Main	Stand-By	Speed		9.9	1.5	0.9		
Aux	Cruising/	Diesel		13	0,4	0,3		
	Hotelling			13	0.4	0.3		

Table 8.5 Concentration in kg/ton of pollutant for main and auxiliary engines (reference values)

Engine	Phase	Engine Type	Fuel Type	CO_2 EF (kg/tn)	CH_4*EF (kg/tn)	N_2O* EF (kg/tn)
Main/ Aux	At Sea/At port	Medium Speed Diesel	MDO/ MGO	3,19	0,18	1.3

Table 8.6 kg/ton of greenhouse gases for main and auxiliary engines (reference values)

These reference values are going to be applied in our investment analysis, since no other data were available for the ULSFO

	Eport	Esea	Eman	
ENERGY	534,17	604	260	tons of polutants/year
NOx	6944,21	7852	3380	5,23474848
NMVOC	213,668	241,6	104	0,161069184
PM10/PM2,5	160,251	181,2	78	0,120801888
CO	3952,858	4469,6	1924	2,979779904
Sox	1068,34	1208	520	0,80534592

Table 8.7 tons of pollutants based on the vessel's operation and energy needs

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

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

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

C. Air emissions and their impacts, Piraeus port case study **[20]** (Tzanatos, 2010)

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

*Table 8.8 Price per ton of pollutant in €$_{2017}$**

Pollutant	PM2.5	PM10	NOX	CO	SOX	NMVOC	CO2	CH4	N20
SUM (tn)	0,12080189	0,1208019	5,23474848	3,07	0,8053459	0,16107	0,1662084		
Values ($)	102466,92	90572,412	4362,228	4800	5412,48	352,836	63244,8		
SUM ($)	14730,0549	13020,169	27173,848	17535,84	5187,1132	67,6289	12509,06225		

Table 8.9 Externalities costs of pollutants based on the vessel's operation and energy needs

TOTAL=90223.72 $

External costs of ship emissions for the environment and Human health (Orfeas Kritikos, 2017)

Since economic crisis stroke Greece, health expenditure has decreased dramatically, reaching a historic low of 5% of GDP in 2017. Therefore, the health problems occurring from ship emissions pose a significant economic burden for Greeks. Thus, every possible solution to improve the health of people should be considered thoroughly. There are many methods to estimate external cost of air pollution caused by ship emissions. The difficult thing is to make a right choice among these various estimation models. Under the 6th framework programme a *project was developed, namely "A New Environmental Accounting Framework Using Externality Data and Input-Output Tools for Policy Analysis" (EXIOPOL). The project started in March 2007 and remained until March 2011. EXIOPOL pursues two main objectives. On the one hand, it focuses on the theoretical-mathematical concepts of linking environmental extensions (EE) to the framework of Supply-and Use-Tables (SUT) for 43 countries (EU-27 Member States and 16 non-EU countries) which have been developed based on economic activities and linked via trade data and extended by environmental factors, such as resource depletion and emissions. On the other hand, research in the field of externalities has been encouraged, i.e. the impacts of human actions on different aspects of the environment are identified and valued in monetary terms (EXIOPOL, 2011). The project has been providing monetary values for the environmental extensions for the emissions of a number of substances into the air. These values will be provided in Euro per ton of emitted substance and will be divided into damages to human health, damages to the ecosystem and the impact on climate change. The related findings of EXIOPOL as summarized in the following table.*

POLLUTANT	HUMAN HEALTH	ECOSYSTEM QUALITY	CLIMATE CHANGE	TOTAL
CO2	**0**	**0**	**28,14**	**28,14**
SO2	**8442**	**268**	**0**	**8710**
NOx	**7638**	**1340**	**0**	**8978**
PM	**46900**	**0**	**0**	**46900**

Table 8.10 External cost factors (in dollars, year 2017) per ton of pollutant

POLLUTANT	cost per pollutant($)
CO2	4,68
SO2	7.014,56
NOx	56.397,09
PM	13.597,46
TOTAL	77.013,79

Table 8.11 Maximum external cost of the emissions per year regarding the impact on human health and the environment

During maneuvering the main engine is decoupled, hence the propeller is moved by the alternator, working as synchronous motor. During that time, the vessel would normally employ each main engine for propulsion with about 5% load.

(Eq. 8.5)

Extra_loadM=5%

At sea, the vessel's main engine is burdened with the extra load of the synchronous generator which is:

(Eq. 8.6) *Extra_loadS=loadgen*Pgen/MCR=0.95*550/7630=***6.85%**

So the additional total capital of HFO that is used annually because of the retrofit is:

*HFO=2*SFOC*(loadgen*Pgen)*abs((Extra_loadM*tman)-*

(Eq. 8.7) *(Extra_loadS*tsea))*Ntrips*days_operation*HFO_price*=**14032.27 $**

Annual operational and maintenance cost=4000 $ for the first 8 years for the machineries installed considering the mean cost of spare parts is about 2000$. So we can make the assumption that we need two of these parts every year and additionally compensating the cost of a bigger damage that may occur for one time in the first 9 years.

*battery packs do not need operational or maintenance cost because they charge from port substations and the shaft generator that its extra cost is included in the calculations (Annual operational cost)

8.3 Feasibility Determination of the case study

In the scenario we are investigating the life expectancy of the battery system was calculated in the previous chapter as 3.15 years. So every 3 years we are going to rebuy the batteries. A reduction of 20% is considered in the price of the batteries each time we buy them, which is applied on their residual value after the 3 years as well. The highlighted columns represent the year we rebuy the batteries and the depth of our calculation is 9 years.

INITIAL INVESTMENT	1650760,00									
TIME (YEARS)	0	1	2	3	4	5	6	7	8	9
BENEFITS FROM ULSFO	0,00	207390,60	210501,46	213658,98	216863,87	220116,82	223418,58	226769,85	230171,40	233623,97
ADDITIONAL OPERATIONAL/MAINTENANCE COST	0,00	-36000,00	-40500,00	-41000,00	-41500,00	-42000,00	-42500,00	-43000,00	-43500,00	-44000,00
ADDITIONAL COST OF HFO DUE TO S.G.	0,00	-14032,27	-14242,76	-14456,40	-14673,24	-14893,34	-15116,74	-15343,49	-15573,65	-15807,25
impact on human health	0,00	77013,79	77013,79	77013,79	77013,79	77013,79	77013,79	77013,79	77013,79	77013,79
pollutants externalities	0,00	90223,72	90223,72	90223,72	90223,72	90223,72	90223,72	90223,72	90223,72	90223,72
RESIDUAL VALUE OF INVESTMENTS	756064,00	0,00	0,00	0,00	92851,20	0,00	0,00	74280,96	0,00	0,00
NPV(6%)	-894696,00	306222,48	287465,47	273245,77	-161719,62	246939,67	234779,59	-36120,03	212275,73	201869,47

Table 8.12 NPV calculation

NPV (6%) = 670.262,53 $

Plotting the NPV for various cost of capitals (i) we get the figure 8.4 and in the point where it reaches the zero value we calculate the IRR.

NPV-Capital Cost Diagram

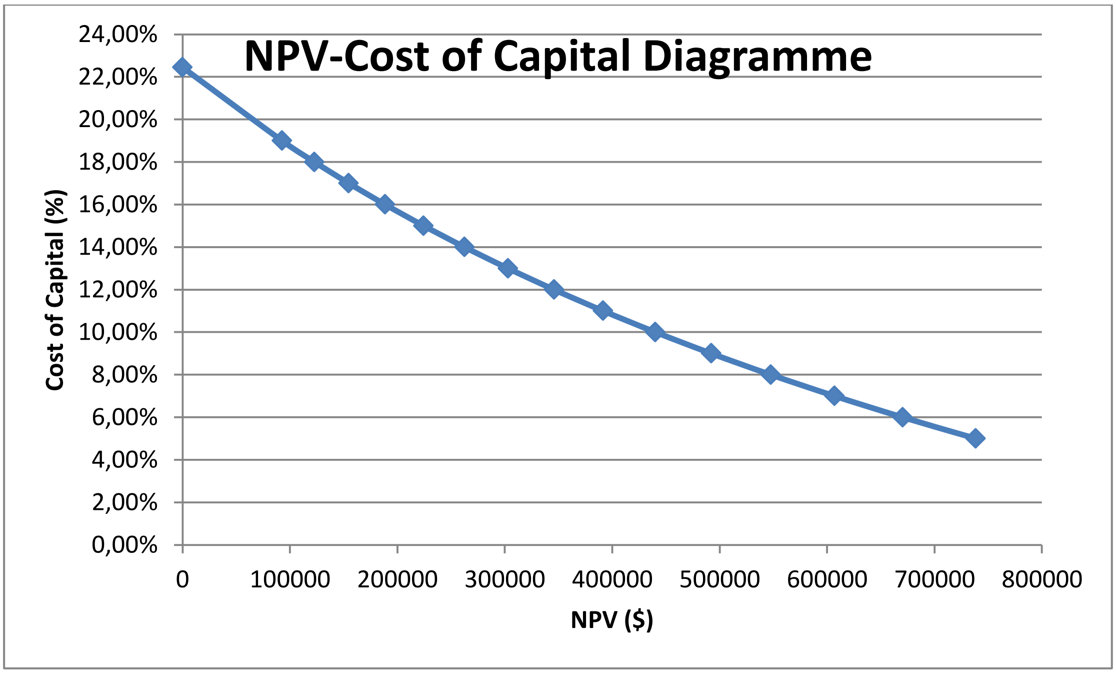


Figure 8.4 NPV-Capital Cost Diagram

IRR = 22,45 %

Both the NPV and IRR indicate that this investment plan is feasible.

Since battery technology is necessary for many hybrid projects, an arising problem that concerns many potential buyers and ship owners is the value of the batteries after the manufacturer proposed operational time limit. This is very important in order to assess an investment plan that requires large capital investment. In order to have a clear view on this subject we employed some calculations regarding the residual value of the batteries as a percent of the initial price. It is clear that for every 5% dropping of the residual value, IRR drops 1.73%. Generally with a web research we can understand that some electric cars after 5 years of operation reach resale values of 15-28% of the original (so the batteries implemented in their power plant may cost less depending on the operational profile). Also, taking into account that the price of batteries is falling, the resale value will also fall. Tesla is the only company that promises good resale values. Potential recipient of the batteries after extensive use are scrapping (recycling) companies, research facilities and other users. There is actually a company called RETRIEVE TECHNOLOGIES that recycles lithium-ion batteries, by extracting some useful metals in order to use them for battery rebuild (not necessarily of identical electrochemistry).

Residual value (% of initial)	Net present value ($) (6% capital	Internal rate of return (%)	IRR Difference
0	431250,61	15,84	1,55
5	491003,59	17,39	1,62
10	550756,57	19,01	1,68
15	610509,55	20,69	1,76
20	670262,53	22,45	1,83
25	730015,52	24,28	1,92
30	789768,5	26,2	1,73

Figure 8.5 IRR-Residual value/Initial investment dependency

The value in red showcases the mean difference in IRR for every 5% drop in the Residual Value of the batteries' initial price.

Chapter 9: Conclusions and recommendations for future work

9.1 Conclusions

9.1.1 Thermal/Electrochemical simulation conclusions

- The simulation procedure that was developed and proposed by ANSYS software to study the electrochemical and thermal behavior of the $LiMn_2O_4$ battery cells was in harmony with the results that we predicted based on the physics that define the problem for discharge currents up to 2C. For bigger discharge currents (3C-5C) the rise in the cell's temperature showed some deviations of 2-5 K.
- We have to consider that the thermal management factor is of great importance because the battery packs will have to ''adapt'' in an environment where the temperature is going to be about 320 K (45 C), hence the temperature rise of the cell, as well as the difference between the passive and active zones will be more noticeable.
- Another assumption that we can safely make is that the battery cells high temperature areas change over time as we can observe from the data derived from Kim's paper, showing us that as time progresses the heat is generated more in the cell area because the electrochemical reaction take place combined with the internal resistance of the cell.
- The ambient temperature plays a strange role in the operation of the battery. As the ambient temperature rises the rise in temperature of the cell becomes smaller!!! This fact can be verified by Kim's paper as well figures for 3C discharge current we calculated. We believe that this can be attributed to the fact that when the ambient temperature is high there is not much heat transfer (convection) between the surface of the battery and the internal region of it due to the low temperature difference. The reverse situation is observed when the temperature is lower and the heat transfer due to convection is larger. The regions that are heated of course become larger as the simulation time passes, but for the same discharge current the overall rise in temperature is smaller.
- The time of the simulation plays a crucial role, because the bigger the current the shorter amount of time the battery cell need to reach its cut-off voltage. So caution is needed when choosing the simulation parameters.
- A major problem with this method is the temperature contours that depict the temperature distribution in the battery domain. We have to mention that this model cannot capture the full effect of the 3D thermal behavior of the battery cell, since it is a 2 dimensional model considering the equations that are implemented in it. Comparing the equivalent battery cell material created by correlating the different parts of the battery we can clearly see a big difference which can be explained if we notice that the e-material is an approach to the battery cell.

- Generally Li-ion batteries behave well when charged from 0-45 Celsius and discharge from -20 - 60 Celsius. Exceeding these values can lead to capacity fade after several cycles. Engine room temperature lies within the aforementioned limits so battery cells can easily be implemented in it. Although the following has to be taken into consideration. (Source Battery University).

Temperature	40% charge	100% charge
0°C	98%	94%
25°C	96%	80%
40°C	85%	65%
60°C	75%	60% (after 3 months)

Estimated recoverable capacity when storing Li-ion for one year at various temperatures. Elevated temperature hastens permanent capacity loss. Not all Li-ion systems behave the same.

9.1.2 Conclusions regarding the hybridization of the medium size RO-PAX

- Equilibrium is achieved after a certain amount of time in the energy of the system meaning that it is moving through some steady energy limits. This happens because the batteries remain to the stage of exponential plus linear charging and discharging after 3-4 trips and the shaft generators keep ''refilling'' their energy. If the batteries SOC were to fall below 50% they would be in the exponential zone and the charging / discharging would be even more noticeable.
- The code that is developed in this diploma thesis is purposed to simulate the battery's energy behavior through time. The equations used to predict that, were assumed for the discharge behavior because no data were available. Of course the equations presented in this chapter refer to C/2 discharge-charge current, which will not be steady throughout the day. We tried to compensate that from data available moving the equation parallel to the y axis by subtracting a value regarding the different currents applied during operation. This is important in order to have more accurate results when experiencing different charge/discharge currents.
- We now can implement the base equations in the matlab code and modify the variables that define the problem to achieve the desirable reserved energy with as low DOD as possible. A first step to achieve this is done by knowing the generic mathematical equations that define the energy behavior of the batteries.
- The DOD dependency is apparent when we are attempting a vessel's hybridization, because as it rises the battery capacity fade becomes larger which leads to degradation in less time, meaning that the modules no longer meet their initial charge/discharge rates.

- Charge time and power of shore substation play a crucial role in the sizing. Bigger power means flexibility for a wide variety of vessels with different energy needs. Time also must be enough, in order to have adequate remaining energy.
- The scenario we created does not need consideration for the number of battery packs as the rules indicate (4 or 2 in order to have safe return in case of failure of the one side depending on the capacity of the ESS) because the hotel loads during sea transiting are covered by the shaft generators.
- With the hybrid configuration developed in this paper we have optimal efficiency during all vessel states (sea transiting, maneuvering) because we can avert grounding or collision when near the port by employing the motor mode by means of ''regenerative braking'' and the incomparable performance of diesel engines at sea compared to the induction motors.
- Lowering the DOD creates a more cost effective system with bigger life. By increasing the DOD capacity fade comes sooner but you have lower initial investment. Although this is often determined by the class rules depending on the flag of the ship the designer must have a clear view on its impacts on a dynamic situation like a sizing/investment analysis project.
- The case study presents a viable choice for a vessel in the stage of newbuilding or retrofitting because considering the penalties that implicate the impact on human health and the stringent regulations in ECAs the investment is worth. Over a 9 year period the owner will help to the preservation of the environment and have economic benefits with a very reasonable internal rate of return.
- A retrofit like this is more appropriate for vessels that were built maximum 10 years ago in order an investment like this to be beneficial.

Our conclusion is that hybridization of a mid-size Ro-Pax is more feasible considering the current technology and battery prices.

9.2 Recommendations for future work

- There should be an investigation of the NTGK semi-empirical method simulation by dividing the battery cell in different zones and by creating for every material a layer with different properties. This should give better results.
- Other semi-empirical models must be employed in order to investigate the battery thermal/electrochemical behavior which can capture more accurately this phenomenon. Suggested models are:
    - Equivalent Circuit Model (ECM) model
    - Newman Pseudo-2D (P2D) model

With emphasis in the second regarding its precision.

- The development of a 3D model would be more accurate than the aforementioned in order to have better results compared to the 2D models.
- Under normal battery operation, the battery's positive and negative electrodes are divided by a separator, usually a thin polymer material that prevents electrons from traveling directly from the negative electrode to the positive electrode. In the case of an internal short-circuit, which could be a result of a nail penetration or a crash accident due to vessel's movements (roll), the separator is ruptured in a localized area. Besides providing the normal tab current, the battery produces a secondary electric current from electrochemical reactions that is wasted through the shorted area. Because this is something that can easily happen on a ship we believe there is a need for investigation in order to design the electrical system in a way to prevent total failure of the battery pack.

- The next step is to have original experimental data for the batteries in order to accurately predict the discharge-charge current equations. Then we can combine them with the ones derived from the matlab code and modify the variables that define the problem to achieve the desirable reserved energy with as low DOD as possible

- Feasibility studies should be investigated for other types of vessels as well that have a variable load profile and operate in part load most of the time like tug boats, special purpose vessels etc.

- The dependency of the different charge /discharge currents must be investigated in order to predict accurately the shore substation output and the charge time when at port. This is an important step for ship owners in order to regulate the vessels' routes and timetables according to an optimized energy performance.

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Appendix

The original electrical load balance created for the vessel under study is presented in below:

CONDITION					PEAK LOADS					
					24 HRS AT SEA		MANOUEVERING		AT PORT	
AUX. MACH. FOR PROPULSION	nominal consumed	NO OF UNITS		CONN. LOAD	fs	KW	fs	KW	fs	KW
	KW	TOTAL	IN USE	KW						
F.O. SUP. UNIT	6,85	1	1	6,85	0,75	5,1375	0,75	5,1375	0,75	5,1375
M/E AIR COMPRESSOR	11	2	1	11	0,2	2,2	0,7	7,7	0	0
M/E F.W. PREHEATER	10,5	2	2	21	0	0	0	0	0,2	4,2
No2 M/E F.W. PREHEATER	10,5	2	2	21	0	0	0	0	0,2	4,2
D/G F.W .PREHEATER	10	1	1	10	0	0	0	0	0,2	2
D/GF.O.LINE HEATER	5	2	1	5	0,2	1	0,2	1	0,2	1
C.W. CIRC. PUMP	22	3	2	44	0,8	35,2	0,8	35,2	0,5	22
M/E L.O.PUMP	19	2	1	19	0,8	15,2	0,8	15,2	0	0
RED & CLUTCH L.O. PUMP	18,5	2	1	18,5	0,8	14,8	0,8	14,8	0	0
BOILLER FEED. PUMP	7,5	2	1	7,5	0,2	1,5	0,2	1,5	0,2	1,5
D/G S.W. PUMP	5,5	3	2	11	0,8	8,8	0,8	8,8	0,8	8,8
H.F.O. PURIFIER	5,5	2	1	5,5	0,8	4,4	0,8	4,4	0,8	4,4
L.O. PURIFIER	5,5	2	1	5,5	0,8	4,4	0,8	4,4	0,9	4,95
BOILLER F.W. PUMP	3,7	4	2	7,4	0,2	1,48	0,2	1,48	0,2	1,48
BURNER	5,5	2	2	11	0,5	5,5	0,5	5,5	0,5	5,5
ST. GEAR	7,5	2	1	7,5	0,7	5,25	0,7	5,25	0	0
H.F.O. X-FER PUMP "A"	1,5	2	1	1,5	0,4	0,6	0,4	0,6	0,4	0,6
D/G C.F.W. PUMP	5,5	3	1	5,5	0,5	2,75	0,5	2,75	1	5,5
M/E C.S.W. PUMP	18,5	2	1	18,5	0,5	9,25	0,5	9,25	0,5	9,25
HFO X-FER PUMP "B"	3,7	2	1	3,7	0,7	2,59	0,7	2,59	0,7	2,59
D/G H.F.O.CIRC. PUMP	0,75	1	1	0,75	0,5	0,375	0,5	0,375	0,5	0,375
				TOTALS		120,43		125,93		83,48

CONDITION					PEAK LOADS					
					24 HRS AT SEA		MANOUEVERING		AT PORT	
MACHINERIES, PUMPS	nominal consumed	NO OF UNITS		CONN. LOAD	fs	KW	fs	KW	fs	KW
	KW	TOTAL	IN USE	KW						
BOW THRUSTER	600	1	1	600	0	0	0,6	360	0	0
FIN. STAB. MOTOR	21	2	2	42	0,5	21	0	0	0	0
ANCHOR / WINDLASS	55	2	2	110	0	0	0,2	22	0	0
CAPSTAN & HYDR. FOR PUMP	55	2	2	110	0	0	0,2	22	0	0
SLUDGE PUMP	1,5	1	1	1,5	0,2	0,3	0,2	0,3	0,2	0,3
D/G L.O. PRIMARY PUMP	0,63	3	3	1,89	0,1	0,189	0	0	0	0
E/R OVERHEAD CRANE	3,8	2	1	3,8	0	0	0	0	0	0
ANT. HEEL. PUMP	28,7	1	1	28,7	0	0	0	0	0,2	5,74
OILY W. SEPARATOR	5,6	1	1	5,6	0,2	1,12	0,2	1,12	0,2	1,12
SPRINKLER PUMP	45	1	1	45	0	0	0	0	0	0
SPRAY/DRENCHER PUMP	55	1	1	55	0	0	0	0	0	0
FIRE & BILGE PUMP	45	2	1	45	0	0	0	0	0	0
AIR COMPRESSOR	11	2	1	11	0,3	3,3	0,3	3,3	0,3	3,3
E/R LOCAL APLICATION	5,5	1	1	5,5	0,5	2,75	0,5	2,75	0,5	2,75
CALORIFIER	35	2	1	35	0,5	17,5	0,5	17,5	0,5	17,5
EM. FIRE & BILGE	30	2	1	30	0	0	0	0	0	0
ELEVATORS/ESCALATOR	28	1	1	28	0,5	14	0,5	14	0,5	14
RESQUE BOAT	45	1	1	45	0	0	0	0	0	0
FIN. STABILIZER	21	1	1	21	0,5	10,5	0	0	0	0
SUBMERCIBLE PUMP	5	1	1	5	0	0	0	0	0	0
VACUUM SYSTEM	15	1	1	15	0,5	7,5	0,5	7,5	0,5	7,5
W.T. DOORS	3,5	1	1	3,5	0	0	0	0	0	0
F W FEED UP PUMP	52	1	1	52	0,5	26	0,5	26	0,5	26
BILGE X-FER PUMP	1,5	1	1	1,5	0,5	0,75	0,5	0,75	0,5	0,75
FIN.STAB. C.F.W. PUMP	2,2	1	1	2,2	0,5	1,1	0,5	1,1	0,5	1,1
DEFROSTER	2	2	1	2	0,5	1	0,5	1	0,5	1
AIR COMPRESSOR	30	1	1	30	0,3	9	0,3	9	0,3	9
AIR COMPRESSOR	30	1	1	30	0,3	9	0,3	9	0,3	9
F.W. HYD. UNIT PUMP	11	2	1	11	0,7	7,7	0,7	7,7	0,7	7,7
HOT WATER C. PUMP	0,75	1	1	0,75	0,7	0,525	0,7	0,525	0,7	0,525
				TOTALS		133,23		505,55		107,29

CONDITION					PEAK LOADS					
					24 HRS AT SEA		MANOUEVERING		AT PORT	
MACHINERIES, PUMPS	nominal consumed	NO OF UNITS		CONN. LOAD	fs	KW	fs	KW	fs	KW
	KW	TOTAL	IN USE	KW						
AC 1.7.2				11	0,7	0	0,7	0	0,7	0
AC 1.7.1	3,7			35	0,7	0	0,7	0	0,7	0
AC 2.8.1				35	0,7	0	0,7	0	0,7	0
AC 1.5.1				11	0,7	0	0,7	0	0,7	0
AC 2.3.1				3	0,7	0	0,7	0	0,7	0
ECR A/C UNIT	4	1	1	4	0,7	2,8	0,7	2,8	0,7	2,8
CHILLER No1	30	1	1	30	0,5	15	0,5	15	0,5	15
CHILLER No2	20	1	1	20	0	0	0	0	0	0
CHILLER ESWC100	80	1	1	80	0,5	40	0,5	40	0,5	40
S.W. PUMP	11	1	1	11	0,5	5,5	0,5	5,5	0,5	5,5
A/C S.W. PUMP	11	3	2	22	0,8	17,6	0,8	17,6	0,5	11
				TOTALS		80,9		80,9		74,3

CONDITION					PEAK LOADS					
					24 HRS AT SEA		MANOUEVERING		AT PORT	
MACHINERIES, PUMPS	nominal consumed	NO OF UNITS		CONN. LOAD	fs	KW	fs	KW	fs	KW
	KW	TOTAL	IN USE	KW						
GARAGE FAN EF-12	22	1	1	22	0	0	0,7	15,4	0,7	15,4
GARAGE FAN EF-13	22	1	1	22	0	0	0,7	15,4	0,7	15,4
GARAGE FAN EF-14	22	1	1	22	0	0	0,7	15,4	0,7	15,4
GARAGE FAN EF-15	22	1	1	22	0	0	0,7	15,4	0,7	15,4
E1 ACC EX. FAN	0,75	1	1	0,75	0,7	0,525	0,7	0,525	0,7	0,525
E2 ACC EX. FAN	0,75	1	1	0,75	0,7	0,525	0,7	0,525	0,7	0,525
E13 ACC EX. FAN	1	1	1	1	0,7	0,7	0,7	0,7	0,7	0,7
E3 ACC EX. FAN	1,5	1	1	1,5	0,7	1,05	0,7	1,05	0,7	1,05
E4 ACC EX. FAN	1,5	1	1	1,5	0,7	1,05	0,7	1,05	0,7	1,05
E9 ACC EX. FAN	0,4	1	1	0,4	0,7	0,28	0,7	0,28	0,7	0,28
E5 GALLEY EX. FAN	1	1	1	1	0,7	0,7	0,7	0,7	0,7	0,7
E6 ACC EX. FAN	1,5	1	1	1,5	0,7	1,05	0,7	1,05	0,7	1,05
E7 ACC EX. FAN	0,75	1	1	0,75	0,7	0,525	0,7	0,525	0,7	0,525
E8 ACC EX. FAN	0,75	1	1	0,75	0,7	0,525	0,7	0,525	0,7	0,525
E11 ACC EX. FAN	1	1	1	1	0,7	0,7	0,7	0,7	0,7	0,7
E12 ACC EX. FAN	1	1	1	1	0,7	0,7	0,7	0,7	0,7	0,7
E/R SUP. FAN No1	22	1	1	22	0,7	15,4	0,7	15,4	0,7	15,4
E/R SUP. FAN No2	22	1	1	22	0,7	15,4	0,7	15,4	0,7	15,4
SHAFT RM SUP. FAN	3,7	1	1	3,7	0,7	2,59	0,7	2,59	0,7	2,59
B. THRUSTER FAN	1,5	1	1	1,5	0,7	1,05	0,7	1,05	0,7	1,05
ST. GEAR RM FAN	3,7	1	1	3,7	0,7	2,59	0,7	2,59	0,7	2,59
E/R SUP. FAN	22	2	2	44	0,7	30,8	0,7	30,8	0,7	30,8
E/R EX. FAN	15	2	1	15	0,7	10,5	0,7	10,5	0,7	10,5
PUMP ROOM SUP FAN	2,2	1	1	2,2	0,7	1,54	0,7	1,54	0,7	1,54
PUMP ROOM SUP FAN	2,2	1	1	2,2	0,7	1,54	0,7	1,54	0,7	1,54
SHAFT RM EX. FAN	1,5	1	1	1,5	0,7	1,05	0,7	1,05	0,7	1,05
SHAFT RM EX. FAN	3,7	1	1	3,7	0,7	2,59	0,7	2,59	0,7	2,59
EP-11	3,7	1	1	3,7	0,7	2,59	0,7	2,59	0,7	2,59
				TOTALS		95,97		157,57		157,57

CONDITION					PEAK LOADS					
					24 HRS AT SEA		MANOUEVERING		AT PORT	
MACHINERIES, PUMPS	nominal consumed	NO OF UNITS		CONN. LOAD	fs	KW	fs	KW	fs	KW
	KW	TOTAL	IN USE	KW						
NAV. EQUIPMENTS				0,3	1	0,3	15,4	4,62	1	0,3
MAIN LIGHTING 220V				78,4	1	78,4	1	78,4	1	78,4
EM. LIGHTING 220V				20	1	20	1	20	1	20
UPS LIGHITNG				11	1	11	1	11	1	11
BAT. CHARGER				2,5	1	2,5	1	2,5	1	2,5
GALLEY & BAR EQUIPMENT 220V				52,1	0,2	10,42	0,2	10,42	0,2	10,42
GALLEY & BAR EQUIPMENT 440V				163,6	0,2	32,72	0,2	32,72	0,2	32,72
REEFER SOCKETS	10	6	6	60	0,3	18	0,3	18	0	0
				TOTALS		173,34		177,66		155,34

24 HRS AT SEA	MANOUEVERING	AT PORT	
603,88	1047,61	577,98	
TIME (hrs)	0,25	1	TOTAL (Kwh)
ENERGY (Kwh)	261,901875	577,9775	839,879375

The case study electrical load balance is presented in the next pages.

CONDITION					PEAK LOADS					
					24 HRS AT SEA		MANOUEVERING		AT PORT	
AUX. MACH. FOR PROPULSION	nominal consumed	NO OF UNITS		CONN. LOAD	fs	KW	fs	KW	fs	KW
	KW	TOTAL	IN USE	KW						
F.O. SUP. UNIT	6,85	1	1	6,85	0,75	5,1375	0	0	0	0
M/E AIR COMPRESSOR	11	2	1	11	0,2	2,2	0	0	0	0
M/E F.W. PREHEATER	10,5	2	2	21	0	0	0	0	0	0
No2 M/E F.W. PREHEATER	10,5	2	2	21	0	0	0	0	0	0
D/G F.W .PREHEATER	10	1	1	10	0	0	0,2	2	0,2	2
D/GF.O.LINE HEATER	5	2	1	5	0,2	1	0,2	1	0,2	1
C.W. CIRC. PUMP	22	3	2	44	0,8	35,2	0,8	35,2	0,5	22
M/E L.O.PUMP	19	2	1	19	0,8	15,2	0	0	0	0
RED & CLUTCH L.O. PUMP	18,5	2	1	18,5	0,8	14,8	0	0	0	0
BOILLER FEED. PUMP	7,5	2	1	7,5	0,2	1,5	0	0	0	0
D/G S.W. PUMP	5,5	3	2	11	0,8	8,8	0,8	8,8	0,8	8,8
H.F.O. PURIFIER	5,5	2	1	5,5	0,8	4,4	0	0	0	0
L.O. PURIFIER	5,5	2	1	5,5	0,8	4,4	0	0	0	0
BOILLER F.W. PUMP	3,7	4	2	7,4	0,2	1,48	0	0	0	0
BURNER	5,5	2	2	11	0,5	5,5	0	0	0	0
ST. GEAR	7,5	2	1	7,5	0,7	5,25	0,7	5,25	0	0
H.F.O. X-FER PUMP "A"	1,5	2	1	1,5	0,4	0,6	0	0	0	0
D/G C.F.W. PUMP	5,5	3	1	5,5	0,5	2,75	0,5	2,75	1	5,5
M/E C.S.W. PUMP	18,5	2	1	18,5	0,5	9,25	0	0	0	0
HFO X-FER PUMP "B"	3,7	2	1	3,7	0,7	2,59	0	0	0	0
D/G H.F.O.CIRC. PUMP	0,75	1	1	0,75	0,5	0,375	0,5	0,375	0,5	0,375
				TOTALS		120,43		55,38		39,68

CONDITION					PEAK LOADS					
					24 HRS AT SEA		MANOUEVERING		AT PORT	
MACHINERIES, PUMPS	nominal consumed	NO OF UNITS		CONN. LOAD	fs	KW	fs	KW	fs	KW
	KW	TOTAL	IN USE	KW						
BOW THRUSTER	600	1	1	600	0	0	0,7	420	0	0
FIN. STAB. MOTOR	21	2	2	42	0,5	21	0	0	0	0
ANCHOR / WINDLASS	55	2	2	110	0	0	0,2	22	0	0
CAPSTAN & HYDR. FOR PUMP	55	2	2	110	0	0	0,2	22	0	0
SLUDGE PUMP	1,5	1	1	1,5	0,2	0,3	0,2	0,3	0,2	0,3
D/G L.O. PRIMARY PUMP	0,63	3	3	1,89	0,1	0,189	0	0	0	0
E/R OVERHEAD CRANE	3,8	2	1	3,8	0	0	0	0	0	0
ANT. HEEL. PUMP	28,7	1	1	28,7	0	0	0	0	0,2	5,74
OILY W. SEPARATOR	5,6	1	1	5,6	0,2	1,12	0,2	1,12	0,2	1,12
SPRINKLER PUMP	45	1	1	45	0	0	0	0	0	0
SPRAY/DRENCHER PUMP	55	1	1	55	0	0	0	0	0	0
FIRE & BILGE PUMP	45	2	1	45	0	0	0	0	0	0
AIR COMPRESSOR	11	2	1	11	0,3	3,3	0,3	3,3	0,3	3,3
E/R LOCAL APLICATION	5,5	1	1	5,5	0,5	2,75	0,5	2,75	0,5	2,75
CALORIFIER	35	2	1	35	0,5	17,5	0,5	17,5	0,5	17,5
EM. FIRE & BILGE	30	2	1	30	0	0	0	0	0	0
ELEVATORS/ESCALATOR	28	1	1	28	0,5	14	0,5	14	0,5	14
RESQUE BOAT	45	1	1	45	0	0	0	0	0	0
FIN. STABILIZER	21	1	1	21	0,5	10,5	0	0	0	0
SUBMERCIBLE PUMP	5	1	1	5	0	0	0	0	0	0
VACUUM SYSTEM	15	1	1	15	0,5	7,5	0,5	7,5	0,5	7,5
W.T. DOORS	3,5	1	1	3,5	0	0	0	0	0	0
F W FEED UP PUMP	52	1	1	52	0,5	26	0,5	26	0,5	26
BILGE X-FER PUMP	1,5	1	1	1,5	0,5	0,75	0,5	0,75	0,5	0,75
FIN.STAB. C.F.W. PUMP	2,2	1	1	2,2	0,5	1,1	0,5	1,1	0,5	1,1
DEFROSTER	2	2	1	2	0,5	1	0,5	1	0,5	1
AIR COMPRESSOR	30	1	1	30	0,3	9	0,3	9	0,3	9
AIR COMPRESSOR	30	1	1	30	0,3	9	0,3	9	0,3	9
F.W. HYD. UNIT PUMP	11	2	1	11	0,7	7,7	0,7	7,7	0,7	7,7
HOT WATER C. PUMP	0,75	1	1	0,75	0,7	0,525	0,7	0,525	0,7	0,525
				TOTALS		133,23		565,55		107,29

CONDITION					PEAK LOADS					
					24 HRS AT SEA		MANOUEVERING		AT PORT	
MACHINERIES, PUMPS	nominal consumed	NO OF UNITS		CONN. LOAD	fs	KW	fs	KW	fs	KW
	KW	TOTAL	IN USE	KW						
AC 1.7.2				11	0,7	0	0,7	0	0,7	0
AC 1.7.1	3,7			35	0,7	0	0,7	0	0,7	0
AC 2.8.1				35	0,7	0	0,7	0	0,7	0
AC 1.5.1				11	0,7	0	0,7	0	0,7	0
AC 2.3.1				3	0,7	0	0,7	0	0,7	0
ECR A/C UNIT	4	1	1	4	0,7	2,8	0,7	2,8	0,7	2,8
CHILLER No1	30	1	1	30	0,5	15	0,5	15	0,5	15
CHILLER No2	20	1	1	20	0	0	0	0	0	0
CHILLER ESWC100	80	1	1	80	0,5	40	0,5	40	0,5	40
S.W. PUMP	11	1	1	11	0,5	5,5	0,5	5,5	0,5	5,5
A/C S.W. PUMP	11	3	2	22	0,8	17,6	0,8	17,6	0,5	11
				TOTALS		80,9		80,9		74,3

CONDITION					PEAK LOADS					
					24 HRS AT SEA		MANOUEVERING		AT PORT	
MACHINERIES, PUMPS	nominal consumed	NO OF UNITS		CONN. LOAD	fs	KW	fs	KW	fs	KW
	KW	TOTAL	IN USE	KW						
GARAGE FAN EF-12	22	1	1	22	0	0	0,7	15,4	0,7	15,4
GARAGE FAN EF-13	22	1	1	22	0	0	0,7	15,4	0,7	15,4
GARAGE FAN EF-14	22	1	1	22	0	0	0,7	15,4	0,7	15,4
GARAGE FAN EF-15	22	1	1	22	0	0	0,7	15,4	0,7	15,4
E1 ACC EX. FAN	0,75	1	1	0,75	0,7	0,525	0,7	0,525	0,7	0,525
E2 ACC EX. FAN	0,75	1	1	0,75	0,7	0,525	0,7	0,525	0,7	0,525
E13 ACC EX. FAN	1	1	1	1	0,7	0,7	0,7	0,7	0,7	0,7
E3 ACC EX. FAN	1,5	1	1	1,5	0,7	1,05	0,7	1,05	0,7	1,05
E4 ACC EX. FAN	1,5	1	1	1,5	0,7	1,05	0,7	1,05	0,7	1,05
E9 ACC EX. FAN	0,4	1	1	0,4	0,7	0,28	0,7	0,28	0,7	0,28
E5 GALLEY EX. FAN	1	1	1	1	0,7	0,7	0,7	0,7	0,7	0,7
E6 ACC EX. FAN	1,5	1	1	1,5	0,7	1,05	0,7	1,05	0,7	1,05
E7 ACC EX. FAN	0,75	1	1	0,75	0,7	0,525	0,7	0,525	0,7	0,525
E8 ACC EX. FAN	0,75	1	1	0,75	0,7	0,525	0,7	0,525	0,7	0,525
E11 ACC EX. FAN	1	1	1	1	0,7	0,7	0,7	0,7	0,7	0,7
E12 ACC EX. FAN	1	1	1	1	0,7	0,7	0,7	0,7	0,7	0,7
E/R SUP. FAN No1	22	1	1	22	0,7	15,4	0,7	15,4	0,7	15,4
E/R SUP. FAN No2	22	1	1	22	0,7	15,4	0,7	15,4	0,7	15,4
SHAFT RM SUP. FAN	3,7	1	1	3,7	0,7	2,59	0,7	2,59	0,7	2,59
B. THRUSTER FAN	1,5	1	1	1,5	0,7	1,05	0,7	1,05	0,7	1,05
ST. GEAR RM FAN	3,7	1	1	3,7	0,7	2,59	0,7	2,59	0,7	2,59
E/R SUP. FAN	22	2	2	44	0,7	30,8	0,7	30,8	0,7	30,8
E/R EX. FAN	15	2	1	15	0,7	10,5	0,7	10,5	0,7	10,5
PUMP ROOM SUP FAN	2,2	1	1	2,2	0,7	1,54	0,7	1,54	0,7	1,54
PUMP ROOM SUP FAN	2,2	1	1	2,2	0,7	1,54	0,7	1,54	0,7	1,54
SHAFT RM EX. FAN	1,5	1	1	1,5	0,7	1,05	0,7	1,05	0,7	1,05
SHAFT RM EX. FAN	3,7	1	1	3,7	0,7	2,59	0,7	2,59	0,7	2,59
EP-11	3,7	1	1	3,7	0,7	2,59	0,7	2,59	0,7	2,59
				TOTALS		95,97		157,57		157,57

CONDITION					PEAK LOADS					
					24 HRS AT SEA		MANOUEVERING		AT PORT	
MACHINERIES, PUMPS	nominal consumed	NO OF UNITS		CONN. LOAD	fs	KW	fs	KW	fs	KW
	KW	TOTAL	IN USE	KW						
NAV. EQUIPMENTS				0,3	1	0,3	15,4	4,62	1	0,3
MAIN LIGHTING 220V				78,4	1	78,4	1	78,4	1	78,4
EM. LIGHTING 220V				20	1	20	1	20	1	20
UPS LIGHITNG				11	1	11	1	11	1	11
BAT. CHARGER				2,5	1	2,5	1	2,5	1	2,5
GALLEY & BAR EQUIPMENT 220V				52,1	0,2	10,42	0,2	10,42	0,2	10,42
GALLEY & BAR EQUIPMENT 440V				163,6	0,2	32,72	0,2	32,72	0,2	32,72
REEFER SOCKETS	10	6	6	60	0,3	18	0,3	18	0	0
				TOTALS		173,34		177,66		155,34

24 HRS AT SEA	MANOUEVERING	AT PORT
603,88	1037,05	534,17

TIME (hrs)	0,25	1	TOTAL (Kwh)
ENERGY (Kwh)	259,2625	534,17	793,4325

The electric load balance of the vessel under study is presented above. Because in the scenario we are considering the vessel when at port or during maneuvering is not using its main engines, the fs values of the machinery related to the main propulsion of the vessel were replaced with zero.

The steering gear is important for the operation of the rudder so cannot be excluded from the calculations as well as the auxiliary machineries that are related to the generators, because the previous gensets will be replaced by two shaft generators. Only the emergency generator will be kept.

AUX. MACH. FOR PROPULSION	nominal consumed	NO OF UNITS		CONN. LOAD	PEAK LOADS 24 HRS AT SEA		MANOUEVERING		AT PORT	
CONDITION	KW	TOTAL	IN USE	KW	fs	KW	fs	KW	fs	KW
F.O. SUP. UNIT	6,85	1	1	6,85	0	0	0	0	0	0
M/E AIR COMPRESSOR	11	2	1	11	0	0	0	0	0	0
M/E F.W. PREHEATER	10,5	2	2	21	0	0	0	0	0	0
No2 M/E F.W. PREHEATER	10,5	2	2	21	0	0	0	0	0	0
D/G F.W .PREHEATER	10	1	1	10	0,2	2	0,2	2	0,2	2
D/GF.O.LINE HEATER	5	2	1	5	0,2	1	0,2	1	0,2	1
C.W. CIRC. PUMP	22	3	2	44	0,8	35,2	0,8	35,2	0,5	22
M/E L.O.PUMP	19	2	1	19	0	0	0	0	0	0
RED & CLUTCH L.O. PUMP	18,5	2	1	18,5	0	0	0	0	0	0
BOILLER FEED. PUMP	7,5	2	1	7,5	0	0	0	0	0	0
D/G S.W. PUMP	5,5	3	2	11	0,8	8,8	0,8	8,8	0,8	8,8
H.F.O. PURIFIER	5,5	2	1	5,5	0	0	0	0	0	0
L.O. PURIFIER	5,5	2	1	5,5	0	0	0	0	0	0
BOILLER F.W. PUMP	3,7	4	2	7,4	0	0	0	0	0	0
BURNER	5,5	2	2	11	0	0	0	0	0	0
ST. GEAR	7,5	2	1	7,5	0,7	5,25	0,7	5,25	0	0
H.F.O. X-FER PUMP "A"	1,5	2	1	1,5	0	0	0	0	0	0
D/G C.F.W. PUMP	5,5	3	1	5,5	0,5	2,75	0,5	2,75	1	5,5
M/E C.S.W. PUMP	18,5	2	1	18,5	0	0	0	0	0	0
HFO X-FER PUMP "B"	3,7	2	1	3,7	0	0	0	0	0	0
D/G H.F.O.CIRC. PUMP	0,75	1	1	0,75	0,5	0,375	0,5	0,375	0,5	0,375
				TOTALS		55,38		55,38		39,68

high voltage induction motor	nominal output	NO OF UNITS		load	24 HRS AT SEA		MANOUEVERING		AT PORT	
	KW	TOTAL	IN USE		fs	KW	fs	KW	fs	KW
	8000	2	2	16000	0,8	12800	0,58	9280	0	0
propulsion motor cooling fan	10	2	2	20	0,7	14	0,7	14	0	0
propulsion motor excitation power	30	2	2	60	0,6	36	0,5	30	0	0
propulsion transformer cooling fan	2	2	2	4	0,7	2,8	0,7	2,8	0	0

	24 HRS AT SEA	MANOUEVERING	AT PORT	
	13391,62	10303,85	534,17	
TIME (hrs)	1	0,25	1	TOTAL (Kwh)
ENERGY (Kwh)	13391,619	2575,9625	534,17	16501,7515

The modifications in the electric load balance for the full electrification investigation is presented above. The tables above depict the changes for the case of the battery ship.

Now in the full electrification scenario we have the option of going full batteries or keeping the diesel generators in order to fulfill the hotel loads and the bow thruster. Since the power output of the high voltage induction motors we are going to employ for main propulsion is much higher from that of the generators onboard, the sole power source for them should be the batteries.

Because every trip lasts for about 1 hour the battery energy needed is 12800 kWh.

The modifications in this diesel/electric scenario are presented below. Basically everything that contributes to the work of the main diesel engines is excluded. The sludge pump and the oily water separators will be kept because even if there will be no diesel engines that create contaminants in the bilge region of the ship, the generators need lub oil and many machineries create leakages of particulate matter than need treatment.

AUX. MACH. FOR PROPULSION	CONDITION				PEAK LOADS					
	nominal consumed	NO OF UNITS		CONN. LOAD	24 HRS AT SEA		MANOUEVERING		AT PORT	
	KW	TOTAL	IN USE	KW	fs	KW	fs	KW	fs	KW
F.O. SUP. UNIT	6,85	1	1	6,85	0,75	5,1375	0,75	5,1375	0,75	5,1375
M/E AIR COMPRESSOR	11	2	1	11	0	0	0	0	0	0
M/E F.W. PREHEATER	10,5	2	2	21	0	0	0	0	0	0
No2 M/E F.W. PREHEATER	10,5	2	2	21	0	0	0	0	0	0
D/G F.W .PREHEATER	10	1	1	10	0	0	0	0	0,2	2
D/GF.O.LINE HEATER	5	2	1	5	0,2	1	0,2	1	0,2	1
C.W. CIRC. PUMP	22	3	2	44	0,8	35,2	0,8	35,2	0,5	22
M/E L.O.PUMP	19	2	1	19	0	0	0	0	0	0
RED & CLUTCH L.O. PUMP	18,5	2	1	18,5	0	0	0	0	0	0
BOILLER FEED. PUMP	7,5	2	1	7,5	0	0	0	0	0	0
D/G S.W. PUMP	5,5	3	2	11	0,8	8,8	0,8	8,8	0,8	8,8
H.F.O. PURIFIER	5,5	2	1	5,5	0,8	4,4	0,8	4,4	0,8	4,4
L.O. PURIFIER	5,5	2	1	5,5	0,8	4,4	0,8	4,4	0,9	4,95
BOILLER F.W. PUMP	3,7	4	2	7,4	0	0	0	0	0	0
BURNER	5,5	2	2	11	0	0	0	0	0	0
ST. GEAR	7,5	2	1	7,5	0,7	5,25	0,7	5,25	0	0
H.F.O. X-FER PUMP "A"	1,5	2	1	1,5	0,4	0,6	0,4	0,6	0,4	0,6
D/G C.F.W. PUMP	5,5	3	1	5,5	0,5	2,75	0,5	2,75	1	5,5
M/E C.S.W. PUMP	18,5	2	1	18,5	0	0	0	0	0	0
HFO X-FER PUMP "B"	3,7	2	1	3,7	0	0	0	0	0	0
D/G H.F.O.CIRC. PUMP	0,75	1	1	0,75	0,5	0,375	0,5	0,375	0,5	0,375
				TOTALS		67,91		67,91		54,76

We are going to investigate the diesel electric scenario for the full electrification because it is more efficient than the full battery one. The reason behind this is that there will not be needed extra batteries for the hotel loads and the bow thruster, which leads to converters, transformers of smaller output power and fewer cables.

The high voltage induction motors that fit our application have nominal power output of 8000 kW. The technical characteristics are shown in the table below:

IP55 - IC 81W - Insulation class F, temperature rise class B

Output kW	Motor type	Product ID	Speed r/min	Efficiency Full load 100 %	Efficiency 3/4 load 75 %	Power factor Full load 100 %	Power factor 3/4 load 75 %	Current I_N A	Current I_S/I_N	Current I_0 A	Torque T_N Nm	Torque T_S/T_N	Torque T_{max}/T_N	Rotor inertia kgm²	Motor weight kg	Sound pressure level L_P dB(A)
1500 r/min = 4 poles				3000 V 50 Hz												
8000	AMI 630L4L B	10549	1491	97.4	97.6	0.89	0.89	1771	5.3	351	51221	0.5	2.3	237.9	12850	84

energy required for every trip	12800	kwh
capacity of battery module	69	Ah
total capacity of batteries	1251936	Ah
maximum cont. current	140	A
cable chosen for batteries	1x35	145 A

required energy installed	32000	kwh
energy of battery module	1,766	kwh
main bus voltage	440	V

bat. Module voltage	24	V
Number of batteries in series	18,33333333	18
number of batteries parallel	1006,669183	1008
total number of batteries	18144	
weight of battery module	18,6	kg
total weight of batteries	337478,4	kg
length of battery module	0,306	m
height of battery module	0,225	m
width of battery module	0,172	m
volume of battery module	0,0118422	m^3
total volume of batteries	214,8648768	m^3
energy installed ON BOARD	32042,304	kwh

It is clear that the diesel electric scenario needs a lot of energy on board that leads to a cost effective investment plan when it is combined with two brand new induction motors of 8000 kW power output each. Another concerning fact is that the weight of the batteries can create various problems in the machine room of the vessel.

First of all the volume of the batteries is very large and there will be a big problem arranging them according to regulations in the engine room. It is not infeasible but very challenging. Of course there will be structural problems that can lead to the reinforcement of the inner bottom plating furthermore, due to concentrated loads. Stiffeners will have to be installed longitudinally and transversely to reduce the bending of the plate under load and maybe some pillars to take the compression loads. Finally the stability will change because the packs will induce trim on the vessel, thus fore ballast tanks must be filled. But these tanks are designed for the operation of the vessel without the additional 337.4* tons so they may reach their limits. Generally aside from the initial investment for the main compartments of the diesel electric configuration many other costs arise that are related to them.

*We assume that the weight of the electric motors and the preinstalled four stroke diesel engines is almost the same.

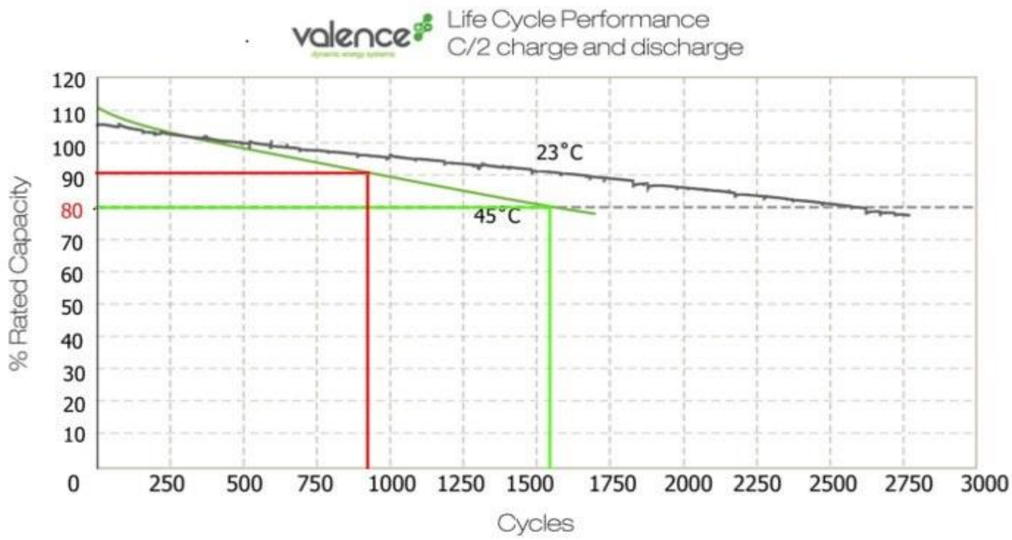
D.O.D investigation

At this point is worth mentioning that a problem is presented before us. The relation between D.O.D and investment.

If we increase the D.O.D then we shorten the life cycle of our batteries as shown in the diagram bellow hence it is possible that we will need sooner to replace the modules.

But on the other hand if we decrease the D.O.D then our initial investment is becoming larger.

We are going to investigate this relationship with some data provided on Valence web page and calculations from our part.



*The diagram is referred to C/2 rate of charge/discharge

We are considering the 45 degrees Celsius line (dark green) because the modules are going to be installed inside the engine room where the average temperature is usually 43-45 degrees Celsius due to the large number of machineries running at the same time.

The difference is that with 80% D.O.D the life cycles are 1550 but with 90% D.O.D they are 900. There is a considerable difference of **41.93** % .

On the other hand in the table bellow we calculated the initial investment in accordance to the D.O.D

DOD	Emin	battery strings	battery strings	investment required ($)
0,95	662,4014	20,83809625	21	378000
0,94	669,4482	21,05977812	22	396000
0,93	676,6466	21,28622735	22	396000
0,92	684,0014	21,51759939	22	396000
0,91	691,5179	21,75405652	22	396000
0,9	699,2015	21,99576826	22	396000
0,89	707,0577	22,24291172	23	414000
0,88	715,0924	22,49567209	23	414000
0,87	723,3119	22,75424303	23	414000
0,86	731,7225	23,01882725	24	432000
0,85	740,331	23,28963698	24	432000
0,84	749,1444	23,56689457	24	432000
0,83	758,1703	23,85083305	24	432000
0,82	767,4163	24,14169687	25	450000
0,81	776,8905	24,43974251	25	450000
0,8	786,6017	24,74523929	25	450000
0,79	796,5586	25,05847017	26	468000
0,78	806,7709	25,37973261	26	468000
0,77	817,2485	25,70933953	26	468000
0,76	828,0018	26,04762031	27	486000
0,75	839,0418	26,39492191	27	486000
0,74	850,3802	26,75161005	27	486000
0,73	862,0292	27,11807046	28	504000
0,72	874,0019	27,49471033	28	504000
0,71	886,3117	27,88195977	28	504000
0,7	898,9733	28,28027348	29	522000

*Every string has 18 modules

The module price is approximately 1500$ and the difference between 80% and 90% of D.O.D. is 54000$. The difference is **12%** of the initial investment.

From the above we can easily understand that lower D.O.D is preferred due to the fact that we are going to spend a small percentage **(12%)** of money more at first when we are sizing our battery system but it is going to last almost **42%** percent longer. This advantage becomes magnified as the system energy needs become larger.

So in the stage of 900 cycles we will have spent 54000 $ more but we will have avoided 396000 $!!!