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Diploma Thesis:

“Techno-economic feasibility study on the retrofit of a conventional harbor tugboat into a battery powered one”

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Abstract

The high fuel oil prices, strict emission regulations as well as improved battery technologies and lower battery prices led to the development and use of novel technologies such as hybrid propulsion systems and cost effective and safe battery systems on the shipping industry. The commercial operation of the world's first fully electric powered car ferry started in 2015. Since this time battery systems have been increasingly adopted successfully on other ships.

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

The tugboat in question will be "Archaggelos" which will be operating inside and near the port of Piraeus in a very narrow and tight environment. Its range will be of maximum 5-10 nautical miles outside the port. The operational profile of the tug is based on a 12-hour daily operation, 365 days per year.

More specifically, two different technologies, a battery pack system built from lithium iron phosphate modules and a battery system based on the vanadium redox flow battery technology, are examined and compared to each other as well as to the conventional diesel-powered propulsion system.

Finally, from the findings of this study it is concluded that even though a battery system based on Lithium iron phosphate modules is technically doable, the present battery prices make the investment of the retrofit profitable but risky without the use of external funding. On the other hand, a battery system based on vanadium redox flow battery technology could be fitted in the tugboat and needs further technological improvements for it to be a viable solution for this specific application.

Key Words: battery ship, all-electric ship, emission quantification, regulations, future vessel, investment appraisal, Li-ion batteries, VRB system, retrofit methodology, harbor tugboat, operational profile, IMO, DNV-Gl, ABS.

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Table of Contents

Acknowledgments 2

Abstract 3

List of Figures: 8

List of Tables: 9

1 Introduction 10

1.1 Background of the Study 10

1.2 Problem Statement and Objectives: 11

1.3 Structure of the Study: 12

2 Environmental effects of shipping 13

2.1 Ship Emissions and their Impacts: 13

2.2 Air Pollution and Climate Change: 14

2.3 Air pollution, eco-system and biodiversity: 15

2.4 Air pollution and human health: 16

2.5 Economic impact of air pollution: 17

2.6 Dependency of shipping with the oil market: 17

2.7 Emission Control Areas and Tier I-III standards: 18

3 Batteries: 23

3.1 Definitions: 24

3.1.1 Battery Basics: 24

3.1.2 Battery Conditions: 24

3.1.3 Battery Technical Specifications: 25

3.2 Types of batteries: 27

3.2.1 Lead Acid: 27

3.2.2 Nickel-based batteries: 28

3.2.3 Lithium based batteries: 29

3.2.4 Summary: 36

3.3 Lithium-Ion Cell Types: 39

3.3.1 Cylindrical: 39

3.3.2 Prismatic Cell: 41

3.3.3 Pouch Cell: 41

3.3.4 Summary: 43

3.4 Future Battery Chemistries: 43

3.4.1 Lithium Based: 43
3.4.2 Redox Flow Batteries: 45
4 Tugboats 49
4.1 Propulsion Arrangements: 49
4.1.1 Conventional Tugs: 49
4.1.2 Azimuth Stern Drive Tugs (ASD): 50
4.1.3 Tractor Tugs: 51
4.1.4 Voith Tugs: 52
4.2 Tug functions: 52
4.2.1 Harbor Tugs: 53
4.2.2 Escort Tugs: 53
4.2.3 Seagoing Tugs: 54
4.2.4 Coastal Tugs: 54
4.2.5 Terminal Tugs: 54
4.2.6 Anchor-handling tugs: 55
4.2.7 Fire-fighting tugs: 55
4.3 Power Systems for tugboats: 55
4.3.1 Mechanical Propulsion: 55
4.3.2 Diesel-Electric Propulsion: 57
4.3.3 Hybrid Propulsion: 58
4.3.4 Electrical Propulsion with Hybrid Power Supply: 58
4.3.5 Hybrid Propulsion with Hybrid Power Supply: 59
4.3.6 All-Electric Propulsion System: 60
5 Legal and Regulatory Framework: 65
5.1 Battery System: 67
5.2 Battery system's outline specification: 69
5.3 Safety Description: 70
5.4 Failure Modes: 70
5.4.1 Internal Cell Failure: 71
5.4.2 Internal Short Circuit: 72
5.4.3 External Heating: 72
5.5 Potential Risks: 72
5.5.1 Gas Development: 72

5.5.2 Thermal Runaway: 73
5.5.3 Explosion Risk: 73
5.5.4 Fire Risk: 73
5.6 Ventilation and Alarm Systems: 74
5.7 Electronic Control System: 75
5.8 Electrical System: 76
6 Design Methodology: 77
6.1 Retrofit Philosophy: 77
6.2 Case Study: 80
6.2.1 Scenario 1: Li-ion Battery System 82
6.2.2 Scenario 2: Redox Flow Battery System 83
6.3 Model inputs & Equations: 84
6.3.1 Battery System Sizing: 85
6.3.2 Emission Quantification: 88
6.3.3 Investment Appraisal: 89
6.4 Results: 89
6.4.1 Battery System Sizing: 92
6.4.2 Emission Quantification: 94
6.4.3 Investment Appraisal: 95
7 Discussion: 101
7.1 Conclusions: 101
7.2 Further Research: 102
8 References 104
Appendix A: Electrical Load Balance Sheet 107
Appendix B: Costing of the Battery Systems 109
Appendix C: Engine Room Arrangement of “Archaggelos” 111
Appendix D: Line Diagram of “Archaggelos” 112

List of Figures:

Figure 1: Global Temperature and CO2 Concentration since 1880 15
Figure 2: History of oil price 17
Figure 3: Present and future emission control areas 20
Figure 4: NOx emission limits VS engine speed 21
Figure 5: Sulfur emission limits VS year 22
Figure 6: Principle of operation of a battery 23
Figure 7: Comparison of specific energy for different types of batteries 38
Figure 8: Qualitative spider web diagram describing key features of LI-ion batteries 38
Figure 9: Cross section of a lithium-ion cylindrical cell. 40
Figure 10: Cross section of a prismatic cell 41
Figure 11: Cross section of a pouch cell 42
Figure 12: Price of different cell types 42
Figure 13: Diagram of an RFB energy storage system: RFB stack and electrolyte tanks are 45
Figure 14: Components of an RFB stack. a) Exploded view of a unit cell and b) Assembled stack 47
Figure 15: Individual cells build up into modular stacks, with strategic electrolyte flow and electrical connections, to create RFB systems. 48
Figure 16: Conventional tugboat sketch 49
Figure 17: ASD tugboat sketch 50
Figure 18: Tractor tugboat sketch 51
Figure 19: Voith tugboat sketch 52
Figure 20: Harbor tugboats assisting a containership during berthing 53
Figure 21: An escort tugboat assisting a vessel in steering 54
Figure 22: Typical mechanical propulsion system of a tugboat 56
Figure 23: Typical Engine Room of a Conventional Tugboat. 56
Figure 24: Typical Diesel-Electric Propulsion system 57
Figure 25: Typical Hybrid Propulsion System 58
Figure 26: Typical Electrical Propulsion with Hybrid Power Supply System. 59
Figure 27: Typical Hybrid Propulsion with Hybrid Power Supply System. 60
Figure 28: All-Electric Propulsion System with an AC distribution system (left) and a DC distribution system (right). 61
Figure 29: first all-electric ferry Mf Ampere 62
Figure 30: A line diagram of the "Ampere" drive system 62
Figure 31: Largest all-electric ferry Tycho Brahe 63
Figure 32: first all-electric cargo ship 63
Figure 33: Concept design of the first all-electric tugboat 64
Figure 34: Relevant battery rules and regulations 66
Figure 35: Supporting rules and regulations for electrical testing 66
Figure 36: Generic maritime battery system 67
Figure 37: Overview of factors that can cause unwanted temperature increase on cell level in a battery system. 71
Figure 38: General principle of a geared ship propulsion. 77
Figure 39: All-electric ship configuration with a DC distribution system 78
Figure 40: Percentage of time spent in each mode according to duty cycle 81

Figure 41: Available spaces found acceptable for the housing of the battery systems. 90

List of Tables:

Table 1: NOx emission limits 20
Table 2: SOx emission limits.. 21
Table 3: Lithium Cobalt Oxide summary table.. 31
Table 4: Lithium Manganese Oxide summary table 32
Table 5: Lithium Nickel Manganese Oxide summary table.. 33
Table 6: Lithium Iron Phosphate summary table... 34
Table 7: Lithium Nickel Cobalt Aluminum Oxide summary table 35
Table 8: Lithium Titanate summary table 36
Table 9: Battery comparison table... 37
Table 10: Main particulars of "Archaggelos" 77
Table 11: Key characteristics of the different XP models 83
Table 12: Key characteristics for the different types of stacks.. 84
Table 13: Vessel's main characteristics.. 89
Table 14: Fuel oil tanks and crew’s cabin capacity 90
Table 15: Tugboat's daily energy demand calculations. 91
Table 16: Other constants vital for the calculations. 91
Table 17: Battery module's key characteristics. 92
Table 18: First’s scenario battery system sizing results. 92
Table 19: Key characteristics of the VRB system. 93
Table 20: Second's scenario battery system sizing results. 93
Table 21: Emission factors of a tugboat... 94
Table 22: Annual emissions of a conventional tugboat. 94
Table 23: Emission factors and electricity generated by each available method in Greece. 95
Table 24: Comparison of annual emissions between onboard power generation in a conventional tugboat and on-shore power suply in a all-electric tugboat during recharging. 95
Table 25: Vessel's retrofit final cost with Li-ion battery system. 95
Table 26: Maintenance savings from a Li-ion battery system. 96
Table 27:Vessel's retrofit final cost with VRB battery system. 97
Table 28: Maintenance savings from a VRB battery system. 98
Table 29: Operation cost savings. 98
Table 30: Fuel and electricity costs estimation for a 20-year period. 99

1 Introduction

1.1 Background of the Study

The purpose of the present dissertation is to evaluate the environmental and economic benefits of the retrofitting of a conventional harbor tug boat into an all-electric one, powered by battery cells.

A tug boat is a small but very powerful vessel used in towing (pulling) or tugging bigger vessels that cannot move by themselves or are not self-propelled like some barges. Tug boats can also be used as fire fighters, ice breakers etc. The strength of a tug boat and its ability to maneuver effectively depends solely on the propulsion system installed. There are different types of propulsion system for marine operation. Although the impacts of these ships on the maritime industry is most times been neglected, the importance of tugboat cannot be overemphasized.

Harbor tugboats are excellent candidates to achieve significant reduction in costs, pollutants and fuel consumption through electrification. This is because traditional diesel tugs have engines sized for full bollard pull, which are used to their optimal capacity for only around 7 percent of the time. For most of the operation time, the main engines are operated in idling mode. However, the transformation of the industry to electric/hybrid vessels will not take place overnight and requires research and development to get the full value of additional cost investments made in ship design, equipment and construction. This requires funding, but prototype construction is a sticking point for most tug owners.

Strict regulations, high fuel price and lower battery prices combined with the Energy Efficiency Design Index (EEDI) requirements and expected additional CO2 and NOx regulations will lead to the development and use of novel technologies and fuels such as biofuel, hybrid propulsion systems and last but not least, cost effective and safe battery systems.

All-electric and hybrid ships with energy storage in large batteries and optimized power control can give significant reductions in fuel costs, maintenance costs, emissions, as well as improved ship responsiveness, regularity, operational performance and safety in critical situations. Hybridization of ships may provide fuel savings of 10 - 40% and payback times as low as less than one year. However, specific results depend heavily on the conditions of each project.

Several projects have investigated battery electrification of various ship types showing that there is considerable potential to reduce both energy consumption and emissions of CO2, NOx and particulate matter. In addition to all-electric cargo-ferries, ideal ship types for battery electrification, typically have large variations in power demands, high redundancy requirements, and/or low utilization of the engine for long periods of time. Ship types of particular interest are ferries, offshore vessels, drill ships, shuttle tankers, wind farm vessels, icebreakers, passenger boats, fishing boats, tugs and other workboats and special ships with large load variations of the main or auxiliary machinery.

Traditionally, batteries have not been utilized on a large scale in maritime and offshore applications. A reason has been that the specific power and energy density of the available batteries have not been able to meet the needs of such applications. Short life time expectations have also been a challenge. Lead-acid and Nickel Cadmium batteries with a very limited capacity compared to weight and size exist on many modern vessels today in different uninterruptible power supply and clean power applications. These are however not intended for continuous use in high power operation and are mostly installed as back up devices. The use of batteries is changing due to the emergence and maturation of new technologies such as lithium-ion batteries with a much higher energy density and cycleability than lead-acid or Nickel Cadmium batteries. Since the invention of the lithium-ion battery in the 1980s and the subsequent commercialization in the 1990s, the development was first driven by consumer electronics and later adopted by the automobile industry to also include higher power and energy applications.

1.2 Problem Statement and Objectives:

The high fuel oil prices, strict regulations and lower battery prices combined with the Energy Efficiency Design Index (EEDI) requirements and expected additional CO_2 and NOx regulations will lead to the development and use of novel technologies and fuels such as hybrid propulsion systems and cost effective and safe battery systems on the shipping industry.

The commercial operation of the world's first fully electric powered car ferry started in 2015. Since this time battery systems have been increasingly adopted, on additional passenger ships while other types are now starting to emerge, proving to be one of the most transformative modern technologies introduced to the maritime sector. This progression is expected to continue as there are ongoing technological developments in the battery sector such as improvements in C-rates/power density, safety, cycle life and energy density, which also lead to lower cost per kWh.

The purpose of the present dissertation is to investigate the technical, environmental and financial viability of retrofitting a conventional harbor tugboat to a battery powered one, utilizing modern commercialized battery chemistries and technologies. More specifically, two different technologies, a battery pack system built from lithium iron phosphate modules and a battery system based on the vanadium redox flow battery technology, are going to be examined and compared to each other as well as to the conventional diesel-powered propulsion system.

The dissertation will focus on three different challenges, vital for the electrification process of the vessel:

The first challenge is the sizing of the battery systems. The energy and power as well as the safety requirements according to the operational profile of the tugboat must be ensured and the battery system as well as the additional equipment must be able to fit inside the available space of the tugboat. Compliance with national and international rules which state the prerequisites for having certified a battery ship must be considered during the sizing, as well as the installation and operation of the vessel. The battery packs must be sufficient for a complete operational working day and at the same time a viable life-span of batteries must be ensured.

The second challenge is the quantification of the amount of pollutants emitted from a conventional tugboat during its operation and the comparison with the amount of emissions emitted from recharging the battery pack from the grid.

The third and last challenge is the investment appraisal of the project. Taking into consideration the net difference of the operational costs between an all-electric and conventional tugboat in a span of 20 years, as well as the costs of retrofitting the tugboat into battery powered one the dissertation tries to answer if such an investment would have been profitable.

From the above challenges the following questions are consequently derived:

- Is a fully electric battery powered harbor tugboat possible according to its operational profile?

- Is the available space inside of an already designed conventional tugboat adequate for the incorporation of a battery system and the needed added equipment of an all-electric vessel?
- Are the new regulations for the installation and operation of a battery system satisfied in such a vessel?
- What is the net difference between the amount of pollutants emitted during the operation of an all-electric and a conventional tugboat?
- Is such an investment economically viable?

1.3 Structure of the Study:

Chapter 2: Environmental effects of shipping

In the second chapter, the environmental effects of conventionally powered shipping are analyzed. More specifically, the most common and harmful types of pollutants found on the emissions of diesel engines on ships are listed, while the effects that these pollutants have on the climate, the eco-system and human health are described. Furthermore, the volatility of the oil market as well the inevitability of the rise of its price due to the depletion of the oil reserves are mentioned. Finally, the ECAs and Tier I-III standards that are gradually implemented in order to reduce the negative effects of emissions are explained.

Chapter 3: Batteries

In the third chapter, the main battery chemistries are described alongside their characteristics and applications in order to evaluate the appropriate battery technology for this thesis. Moreover, basic technical definitions and terminologies concerning battery technology and operation are explained. Lastly, future technologies and their possible applications are mentioned.

Chapter 4: Tugboats

In the fourth chapter of this dissertation, the different types of tugboats and their propulsion arrangements as well as their operational role are listed. In addition, the different power systems, such as diesel, diesel-electric and hybrid system that have been implemented on tugboats until now are described. Finally, the prospect of an all-electric tugboat is examined and examples of other types of ships that have been retrofitted are presented.

Chapter 5: Legal and Regulatory Framework

In the fifth chapter, the regulation framework concerning the outline specification, design, installation, operation and maintenance of large Lithium-ion based battery systems is laid out. In addition, the failure modes and potential risks of such a system are discussed. Lastly, the main system for safe operation, such as alarms, ventilation and battery management are described.

Chapter 6: Design Methodology

In the sixth chapter, the retrofit design philosophy for the particular case study in which the present dissertation focuses as well as the methodology developed for the sizing of the battery system are presented. Its inputs and equations are described and the most important guidelines generated from the methodology are outlined. In the last part, the results of the study are presented.

Chapter 7: Discussion

Final conclusions on vessel's retrofit concerning its technical, financial and environmental viability and recommendations for future investigation are presented.

2 Environmental effects of shipping

Shipping is the most energy-efficient way of transportation, both for goods and people, however environmental pollution caused by maritime transportation is increasing due to its rapid development. The different types of pollution caused by shipping are divided into two major groups which are, discharges to the sea that impact the marine environment and fuel emissions to the air that impact the atmosphere.

The International Maritime Organization (IMO) is a special agency of the United Nations which regulates international shipping and is responsible, amongst other things, for developing and maintaining a comprehensive framework about environmental concerns. Releases into the oceans of oils, noxious liquids, harmful substances, swage and garbage have been restricted since the 1980s by the International Convention for the Prevention of Pollution from Ships (MARPOL) following a spate of oil-tanker accidents. Air-pollution limits for shipping on the other hand were not as quick to follow as they were adopted in 1997 but came into force only in 19 May 2005.

Energy efficiency is the IMO's present focus. Starting in 2013, its Energy Efficiency Design Index and Ship Energy Efficiency Management Plan aim to lower CO_2 emissions from shipping through tighter technical requirements on engines and equipment, maintenance regimes and voyage plans. No absolute emissions-reduction targets were set. Unfortunately, long-term expansion in global trade and growing ship numbers mean that even if these measures are fully implemented, total shipping emissions are projected to quadruple from 1990 to 2050 (Zheng Wan et al, 2016).

2.1 Ship Emissions and their Impacts:

The most common engines used to produce either mechanical or electrical energy are diesel engines. Some of the advantages of diesel engines are high reliability, high efficiency, low costs (with respect to initial costs), high maintainability due to a simple and established technology and the fact that they are load flexible (can operate fairly efficiently at a low load). Fuel flexibility leads to low-quality fuel being usually used. The types of fuel used in marine industry are mainly heavy fuel oil (HFO) and marine diesel oil (MDO) for low-speed engines and medium or high-speed engines respectively (Karin Andersson et al, 2016).

The process of fuel combustion by the engine causes exhaust gases that consequently are being released into the atmosphere. Air emissions may be grouped, with respect to their general impact into two categories: A) Greenhouse gasses (GHGs) which are emissions contributing to the climate change phenomenon B) Other emissions.

The first group consists of emissions such as Carbon Dioxide (CO_2), Methane (CH_3) and Hydrochlorofluorocarbons (HCFCs) while the second group consists of emissions such as Sulphur Oxides (SO_x), Nitrogen Oxides (NO_x), Particular Matters (PMs), Volatile Organic Compounds (VOCs) and Carbon Monoxide (CO).

Air pollutants can be further categorized into primary and secondary air pollutants. Primary air pollutants are directly emitted from the source (engine) while secondary pollutants are those which are derived from the primary pollutants due to chemical or photochemical reactions in the atmosphere in a radius approximately 50 km from the source. Pollutants such as SO2, NO2, O3, sulphate and nitrate salts are included in this category. Ship emissions and their byproducts have a negative effect in climate change, the ecosystem and human health

These pollutants are created by different circumstances and chemical reactions:

CO_2: is a gas formed by the combustion of the carbon inside of fossil fuels. CO_2 is a greenhouse gas and is found naturally in the Earth's atmosphere, where it plays an important role in regulating its temperature.

SO_x: are the outcome of the reaction of sulfur content of fuel with oxygen during combustion which forms different Sulphur oxides, although the majority of Sulphur present is emitted as SO_2. The amount of SO_x emissions from ships depend solely on the Sulphur content of the fuel.

NO_x: formed in a diesel engine is dependent on a combination of high temperatures and pressure, the availability of oxygen and nitrogen and the duration of the combustion. Most NO_x are emitted as NO which is rapidly oxidized in the atmosphere to NO_2 and then to nitric acid and other nitrates.

PMs: is the generic term used for a type of air pollutants, consisting of complex and varying mixtures of particles suspended in the breathing air. They are usually consisted of soot, metal oxides and sulfates, all of them produced during the incomplete combustion of hydrocarbons in the fuel. PMs are of great range in terms of size, shape and chemical composition. The abbreviation that of typically used for particular matter are PM10 and PM2.5, which refer to the masses of particles with diameters less than 10 and 2.5 μm respectively.

VOCs: are organic chemicals that have a high vapor pressure at ordinary room temperature. Their high vapor pressure results from a low boiling point, which causes large numbers of molecules to evaporate or sublimate from the liquid or solid form of the compound and enter the surrounding air, a trait known as volatility. VOC emissions in the context of shipping arise primarily from the production, transportation and storage of crude oil.

CO: is a gas emitted from incomplete combustion of fossil fuels and therefore is emitted directly from the ship's funnel. In the atmosphere CO has a lifespan of three months because it slowly oxidizes into CO_2 forming O_3 in the prosses.

O_3: ground level ozone unlike primary air pollutants is not directly emitted into the atmosphere but is instead formed when hydrocarbons or oxides of nitrogen react in the presence of sunlight in a reaction called photochemical.

2.2 Air Pollution and Climate Change:

Air pollution and global warming are closely related. Global warming is the phenomenon where increasing concentration of greenhouse gases cause a rise on the temperature of the earth's atmosphere through the absorption and emission of infrared radiation. The main contributor of gas emissions from shipping is CO_2. In addition to carbon dioxide, ozone is considered an important greenhouse gas. Ozone's global warming potential occurs because it absorbs both incoming solar radiation in the ultraviolent and visible spectrum.

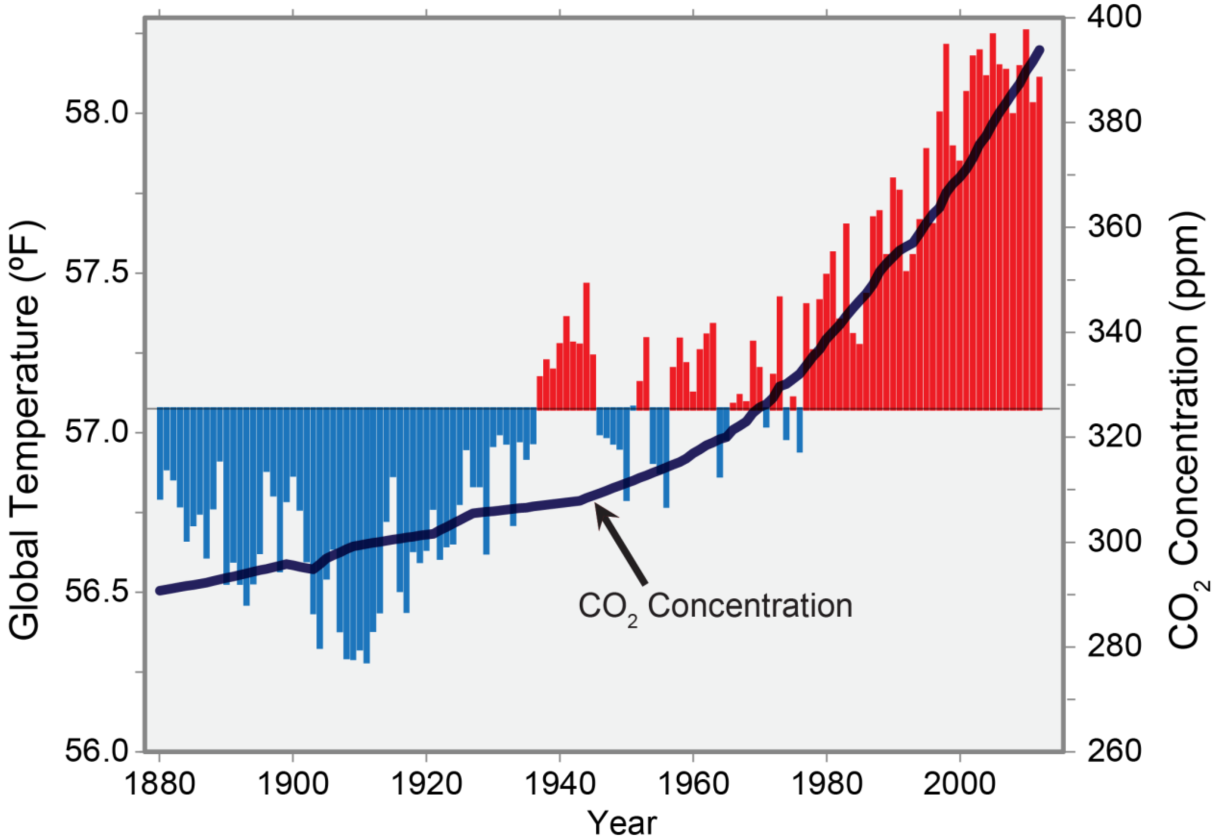

Figure 1: Global Temperature and CO2 Concentration since 1880

Currently, the global mean temperature is increasing and the effects of global warming are visible in the form of shrinking glaciers, melting permafrost and costal erosion. Although long term effects are going to be changes in rainfall patterns and droughts, rise of the sea level, ocean acidification and changes on the ecosystem which supports human, animal and plant life. Climate change is expected to also affect shipping through more severe weather and the disruption of established trade routes.

2.3 Air pollution, eco-system and biodiversity:

Ecosystems are impacted by air pollution, particularly Sulphur and nitrogen emissions as well as ground level ozone all of which affect their ability to function and grow. Nitrogen and Sulphur oxide emissions deposit in bodies of water and on soil in the form of acid rain. This affects the ability of ecosystems to provide critical functions, such as nutrient and carbon cycling, and most importantly water provision on which human life is depended. This acidification has adverse effects on both flora and fauna.

Increased ground-level ozone also causes damage to cell membranes on plants inhibiting key processes required for their growth and development. Trees and other vegetation absorb pollutants such as excessive nitrogen dioxides, ozone and particular matter thereby helping to improve air quality. Thus, less plants means less filtering capacity.

In addition, toxic metals and organic pollutants may have severe impact on the eco-system. This is mainly because of their environmental toxicity, and in some cases their ability to bio-accumulate, a process in which toxins cannot be metabolized by an animal and build up. These toxins are then passed to other animals through the food chain in a process called Bio-magnification. Animals at the top of the food chain are affected most severely, one of them is humans.

Eutrophication, the process of accumulation of nutrients, including nitrogen in water bodies often result from air pollution. Nutrient overloads in aquatic ecosystems can cause algae blooms and ultimately a loss of oxygen, an important prerequisite for any form of life. As ecosystems are impacted, so is the biological diversity. Shipping contributes to the excess of nutrient nitrogen through NO_x emissions.

Ultimately human populations are also affected directly. Harmful concentrations of pollutants such as heavy metals, can enter drinking water through ground water seepage. Equally, water quality may be deteriorated as air pollution negatively affect vegetation which helps in naturally filtering water systems.

The impacts of air pollution on the environment depend not only on the air pollutant emission rates but also on the location, potency and reaction products of the emissions. Factors such as meteorology, physiography and topography are important, as these determine the transport, chemical transformation and deposition of air pollutants.

2.4 Air pollution and human health:

Humans enter in contact with different air pollutants primarily via inhalation and ingestion, while dermal contact represents a minor route of exposure. As previously stated air pollution contributes to the contamination of food and water, which makes ingestion in several cases the major route of pollutant intake. Via the gastrointestinal and respiratory tract, absorption of pollutants may occur.

A constant finding is that air pollutants contribute to increased mortality and hospital admissions while recent estimates suggest that is the single largest environmental health risk in Europe. Human health effects can range from nausea and difficulty breathing to heart diseases and cancer. They also include birth defects, serious development delays in children and reduced activity of the immune system. While air pollution is harmful to all population, some groups suffer more because of their proximity to areas with higher level of air pollution, or they are more vulnerable to these effects (i.e. Elders, children etc.).

The health impacts of air pollution can be quantified and expressed as premature mortality and morbidity. Mortality reflects reduction of life expectancy attributed to premature deaths due to air pollution, while morbidity relates to occurrences of illness and years lived with a disease or disability that may require hospitalization. Less severe effects might have some public health implications, especially in major cities and industrialized regions, but are more difficult to pinpoint.

Some of the pre-examined pollutants are responsible for health risks such as:

PM: Can cause aggravating cardiovascular and lung diseases, heart attacks and arrythmias, can affect the central nervous and reproductive system and may lead to some forms of cancer.

SO_x: can cause aggravating asthma and reduce lung function. This leads to cough, irritation and generally headache, discomfort and anxiety.

NO_x: can affect the liver, lungs and blood. Can cause aggravating heart and lung diseases, and may lead to some forms of cancer

O_3: can decrease lung function, aggravate asthma and other lung diseases.

CO: can lead to heart disease and damage to the nervous system and can also cause headache, dizziness, loss of consciousness, fatigue and finally death.

2.5 Economic impact of air pollution:

External costs occur when producing or consuming a good or service imposes a cost upon a third party. The existence of external costs can lead to market failure because the free market generally ignores the existence of these costs. These costs include: the cost of disposing the product at the end of its useful life, the environmental degradation caused by emissions, the costs of health problems caused by harmful materials and ingredients and social costs associated with increasing unemployment due to automation.

Air pollution caused by transport activities leads to different types of external costs. The most important of them are health costs due to cardiovascular and respiratory diseases caused by air pollutants. Other external costs of air pollution include building and material damage, crop losses and impacts to the biodiversity and eco-system. Most important transport related air pollutants are particulate matter, Nitrogen oxides, Sulphur dioxides, volatile organic compounds and ozone. Greenhouse gasses are covered within the climate change cost category.

Total health-related external costs in the Eu are in the range of 330-940 billion euros per year, including direct economic damages of 15 billion euros from lost workdays, 4 billion euros healthcare costs, 3 billion euros crop yield loss and 1 billion euros damage to buildings according to the European Commission, 2010.

2.6 Dependency of shipping with the oil market:

While air and water related emissions already influence the design and operation of ships, of more immediate concern to ship operators is the current and future oil price as the cost of fuel amounts between 50% and 60% of the total operating cost. As such the erratic and unpredictable nature of the oil market have implications for ship operating economics and margins.

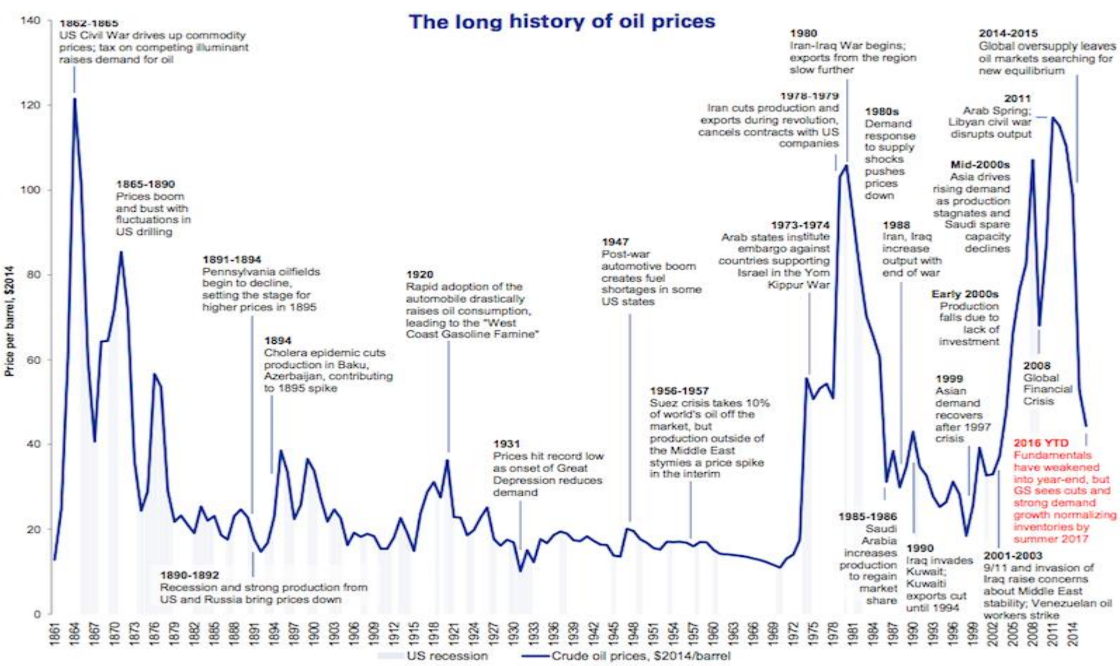

Figure 2: History of oil price

The price of oil has seen wide swings throughout history from the high prices of the 1970s and early 2000s to the plummeting prices of the post Global Financial Crisis of 2008. Today the oil price is once again rising and it will keep rising according to future projections. (Annual Energy Outlook 2018 with projection to 2050, US Energy Information Administration).

The reasons for these swings are multifaceted a few of which are:

- OPEC's influence: Organization of Petroleum Exporting Countries is a consortium consisting of 14 countries which control about 40% of the world's supply of oil. This organization sets production levels to meet global demand and can influence the price of oil by regulating the production.
- Supply and Demand: As with any commodity the dependency of supply and demand cause oil prices to fluctuate. When supply exceeds demand, prices fall and vice versa.
- Production Costs: Production costs is another factor that impacts oil prices. As the supply of cheaply extracted oil is expected to dwindle more costly methods of extraction are going to force the price up.
- Geopolitics: political instability and conflicts worldwide and especially in the middle east which accounts for the majority of the oil supply play a big role in oil prices swings. For example, the Iraq and Afghanistan wars, the Syrian conflict and the Arab spring as well as the Iranian nuclear deal, from which the US backed out recently, are key factors on the fluctuations of the oil price.

There have been concerns over the years that supplies are dwindling and that production may one day fail to meet demand, a concept known as "peak oil". With demand growing, especially in developing countries, and the apparent rate of discovery of new fields dropping, the prospect of global peak in oil production has led some to speculate that the price of oil will rise significantly in the future (Royal Academy of Engineering, July 2013).

Another more immediate issue is that low sulfur fuel requirements are expected to lead to a 30 – 50 % fuel cost increase over the next decade. In some countries and ports there will be local regulations pushing for reduction of local air pollution as well as use of shore electric power. Ultimately humanity has to recognize that oil is a finite resource and move towards more sustainable and green solutions for both industrial and transportation use. One of these solutions are batteries.

2.7 Emission Control Areas and Tier I-III standards:

IMO ship pollution rules are contained in the "International Convention on the Prevention of Pollution from Ships", known as MARPOL 73/78. On 27 September 1997, the MARPOL Convention has been amended by the "1997 Protocol", which includes Annex VI titled "Regulations for the Prevention of Air Pollution from Ships". MARPOL Annex VI sets limits on NOx and SOx emissions from ship exhausts, and prohibits deliberate emissions of ozone depleting substances from ships of 400 gross tonnage and above engaged in voyages to ports or offshore terminals under the jurisdiction of states that have ratified Annex VI.

The IMO emission standards are commonly referred to as Tier I-III standards. The Tier I standards were defined in the 1997 version of Annex VI, while the Tier II/III standards were introduced by Annex VI amendments adopted in 2008, as follows:

Protocol (Tier I)—The "1997 Protocol" to MARPOL, which includes Annex VI, becomes effective 12 months after being accepted by 15 States with not less than 50% of world merchant shipping tonnage. On 18 May

2004, Samoa deposited its ratification as the 15th State (joining Bahamas, Bangladesh, Barbados, Denmark, Germany, Greece, Liberia, Marshal Islands, Norway, Panama, Singapore, Spain, Sweden, and Vanuatu). At that date, Annex VI was ratified by States with 54.57% of world merchant shipping tonnage.

Accordingly, Annex VI entered into force on 19 May 2005. It applies retroactively to new engines greater than 130 kW installed on vessels constructed on or after January 1, 2000, or which undergo a major conversion after that date. The regulation also applies to fixed and floating rigs and to drilling platforms (except for emissions associated directly with exploration and/or handling of sea-bed minerals). In anticipation of the Annex VI ratification, most marine engine manufacturers have been building engines compliant with the above standards since 2000.

Amendments (Tier II/III)—Annex VI amendments adopted in October 2008 introduced new fuel quality requirements beginning from July 2010, Tier II and III NOx emission standards for new engines, and Tier I NOx requirements for existing pre-2000 engines.

The revised Annex VI entered into force on 1 July 2010. By October 2008, Annex VI was ratified by 53 countries (including the Unites States), representing 81.88% of tonnage.

Emission Control Areas. Two sets of emission and fuel quality requirements are defined by Annex VI: global requirements, and more stringent requirements applicable to ships in Emission Control Areas (ECA). An Emission Control Area can be designated for SOx and PM, or NOx, or all three types of emissions from ships, subject to a proposal from a Party to Annex VI.

Existing Emission Control Areas include:

- Baltic Sea (SOx: adopted 1997 / entered into force 2005; NOx: 2016/2021)
- North Sea (SOx: 2005/2006; NOx: 2016/2021)
- North American ECA, including most of US and Canadian coast (NOx & SOx: 2010/2012).
- US Caribbean ECA, including Puerto Rico and the US Virgin Islands (NOx & SOx: 2011/2014).

While Norway, Japan and Mediterranean areas are being considered for further ECA proposal.

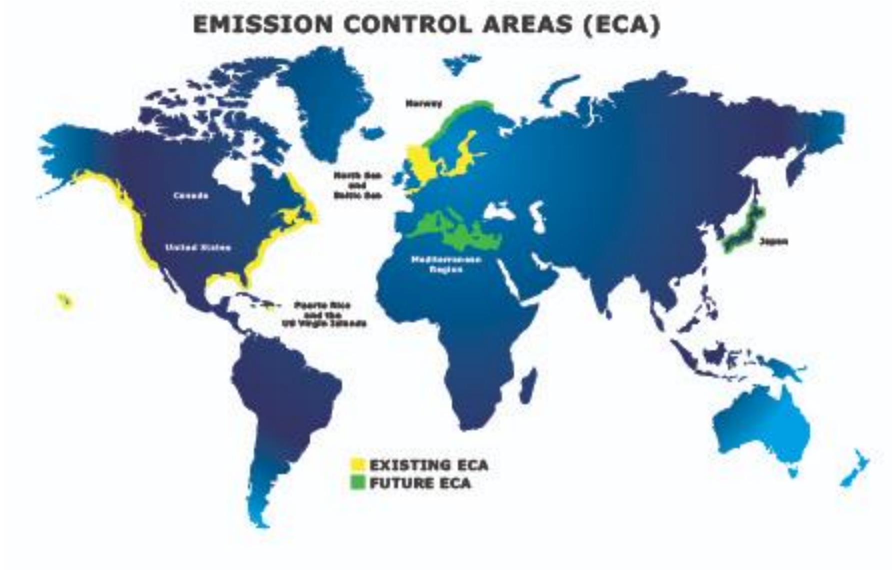

Figure 3: Present and future emission control areas

Greenhouse Gas Emissions**.** 2011 Amendments to MARPOL Annex VI introduced mandatory measures to reduce emissions of greenhouse gases (GHG). The Amendments added a new Chapter 4 to Annex VI on "Regulations on energy efficiency for ships".

The NOx emission limits of Regulation 13 of MARPOL Annex VI apply to each marine diesel engine with a power output of more than 130 kW installed on a ship. A marine diesel engine is defined as any reciprocating internal combustion engine operating on liquid or dual fuel.

NOx emission limits are set for diesel engines depending on the engine maximum operating speed (n, rpm), as shown in Table 1 and presented graphically in Figure 4. Tier I and Tier II limits are global, while the Tier III standards apply only in NOx Emission Control Areas.

Table 1: NOx emission limits

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

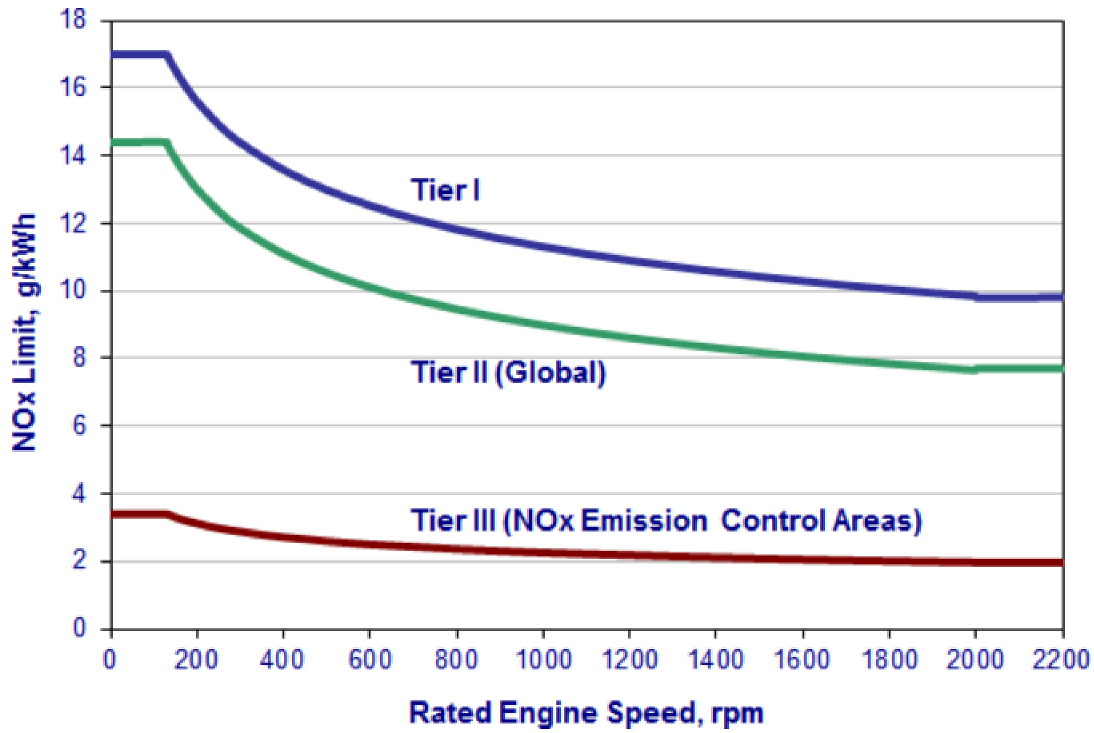

Figure 4: NOx emission limits VS engine speed

Annex VI regulations include caps on sulfur content of fuel oil as a measure to control SOx emissions and, indirectly, PM emissions (there are no explicit PM emission limits). Special fuel quality provisions exist for SOx Emission Control Areas (SOx ECA or SECA). The sulfur limits and implementation dates are listed in Table 2 and illustrated in Figure 5.

Table 2: SOx emission limits

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

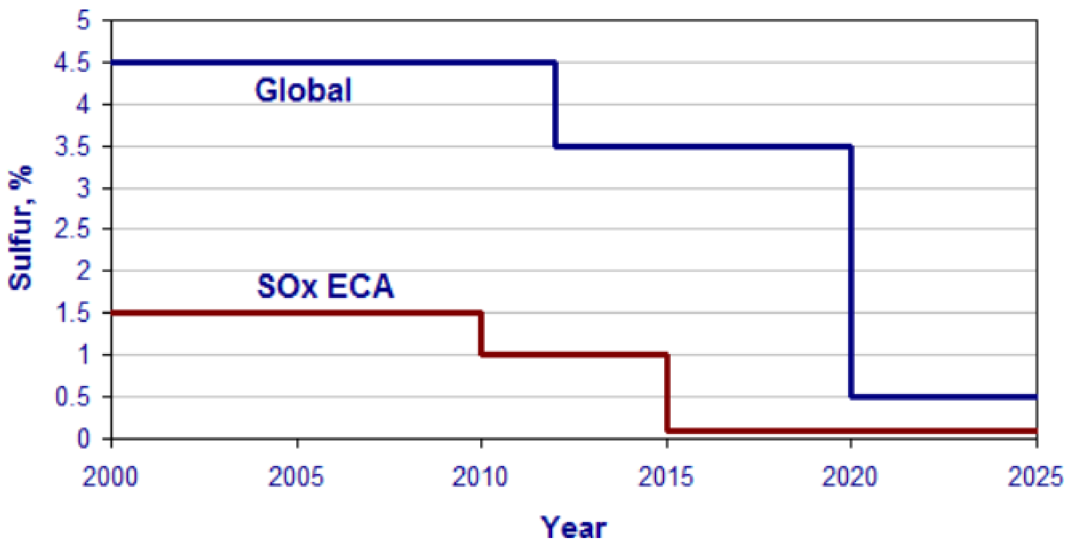

Figure 5: Sulfur emission limits VS year

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

- The EEDI is a performance-based mechanism that requires a certain minimum energy efficiency in new ships. Ship designers and builders are free to choose the technologies to satisfy the EEDI requirements in a specific ship design.
- The SEEMP establishes a mechanism for operators to improve the energy efficiency of ships.

The regulations apply to all ships of 400 gross tonnage and above and enter into force from 1 January 2013. Flexibilities exist in the initial period of up to six and a half years after the entry into force, when the IMO may waive the requirement to comply with the EEDI for certain new ships, such as those that are already under construction.

In April 2018, the IMO adopted an Initial Strategy on the reduction of GHG emissions from ships. The strategy calls for strengthening the EEDI requirements and a number of other measures to reduce emissions, such as operational efficiency measures, further speed reductions, measures to address CH_4 and VOC emissions, alternative low-carbon and zero carbon fuels, as well as market-based measures (MBM).

The vision confirms IMO's commitment to reducing GHG emissions from international shipping and, as a matter of urgency, to phasing them out as soon as possible. More specifically, under the identified "levels of ambition", the initial strategy envisages for the first time a reduction in total GHG emissions from international shipping which, it says, should peak as soon as possible and to reduce the total annual GHG emissions by at least 50% by 2050 compared to 2008, while, at the same time, pursuing efforts towards phasing them out entirely.

On this regulatory framework research on battery technology seems ideal.

3 Batteries:

Batteries operate by converting chemical energy into electrical energy through electrochemical discharge reactions. A battery is an arrangement of one or more cells connected in series or parallel, each containing:

- The cathode, which is the "positive" half of the battery cell. It is made up of a substance that is coated with the active material.
- The anode, which is the "negative" half of the battery cell and is usually made up of a thin copper substrate that is coated with the active anode material.
- The separator, which is a material placed between the anode and the cathode. Its purpose is to prevent those two parts from creating a short circuit.
- The electrolyte, which is the medium that allows the ions to pass through the cell.

Upon discharge, chemical reactions initiate a flow of electrons from the anode to the cathode, which produces an electric current in the external circuit. The separator allows for positive charges to migrate from the anode to the cathode without the passage of other molecules.

Batteries can be grouped into two major categories:

- Primary batteries: The chemical reactions found on these batteries are irreversible and thus cannot be recharged. When the supply of reactants in the battery is exhausted, the battery stops producing current and is useless.
- Secondary batteries: These batteries are rechargeable and require an external electric current by a DC source to restore reactants to their fully charged state. The current triggers the chemical reactions to operate in reverse bringing the battery to state of high energy, so they can be used multiple times. Batteries used in marine applications are primarily rechargeable.

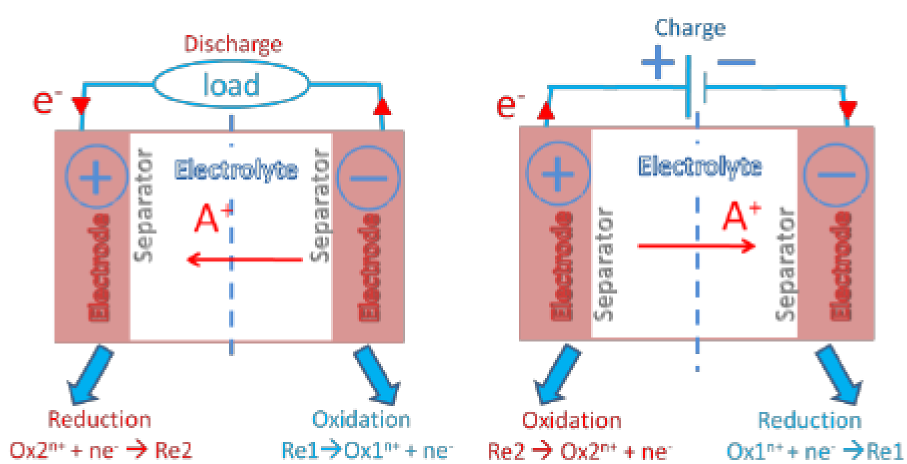

Figure 6: Principle of operation of a battery

3.1 Definitions:

The definitions presented below are taken from "A Guide to Understanding Battery Specifications", MIT Electric Vehicle Team, December 2008. These definitions will help in understanding the fundamental terminology used to describe, classify and compare different types of batteries used in hybrid and/or electric power trains.

3.1.1 Battery Basics:

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 classification is 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.

3.1.2 Battery Conditions:

This section defines some of the variables used to describe the condition of a battery

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

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

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

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

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

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.

3.1.3 Battery Technical Specifications:

This section defines specifications used to describe battery cells, modules and packs on battery technical specification sheets.

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.

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

Reduced lifespan, or State of Health (SOH) must be accurately calculated and monitored by the system controls, typically referred to as Battery Management System.

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

3.2 Types of batteries:

3.2.1 Lead Acid:

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

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

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

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

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

Charging a lead acid battery is simple, but the correct voltage limits must be observed. Choosing a low voltage limit shelters the battery, but this produces poor performance and causes a buildup of sulfation on the negative plate. A high voltage limit improves performance but forms grid corrosion on the positive plate. While sulfation can be reversed if serviced in time, corrosion is permanent.

Lead acid does not lend itself to fast charging and with most types, a full charge takes 14–16 hours. The battery must always be stored at full state-of-charge. Low charge causes sulfation, a condition that robs the battery of performance. Adding carbon on the negative electrode reduces this problem but this lowers the specific energy.

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

Advantages:

- Inexpensive and simple to manufacture i.e. low cost per watt-hour.
- Low self-discharge.
- High specific power, capable of high discharge currents.
- Good low and high temperature performance.

Disadvantages:

- Low specific energy i.e. poor weight to energy ratio.
- Slow charge i.e. between 14-16 hours.
- Must be stored in charged condition to prevent sulfation.
- Limited cycle life. Repeated deep-cycling lowers battery life.
- Not environmentally friendly.

3.2.2 Nickel-based batteries:

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

3.2.2.1 Nickel-cadmium:

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

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

Advantages:

- Rugged, high cycle count with proper maintenance.
- Only battery that can be ultra-fast charged with little stress.
- Good load performance.
- Long shelf life.
- Simple storage and transportation.
- Good low-temperature performance.

- Currently most economically priced in terms of cost per cycle.
- Available in a wide range of sizes and performance options.

Disadvantages:

- Relatively low specific energy compared to newer systems.
- Battery has a memory effect.
- Cadmium is a toxic metal.
- High self-discharge.
- Low cell voltage. Requires many cells to achieve high voltage.

3.2.2.2 Nickel-metal-hydride:

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

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

Advantages:

- Higher capacity than a NiCd by 30-40%.
- Less prone to memory than NiCd.
- Simple storage and transportation.
- Environmentally friendly.
- Wide temperature range.

Disadvantages:

- Limited service life.
- Sensitive to overcharging.
- Generates heat during fast charge and high-load discharge.
- Higher self-discharge than NiCd.

3.2.3 Lithium based batteries:

The lead acid and nickel-cadmium batteries have been the most common batteries of the past 150 years, in this period of time they have evolved little. Various limitations of these batteries, such as low power or energy density, memory effects or other weaknesses, have prevented them from being used as large-scale means of power for marine propulsion.

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

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

The inherent instability of lithium metal, especially during charging, shifted research to a non-metallic solution using lithium ions. Li-ion is a low-maintenance battery, an advantage that most other chemistries cannot claim. The battery has no memory and does not need deliberate full discharge to keep it in good shape. Self-discharge is less than half that of nickel-based systems. The nominal cell voltage of 3.60V can directly power mobile phones, tablets and digital cameras, offering simplifications and cost reductions over multi-cell designs. The drawbacks are the need for protection circuits to prevent abuse, as well as high price.

Lithium-ion uses a cathode (positive electrode), an anode (negative electrode) and electrolyte as conductor. The cathode is metal oxide and the anode consists of porous carbon. During discharge, the ions flow from the anode to the cathode through the electrolyte and separator; charge reverses the direction and the ions flow from the cathode to the anode. Li ion batteries come in many different types.

3.2.3.1 Lithium Cobalt Oxide – $LiCoO_2$:

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

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.

Table 3: Lithium Cobalt Oxide summary table

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

3.2.3.2 Lithium Manganese Oxide – $LiMn_2O_4$:

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.

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.

Table 4: Lithium Manganese Oxide summary table

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

3.2.3.3 Lithium Nickel Manganese Cobalt Oxide – $LiNiMnCoO_2$:

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

The secret of NMC lies in combining nickel and manganese. Nickel is known for its high specific energy but poor stability; manganese has the benefit of forming a spinel structure to achieve low internal resistance but offers a low specific energy. Combining the metals enhances each other strengths.

NMC is the battery of choice for power tools, e-bikes and other electric powertrains. The cathode combination is typically one-third nickel, one-third manganese and one-third cobalt, also known as 1-1-1.

This offers a unique blend that also lowers the raw material cost due to reduced cobalt content. Another successful combination is NCM with 5 parts nickel, 3 parts cobalt and 2 parts manganese (5-3-2). Other combinations using various amounts of cathode materials are possible. 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.

Table 5: Lithium Nickel Manganese Oxide 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.

3.2.3.4 Lithium Iron Phosphate – $LiFePO_4$:

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. This can be mitigated by buying high quality cells and/or using sophisticated control electronics, both of which increase the cost of the pack. Cleanliness in manufacturing is of importance for longevity. There is no tolerance for moisture, lest the battery will only deliver 50 cycles.

Table 6: Lithium Iron Phosphate summary table

Lithium Iron Phosphate: $LiFePO_4$ cathode, graphite anode Short form: LFP or Li-phosphate Since 1996	
Voltages	3.20, 3.30V nominal; typical operating range 2.5–3.65V/cell
Specific energy (capacity)	90–120Wh/kg
Charge (C-rate)	1C typical, charges to 3.65V; 3h charge time typical
Discharge (C-rate)	1C, 25C on some cells; 40A pulse (2s); 2.50V cut-off (lower that 2V causes damage)
Cycle life	1000–2000 (related to depth of discharge, temperature)
Thermal runaway	270°C (518°F) Very safe battery even if fully charged
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.

3.2.3.5 Lithium Nickel Cobalt Aluminum Oxide – $LiNiCoAlO_2$:

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

Table 7: Lithium Nickel Cobalt Aluminum Oxide summary table

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

3.2.3.6 Lithium Titanate – $Li_4Ti_5O_{12}$:

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

LTO (commonly $Li4Ti_5O_{12}$) has advantages over the conventional cobalt-blended Li-ion with graphite anode by attaining zero-strain property, no SEI film formation and no lithium plating when fast charging and charging at low temperature. Thermal stability under high temperature is also better than other Li-ion systems; however, the battery is expensive. At only 65Wh/kg, the specific energy is low, rivalling that of NiCd. Li-titanate charges to 2.80V/cell, and the end of discharge is 1.80V/cell. Typical uses are electric powertrains, UPS and solar-powered street lighting.

Table 8: Lithium Titanate 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)	50–80Wh/kg
Charge (C-rate)	1C typical; 5C maximum, charges to 2.85V
Discharge (C-rate)	10C possible, 30C 5s pulse; 1.80V cut-off on LCO/LTO
Cycle life	3,000–7,000
Thermal runaway	One of safest Li-ion batteries
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.

3.2.4 Summary:

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

Li-ion based batteries seems to be the most promising technology in high power density applications as they possess the greatest potential for future development and optimization. In addition to small size and low weight the li-ion batteries offer the highest energy density, storage efficiency and do not require maintenance. However, one of the major drawbacks is its higher cost due to its manufacturing complexity arising from the special circuitry needed to protect the battery and to assure safety. All the characteristics discussed above are shown on the next table.

Table 9: Battery comparison table

	Lead Acid	Ni-Cad	NiMh	LiCoO2	LiMnO4	LiNiMnCoO2	LiFePO4	LiNiCoAlO2	Li4Ti5O12
Inittial Purchace Cost per kWh	150-200	400-800	200-300	250-450	400-900	500-900	400-1200	600-1000	600-2000
Maintenance	3-6 months	30-60 days	60-90 days	-	-	-	-	-	-
Safety	Good	Good	Good	Medium	Good	Good	Very Good	Medium	Very Good
Enviromental Impact	High	High	Midium	Low	Low	Low	Low	Low	Low
Cycle Life	300-800	1000-2000	500-1500	500-1000	300-700	1000-2000	1000-2000	1000	3000-7000
Nominal Voltage [V]	2	1.2	1.2	3.6-3.8	3.8	3.6	3.2-3.3	3.6	2.4
Specific Energy [Wh/Kg]	30-40	40-60	30-80	120-150	105-120	140-180	80-130	80-220	70
Energy Density [Wh/L]	60-70	50-150	140-300	250-450	250-265	325	220-250	210-600	130
Specific Power [W/kg]	60-180	150	250-1000	600	1000	500-3000	1400-2400	1500-1900	750
Power Density [W/L]	100	210	400	1200-3000	2000	6500	4500	4000-5000	1400
Self Discharge [%/month]	3-5	20	30	1-5	5	1	1	2-10	2-10
Memory Effect	No	Yes	Rarely	No	No	No	No	No	No
Operating Temperature	-20 to 60	-40 to 60	-20 to 60	-20 to 60	-20 to 60	-20 to 55	-20 to 60	-20 to 60	-40 to 55

The characteristics of lightweight and high specific energy makes Lithium ion batteries an ideal candidate for marine applications. As shown on the figure bellow Lithium aluminum or NCA is the clear winner in terms of specific energy, but as stated above it has its drawbacks, mainly cost and safety issues.

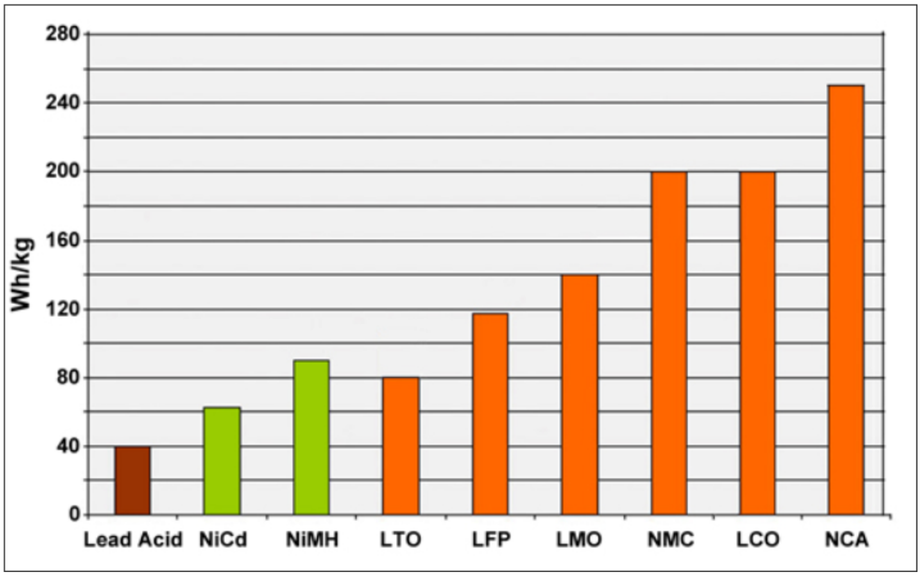

Figure 7: Comparison of specific energy for different types of batteries

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

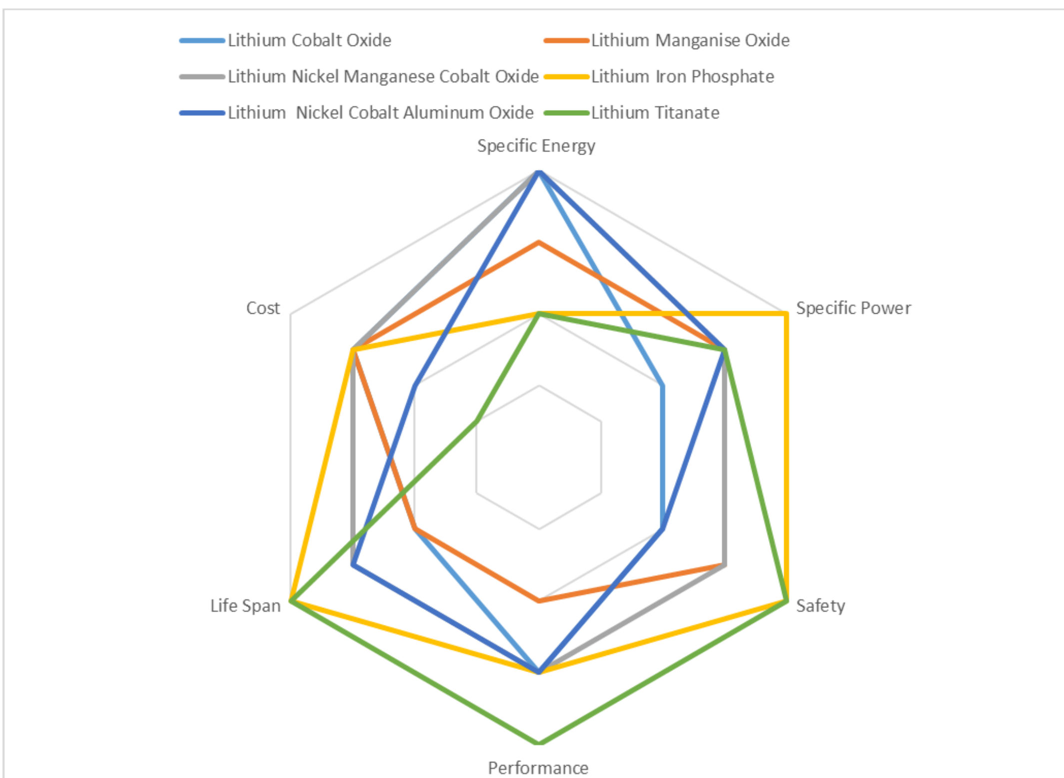

Figure 8: Qualitative spider web diagram describing key features of LI-ion batteries

As shown above:

- Lithium Cobalt Oxide has a high specific energy it also has a low cost and a moderate performance. However, it is highly unfavorable in all the other aspects when compared to the other lithium-ion batteries. It has a low specific power, low safety, and a low lifespan.
- Lithium Manganese Oxide has a moderate specific power, moderate specific energy, and a moderate level of safety when compared to the other types of lithium-ion batteries. It has the added advantage of a low cost. The downsides are its low performance and low lifespan.
- Lithium Nickel Manganese Cobalt Oxide has two major advantages as compared to the other batteries. The first one is its high specific energy which makes it desirable in electric powertrains, electric vehicles and electric bikes. The other is its low cost. It is moderate in terms of specific power, safety, lifespan and performance when compared to the other lithium-ion batteries. It can be optimized to either have a high specific power or a high specific energy.
- Lithium Nickel Cobalt Oxide only has one major disadvantage when compared to other types of lithium-ion batteries and that is its low specific energy. Other than that, it has a moderate to high rating in all the other characteristics. It has high specific power, offers a high level of safety, has a high lifespan and comes at a low cost. The performance of this battery is also moderate.
- Lithium Nickel Cobalt Aluminum Oxide only offers one strong advantage and that is a high specific energy. Apart from this, it doesn't really offer much as compared to the five other batteries. It provides a low level of safety as compared to the other batteries. It is also pretty moderate in the rest of the characteristics. Its high specific energy and moderate lifespan makes it a good candidate for electric powertrains.
- Lithium Titanate offers high safety, high performance and a high lifespan. Its specific energy is low compared to the five other lithium-ion batteries but it compensates for this with a moderate specific power. Li-titanate may have low capacity buy this chemistry outlives most other batteries in terms of life span and also has the best cold temperature performance. The only major disadvantage of lithium titanate as compared to the other lithium-ion batteries is its extremely high cost.

The huge developments in li-ion batteries of the past years have made the use of batteries a viable solution for marine applications. Maritime focused battery systems have been mainly based on Lithium Manganese Cobalt Oxide or Iron-Phosphate type cathodes and graphite anodes, both of which represents a good compromise between the parameters discussed above.

Together with the continuous improvement and optimization of the existing technologies some of today's limitations will be eradicated. Improvements in energy and battery density, safety, life cycles, performance and lower cost per KWh will further expand the market for marine applications.

3.3 Lithium-Ion Cell Types:

There are essentially three main types of lithium-ion cells:

3.3.1 Cylindrical:

The advantages are ease of manufacture and good mechanical stability. The tubular cylinder, made out of steel, nickel-coated steel or aluminium, can withstand high internal pressures without deforming. There are also a significant number of cell assembly and manufacturing equipment suppliers that provide "off-the-shelf" manufacturing solutions for this product today.

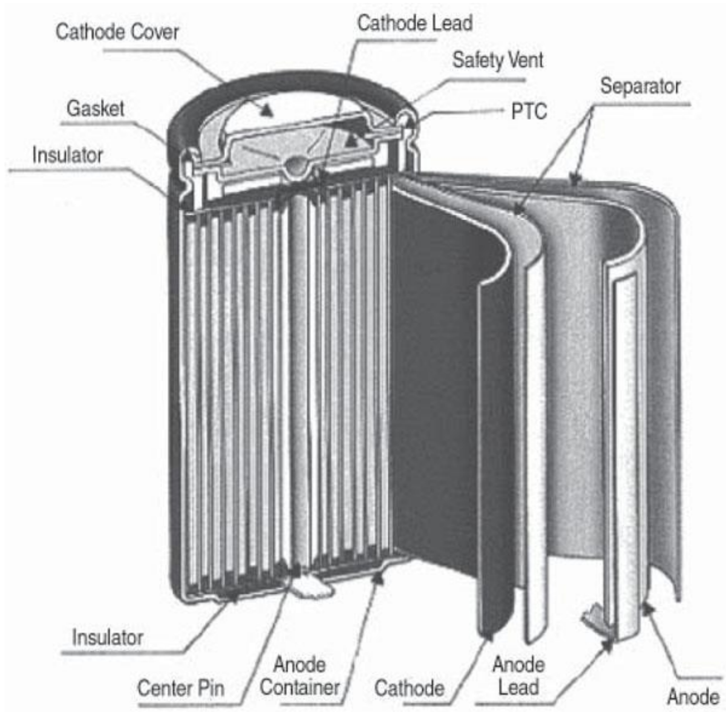

Figure 9: Cross section of a lithium-ion cylindrical cell.

Many lithium and nickel-based cylindrical cells include a positive thermal coefficient (PTC) switch. When exposed to excessive current, the normally conductive polymer heats up and becomes 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 consumer Li-ion cells include the Charge Interrupt Device (CID) that physically and irreversibly disconnect the cell when activated to an unsafe pressure builds up.

By far the highest volume lithium-ion cell format in production today is the 18650 cylindrical cell. The nomenclature 18650 means that the cell is 18 mm diameter by 65 mm in length. Although the switch to a flat-design in consumer products and larger format for the electric powertrain will eventually saturate the 18650.

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. A well-designed cylindrical-type lithium battery cell takes advantage of the structure's energy dense nature, using free space to install thermal regulation solutions.

3.3.2 Prismatic Cell:

Introduced in the early 1990s, the prismatic cell's key advantages lie in its thin profile, lightness and effective use of space. These characteristics facilitates better layering and gives product designers increased flexibility. Prismatic 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.

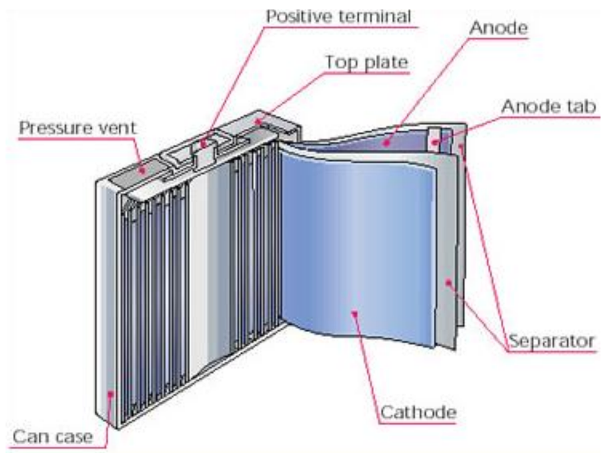

Figure 10: Cross section of a prismatic cell

The prismatic cell format has its share of disadvantages. They are expensive to design and manufacture, making them more expensive for the consumer. Thermal management is less effective and are relatively sensitive to deformation in high pressure situations which in turn make them less durable.

3.3.3 Pouch Cell:

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. As already stated the energy density can be lower and be less durable than the cylindrical package counterpart. Swelling as a result of gas generation during charge and discharge, mostly due to faulty manufacturing, is a concern. The pressure created can crack the battery cover, and in some cases, break the display and electronic circuit boards. 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.

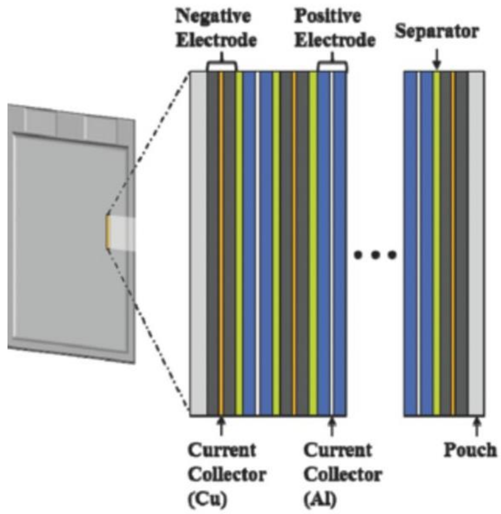

Figure 11: Cross section of a pouch cell

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, avoiding sharp edges that can stress the pouch cells as they expand.

Swelling can occur due to gassing, but improvements are being made with each new design limiting the effect. The gasses are largely consisting of carbon dioxide and carbon monoxide and are the cause of electrolyte decomposition during usage and aging and can be promoted by overheating and overcharging. Larger pouch cell designs experience less swelling.

One method to combat swelling is by adding a temporary gasbag on the side of the pouch in which gasses escape while forming the solid electrolyte interface (SEI) during the first charge. The gasbag is then cut-off. Forming a solid SEI is key to good formatting practices. Gas generation cannot be avoided during subsequent charges but the gasses released should be minimal.

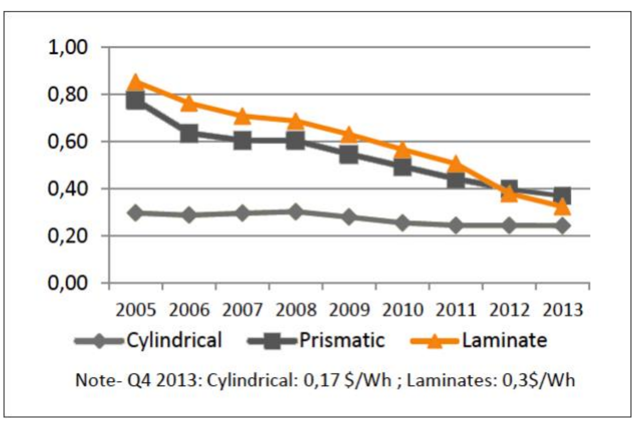

Figure 12: Price of different cell types

The cost per kWh in the prismatic/pouch cell is still higher than a cylindrical cell such as 18650 but this is changing. Flat cell designs are getting price competitive, as the above figure suggests, and experts predict a shift to these cell formats if the same performance criteria can be met.

3.3.4 Summary:

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 cells** 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.

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

3.4 Future Battery Chemistries:

3.4.1 Lithium Based:

Most experimental batteries in the lithium family have one thing in common; they use a metallic lithium anode to achieve a higher specific energy than what is possible with the oxidized cathode in lithium-ion, the battery that is in common use today.

Moli Energy was the first company to mass-produce a rechargeable Li-metal battery in the 1980s, but it posed a serious safety risk as the growth of lithium dendrites caused electric shorts leading to thermal runaway conditions. After a venting event all lithium-metal packs were recalled in 1989. Research continues and a possible solution with new materials as part of the solid-state lithium could be on hand.

Researchers have also developed an anode structure for Li-ion batteries that is based on silicon-carbon nanocomposite materials. A silicon anode could theoretically store 10 times the energy of a graphite anode, but expansions and shrinkage during charge and discharge make the system unstable. Commercialization appears to dwell on a moving target that is always a decade ahead, but researchers are not giving up as some of the chemistries seem promising.

3.4.1.1 Lithium Air – Li-air:

Lithium-air provides an exciting new frontier because this battery promises to store far more energy than is possible with current lithium-ion technologies. Scientists borrow the idea from zinc-air and the fuel cell in making the battery “breathe” air. The battery uses a catalytic air cathode that supplies oxygen, an electrolyte and a lithium anode.

The theoretical specific energy of lithium-air is 13kWh/kg. Aluminum-air is also being tried, and it is a bit lower at 8kWh/kg. If these energies could indeed be delivered, metal-air, as the battery is also known, would be on par with gasoline at roughly 13kWh/kg. But even if the end product were only one quarter of the theoretical energy density, the electric motor with its better than 90 percent efficiency would make up for its lower capacity against the internal combustion engine with a thermal efficiency of only 25–30 percent.

Li-air was proposed in the 1970s and gained renewed interest in the late 2000s, in part because of advancements in material science and the endeavor to find a better battery for the electric powertrain. Depending on the materials used, lithium-air produces voltages of between 1.7 and 3.2V/cell. IBM, MIT, the University of California and other research centers are developing the technology.

As with other air-breathing batteries, the specific power may be low, especially at cold temperatures. Air purity is also said to be a challenge as the air in cities is not clean enough for lithium-air and would need to be filtered. The battery may end up with compressors, pumps and filters resembling a fuel cell, consuming 30 percent of its produced energy on auxiliary support to stay functional.

Another problem is the sudden death syndrome. Lithium and oxygen form lithium peroxide films that produce a barrier, which prevents electron movement and results in an abrupt reduction in the battery's storage capacity. Scientists are experimenting with additives to prevent the film formation. The cycle life will also need to improve; lab tests currently produce only 50 cycles.

3.4.1.2 Lithium Metal:

Lithium-metal has long been seen as the future rechargeable battery because of its high specific energy and good loading capability. However, uncontrolled lithium deposition causes dendrite growth that induces safety hazards by penetrating the separator and producing an electrical short.

After several failed attempts to commercialize rechargeable lithium-metal batteries, research and limited manufacturing of this battery continues. In 2010, a trial lithium-metal with a capacity of 300Wh/kg was installed in an experimental electric vehicle. DBM Energy, the German manufacturer of this battery, claims 2,500 cycles, short charge times and competitive pricing if the battery were mass-produced.

A solution to inhibit the growth of dendrite may be imminent. To produce dendrite-free deposits on Li-metal batteries, tests are being conducted by adding nano-diamonds as an electrolyte additive. This works on the principle that lithium prefers to absorb onto the surface of a diamond, leading a uniform deposit and enhanced cycling performance. Tests have shown stable cycling for 200 hours, but this would not provide sufficient guarantee for consumer applications. In conjunction with the research work, Li-metal batteries may need other precautions including non-flammable electrolytes, safer electrode materials and stronger separators.

3.4.1.3 Lithium Sulfur – LI-S:

By virtue of the low atomic weight of lithium and the moderate weight of sulfur, lithium-sulfur batteries offer a very high specific energy of 550Wh/kg, about three times that of Li-ion. Li-S also has a respectable specific power of 2,500W/kg. During discharge, lithium dissolves from the anode surface and reverses itself when charging by plating itself back onto the anode. Li-S has a cell voltage of 2.10V, offers good cold temperature discharge characteristics and can be recharged at –60°C (–76°F). The battery is environmentally friendly; sulfur, the main ingredient, is abundantly available. A price of US$250 per kWh is said to be possible.

A typical Li-ion has a graphite anode. On discharge, the battery releases the ions to the cathode. In Li-S, graphite is replaced by lithium metal, a catalyst that provides double duty as electrode and supplier of lithium ions. The Li-S battery gets rid of "dead weight" by replacing the metal oxide cathode used in a Li-ion with cheaper and lighter sulfur.

A challenge with lithium-sulfur is the limited cycle life of only 40–50 charges/discharges as sulfur is lost during cycling by shuttling away from the cathode and reacting with the lithium anode. Other problems are poor conductivity, a degradation of the sulfur cathode with time and poor stability at higher temperatures. Since 2007, Stanford engineers have experimented with nanowire. Trials with graphene are also being done with promising results.

3.4.2 Redox Flow Batteries:

A flow battery is an electrical storage device that is a cross between a conventional battery and a fuel cell. Liquid electrolyte of metallic salts is pumped through a core that consists of a positive and negative electrode, separated by a membrane. The ion exchange that occurs between the cathode and anode generates electricity. The most appealing features of this technology are: scalability and flexibility, independent sizing of power and energy, high round-trip efficiency, high DOD, long durability, fast responsiveness, and reduced environmental impact

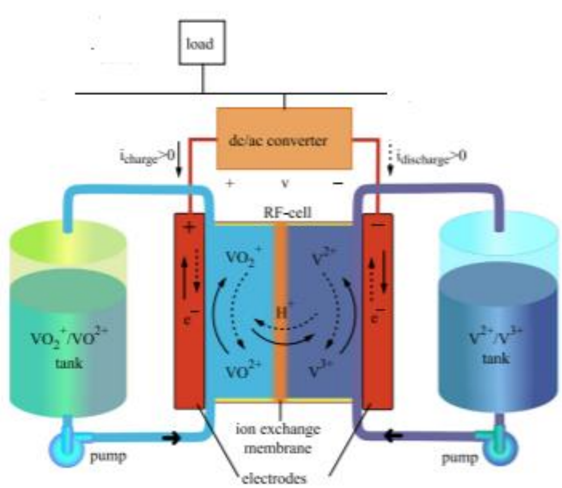

Figure 13: Diagram of an RFB energy storage system: RFB stack and electrolyte tanks are

Compared to other electrochemical storage technologies, in RFBs, power conversion is separated from energy storage, thus allowing for independent power and energy sizing. This feature allows for virtually unlimited capacity simply by using larger storage tanks. Practically speaking, energy of present designs spans from 10^2 to 10^7 Wh, a range exceeding that of most ECES at least by one order of magnitude. RFBs have more advantages than other electrochemical devices when storage times longer than 4–6 h are required.

The electrochemical heart of RFBs is the MEA (membrane electrode assembly), a sandwich consisting of two catalyzed electrodes with an interposed polymeric membrane. In order to allow electrolyte flow toward the electroactive sites, the electrodes have a porous structure that can be obtained with carbon base materials such as carbon felt, carbonfiber paper, or carbon nanotubes. RFB's reactions are completely reversible, enabling the same cell to operate as converter of electricity into chemical energy and vice-versa. RFBs operate by changing the metal ion valence, without consuming ion metals, thereby allowing for long cycle service life.

RFB's liquid electrolytes can be kept inside two low-cost tanks. Only two pumps are needed in RFBs for circulating the electrolytes between the tanks and the cell electrodes. Cell temperature can be easily controlled by regulating the electrolyte flow, allowing to operate the cells in the optimal conditions, e.g. at maximum efficiency. The SOC (state of charge) can be easily monitored through the cell voltage while very deep discharges are viable which do not affect the cell morphology. No self-discharge occurs because the two electrolytes are stored in different tanks, and cells can be left completely discharged for long periods with no ill effects. RFBs are capable of rapid response that allows them to span from power quality to energy management services. They can be overloaded over a short period. Moreover, rapid refueling by solution exchange is possible, in case of need, and furthermore, they require low maintenance.

On the other hand, the power and energy density of RFBs are significantly lower compared to other technologies. making them unsuitable for mobile applications at present. Accordingly, cell active areas and membranes are quite large, increasing the dimensions of the battery and causing high transverse gradients of the solutions flowing toward the sites of electrochemical activity inside the electrodes. Consequently, this reduces the average current density and nominal current with respect to the maximum theoretical values, achievable with uniform maximum current density.

Most commercial flow batteries use acid sulfur with vanadium salt as electrolyte; the electrodes are made of graphite bipolar plates. Vanadium is one of few available active materials that keeps corrosion under control. Flow batteries have been tried that contain precious metal, such as platinum, which is also used in fuels cells. Research is continuing to find materials that are low cost and readily available.

Several makers of redox-flow batteries use vanadium oxide as the electrolyte and experiments are underway that involve other compounds such as uranium oxide. It is possible to recharge the liquid electrolyte of a redox-flow battery while the battery is delivering power.

It is important to realize that RFBs are electrochemical reactors applied to energy storage. A typical filter-press reactor or stack of an RFB is shown in the next figure.

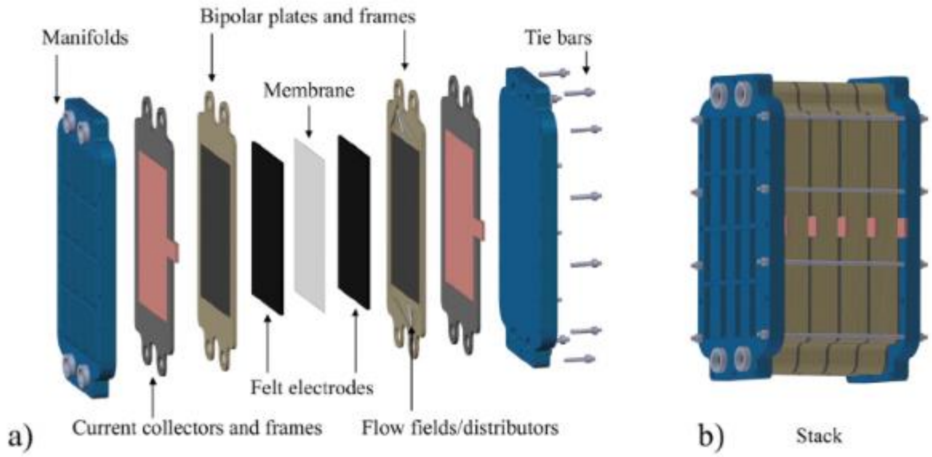

Figure 14: Components of an RFB stack. a) Exploded view of a unit cell and b) Assembled stack

The stack is made of a number if cell frames encasing bipolar electrodes hold together by rigid endplates. The rate of conversion of active redox species at the electrodes (charge or discharge), the stack voltage and the produced current are governed by the principles of electrochemical engineering (Electrode material and structure, electrolyte properties, separator, reaction environment etc.). Such factors are influence the performance of an RFB and their interrelation must be taken into account while designing and scaling such systems.

The fundamental RFB unit is the electrochemical flow cell, normally divided by a membrane into two half-cells fed by their corresponding electrolytes. As shown in the nest figure, a number of individual cells build up to create bipolar stacks, the basic modules of an RFB system. The potential difference developed across each stack is the summation of that of the individual cells. In turn, the stacks are arranged (using convenient series and parallel electrical connections) into banks or arrays, which are fed by centrifugal pumps with electrolyte circulating to and from its reservoirs, and electrically connected to the power converter and control system.

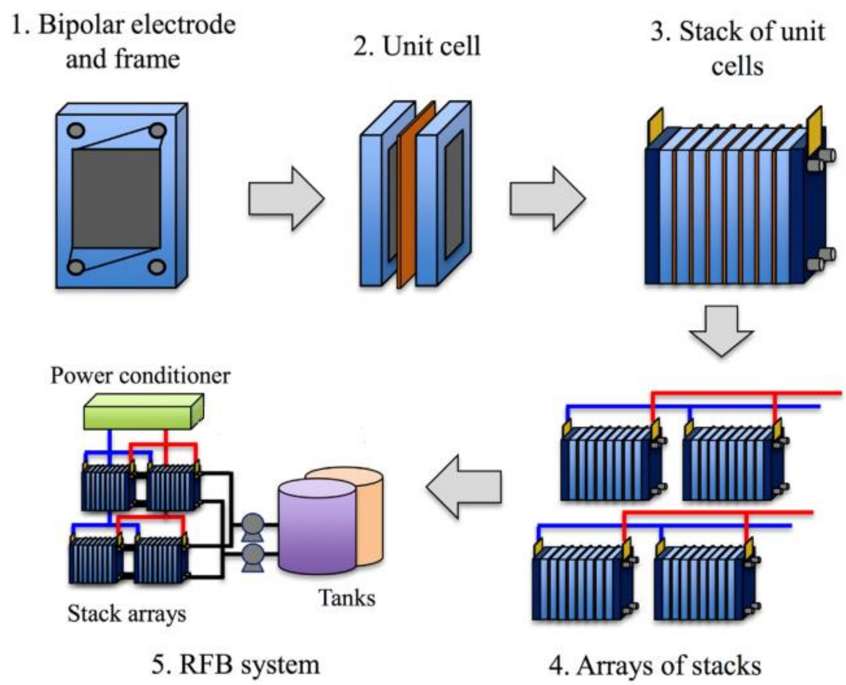

Figure 15: Individual cells build up into modular stacks, with strategic electrolyte flow and electrical connections, to create RFB systems.

The main components of such RFB energy storage systems are:

- Electrolyte flow and storage: electrolyte circuit (piping), pumps, heat exchanger, switch valves, valve actuators and electrolyte tanks.
- Electrical connections and power conversion: electrical circuits, power electronics, power conditioner, AC/DC rectifier, transformer, AC breaker, cooling system, etc.
- Control and monitoring: sensors for electrolyte flow rates, SOC, temperature, pH, gas release, etc.; instruments for measuring stack potential and current; control system and software.

Suppliers such as Prudent Energy offer banks of redox-flow batteries of 22 Mw output over 7.5-hours. The volume of the battery energy storage system can fit into the hold of a ship. Variations in the volume and capacity of the energy storage system can offer higher output over an extended service cycle. During layovers at port or terminals, it may be possible to exchange the electrolyte in a similar operation to dialysis. The operation would involve pumping out the spent electrolyte and replacing it with freshly recharged electrolyte.

4 Tugboats

Tugboats are an integral part of the marine industry and seaports globally as restricted ship maneuverability in harbors, canals and rivers has always been a major problem. Tugs are characterized as the family of marine vessels with disproportionally large power compared to their size. However, this large installed power is utilized only for a short time of its operations. Yet tugs have not attracted much attention of researchers in comparison to other types of vessels. Tugboat design modifications are based on owner's requirements without much consideration of hydrodynamics of hull form, energy efficiency or environmental impacts. They can be categorized in many sub-groups according to their function or their propulsion arrangement.

4.1 Propulsion Arrangements:

In the context of towing, tugs with different design features have different handling characteristics. These could be a combination of hull profile, engine, rudder and thruster's configurations. There are various types of propulsion configurations but four of them are most common: Conventional propulsion system, Azimuth Stern Drive (ASD), Tractor tug with rudder propellers and Voith Water Tractors. Apart from these main categories there are other sub-groups, such as the "Rotor" tugs, which can be considered a development of the tractor tug.

4.1.1 Conventional Tugs:

These tugs are fitted with a standard propulsion system and are used worldwide. Their characteristics vary, but generally are equipped with fixed or variable pitch propellers, single or twin screw and fixed nozzles and steerable rudders or steerable nozzles.

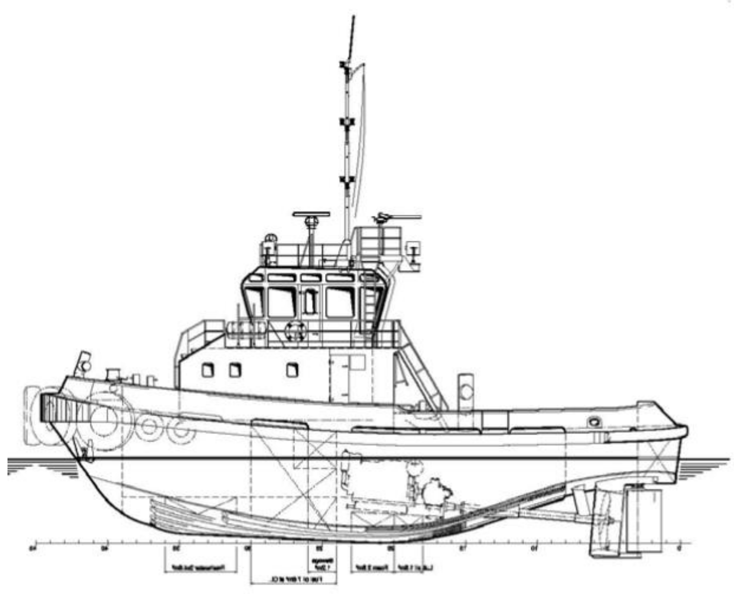

Figure 16: Conventional tugboat sketch

Conventional tug's general characteristics are:

- Maneuverable and effective for most work, but less maneuverable than azimuth stern drive tugs or tractor tugs.

- Good steering ability, especially as a forward pulling tug.
- Good sea-keeping ability.
- Good bollard pull to power output.
- Towing point is usually situated just aft of amidships.
- Astern bollard pull reduced by up to 50% of forward bollard pull.
- Increased risk of girting/grinding when towing.

Conventional tugs deliver the highest bollard pull in the forward direction and will mostly be used as a bow tug on a hawser. When connected at the stern of the vessel being assisted, they will effectively be working in the conventional mode, also referred to as “stern to stern”. The position of the pivot point when no tow line is fast is similar to a conventional ship, about one quarter from the tug’s bow. Once the towline is attached the pivot point moves astern to the towing point, usually the towing hook. This distance from the rudder has been reduced although the turning moment is still appreciable. If the tug is dragged astern there is an increased risk of girting. The use of a gob wire moves the towing point aft, allowing the tug to be dragged astern with a reduced risk of girting. This is an appreciable risk to conventional tugs and getting out of a girting situation by maneuvering alone is not possible.

4.1.2 Azimuth Stern Drive Tugs (ASD):

These tugs are fitted with two azimuth thrusters in nozzles at the stern and with bow tunnel thrusters. The thrusters can be rotated independently in a 360^{O} angle; thus, the propeller’s thrust can be directed in any direction is needed. Azimuth thrusters can have either fixed pitch propellers or variable pitch propellers with the latter providing for reversing of the propeller thrust.

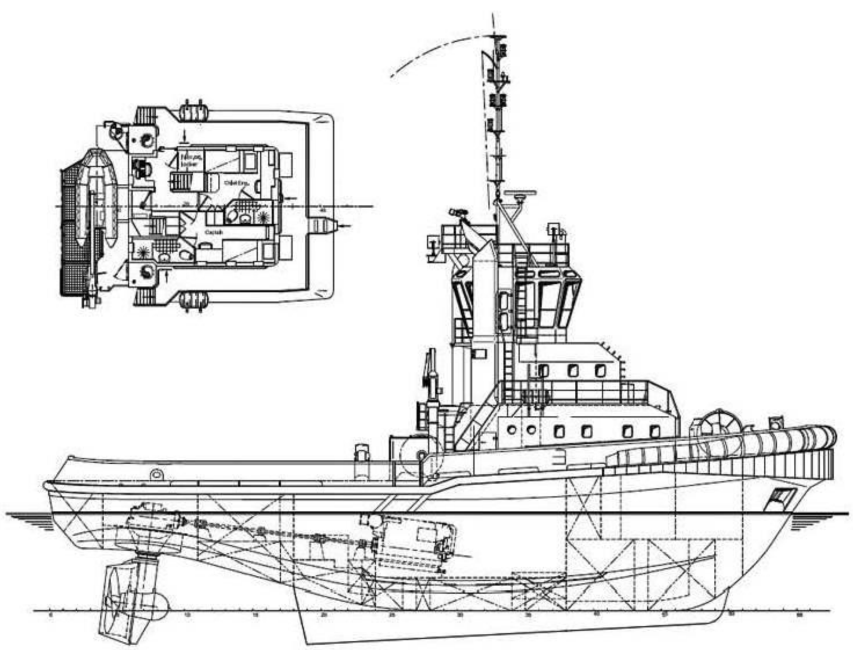

Figure 17: ASD tugboat sketch

General characteristics of ASD tugs are:

- Low relative draught.

- Good steering characteristics, except when going astern at higher speeds.
- Towing point is just forward or just aft of amidships.
- Underwater hull form improves the dynamic stability of the tug.
- Bollard pull going astern is reduced only by approximately 10%.
- Maneuverable and able to pull effectively over the stern or bow. Towing winches often fitted both fore and aft.
- Risk of girting/grinding when towing over the stern.
- Enhanced training of tug masters required when operating the forward winch.

This type of propulsion system provides for high maneuverability particularly during transit sailing, however it does have some limitations when combining thrust and direction resulting in a lower bollard pull.

4.1.3 Tractor Tugs:

The design of tractor tugs is unlike that of conventional tugs. The propulsion units are fully turning controllable pitch blades, able to give thrust in any direction and act as steering units or azimuthing fixed or controllable pitched propellers. The propulsion units are placed far ahead of the towing point, close to the pivot point thereby producing a large turning momentum. This potentially gives a poor steering performance, which is overcome by fitting a large centerline skeg.

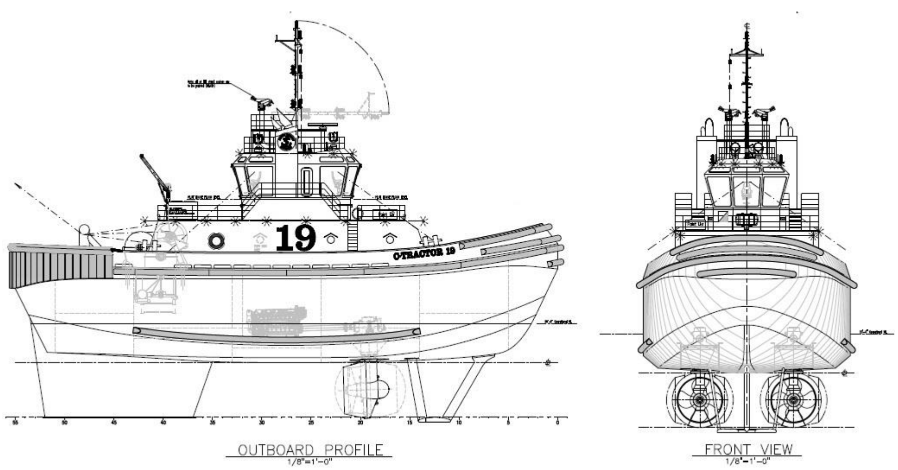

Figure 18: Tractor tugboat sketch

Their general characteristics are:

- Full power in all directions.
- Quick response to engine movements.
- Very maneuverable especially in tight sea space.
- Reduced risk of girting/girding
- Reduced maneuverability if towing from forward at higher speeds.
- Reduced directional stability, particularly in open waters.
- Reduced bollard pull per kilowatt output.
- Relatively deeper in draught therefore increased risk of bottom damage from grounding
- Increased training required of the tug crew.

As previously stated a further advancement of a tractor tug is a rotor tug. It uses a propulsion configuration consisting of three azimuthing thrusters placed in a triangular configuration, sometimes called a triple Z drive. Two units are placed forward and one astern on the centerline of the tug. This arrangement is used to further enhance maneuverability and transverse bollard pull. Many ports are adopting this type of design for ship assistance.

4.1.4 Voith Tugs:

Voith water tractor tugs are fitted with two cycloid propellers located at the bow (forward of midship). The Voith units are basically composed of a circular plate, rotating around a vertical axis and a circular array of vertical blades (normally 5 of a hydrofoil cross section) protruding out of the bottom of the tug. Each blade can rotate itself around a vertical axis. The internal gear changes the angle of attack of the blades in synchronization with the rotation of the plate, so that each blade can provide thrust in any direction, these tugs are fitted with a harbor towing winch which is located on the aft deck and a towing staple which is fitted aft of the winch.

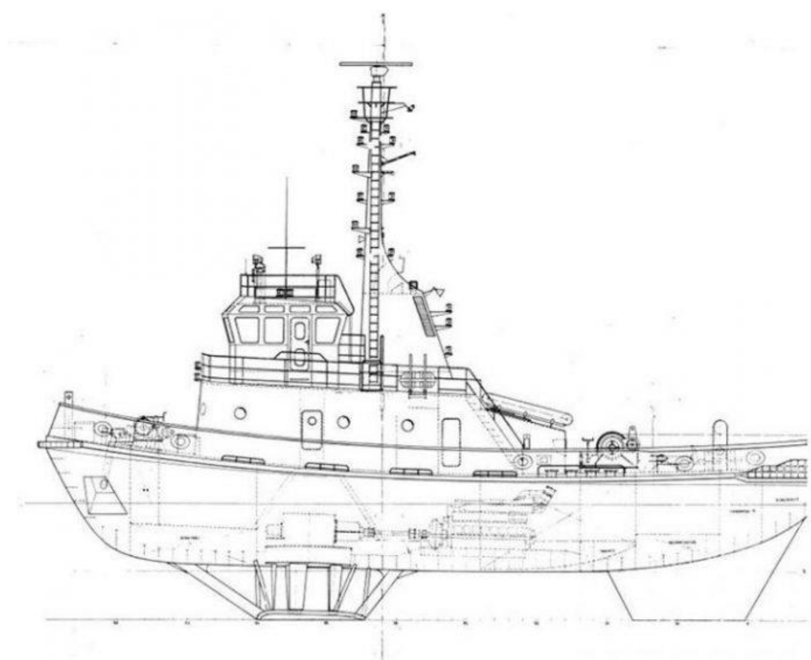

Figure 19: Voith tugboat sketch

4.2 Tug functions:

Modern tugboats perform a variety of different operations including guidance in mooring operations, firefighting, oil spill response, icebreaking and pushing, pulling and directing large ships in docking and undocking, helping them maneuver in confined spaces where their own speed is too low. Broadly speaking tugs are designed to perform one or more of the above functions and thus categorized accordingly. The more diverse the duties of a tug are, the more compromised its ability to perform each of these tasks is. Although every vessel is still customizable to perform in applications and new designs are continuously developed for unique projects.

4.2.1 Harbor Tugs:

They are used to assist ships while entering or leaving a port and during berthing and unberthing operations. These tugs are necessary because most large ships have no control over their own steering when operating at very low speeds, and thus are very susceptible to the forces of wind and current. A large ship navigating in confined waters is faced with many hazards, including the risk of collision or grounding which may have severe environmental consequences. The crew is very familiar with the operating area and shore side facilities and need to be highly skilled as each ship needing towing would have its unique steering characteristics.

Figure 20: Harbor tugboats assisting a containership during berthing

Today the vast majority of modern ship-assist tugs are fitted with Z-drive or VSP propulsion. Harbor tugs typically range from 20 to 32 meters in length, and have power ranging from 2,000 to 4,000 kW, although there are exceptions to this depending on the size of port and types of ships handled. Many harbor tugs are simple day boats where the crew is aboard only to do each job.

4.2.2 Escort Tugs:

Escort tugs are the newest and most challenging of tug designs. These tugs are designed to provide emergency steering and braking functions to tankers and occasionally other ships in sensitive or critical coastal areas. Accidents have occurred in the past, which have led to major oil damages, which accelerated pressure toward improvements in safety in marine oil transports. Some of these accidents led to oil damage which resulted from an oil tanker that lost either its maneuverability or propulsive thrust at a critical moment. In addition to stricter rules concerning tanker structures, development of escort tugboats has been necessary to provide assistance to and escort tankers in dangerous and coastal waters.

Figure 21: An escort tugboat assisting a vessel in steering

The tug's role is to be available to bring a disabled oil tanker rapidly and safely under control in the event of a machinery system failure while imposing the minimum possible effect on the tanker's normal operations. Escorting is distinguished from regular ship-handling because, by definition, it takes place at higher speeds, from 7 to 10 knots typically. Escort tugs can generate forces for steering and braking a disabled tanker which are greater than the bollard pull delivered by the propulsion system. This is achieved by using a hull shape and appendages that can generate very high forces at yaw angles up to 45 degrees, combined with an azimuthing propulsion system to resist the resulting yaw moments generated from the hydrodynamic forces. This mode of operation is known as indirect steering or braking and results in a high degree of interaction between the flow around the hull and the flow due to the propellers.

4.2.3 Seagoing Tugs:

They are used to assist ships in ports as well as at sea. Seagoing tugs can either operate without any restriction (deep sea towage, in any sea area and any period of the year) or within short distance from shore (coastal towage) or at a specified location (offshore terminal tugs). Good sea keeping characteristics is an additional requirement compared with other type of tugboats. These tugs are single or more frequently twin screw and have large fuel capacity and quite large crews; and must be capable of coping with extreme ocean conditions.

4.2.4 Coastal Tugs:

The majority of tugs categorized as coastal, are designed for towing barges between coastal ports. These tugs must be able to handle more weather than a harbor tug and also don't need the same degree of fendering. They have larger crews and hence more crew facilities. In general, these tugs will have conventional propulsion with single or twin screws and a towing winch aft.

4.2.5 Terminal Tugs:

This is a relatively new category of tug used to provide ship-handling and other services at either offshore oil terminals or at LNG terminals situated in more exposed locales. Because they work in typically rougher waters, they tend to be larger and more powerful than normal ship-handling tugs and will frequently also have fire-fighting and anchor-handling capabilities. Some may also have some deck or bulk fuel or water cargo capacity

4.2.6 Anchor-handling tugs:

Some tugs are designed to deploy, relocate or retrieve the large anchors used in offshore drilling applications. Although typically this operation is done by larger AHTS (Anchor-Handling Tug/Supply vessels), tugs are very useful for working with smaller anchors. This operation requires a large roller at deck level aft, an open stern and a powerful winch, as well as typically wooden sheathing to protect the steel deck from the impact of anchors coming aboard.

4.2.7 Fire-fighting tugs:

In most ports in the world, the tug fleets are equipped with firefighting capability to provide a "first response" capability as tugs are nearly always in the vicinity. In some cases, the "tug" function takes a back seat to the fire-fighting capabilities of the boat. Almost any tug can be equipped for fire-fighting although due to the size and cost of the equipment involved, typically this is left to larger sizes of tugs.

4.3 Power Systems for tugboats:

The power of a tug boat depends entirely on the propulsion system installed. Today the primary source of propeller power especially for tug boats is the diesel engine. Tugboat engines produces power ranging from 500 - 2500 KW (680 - 3400 HP). Although diesel engines as the prime mover is a tested and well understood technology the fact that traditional diesel tugs have engines sized for full bollard pull, which is used for only around 7-15% of the time lead to poor specific fuel consumption and high emissions as well as engine wear. Thus, the power and propulsion configuration has been adapted to a varied operating profile with electric propulsion. Although electrical propulsion is more efficient at low speed, it introduces additional conversion losses of 5–15% of the propulsive power in electrical components such as generators, power converters, transformers and electric motors.

This trade-off between efficiency and adaptability to diverse operating profiles has led to a growing variety of power and propulsion architectures, which can be categorized as follows:

- Mechanical propulsion
- Diesel-Electric propulsion
- Hybrid propulsion
- Electrical propulsion with hybrid power supply
- Hybrid propulsion with hybrid power supply
- All Electric propulsion

4.3.1 Mechanical Propulsion:

A typical architecture of a propulsion system of a tug boat with mechanical propulsion mainly consists of the prime mover (diesel engine) with a reduction gear attached, and a shaft line connecting the gear box to the propeller which provides the thrust for propelling the tugboat. In conventional tugboats, i.e equipped with FPP or CPP propellers, this architecture is used for each of the propellers of the tugboat.

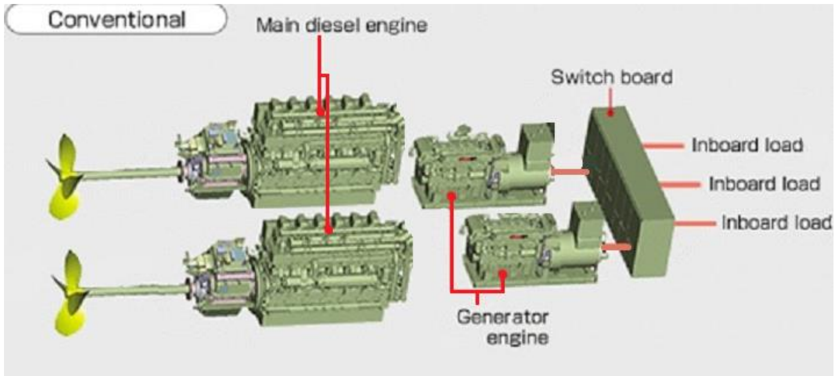

Figure 22: Typical mechanical propulsion system of a tugboat

A separate electrical AC network is required for generating and distributing electric power of auxiliary loads, such as variable speed drives, heating ventilation and air-conditioning (HVAC) and other mission-critical and auxiliary systems. Diesel, steam-turbine or gas-turbine generators feed this electrical network. An example of this type of engine room arrangement is given on the next figure.

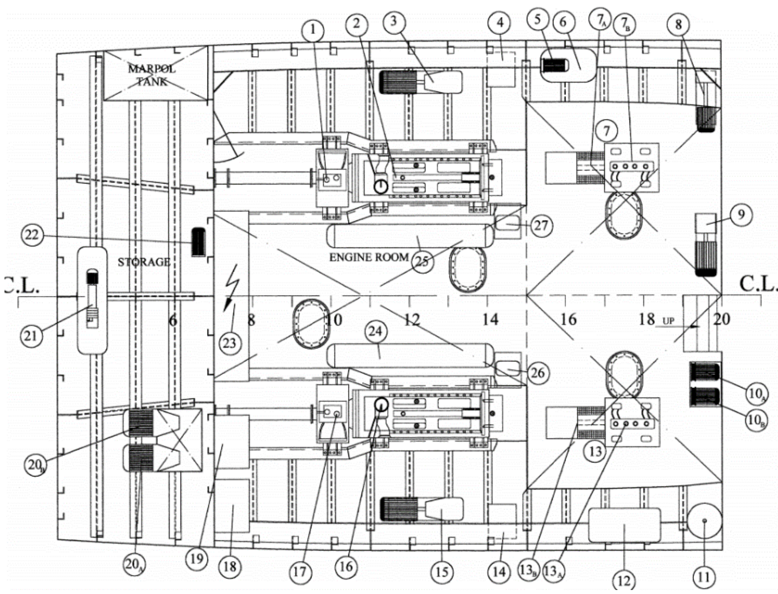

Figure 23: Typical Engine Room of a Conventional Tugboat.

Mechanical propulsion is particularly efficient at design speed, between 80 and 100% of top speed. In this range the diesel engine operates in its most efficient working point. Moreover, mechanical propulsion consists of only three power conversion stages, the main engine, the gearbox and the propeller, which leads to low conversion losses. For example tugs, only require 20% of their maximum power required for towing during transit, and offshore vessels operate at very low power during DP. For these ship types, mechanical propulsion would lead to poor specific fuel consumption and high emissions. Nevertheless, over 50% of tugs operating around the globe consist of mechanical propulsion.

4.3.2 Diesel-Electric Propulsion:

Compared to direct diesel drives, diesel electric propulsion systems are technically and operationally superior in virtually all applications. This superiority has been a major reason for the steadily growing demand for diesel-electric main drives in marine engineering applications. Multiple diesel generator sets feed a fixed frequency high voltage electrical bus. This bus feeds the electrical propulsion motor drive and the hotel load, in most cases through a transformer. The electric propulsion motor drive consists of a power electronic converter used to control shaft line speed and thus ship speed.

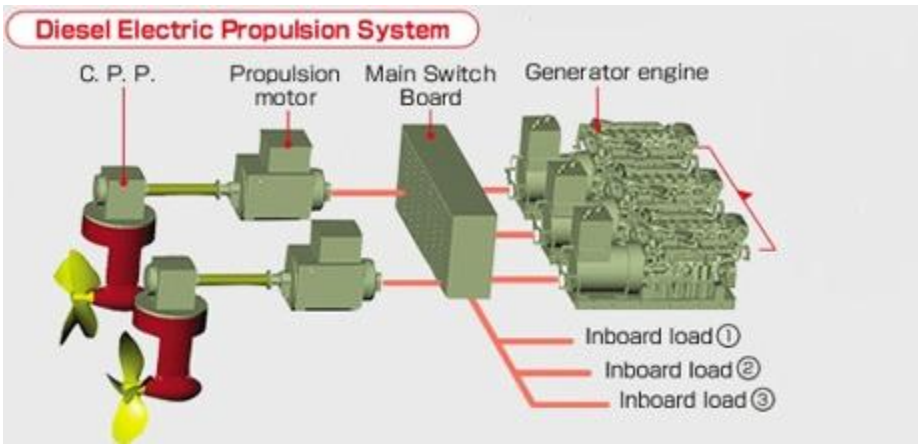

Figure 24: Typical Diesel-Electric Propulsion system

Electrical propulsion systems are rated as particularly economical, environmentally friendly and reliable, offer considerable comfort in terms of operation and control, have optimal maneuvering and positioning properties, low vibration and noise levels, and additionally enable the best possible utilization of space.

The most commonly used diesel electrical propulsion systems are not a new concept. In the past these systems were usually diesel engine driven D.C generators that supplied power to D.C motors. Their applications were generally limited to vessels that required a degree of low speed maneuvering. Vessels such as ferries, harbor tugs, and various other applications used diesel electrical systems for features that were not available in mechanical systems at that time like speed control and maneuverability.

The two systems dominating the market today are Frequency controlled A.C Motors and SCR controlled D.C Motors. To date, electrical propulsion systems have been used mainly for specialized vessels rather than for cargo ships in general. These include dredgers, tugs, trawlers, lighthouse tenders, cable ships, ice breakers, research ships, floating cranes, and vessels for the offshore industries. Electrical-drive systems have made substantial progress in recent years.

Diesel-electrical propulsion becomes viable when the installed KW for propulsion approaches or is exceeded by the KW installed for other purposes. A large variation in propulsion power requirements, such as long periods of low speed operation or the necessity to shift power from main propulsion to thrusters for dynamic positioning purposes, can also justify diesel electric systems. The ability to generate only the power required to meet the needs of the duty cycle of vessels utilizing multiple generator sets reduces fuel consumption and maintenance cost. It also provides redundancy in power capacity.

4.3.3 Hybrid Propulsion:

In hybrid propulsion, a direct mechanical drive provides propulsion for high speeds with high efficiency. Additionally, an electric motor, which is coupled to the same shaft through a gearbox or directly to the shaft driving the propeller, provides propulsion for low speeds, thus avoiding running the main engine inefficiently in part loads. This motor could also be used as a generator for electrical loads on the ships services electrical network.

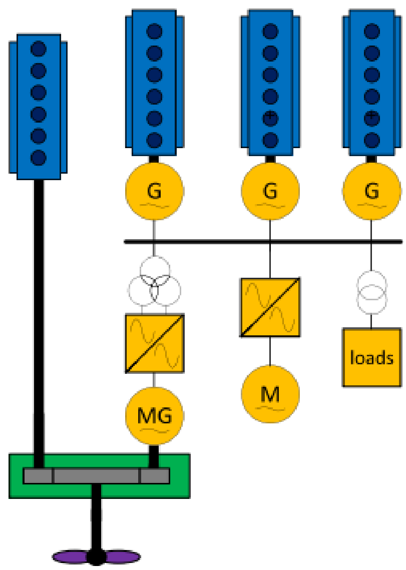

Figure 25: Typical Hybrid Propulsion System

Ships that frequently operate at low speeds can benefit from a hybrid propulsion system. Because hybrid propulsion is a combination of electrical and mechanical propulsion, it can benefit from the advantages of both, however, in order to achieve these benefits, a proper design (of the hybrid propulsion) is required and often a trade-off between these requirements has to be made. Typical applications of hybrid power and propulsion systems are towing vessels of which the operational profile, the engine power can be at 20% or less at 90% of its operational time.

Hybrid propulsion is typically economical when the operational profile has distinct operating modes with a significant amount of time at low power. Also, the power system is not over-sophisticated making it cheap to install but the fuel savings that can be achieved by this topology are not that impressive and today greener solutions exist.

4.3.4 Electrical Propulsion with Hybrid Power Supply:

In electrical propulsion with hybrid power supply, a combination of two or more types of power source can provide electrical power:

- Combustion power supply, from diesel engines coupled with a generator.
- Electrochemical power supply from fuel cells

- Stored power supply from energy storage systems such as batteries, flywheels or super-capacitors.

Commercial application of electrochemical power supply from fuel cells, outside of submarine applications, in the maritime environment is limited. On the other hand, technologies such as flywheels and super-capacitors are fairly new and exotic technologies. Batteries are the preferred energy storage device and thus is the technology most studied and understood by marine engineers. The idea to use battery energy storage for propulsion originates from the automotive industry, which increasingly uses batteries to store braking energy instead of dissipating it, to run the engine in a more efficient operating point, and to enable switching off the main engine, particularly when operating at no load or part load

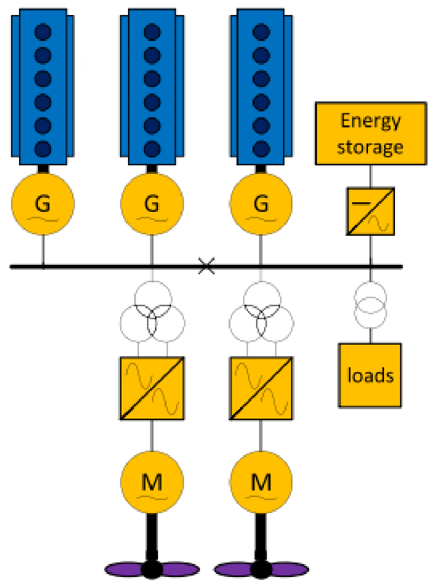

Figure 26: Typical Electrical Propulsion with Hybrid Power Supply System.

Batteries have only recently been applied in maritime applications, but their popularity is growing very quickly. For tugs for example, the potential reduction of fuel consumption and emissions has led to investigation and application of electrical propulsion with hybrid power supply. The calculated fuel savings of the hybrid propulsion plant are marginal when the battery is not recharged from the shore grid. The results of studies like these, however, strongly depend on the operational profile. Moreover, no sensitivity studies have been performed.

4.3.5 Hybrid Propulsion with Hybrid Power Supply:

Hybrid propulsion with hybrid power supply utilizes the maximum efficiency of direct mechanical drive and the flexibility of a combination of combustion power from prime movers and stored power from energy storage for electrical supply. At low propulsive power an electric drive is available to propel the ship and switch off the main engine. The machine providing electric drive can also be used as a generator.

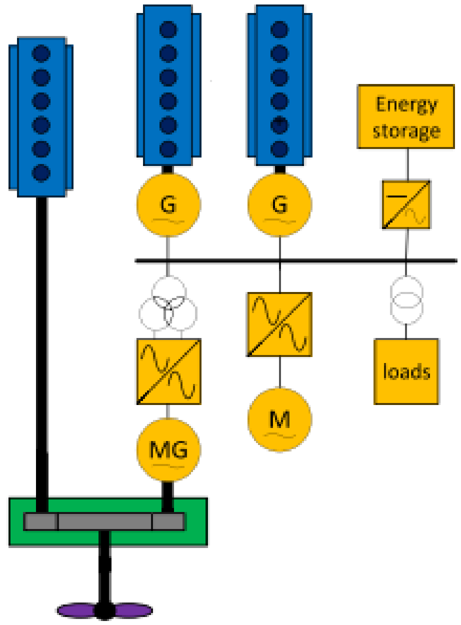

Figure 27: Typical Hybrid Propulsion with Hybrid Power Supply System.

Hybrid propulsion with hybrid power supply has first been researched extensively in harbor tugs. Following this research, Damen delivered the first tug with hybrid propulsion and hybrid power supply in 2014. Hybrid propulsion with hybrid power supply can deliver significant savings in local emissions, partly by using energy from the batteries that are recharged with a shore connection. These savings can be achieved with a heuristic rule-based approach. In this approach the control mode of the plant is determined by the operating mode of the vessel (towing, high speed transit, low speed transit or standby) and the battery state of charge.

4.3.6 All-Electric Propulsion System:

In contrast to the hybrid topologies discussed above an All-electric propulsion system utilizes only energy storage systems such as batteries, flywheels or super-capacitors as the main way of providing power. Super-capacitors have a high-power density but offer lower efficiency, while both them and flywheels are better at delivering higher power for short periods of time compared to batteries. Flywheels offer a superior lifecycle but their power density is lower. Currently, for shipboard propulsion, Li-ion batteries offer the highest energy density, a suitable power density, high efficiency and an acceptable lifetime. This energy storage systems are used in order to provide both electrical and propulsive power to the ship. A battery powered ship would have no need for fuel tanks, fuel processing, exhaust, air trunking and diesel engines. In addition to the batteries though there would be need for power electronic modules and electric propulsion motors, equipment already widely used in diesel-electric ships.

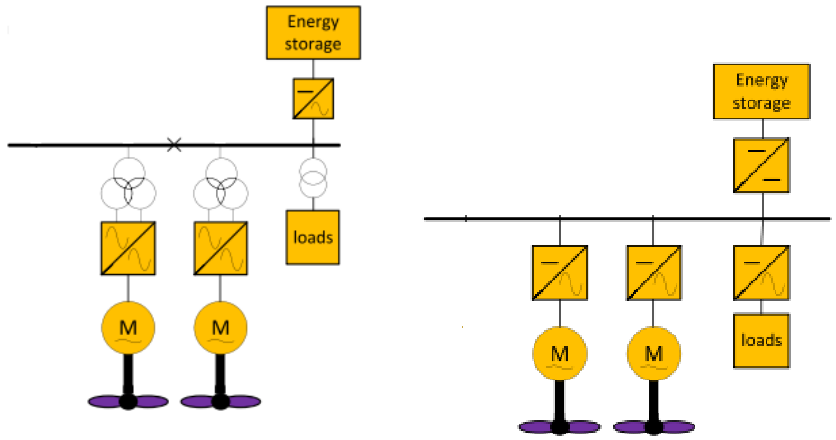

Figure 28: All-Electric Propulsion System with an AC distribution system (left) and a DC distribution system (right).

In most battery powered ships, improving energy efficiency to reduce atmospheric emissions seems to have been the key driver. However, considering batteries have technical limitations that include energy density, power density and lifetime, and their adoption potentially influences operational performance such as speed and range of the vessel as well as impacting on ports such as the need to provide a recharging infrastructure, then the applicability of battery propulsion power for wider commercial shipping is not quite so obvious.

Considering these, it is not surprising that real life applications of tugboats with all-electric propulsion system have not been implemented yet. As to the time this dissertation is being written the only all-electric tugboat fully operational is for training purposes solely (August 11, 2010 by Dr Peter Harrop) but, as electro-chemistry of battery technology is developing rapidly, future all-electric tugboats can be a viable solution.

Applications concerning fully electric battery powered commercial ships are mainly confined to passenger and car ferries until now. Ferries are a perfect place for this technology to start since they often travel only short distances and stay for relatively long periods of time at the same ports, where they can be charged.

In January 2015, world's first fully electric battery powered passenger and car ferry, "MF Ampere", was set in operation in Norway. The vessel, certified by DNV-GL is powered by a lightweight Corvus Energy Storage System (ESS), weighting only 20 metric tons, and which supplies all the vessel's power demands while at sea. The vessel, which is 80 meters long, can carry 120 cars and 360 passengers. The ferry's crossing takes about 30 minutes. After 1,5-year five new double-ended battery powered vessels with very similar principal dimensions to "Mf Ampere" have been ordered by Norwegian companies in order to serve routes along Norwegian coastline.

Figure 29: first all-electric ferry Mf Ampere

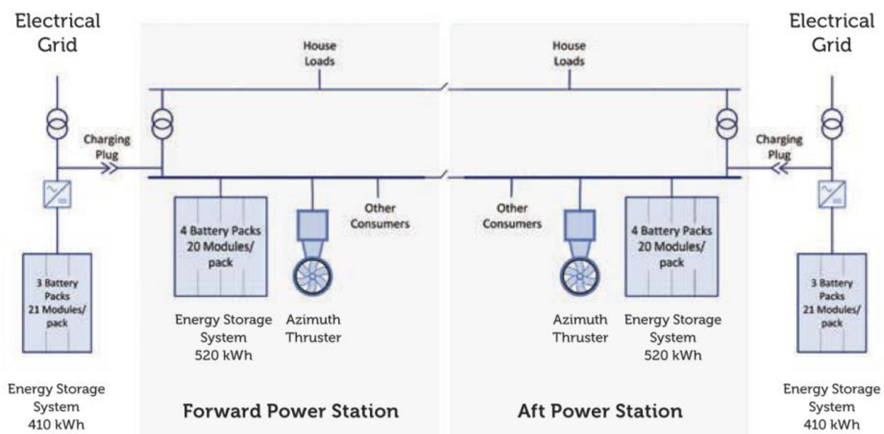

Figure 30: A line diagram of the "Ampere" drive system

Furthermore, ABB has converted two of Sweden's HH Ferries Group's massive ferries from diesel engines to completely battery-powered. "Tycho Brahe" and "Aurora", the two ferries retrofitted with 4 MWh batteries each, operate a 2.5 miles ferry route between Helsingborg, Sweden and Helsingör, Denmark. They are 238 meters long and weight 8414 tons and they carry 7.4 million passengers and 1.9 million vehicles annually.

Figure 31: Largest all-electric ferry Tycho Brahe

Another fairly new application is the first all-electric cargo ship which is in operation in China's Pearl River. Constructed by Guangzhou Shipyard International Company Ltd, it can travel 80 kilometers after being charged for 2 hours, which is approximately the amount of time it would take to unload the ship’s cargo. The ship has a cargo capacity of 2000 metric tons and its principal dimensions are 70.5 meters length, 13.9 meters breadth, 4.5 meters depth and 3.3 meters draft design. The powertrain is equipped with two 160 kW electric propellers and a mix of supercapacitors and lithium batteries for a total energy capacity of 2.4 MWh. This cargo ship is being used in order to transport coal down the Pearl River in Guangdong Province.

Figure 32: first all-electric cargo ship

Lastly, Turkish ship designer and builder Navtek Naval Technologies has selected Corvus Energy to provide its Corvus Orca energy storage system (EES) for the world's first battery-powered, all-electric tugboat. This tugboat is to operate mainly in Istanbul's harbor from the beginning of 2019. With an energy storage capacity of 1500KWh, the Corvus EES battery will supply power to two Siemens propulsion motors, driving the conventional propulsion system through ABB thrusters and drive systems. The tugboat will work in a very narrow and tight environment and this is the reason for witch a battery powered propulsion system had been chosen instead of a hybrid one (Corvus Energy, July 2018).

Figure 33: Concept design of the first all-electric tugboat

5 Legal and Regulatory Framework:

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

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

The technical design of the battery system and its arrangement in the vessels is described based on the “DNV-GL Handbook for Maritime and offshore Battery Systems” (Dec 2016). This handbook was chosen by the writer of the present disertation because even though target applications are hybrid offshore vessels and all-electric ferries and passenger ships, it is also valid for most ship types where Lithium-ion based battery power, larger than 50 kwh, in all-electric configurations are being considered. In addition to addressing safety risks, the Handbook addresses economic risks such as failure of the business case due to improper selection or integration of the battery system.

The next tables list relevant standards, rules and regulations in regards to the battery handbook. Alternatives to the requirements stated in the mandatory rules and regulations listed in the first table may be applicable provided that the overall safety and reliability level is found to be equivalent or better than that stated. It also has to be noted that the authorities of the applicable flag state may have additional or supplementary requirements

Rules and standards
DNV GL Rules for classification of ships Oct-2015, Battery Power
DNV GL Rules for classification of ships Oct-2015, Dynamic positioning
DNV GL Rules for classification of ships Oct-2015, Electrical installations
DNV GL Rules for classification of ships Oct-2015, control and monitoring systems
DNV GL CP-0418, Type Approval of lithium batteries
Norwegian Maritime Authority, Circular Series V, Guidelines for chemical energy storage - maritime battery systems
IEC 62619 Secondary cells and batteries containing alkaline or other non-acid electrolytes (will be published in 2017)
IEC 62620 Secondary cells and batteries containing alkaline or other non-acid electrolytes - Secondary lithium cells and batteries for use in industrial applications Edition: 1.0 (2014-12-01)
UN Manual of Tests and Criteria, UN38.3[6]
IEC 62281 Safety of primary and secondary lithium cells and batteries during transport Edition: 2.0 (2014-02-01)
UL1642 Standard for Lithium Batteries, edition 5 (2012-03-13)
UL1973 Standard for Batteries for Use in Light Electric Rail (LER) Applications and Stationary Applications
International Convention for the Safety of Life at Sea (SOLAS),1974
IEC 60529 Degrees of protection provided by enclosures (IP Code) Edition: 2.2 (2013-10-01)

Figure 34: Relevant battery rules and regulations

Rules and standards	Section	Comments
IEC 61508 Functional safety of electrical/electronic/ programmable electronic safety-related systems - Part 0: Functional safety and IEC 61508 Edition: 1.0 (2010)	-	Relevant for the BMS
IEC 60092-504 Electrical installations in ships - Part 504: Special features - Control and instrumentation Edition: 3.0 (2001-03-22)	-	Relevant for the BMS
DNV Recommended Practice DNV-RP-A203, Technology Qualification, July 2013	-	Technology qualification
EN 50110 Operation of electrical installations -- Part 1: General requirements Edition: 2.N (2013-06-01)	-	Supporting standard
IEC 61508 Functional safety of electrical/electronic/programmable electronic safety-related systems Edition: 1.0 (2005-01-20)	-	Supporting standard
IEC 61511 Functional safety - Safety instrumented systems for the process industry sector Edition: 1.0 (2003-12-19)	-	Supporting standard
IEC 62061 Guidance on the application of ISO 13849-1 and IEC 62061 in the design of safety-related control systems for machinery Edition: 1.0 (2010-08-01)	-	Relevant for the BMS
ISO 26262 Road vehicles -- Functional safety Edition: 1 (2011-11-14)	-	Supporting standard
IEC 62133 Safety Test Standard of Li-Ion Cell and Battery	-	Relevant for battery

Figure 35: Supporting rules and regulations for electrical testing

5.1 Battery System:

Battery system is the single most important part of an all-electric battery powered vessel. It is responsible for every function and power need of the vessel. The main components of a generic battery system are the cells which are the building block of the modules, the required components for thermal management, safety features such as contactors and fuses, bus-bars and high voltage cabling, electronics, voltage and temperature sensors and low voltage cabling and connectors. In the next figure shows in the form of a block diagram one such battery system.

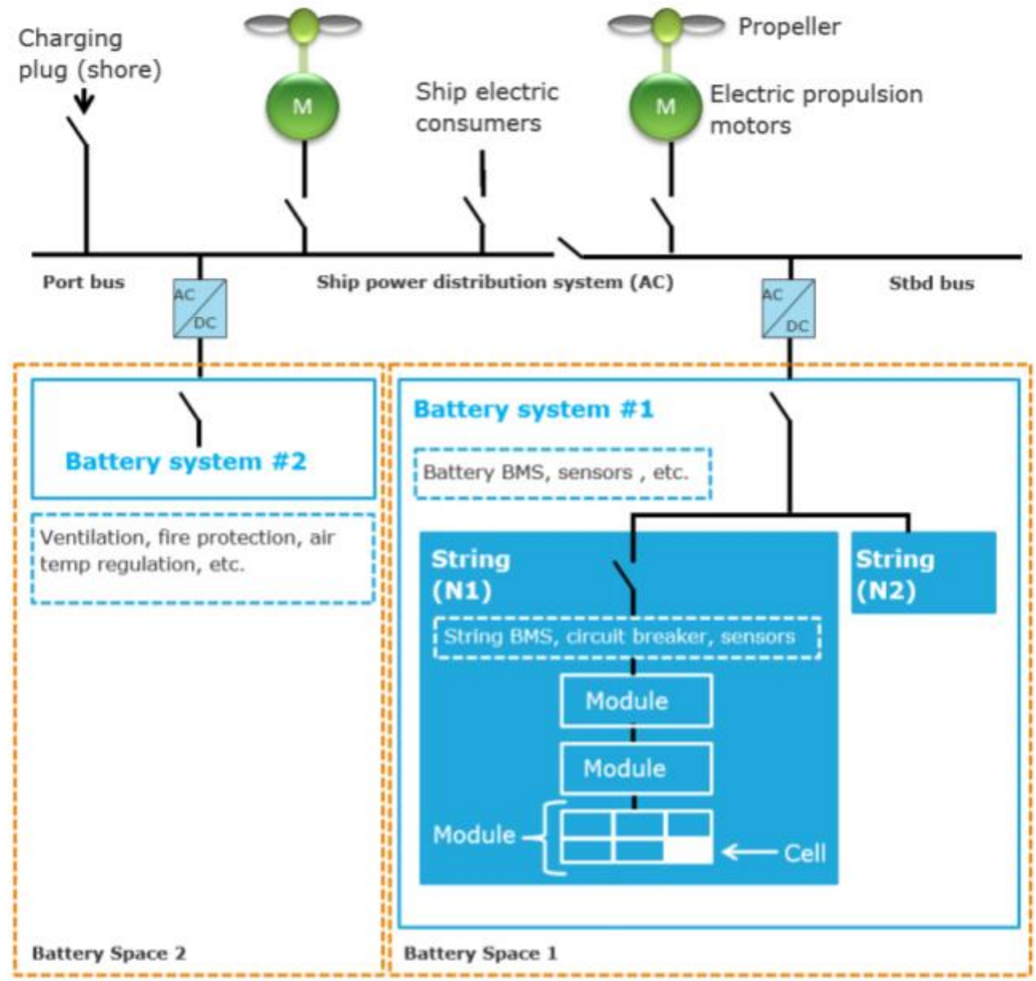

Figure 36: Generic maritime battery system

- Cell – The cell is the smallest electrochemical unit.
- Module – Assembly of cells including some level of electronic control and/or monitoring. The smallest unit that can be electrically isolated in an assembled battery system. For some systems, the modules may consist of blocks of cells with some electronic monitoring included.
- String – Smallest unit with same voltage as the system level (e.g. serial connected cells or modules). This can also work for the intended purpose as a standalone unit.

- Battery system – One or more battery strings including all required systems for the intended purpose
- Battery space – Physical installation 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 humidity level)
- Battery Management System (BMS) – A collective terminology comprising control, monitoring and protective functions of the battery system. The main battery control software and protection is as important to ensuring battery safety and performance as the energy storage technology itself. The BMS must monitor system voltage, State of Charge (SOC), State of Health (SOH) and temperature. In addition, the BMS is responsible for ensuring adequate voltage balance between cells in the system. This primarily requires compensating for individual self-discharge rates between the cells by draining the cells with the lowest self-discharge rate through a resistor. The BMS is responsible for ensuring these systems operate within design spec and that the battery accurately responds to the operational commands it receives from the ship power system.
- Ventilation – In the case of abuse or failure, lithium-ion batteries will typically generate gases before and during combustion events. The composition of these off-gases depends mostly on the electrolyte composition, state of charge, temperature, internal cell pressure and cell age, but has been found to be corrosive, toxic and flammable, as well as potentially explosive. These characteristics need to be considered in design of the battery space and its ventilation system, and the design should prevent build-up of flammable gases and dispersion of toxic gases to other ship compartments. Utilization of sensors for off-gas detection is a vital aspect of safe system design. The total amount of gas generated in a thermal event depends mostly on cell size, cell design, electrolyte composition, cell temperature, cell internal pressure, state of charge, cell age and whether a thermal event spreads from cell to cell. The consequences can therefore range in severity from less than that of a thermal event in a mobile phone to very severe.
- Fire protection – Battery systems pose a fire risk and the design therefore need to include an appropriately designed containment and/or fire extinguishing system. One challenge related to a battery fire is the range of different substances that might burn. This includes solid combustibles, flammable combustible liquids and electrical fires. Battery system fires can include all these categories of substances at different stages making efficient fire protection (and cooling) quite challenging. Due to the importance of heat dissipation, water is often being selected as the preferred cooling medium.
- Thermal Management System – Depending on operational conditions, battery systems may produce significant quantities of heat. At the same time, they are sensitive to operation at high temperature, which can pose both a safety risk and a performance risk leading to accelerated degradation. Therefore, many battery systems require cooling systems, which are typically by air circulation or liquid cooling. Each approach has its pros and cons, and the cooling system design should be appropriate to the application, battery type, design and location.
- Power system integration – The battery installation must be properly integrated into the power system as well as the power management system. The power system may consist of shore connection, generators, distribution and consumers.
- Inverter – A battery system operates electrochemically using DC power and will require an inverter or power converter in order to interface with an AC ship distribution system. However, these inverters provide the additional capability to produce reactive power, voltage and

frequency support as well as increase power factor throughout the ship. Depending on interface voltage and desired function, the battery can be installed on any bus or switchboard on the ship, allowing a great deal of flexibility with regard to placement.

5.2 Battery system's outline specification:

The battery space is the physical enclosure in which the batteries are located and it includes all functions and components which contribute to keep the battery system in the defined space at a specified set of environmental conditions. Depending on the application of the battery system, there are certain important elements to consider. The arrangement of the battery spaces must be such that the safety of the vessel and the crew is ensured.

First of all, the battery space has to meet a general fire integrity level of A-0 and A-60 towards any muster stations or evacuation routes. If the battery power shall be used for propulsion under normal operation, dynamic positioning or other relevant operations, it shall also meet a fire integrity level of A-60 towards any machinery space of category A as defined in SOLAS Reg. II-2/3.

Also, the battery space cannot be positioned at the forward collision bulkhead. Boundaries of the battery space shall be part of the vessel's structure or enclosures with equivalent structural integrity. The battery space shall be a dedicated room if applicable. Walls and structures surrounding the battery shall be built to protect the vessel against fire and explosion risks. Battery space shall be accessible for replacement of parts of the system.

The battery and battery systems should be fixed within the battery compartment such that they can endure the maximum predicted vessel motions. Heavy items or items which could cause physical damage to the battery should not be co-located with the battery unless these are retained within the same parameters. Consideration should be given to fixing the battery adjacent to any potential heat source which could result in inadvertent heating of the battery, e.g. exhaust, heavily loaded electrical cabling and direct sunlight.

In an all-electric propulsion system, the battery pack is the main, and often the only source of propulsion power. For this reason, it is vital that any malfunction of the batteries (i.e. fire, explosion, gassing etc.) cannot lead to loss of propulsion and other vital functions of the vessel. For this reason, two completely independent battery systems need to be installed. The reliability of the complete system must be at least as good as a conventional vessel. This means that single failure of critical modules, shall not compromise the integrity of the vessel and also If one of the battery systems fails the vessel shall have sufficient useable energy for safe return to port.

Finally, the battery system:

- Shall demonstrate robustness for long term exposure in a marine environment (temperature, moisture, list, trim, roll, etc.).
- Shall be maintainable such that defect parts can be substituted safely and effectively.
- Battery lifetime should be such that the business case is economically reasonable.
- The BMS shall communicate critical battery parameters.
- The BMS shall ensure that the battery operates in the safe operating window of the cells.
- SOC and SOH shall be monitored.
- There shall be alarms and shutdown functions on several levels.

- Important battery parameters shall be logged and stored in a non-volatile memory.
- If the battery system is equipped with a remote logging/diagnostic system, it should be protected sufficiently against intrusion.
- A maintenance and operational plan including emergency operation shall be established.
- Enough charging shall be possible during port stay to keep an acceptable state of charge.
- Remaining range or time shall be displayed on the bridge as well as the engine control room.

5.3 Safety Description:

The safety aspects and failure modes that should be considered specifically for the battery system and design itself include:

- Internal cell failure
- Internal or external short circuit
- Overcharge or over-discharge
- Over-temperature
- Excessive external heating or fire

These events can cause one, or a combination, of the following:

- Gas development (toxic, flammable, corrosive)
- Thermal runaway (including cascading protections and isolation mechanisms)
- Fire risk, including external heating or external fire
- Explosion risk

Other relevant safety issues that need to be included are:

- External damage (due to grounding, collision etc)
- Submersion risk (due to flooding or fire extinguishing)
- Safe charging and discharging characteristics (deviations from this is a relevant failure mode)

5.4 Failure Modes:

At a certain level of temperature increase, internal components of battery cells will break down; presenting a high risk of fire, ventilation of gasses, exothermic reaction, or even explosion. The most critical failures are those that can lead to an internal short circuit, as an internal short circuit is not likely to be detected by the BMS. Therefore, proper battery cell and enclosure design is critical to minimize fire and explosion risks posed by internal short circuits.

Other sources of failure risk would nominally be detected by a functioning, capable BMS system, either through electrical sensors (voltage, current), passive electrical protections (fuses, power electronics), or an atypical or excessive temperature increase. Thus, a high degree of monitoring, BMS control and electrical protection are advantageous with respect to safety.

More specifically the Battery Management System shall:

- Provide limits for charging and discharging.
- Protect against over-current, over-voltage and under-voltage.

- Protect against over-temperature.

The BMS is a vital protection for these failure modes, through its function of voltage monitoring. A high degree of voltage instrumentation is recommended, including the voltage of every cell being monitored. In addition, voltage will vary based on temperature or charge current so the BMS must accurately calculate SOC and voltage by compensating for these factors. This provides the primary preventative measure against over-charging or over discharging of the batteries.

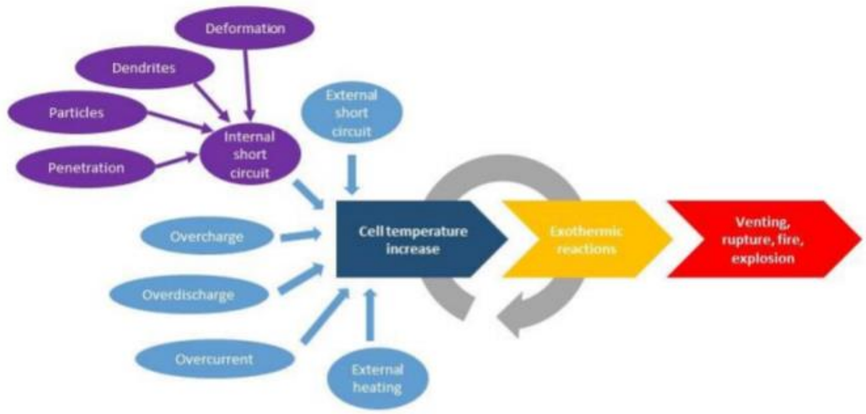

Figure 37: Overview of factors that can cause unwanted temperature increase on cell level in a battery system.

5.4.1 Internal Cell Failure:

Abusive operation, outside of the rated specifications, of a battery cell can cause breakdown of the physical components inside a battery. This can be expected to result in failure of the battery and poses significant safety risks or highly shortened lifetime.

In case of charging voltage significantly above the allowable upper cell voltage, the electrolyte will start to decompose generating flammable and toxic battery gasses and an increasing proportion of the energy input will be converted to heat due to increased internal cell resistance.

The resulting effects from overheating of Li-ion cells go through several stages: around 60 o C irreversible processes start. If the temperature passes around 80 ^{o}C gas generating processes accelerate and pouch cells typically visibly inflate. All Li-ion cells are supposed to handle 130 ^{o}C for 10 minutes whereas exposing most Li-ion cells to temperatures above 160 ^{o}C usually results in a thermal event. In a thermal runaway situation, the temperature will increase without adding any energy and the cell can catch fire.

Electrical abuse by over-discharging or allowing the cell voltages to drop below the lower voltage limit through storage at low SOC for an extended period of time, can cause progressive breakdown of the electrode materials. The anode current collector can become partly dissolved into the electrolyte. In such a scenario, when the voltage is increased again, the ions which are dispersed throughout the electrolyte are precipitated as metallic particles. This situation represents a possible cause of a short circuit between the electrodes.

5.4.2 Internal Short Circuit:

An internal short-circuit means that an electrically conductive bridge has been formed between the positive and the negative electrodes inside the battery cell. The majority of such internal-short-circuits do not result in a thermal event but it is possible under some circumstances.

A common root cause which presents the greatest potential consequence is considered to be cell level contamination (internal defect), originating from the manufacturing process, often in combination with cell design flaws or damage during service. Such conditions can produce a short circuit which is one of the greatest risks for undetected, uncontrolled heating (off-gassing) or thermal runaway in a lithium ion battery. To reduce the frequency of thermal events a strong quality focus has to be maintained by the cell manufacturer. It is often this failure mechanism which introduces the design requirement to protect against worst case failure scenarios

Most internal short circuits are benign and the only noticeable effect is an increase in the self-discharge rate. This increase may be detectable if the increase is large. A small and undetectable increased self-discharge rate is usually not a concern neither for operation nor for safety of the battery system. Spontaneous, severe internal short-circuits are usually impossible to predict or mitigate and their likelihood is extremely low.

Although the probability of such an event is low, ensuring an acceptable outcome from a cell level internal short circuit in a large battery system is necessary. If propagation of a thermal event is limited so that it does not spread throughout the entire battery system, this is normally considered adequate. If a thermal event can be limited to cell level, this is from a safety point of view usually the best.

5.4.3 External Heating:

Active, and especially liquid-based, cooling systems provide the greatest capability as far as prevention of excessive battery temperatures. However, in many systems which can claim advanced thermal and power management of the battery system, external fires still remain a high potential risk. The effects of an external fire or excessive external heating, and whether the design has taken this into account, shall be covered.

5.5 Potential Risks:

5.5.1 Gas Development:

Li-ion battery systems are sealed systems with nominally insignificant external gas generation during normal operation. A range of abusive factors affecting a battery cell, as described above, can lead the electrolyte to start to decompose which may lead to the formation of gasses inside the cell. The gas quantity and composition will depend on the chemistry of the cell, the voltage, the temperature and also the failure mode. Those gases can potentially be toxic, flammable and even explosive.

More specifically, the gasses produced during a lithium-ion cell failure will typically consist of many individual components, including, but not limited to: hydrogen, CO, CO_2, DEC, MEC, C_2H_4, CH_4, HF, HCl, HCN. Gases that are produced, and whether they are self-consumed by the fire, will also depend on the temperature of the fire. Mixing of different gases might pose a combined risk effect that would not be identified by analyzing the individual gases separately. Lower and Upper Explosive Limits, self-ignition levels and toxicity are parameters that can be found by analyzing the combined composition of the emitted gases. These factors are key for determining ventilation requirements.

Quantities of gas produced will depend on factors like SOC, temperature, and failure mode. When gases are emitted, they will create a gas cloud which will mix with the surrounding air. In order to determine the fire and explosion risk, the size of the flammable gas cloud should be determined. The cloud size depends on the rate at which the gas is emitted and the ventilation conditions in the room. The transient rate of gas emitting from the battery should be included in the safety description expressed as a function of time, or with a constant rate over a given time.

5.5.2 Thermal Runaway:

Thermal runaway is normally defined as a temperature increase exceeding 20˚C/min and refers to rapid self-heating of a cell (or several cells) derived from an exothermic chemical reaction. The internal temperature and pressure increase may lead to melting of the separator (causing an internal short). The consequence is evaporation and decomposition of the electrolyte and subsequent venting of the cell as the pressure increases above the mechanical strength of the housing. The cell temperature will typically exceed 200˚C, potentially reaching 680˚C or peaks of 800˚C during a thermal runaway event.

Oxygen is available when gas vents out from the cell and mix with the surrounding air. Limited amounts of oxygen can also be available from oxide-based cathode materials. Ignition can be caused by sparks from the battery, electronic equipment or by the high temperature. The auto-ignition temperature of the most common electrolyte solvents is in the range of 440˚C - 465˚C. The further consequences can be a gas fire if it is ignited immediately or an explosion followed by a fire if it is ignited at a later stage. The risk for a thermal runway situation to propagate to adjacent cells, or modules and quickly spread out through the whole battery installation depends on the battery configuration and safety system. It is therefore important that this risk is properly addressed and managed.

5.5.3 Explosion Risk:

The risk of an explosion is closely related to the gas development and has to be analyzed based on the gases that can be emitted from a battery system in a failure situation. An assessment of the risk of an explosion within the battery module(s) is a part of the safety description. Data regarding expected gas release should be collected from testing on the specific cell in use, based on clearly stated conditions, because significant variation exists between manufacturers, chemistries, etc.

There is a plethora of ways which can protect the battery space from the development of gasses which can lead to a higher risk of explosion such as by installing pressure relief panels, weak walls or increasing the size of the room. Ventilation is also vital to reduce the probability of explosions from smaller gas releases, hence a reliable continuous ventilation system is assumed.

5.5.4 Fire Risk:

A thermal runaway event is likely to produce a fire that will combust materials and systems nearby. The heat load from such an event should be taken into account. Current classification rules state that a water-based fixed fire extinguishing system shall be in place. If this is not suitable for the applicable chemistry or battery system design, it has to be covered by the safety description. Battery fires often have the characteristics of both ABC as well as D class fire at different stages, and thus likely require an advanced consideration of fire-fighting capabilities. In many cases water and/or standard engine room inert gas fire extinguishing is preferred for the battery installation. In any case whichever fire-fighting mediums are chosen, they must be able to adequately penetrate the battery casings to extinguish and/or quench a potential fire.

Many lithium-ion battery fires are self-oxygenating and thus very challenging to extinguish. Cell size, the number of cells on fire and access to the fire are generally very important in terms of how difficult it is to extinguish the fire. Heat removal and extraction is a key requirement of the extinguishing system in order to minimize damage.

5.6 Ventilation and Alarm Systems:

During battery system's operation for optimal efficiency, battery space must establish the appropriate ambient conditions as the various hazards discussed above may arise.

Therefore, specified procedures should be followed, and relevant controls or alarms must be installed. For optimal battery operation, battery space must ensure proper environmental 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 shall give an alarm in both the engine room control panel and the bridge in case of:

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

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 temperature control. 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 time.

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-energize any electrical circuit within the space upon detection exceeding lower explosion limit. These LEL conditions shall give an alarm to the bridge. A failure in the gas detection system should not lead to disconnection or de-energizing 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 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.

5.7 Electronic Control System:

The electronic control system specific to the battery is typically referred to as the Battery Management System (BMS). The BMS is responsible for monitoring voltage, current and temperature limits inside the battery system and evaluating signals to provide indication of when the system operations need to be curtailed.

Voltage and current limits are dependent on each other as well as temperature – thus these represent calculations that are both complex and crucial, and are a key responsibility of the BMS. In addition, the BMS is responsible for calculating SOC and SOH. SOC is analogous to the fuel gauge on a car or the percentage remaining on a mobile phone. Accurate SOC is required to give a clear indication of how far a vessel may go on its remaining battery power. Likewise, SOH is a calculation of how much a battery has degraded over time. This calculation requires a BMS that is highly developed through experience and specifically calibrated to the battery cell being used.

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

A key feature of the BMS is its ability to monitor cells and ensure balanced operation. If a single cell’s voltage differs substantially from those of the rest of the pack it is at a much higher risk of getting overcharged or over-discharged as the system is cycled up and down. In the case that this type of scenario is detected, it is highly advantageous for the BMS to have some capability to actively correct voltage and rebalance the cell(s).

It is clear that there can exist a large variation in quality between different BMS systems, and this is a prime indicator of overall battery system quality.

5.8 Electrical System:

As previously stated battery cells are electrically configured through arrangements of series and parallel connections to form a module. These modules are then often connected in series (strings) to produce the system-voltage level. Strings are then arranged in parallel to produce the required levels of energy for the whole battery system.

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

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

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

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

6 Design Methodology:

6.1 Retrofit Philosophy:

The tugboat being considered for retrofit is “Archaggelos”. It is a conventional tugboat with main particulars:

Table 10: Main particulars of "Archaggelos"

Main Particulars	
Length O.A.	21.8 m
Breadth	6.5 m
Depth	3.25 m

The machinery space consists of two diesel main engines coupled with a gearbox each of which drives a CPP propeller. Two gensets are also installed, tasked with covering the electrical loads of the tugboat.

The main goal of this retrofit is the complete electrification of the tugboat, i.e. the replacement of the main diesel engines, as well as the gensets of the tugboat by batteries. These batteries are going to cover both propulsion and electrical loads of the ship.

One of the main prerequisites during the retrofit is that the propulsion system, up to the gearbox remains unchanged. This means that the revolutions of the shaft as well as the power output of the shaft after the reduction gear must remain approximately the same. This is being realized by the installation of two electric induction motors of nominal power output equal to the nominal power output of the diesel engine that was installed.

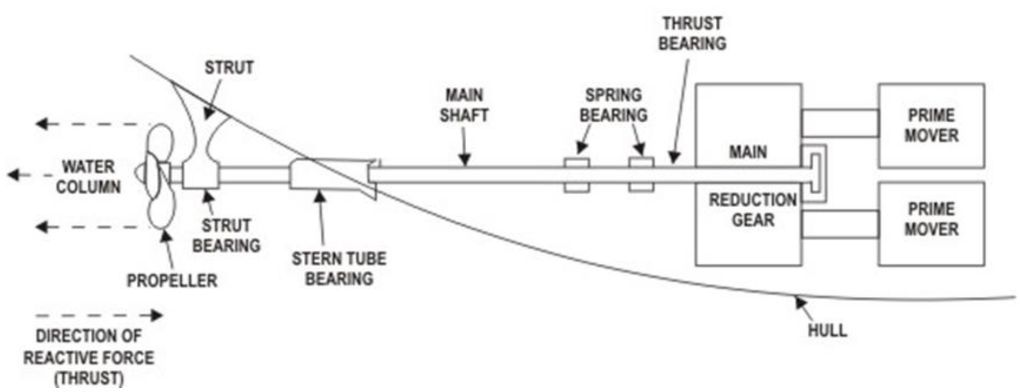

Figure 38: General principle of a geared ship propulsion.

The batteries are divided in two distinguished yet same battery packs each of which powers one of the motors as well as the hotel loads.

The above configuration is conceptualized in the next figure and it consists of:

- Two electric induction motors.

- Two gearboxes.
- Two battery packs.
- Two inverters (DC/AC), one before each of the induction motors for the conversion of DC to AC.

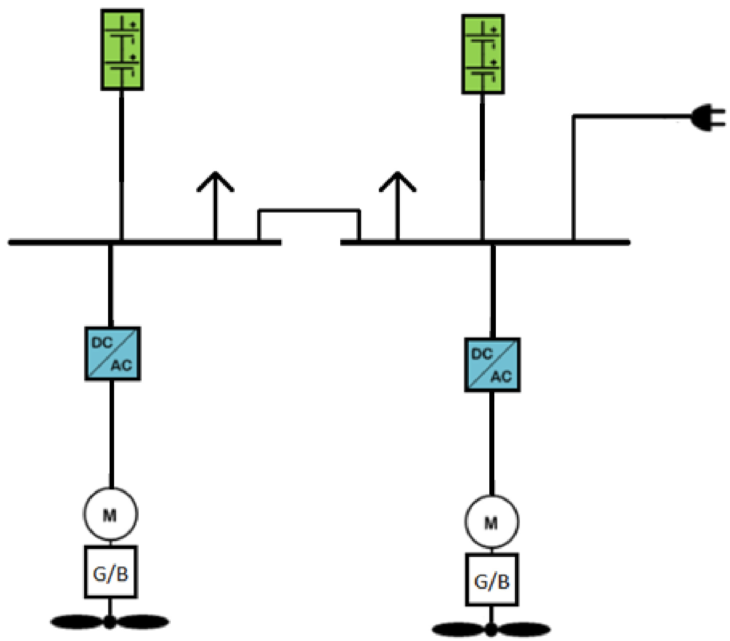

Figure 39: All-electric ship configuration with a DC distribution system

The most important aspect during the electrification process of a vessel is the sizing and the placement of the battery packs. Battery packs are going to be the sole power source of the vessel for both its electrical and propulsive power needs. With this in mind the battery sizing has to ensure redundancy and sufficiency for the intended operation of the vessel. Reliability and safety of the system must be at least the same as a conventional vessel counterpart. Another fact that must be taken into account is the expenses of purchasing such equipment and retrofitting it into a conventional vessel. Batteries cost will be the highest expense for this retrofit so finding a golden rule between reliability and economic viability is of the utmost importance. Furthermore, batteries are a steady weight, unlike fuel, creating another problem concerning vessel's stability and trim. The specific energy of the batteries is considerably lower, compared to fuel, meaning that finding enough available space inside the vessel for the installation of the batteries is a challenge. As it is shown above, the sizing of a battery pack is of delicate balance with many parameters to consider.

The replacement of the emergency accumulators of the vessel will not be investigated by the present thesis. This thesis is focused on the technological and economic viability of the replacement of the main and auxiliary engines with a battery pack. Although this issue is not discussed, it is an important part of the electrification prosses. The new systems that are installed on the vessel such as the ventilation, cooling and control systems of the batteries are very important for the safety of the vessel and their normal operation must be guaranteed even during emergencies. This means that the emergency accumulators already installed on the vessel prior to the electrification process may not be adequate and must be replaced.

Battery system's size depends on its energy consumption and available time for charging during its shift. In order to determine vessel's daily energy requirements, 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 also depends on market available battery solutions. While at berth, it will be recharged either between missions and/or after the end of the shift from the utility grid.

The power of a tug boat depends entirely on the propulsion system installed. The power required and rate of propeller revolution depends on the shape and size of the tug hull and the design of the propeller i.e the resistance of the vessel. Tugboat engines produce power ranging from 500 - 2500 KW (680 – 3400 HP). However, lack of vital information needed for these calculations created the need for a different approach in calculating vessel's installed energy.

Due to data limitations the methodology chosen to calculate the installed energy is simpler. One of the main prerequisites of this thesis is that the power output after the gear box will stay approximately the same before and after the electrification process of the vessel. This means that the installed power of the battery pack after its electrification can be calculated by adding the power losses in the wiring and the inverter to the nominal power output of the existing diesel engine before the retrofit. After the installed power have been calculated combining it with an operational profile of a harbor tugboat, the installed energy needed for propulsion could be estimated.

In order to calculate the installed energy for hoteling and auxiliary loads, an electrical balance sheet with all the auxiliary and hotel systems and their power output was created.

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

Vessel's 12-hour shift itinerary will be divided into missions. Each mission will consist of the time period during which the tugboat will participate in operations near and inside the port. In between missions the tugboat will be idling at the port; this is the time in which the vessel should be recharging its batteries.

$$\text{Shift} = \text{Time per mission} + \text{Time idling}$$

As it is understandable, more missions during a shift means more required batteries on board, as well as less available charging time. Charging procedure and routine will also affect decisively the outcome. Choices upon the available charging frequency, charging currents applied and time needed to plug-in/off and start charging from grid are translated into alternations of provided quantity of energy to the system, therefore suggesting smaller or larger battery system, more or less lifecycles etc. All the above are, of course, interrelated with available battery solutions in the market, their chemistry and technical characteristics, and finally offered prices.

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

6.2 Case Study:

Purpose of this study is the investigation of the technological and economic viability of the replacement of the main and auxiliary engines with a battery pack in a harbor tugboat. As previously stated the tugboat chosen for this preliminary study is vessel "Archaggelos". It is a conventional tugboat with two diesel main engines coupled with a gearbox each of which drives a CPP propeller. Two gensets are also installed, tasked with covering the electrical loads of the tugboat.

The tugboat will be operating inside and near the port of Piraeus in a very narrow and tight environment. Its range will be of maximum 5-10 nautical miles outside the port. The Port of Piraeus is the largest Greek seaport and one of the biggest in the Mediterranean Sea and Europe. Piraeus handled 3.67 million TEUs in 2016. The port of Piraeus is expected to become the busiest port of the Mediterranean in terms of container traffic by 2019. The container part of the port is made up of three terminals. Terminal 1 with a total capacity of 1 million TEUs, Terminal 2 with a total capacity of 3 million TEUs and Terminal 3, completed in 2016 with a total capacity of roughly 2,7 million TEUs, in total 6.7 million TEUs. Additionally, the cargo terminal has a storage area of 180,000 m^2 and an annual traffic capacity of 25,000,000 tones. According to the official web site of the port, the average annual traffic from 2010 to 2013 was 3960 cargo ships both domestic and overseas. This translates to roughly 11 cargo ships per day.

The operational profile of the tug is based on a 12-hour daily operation, 365 days per year. It is a combination of data found on the paper "Raptures: Resolving the Tugboat Energy Equation" as well as personal observation, that took place between 13 and 15 of June, of multiple tugboat operations on the port of Piraeus through the site "Marine Traffic".

The operational profile is divided into three different periods:

- Harbor Duty: During this period the tug is primarily engaged in ship berthing/unberthing in a harbor environment, where transits are short. On harbor duty the tug spends a significant amount of time idling and transiting on low speeds mixed in with short periods of high BP operations.
- Ship Assist Duty: In this period the tug is tasked with accompanying ships entering or leaving the harbor over a greater distance for light escort operations. During this period the tug spends more time at higher transit speeds and less time at operations involving high static thrust compared to harbor duty.
- Port Stay: This is the time in-between missions where the tugboat is berthed and completely idle. This is the time window in which a hypothetical battery powered tugboat has to recharge its batteries.

The first two periods are subsequently divided into six different modes. Each mode is represented by a percentage of the nominal installed power of the tugboat's battery pack. These modes are Standby (5%), Low Speed Transit (10%), High Speed Transit (15%), Low Bollard Pull (30%), Medium Bollard Pull (70%), High Bollard Pull (100%). Each of these modes are utilized for different amount of time for each of the two periods as shown on the next figure.

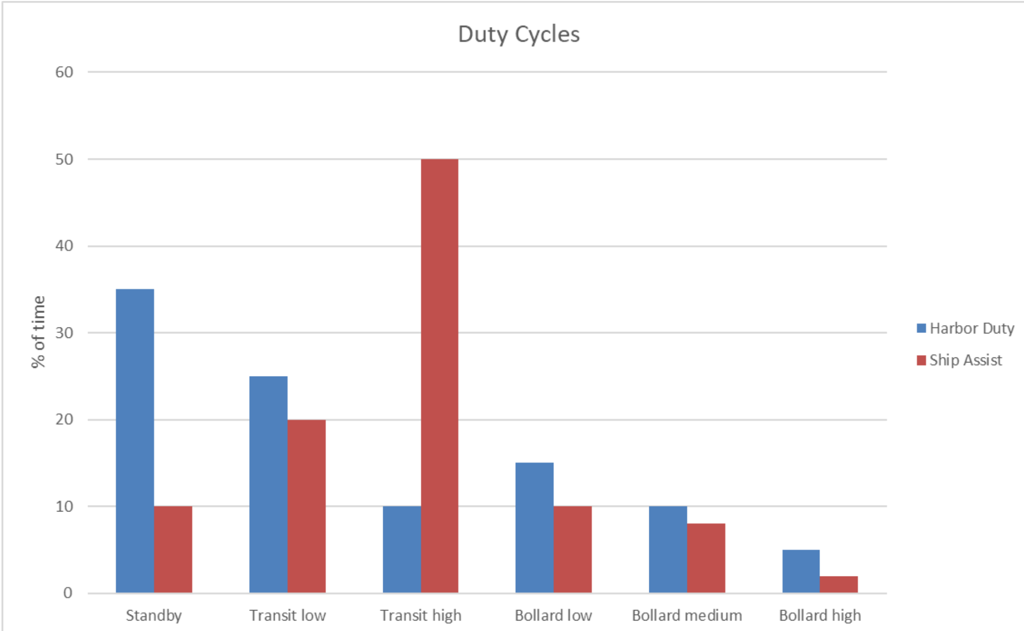

Figure 40: Percentage of time spent in each mode according to duty cycle

Every mission takes 3 hours to complete and it is divided into two parts. The first part consists of the time period in which the tugboat departs from the port and assists the ship entering the harbor. This part is described by the “Ship Assist Duty” mode and takes approximately 2 hours to complete. The second part consists of the time period in which the tugboat is engaged in berthing the ship and arrives back to its station. This part is described by the “Harbor Duty” mode and takes approximately 1 hour to complete. In between missions the tugboat is idling for approximately 1.5 hours. In total the tugboat is going to take part in 3 missions during its 12-hour shift.

The electrification process will be studied with two different scenarios each of which will utilize a different battery technology. In the first scenario a lithium ion battery system will be studied while in the second one a redox flow battery system will be considered.

Each system has its unique advantages and disadvantages that have been already discussed in length throughout the present dissertation. In summary a lithium-ion battery system has good energy and power density with mediocre life cycle and almost no need for maintenance, it is a relatively mature and preferred battery technology in the maritime industry and there are comprehensive and detailed regulations concerning the installation and operation of such system. On the other hand, it is an expensive system with a higher risk of fire and even explosion in extreme circumstances, compared to other technologies.

In comparison, redox flow batteries are considerably cheaper with almost four times longer life cycle, with no irreversible degradation during the years of operation and has a lower risk of fire compared to li-ion batteries. Energy and power sizing are independent from one another, making design of such system more flexible. Finally, this system is capable of “instant recharge” by mechanical refueling, i.e. spent solution can be exchanged and recharged on-shore, a feature which might be of considerable importance for commercial shipping. On the other hand, the energy density of the present commercialized solutions is low, making installation of such a system on a ship, especially a tugboat, a difficult task due to limited space. It is also a new technology with no applications on the maritime industry as of the time of this dissertation. This means that there are no regulations concerning the installation and operation of such system.

The present study will be divided into three parts:

- Battery System Sizing: In this part, the battery system of each scenario is going to be sized. The purpose of this part is to prove that a battery system with commercially available equipment is technically viable. The energy and power as well as the safety requirements of the tugboat must be ensured and the battery system as well as the additional equipment must be able to fit inside the available space of the tugboat.
- Emission Quantification: Even though a battery powered ship is considered to have zero emissions, in reality during recharging from the grid's electricity, the electric power plants emit pollutants to the environment. In this part, the amount of pollutants emitted in the environment during the time of recharging is calculated and compared to the amount created by a conventional tugboat with the same operational profile.
- Investment Appraisal: Lastly the economic feasibility of such an investment is considered. In this part the cost of the retrofit for each scenario as well as the net difference between the costs of operation and maintenance between a battery powered and a conventional tugboat are calculated in a span of 20 years.

As shown above the comparison between the two scenarios with each other and with their conventional counterpart is multileveled and has quantitative as well as qualitative aspects. For example, even if the redox flow battery system is cheaper from the lithium battery one the fact that the li-ion is a more mature and established technology might keep an investor away from the redox flow battery solution.

It should be noted that the only difference between the two scenarios is the battery system while the additional equipment used, i.e. the power electronics, electric motors etc. remain the same. Another similarity between the two scenarios as well as their conventional counterpart, is the operational profile of the tugboat as well as the vessel's 12-hour shift itinerary. For example, a tugboat with a li-ion battery system will be forced to stay in port for recharging while one with redox flow batteries could resupply its solution within minutes, meaning that it could be possible to take part in more missions. Another thing to consider is that a conventional tugboat will be more autonomous compared to either of the battery powered scenarios as it will have a longer range due to the higher specific energy of fuel oil. By keeping the operational profile the same, as well as the number of missions in which the tugboat will be taking part in, the comparison between the three technologies becomes clearer.

6.2.1 Scenario 1: Li-ion Battery System

In this scenario the battery modules used on the retrofit are manufactured by Valence and the specific model is going to be the U-Charge U27-36XP of the XP Series. U-Charge® XP is a range of 12, 18, 24 and 36 volt Lithium Iron Magnesium Phosphate battery modules, offering intrinsic safety with twice the run-time and 70% the weight of similarly sized sealed lead-acid batteries. The specific model was chosen as it provides the most economical solution for this specific application.

Table 11: Key characteristics of the different XP models

Specifications		U1-12XP	U24-12XP	U27-12XP	UEV-18XP	U24-24XP	U27-24XP	U27-36XP
Nominal Module Voltage		12.8 V	12.8 V	12.8 V	19.2 V	25.6 V	25.6 V	38.4 V
Nominal Capacity (C/5, 23°C)		40 Ah	110 Ah	138 Ah	69 Ah	56 Ah	69 Ah	46 Ah
Weight (approximate) kg		6.5 kg	15.8 kg	19.5 kg	14.9 kg	15.8 kg	18.6 kg	19.6 kg
Weight (approximate) lbs		14.3 lbs	34.8 lbs	42.9 lbs	32.8 lbs	34.8 lbs	42.9 lbs	43.1 lbs
Dimension incl. Terminals LxWxH (mm) Dimension incl. Terminals LxWxH (inches)		197 x 131 x 182 7.8 x 5.1 x 7.2	260 x 172 x 225 10.2 x 6.8 x 8.9	306 x 172 x 225 12.0 x 6.8 x 8.9	269 x 148 x 245 10.6 x 5.8 x 9.7	260 x 172 x 225 10.2 x 6.8 x 8.9	306 x 172 x 225 12.0 x 6.8 x 8.9	306 x 172 x 225 12.0 x 6.8 x 8.9
BCI Group Number		U1R	Group 24	Group 27	N/A	Group 24	Group 27	Group 27
Terminals, Female-Threaded		M6 x 1.0	M8 x 1.25	M8 x 1.25	M8 x 1.25	M8 x 1.25	M8 x 1.25	M8 x 1.25
Specific Energy		79 Wh/kg	89 Wh/kg	91 Wh/kg	89 Wh/kg	91 Wh/Kg	95 Wh/kg	91 Wh/kg
Energy Density		110 Wh/l	139 Wh/l	148 Wh/l	136 Wh/l	142 Wh/l	148 Wh/l	148 Wh/l
Standard Discharging @ 25°C	Max. Cont. Load Current Peak Load Current (30 sec) Cut-off Voltage	80 A 120 A 10 V	150 A 300 A 10 V	150 A 300 A 10 V	120 A 200 A 15 V	112A 168 A 20 V	138 A 207 A 20 V	90 A 135 A 30 V
Standard Charging	Charge Voltage Recommended Current C/2 Charge Time C/2 *	14.6 V 20A 2.5 hrs	14.6 V 55A 2.5 hrs	14.6 V 70A 2.5 hrs	21.9 V 35A 2.5 hrs	29.2 V 28 A 2.5 hrs	29.2 V 35A 2.5 hrs	43.8 V 23A 2.5 hrs
DC internal resistance (max)		15 mΩ	6 mΩ	5 mΩ	10 mΩ	18 mΩ	15 mΩ	25 mΩ
Part Number		1004434	1004425	1004428	1004431	1007735	1007520	1005199

U-Charge® XP modules are designed to be assembled in series and parallel to reach application's voltage and capacity requirements.

The battery pack's position, according to the regulations, must be as close to the center of floatation of the vessel's design waterline to avoid trim and symmetrical to the center line of the ship in order to avoid rolling motions. Considering these limitations as well as the available space on the tugboat, it was decided that the fuel oil tanks of the tugboat should be retrofitted in order to house the batteries. The proper ventilation and fire safety systems must be installed as well as adequate space for inspection and maintenance between the battery strings and packs must be ensured.

6.2.2 Scenario 2: Redox Flow Battery System

In this scenario the electrolyte used on the VFB system is provided by "UniEnergy Technology". To improve performance, reliability and economics of VFB's, UET has licensed and utilized a new generation electrolyte chemistry initially developed at the US Department of Energy's (DOE) Pacific Northwest National Laboratory (PNNL), with the support of the US DOE Office of Electricity Delivery and Energy Reliability's Grid Storage Program. As shown on this publication, "A Stable Vanadium Redox-Flow Battery with High Energy Density for Large-Scale Energy Storage," Li, Kim, Wang et al., Volume 1, pages 394–400, May 2011 found on UET's website, this new electrolyte has an energy density of 40 kWh/m^3 while its specific energy is 32.5 Wh/kg.

The stacks used on the system were taken by "Volterion". The characteristics of these stacks are shown below:

Table 12: Key characteristics for the different types of stacks

Power (nominal)	2,5 kW	5 kW	10 kW
Power (peak)	3,5 kW	7 kW	14 kW
Number of cells	38	76	152
Current	50 A	100 A	200 A
Voltage	40 – 60,8 V		
Dimensions (L x W x H)	310 x 260 x 222 mm	680 x 260 x 222 mm	680 x 570 x 222 mm
Mass	6 kg	12 kg	24 kg

Although no current regulations exist for this specific technology concerning onboard installations, some general principles could be taken from the existing regulations concerning other battery chemistries. For this reason, the electrolyte was decided to be stored inside the fuel oil tanks of the tugboat after the appropriate modifications (i.e. the tanks are going to be covered with a plastic coating which will protect them from the corrosive nature of the electrolyte). Due to the lower energy density of the electrolyte the available space of the fuel oil tanks will not be adequate for the accommodation of the whole system, for this reason the decision was taken for the crew's cabins to be retrofitted in order for the stacks to be housed. The proper ventilation and fire safety systems must be installed as well as adequate space for inspection and maintenance between the stacks must be ensured.

It must be noted that even though the cabins of the crew will be retrofitted for the housing of the stacks, there are other closed rooms on the main deck of the tugboat such as the mess room and one more cabin. These spaces are vital for the safety of the crew members from extreme weather and will not be tampered with in any way.

6.3 Model inputs & Equations:

The data required for the calculations done on the present thesis are the following:

Concerning vessel's characteristics before the electrification:

- Number of Main Engines for propulsion and their nominal output.
- Main Engine Load Factors.
- Number of Electric Generators and their nominal output.
- Electric Generators Load Factors.
- Electrical Load Balance at Sea.
- Electrical Load Balance during Maneuvering.
- Electrical Load Balance at Port.
- Electric Motors Diversity factor.
- Electric Motors Efficiency number.
- Number of thrusters.

Concerning vessel's characteristics after the electrification:

- Efficiency factors of the power electronics.
- Electric motor's power output and efficiency factor.
- Electric motor's voltage.

Concerning operation characteristics:

- Time of each mission.
- Time idling in between missions.
- Time of one day shift.
- Number of missions per shift.

Concerning battery module's characteristics:

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

6.3.1 Battery System Sizing:

The energy demand concerning the propulsion of the vessel per mode per operational profile is:

$$E_{Pr_{i,j}} = P \times N \times Lf_{i,j} \times \frac{t_{i,j}}{60} \ \ (kWh)$$

Where, P: Nominal installed Power (kW)

N: Number of propellers

$Lf_{i,j}$: Load factor per mode (%)

$t_{i,j}$: time cruising per mode (min)

i: Stands for the six different modes of each operational profile

j: Stands for the three different operational profiles.

The total energy demand concerning the propulsion loads of the vessel per mission is then subsequently taken by the equation:

$$E_{pr} = \sum_{j=1}^{3}\sum_{i=1}^{6} E_{pr_{i,j}} \ \ (kWh)$$

The energy demand concerning the electrical/hoteling loads per mode per operational profile is:

$$E_{el_{k,j}} = P_{k,j} \times Df \times \frac{t_{k,j}}{60} \ \ (kWh)$$

Where, $P_{k,j}$: Electric Load per mode i.e. standby, transit and assist (kW)

D*f*: Diversity factor (%)

$t_{k,j}$: Time spent in each of the modes

k: Stands for the three different modes of each operational profiles*

j: Stands for the three different operational profiles.

*Note that when calculating the energy demand of electrical loads, the modes are not six but actually three. This is because there are no meaningful differences between some modes concerning their electrical loads. For example, the hoteling loads during transit stay the same regardless of whether the vessel is operating in high or low speed. Thus, the three modes that are created are standby, transit and assist.

The energy demand concerning the electrical/hoteling loads per mission is:

$$E_{el} = \sum_{j=1}^{3} \sum_{k=1}^{3} E_{el_{k,j}} \quad (kWh)$$

Subsequently the total energy demand per mission is calculated:

$$E_{mission} = E_{pr} + E_{el} \quad (kWh)$$

The total energy demand per shift is then found:

$$E_{shift} = N_{missions} \times E_{mission} \quad (kWh)$$

Where, $N_{missions}$: The number of missions in which the tugboat participates in one shift

The minimum installed energy on board for fulfilling the number of missions per shift while operating at nominal DOD for maximum lifecycles, may be calculated according to vessel's time available for charging:

$$E_{installed\ min} = \frac{E_{shift}}{(N_{missions} - 1) \times f \times DOD} \quad (kWh)$$

$$f = \frac{C_1}{C_2} \times \frac{t_{port} - t_{plug}}{t_{100}}$$

Where, DOD: Depth of discharge of battery system for maximum life cycles (%)

f: a parameter used to estimate how the different charging currents and time needed to connect the vessel to the charging station impacts the charging load transferred on board (%)
C_1: Actual charging current used at the charging station
C_2: Nominal charging current
t_{100}: Total time needed to completely charge the battery pack at nominal charging current
t_{plug}: Total time needed to plug-in and then plug-off the charging station
t_{port}: Total time spent on port idling

The number of modules connected in series is calculated:

$$N_{series} = \frac{V_{system}}{V_{module}}$$

Where, V_{system}: System's main bus bar's voltage (V)

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

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

$$N_{parallel} = \frac{E_{installed\ min}}{N_{series} \times V_{module} \times Ah_{module}}$$

Where, Ah_{module}: Module's nominal capacity (Ah)

Of course, both of the values stated above will be rounded up to the nearest number. According to the regulations the battery system will be separated into two packs in order to ensure redundancy and safety.

The total number of batteries installed on the vessel will be:

$$N_{total} = N_{series} \times N_{parallel}$$

Finally, the installed energy on board of the vessel is:

$$E_{installed} = N_{total} \times V_{module} \times Ah_{module} \ \ (kWh)$$

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

$$E_{remaining} = \frac{(1 - DOD) \times E_{installed}}{N_{total}} \ \ (kWh)$$

must be greater than the energy needed in order for the vessel to return to the port.

$$E_{return} = P_{pr} \times N \times Lf_{emergency} \times \frac{t_{emergency}}{60} \ \ (kWh)$$

The total weight of the installed battery system will be:

$$W_{total} = N_{total} \times W_{module} \ \ (tn)$$

While the total volume of the battery system will be:

$$\nabla_{total} = \mathrm{N}_{total} \times \nabla_{module} \ \ (m^3)$$

Where, W_{module}: Battery module's weight

∇_{module}: Battery module's weight

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

$$Cycles = \frac{t_{charging} \times (N_{missions} - 1)}{DOD \times t_{0-100}} + 1$$

Where, $t_{charging}$: The total amount of time available to charge the batteries in-between missions

$t_{0\text{-}100}$: The amount of time needed to recharge the batteries from 0-100% at nominal charging current

Life expectancy is calculated as:

$$Life\ Expectnancy = \frac{Cycles_{nominal}}{Cycles}\ \ (years)$$

Where, $Cycles_{nominal}$: Nominal number of cycles if system is operated at nominal values

6.3.2 Emission Quantification:

The quantification of the volume of emissions emitted to the atmosphere by the vessel before the 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 a mission.

For a single mission the emission can be expressed as:

$$EM_{mission_p} = EM_{auxulliary_{i,k,p,m}} + EM_{main\ engine_{i,j,p,m}}\ \ (g)$$

The emission of a single pollutant for each operational profile and mode for one mission can be computed as:

$$EM_{auxilliary_{i,k,p,m}} = N \times t_{i,j} \times Lf_{i,j} \times P_{i,j} \times EF_{i,j,p,m,f}\ \ (g)$$

$$EM_{main\ engine_{i,j,p,m}} = N \times t_{i,j} \times Lf_{i,j} \times P_{i,j} \times EF_{i,j,p,m,f}\ \ (g)$$

Where, k, i: Stands for the different modes of each operational profile.

j: Stands for the three different operational profiles.

p: Stands for the pollutant

m: Stands for the engine type (slow, medium or high-speed diesel)

f: Stands for the fuel type used

$P_{i,j}$: Engine's nominal Power

$T_{i,j}$: time spend in each mode

$Lf_{i,j}$: Engine's load factor

N: Number of engines

$EF_{i,j,p,m,f}$: Emission factor according to vessel type

This equation is used when fuel consumption per trip phase is not known. It is based on installed power and time spent in the different navigation phases. Emissions can be calculated from a detailed knowledge of the installed main and auxiliary engine power, load factor and total time spent, in hours, for each phase using the following equation.

The annual emission generation of each pollutant can be calculated:

$$EM_{annual_p} = EM_{mission_p} \times N_{missions} \times 365 \times 10^{-6}\ \ (tn)$$

Where, $N_{missions}$: Number of missions in every shift.

After the retrofit the onboard emissions will be virtually zero. Although during recharging the shore power plants used by the grid will still be polluting. The emissions emitted by the power plants due to the vessel is calculated:

$$EM_{charging_p} = DOD \times E_{installed} \times EF_{total_p} \ \ (g)$$

$$EF_{total_p} = \sum_b k_b \times EF_b \ \ (\frac{g}{kWh})$$

Where, p: Stands for the type of pollutant

b: Stands for the type of power plant

k_b: The percentage of production of electric energy from each type of power plant

The new annual emission generation of each pollutant can be calculated:

$$EM_{annual_{new_p}} = EM_{charging_p} \times N_{charging} \times 365 \times 10^{-6} \ \ (tn)$$

Where, $N_{charging}$: Number of re-chargings in every shift

6.3.3 Investment Appraisal:

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

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

6.4 Results:

Vessel's characteristics and machinery description before the retrofit are shown on the tables below:

Table 13: Vessel's main characteristics

Main Particulars	
Length O.A.	21.8 m
Breadth	6.5 m
Depth	3.25 m

Description of Machinery	
Main Diesel Engine	2 x Caterpillar 3412 4-stroke 671 Hp 1800 RPM
Gen-set	2 x Daewoo 60 KVa 50 Hz
Gearbox	2 x Advance HCD400A 720 Hp 1800 RPM

Vessel's spaces that were chosen to accommodate the new systems, as discussed earlier, were all the fuel tanks as well as the crew's cabin. The volume of these spaces was calculated to be:

Table 14: Fuel oil tanks and crew's cabin capacity

	Conventional Tug Archaggelos: Fuel Tanks					
Diesel Oil Double Bottom Tanks	Length	2.5	m	Total Volume	34.74	m^3
	Width	2.5	m			
	Height	1	m	Total Weight	31.27	t
Diesel Oil Settling Tanks	Length	1.5	m			
	Width	2.5	m		31266	kg
	Height	2.7	m			
Diesel Oil Daily tanks	Length	1.5	m			
	Width	3.25	m			
	Height	0.6	m			

	Conventional Tug Archaggelos: Crew's Cabin				
Length	4	m	Total Volume	42.32	m^3
Width	2.3	m			
Height	4.6	m			

The aforementioned spaces are shown highlighted on the next figure:

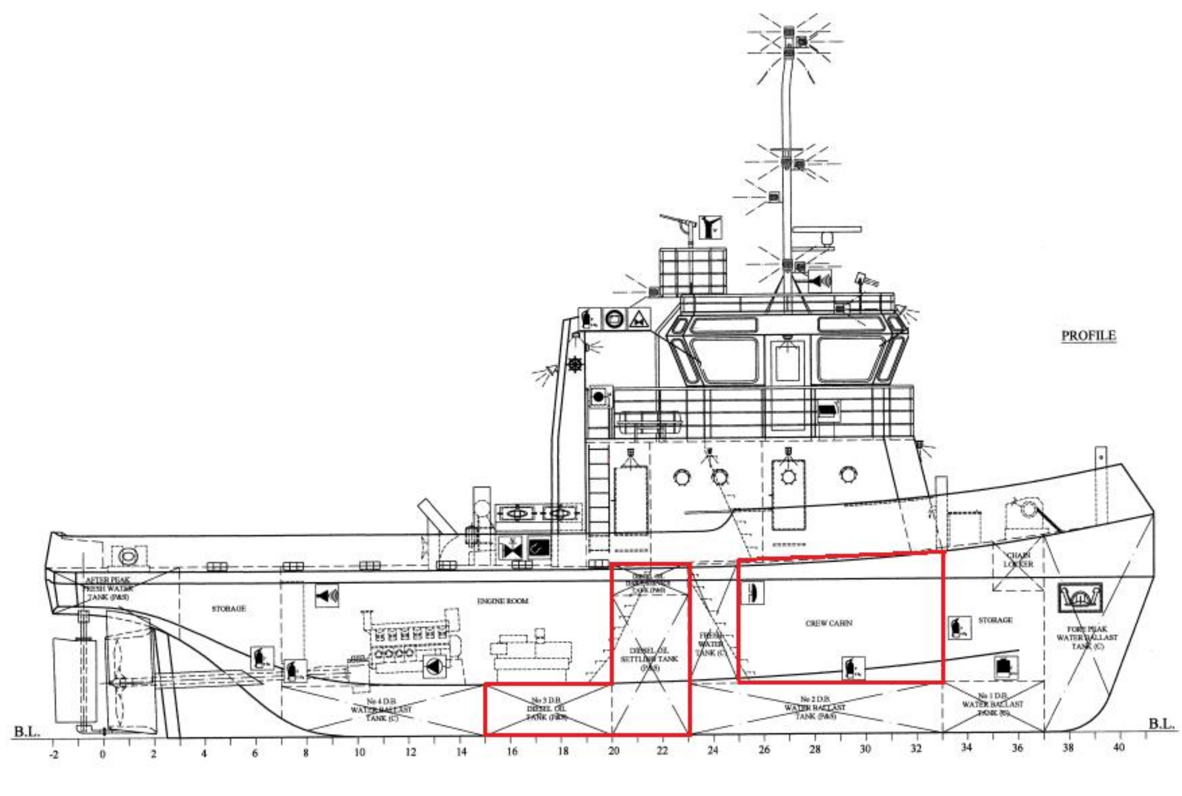

Figure 41: Available spaces found acceptable for the housing of the battery systems.

Note that the machinery space was not considered for the housing of the battery packs for either of the scenarios as it will be housing other equipment such as the induction motors and power electronics. Another reason for this decision is that the battery systems need a dedicated battery room.

Taking into consideration power losses in the wiring, the inverter as well as the added auxiliary systems such as battery ventilation, cooling etc. the installed power of each battery pack must be approximately 615 kW. The energy demand of the hotel loads was taken by an electrical load balance sheet provided by the tugboat operator, while the energy demand of the propulsion was taken by the nominal power of battery packs combined with the operational profile discussed earlier.

Table 15: Tugboat's daily energy demand calculations.

	Harbor Duty						Ship Assist						Port
	Standby	Transit		Bollard			Standby	Transit		Bollard			
	-	Low	High	Low	Midium	High	-	Low	High	Low	Midium	High	
Period of mode of each operation [%]	35	25	10	15	10	5	10	20	50	10	8	2	100
Time Cruising on each Mode [min]	21	15	6	9	6	3	12	24	60	12	9.6	2.4	90
Load Factor [%]	5	10	15	30	70	100	5	10	15	30	70	100	0
Power per mode [kW]	30.75	61.5	92.25	184.5	430.5	615	30.75	61.5	92.25	184.5	430.5	615	0
Energy Demand for Propulsion per mode [kWh]	21.53	30.75	18.45	55.35	86.10	61.50	12.30	49.20	184.50	73.80	137.76	49.20	0.00
Electric Load Balance per mode [kW]	21.16	21.38		22.51			21.16	21.38		22.51			21.16
Power Demand per mode [kW]	51.91	82.88	113.63	207.01	453.01	637.51	51.91	82.88	113.63	207.01	453.01	637.51	21.16
Energy Demand fo Hoteling per mode [kWh]	6.67	6.74		6.08			3.81	26.94		8.10			28.57
Total Energy per Operation [kWh]	293.16						545.62						28.57
Total Energy per trip [kWh]	867.34												
Total Energy per shift [kWh]	2602.01												

Table 16: Other constants vital for the calculations.

Constants of operation			
Hours per Shift [hrs]	12		
Time Cruising [min]	Harbor Duty	Ship Assist	Port
	60	120	90
Number of missions	3		
Time needed to plug in/off to the grid [min]	4		
Constants			
Number of thrusters	2		
Diversity factor	0.9		
D.O.D	0.7		
Induction motor Voltage [V]	380		

6.4.1 Battery System Sizing:

6.4.1.1 Scenario 1: Li-ion Battery System

The battery characteristics chosen for the retrofit are:

Table 17: Battery module's key characteristics.

<table>
<tr><td colspan="4">Battery module Specifications / U27-36XP</td></tr>
<tr><td colspan="2">Nominal Module Voltage</td><td>38.4</td><td>V</td></tr>
<tr><td colspan="2">Nominal Capacity</td><td>46</td><td>Ah</td></tr>
<tr><td colspan="2" rowspan="3">Dimensions</td><td>306</td><td rowspan="3">mm</td></tr>
<tr><td>172</td></tr>
<tr><td>225</td></tr>
<tr><td colspan="2">Weight</td><td>19.6</td><td>kg</td></tr>
<tr><td colspan="2">Volume</td><td>0.01421064</td><td>m^3</td></tr>
<tr><td colspan="2">Specific Energy</td><td>91</td><td>Wh/kg</td></tr>
<tr><td colspan="2">Energy Density</td><td>148</td><td>Wh/lt</td></tr>
<tr><td rowspan="3">Standard Discharging at 25 C</td><td>Max. Cont Current</td><td>90</td><td>A</td></tr>
<tr><td>Peak Load Current (30 sec)</td><td>135</td><td>A</td></tr>
<tr><td>Cut-off Voltage</td><td>20</td><td>V</td></tr>
<tr><td>Standard Charging</td><td>Rec. Current C/2</td><td>23</td><td>A</td></tr>
<tr><td colspan="2">Charging time for max l.f</td><td>2.5</td><td>h</td></tr>
<tr><td colspan="2">Internal Resistance</td><td>25</td><td>mΩ</td></tr>
</table>

Concerning the number of batteries installed and their life expectancy:

Table 18: First's scenario battery system sizing results.

Minimum Total Energy Installed [kWh]	1442.07
Number of Modules in Series	10
Number of parallel battery strings	82
Total Number of batteries	820
Energy Installed on Board [kWh]	1448.45
Remaining Energy after failure of one battery pack [kWh]	217.27
Total Weight of the battery System [kg]	16072
Total Volume of the Battery System [m^3]	11.65
Cycles Daily	3
Life expectancy [years]	5.02

As shown above the first scenario's battery system can be easily housed inside the tugboat. The weight of the battery packs is lower than this of the fuel oil if the fuel oil tanks were filled. This could mean lower draft which could lead to lower energy consumption due to lower resistance, while changes in trim or even propeller emergence could be countered with ballast water. The energy that the vessel needs in order to safely return to its station in case of an emergency is calculated to be E_{return} = 123 kWh < E_{remain} = 217.27 kWh. This means that one battery pack has enough energy for the vessel to return safely to the port in case of an emergency. The life expectancy is estimated approximately 5 years. After the passage of this time period the battery modules must be replaced.

6.4.1.2 Scenario 2: Redox Flow Battery System

The electrolyte's and stack's characteristics are:

Table 19: Key characteristics of the VRB system.

Electrolyte		
Specific Energy	32.5	Wh/kg
Energy Density	40	kWh/m^3
Charging time for max l.f	1.2	h
Stack		
Nominal Voltage	40	V
Nominal Power	10	kW
Dimensions	680	mm
	570	
	222	
Weight	24	kg
Volume	0.103257	m^3

Concerning the sizing of the VRB system and its life expectancy:

Table 20: Second's scenario battery system sizing results.

<table>
<tr><td>Minimum Total Energy Installed [kWh]</td><td colspan="2">1217.61</td></tr>
<tr><td>Maximum Energy installed [kWh]</td><td colspan="2">1320.12</td></tr>
<tr><td>Number of Stacks in Series</td><td colspan="2">10</td></tr>
<tr><td>Number of Parallel Stack Strings</td><td colspan="2">88</td></tr>
<tr><td>Total Number of Stacks</td><td colspan="2">880</td></tr>
<tr><td>Energy Installed on Board [kWh]</td><td colspan="2">1320.12</td></tr>
<tr><td>Remaining Energy after failure to one battery pack [kWh]</td><td colspan="2">198.018</td></tr>
<tr><td rowspan="4">Weight of the battery System [kg]</td><td>Stacks</td><td>Electrolyte</td></tr>
<tr><td>21120</td><td>40619</td></tr>
<tr><td colspan="2">Total</td></tr>
<tr><td colspan="2">61739</td></tr>
<tr><td rowspan="4">Volume of the Battery System [m^3]</td><td>Stacks</td><td>Electrolyte</td></tr>
<tr><td>90.87</td><td>33</td></tr>
<tr><td colspan="2">Total</td></tr>
<tr><td colspan="2">123.87</td></tr>
</table>

As shown above the second scenario's battery system cannot be fitted inside the tugboat. Although the electrolyte can barely fit inside the available tanks the rest of the battery system cannot be fitted inside the vessel. The weight of this battery system is considerably higher than this of the fuel oil tanks if they were filled. This means that the vessel after the retrofit would have had a higher draft which would have led to higher energy consumption due to added resistance. Another thing to consider is that the added weight could interfere with the longitudinal strength of the vessel. The energy that the vessel needs in order to safely return to its station in case of an emergency is calculated to be E_{return} = 123 kWh < E_{remain} = 198 kWh. It is evident that this battery technology has been developed without limited space and weight optimization in mind and the battery system suggested in the second scenario is not technically viable especially in a small vessel such as a tugboat. However, future commercialized VRB battery systems could solve these problems.

6.4.2 Emission Quantification:

The emission factors for this specific ship category were taken from "Quantification of emissions from ships associated with ship movements between ports in the European Community", Entec, 2002

Table 21: Emission factors of a tugboat.

Engine	Phase	Engine Type	Fuel Type	Nox [g/kWh]	NMVOC [g/kWh]	PM10 PM2.5 [g/kWh]	SO2 [g/kWh]	CO2 [g/kWh]	HC [g/kWh]
Main	Transit	Medium Speed	MDO/MGO	11	1.5	2.3	11.8	740	1.2
	Assisting			13.7	0.5	0.9	10.8	673	0.4
	Idling			11.8	1.5	1.8	12	734	1
Auxiliary	Hoteling	Medium Speed	MDO/MGO	13	0.4	0.3	2.5	690	0.4

Combining these emission factors with the operational profile of the tugboat, the annual emissions of the tugboat before the retrofit were found to be:

Table 22: Annual emissions of a conventional tugboat.

	NOx	NMVOC	PM10 PM2.5	SO2	CO2	HC
Total Annual Emissions [tn]	13.55	0.86	1.30	10.11	744.06	0.70

Electricity in Greece is produced with various methods. Based on information found in the "Annual energy report" (ΑΔΜΗΕ, 2018) the different methods used and their emission factors are shown on the next table:

Table 23: Emission factors and electricity generated by each available method in Greece.

	Generation [GWh]	Percentage [%]	CO2 [g/kWh]	SO2 [g/kWh]	NOx [g/kWh]	PM [g/kWh]
Natural Gas	7177	26.65	584.844	0.02	0.3	0.03
Lignite	8411	31.24	984.29	2.8	2.3	1.02
Hydroelectric	3484	12.94	0	0	0	0
Renewable	3376	12.54	0	0	0	0
Exchange	4479	16.63	0	0	0	0
Total	26927	100.00	463.34	0.88	0.80	0.33

The annual amount of pollutants produced by on-shore power supply and the difference with the amount of pollutants generated by onboard power generation is calculated to be:

Table 24: Comparison of annual emissions between onboard power generation in a conventional tugboat and on-shore power suply in a all-electric tugboat during recharging.

		CO2	SO2	NOx	PM
Emissions per year [tn]	Electric	297.89	0.57	0.51	0.21
	Conventional	744.06	10.11	13.55	1.30
Reduction of Emissions [%]		59.96	94.41	96.21	83.84

As shown above the reduction of emissions is substantial even in an environment of electric power production such as this of Greece, where almost 31% of power generation is produced in lignite power plants. Considering that the use of renewable technologies is going to further expand in Europe and consequently to Greece in the next years a truly zero-emission vessel is not farfetched.

6.4.3 Investment Appraisal:

6.4.3.1 Retrofit and Maintenance Cost Estimation

Scenario 1: Li-ion Battery System

The final installation cost of the Li-ion battery system is calculated to be:

Table 25: Vessel's retrofit final cost with Li-ion battery system.

Installation Cost			
Machinery	Price per Unit [€]	Number of units	Price [€]
Battery Packs	451000	2	902000
BMS	541200	1	541200

Electric Induction Motor	78400	2	156800
Inverter	90000	2	180000
Gearbox	12000	2	24000
Other and Labor Costs			180400
Total			1984400
Sales of Existing Machinery			
Machinery	Price per Unit [€]	Number of units	Price [€]
Medium Diesel Engine	32110	2	64220
Generator Set	7594	2	15188
Gearbox	4800	2	9600
Total			89008
Final Initial Cost			1895392

The maintenance cost of both a conventional and an all-electric tugboat with a Li-ion battery system and their net difference are shown on the next table:

Table 26: Maintenance savings from a Li-ion battery system.

Maintenance Savings for 1 year	
All-electric Tugboat	
Maintenance Costs Concerning the Battery Pack [€]	724.224
Maintenance Costs Concerning Other Equipment [€]	19844
Total cost [€]	20568.22
Conventional Tugboat	
Maintenance Costs of conventional equipment [€]	37448.92
Total Maintenance Savings [€]	16880.7

6.4.3.2 Scenario 2: Redox Flow Battery System

Although the second scenario could not be fitted inside the vessel due to limited space the economic estimation of the retrofit will be calculated for thoroughness' sake.

The final installation cost of the VRB battery system is calculated to be:

Table 27:Vessel's retrofit final cost with VRB battery system.

Installation Cost			
Machinery	Price per Unit [€]	Number of units	Price [€]
Battery System	396036	1	396036
BMS	237621.6	1	237621.6
Electric Induction Motor	78400	2	156800
Inverter	90000	2	180000
Gearbox	12000	2	24000
Other and Labor Costs			99445.76
Total			1093903
Sales of Existing Machinery			
Machinery	Price per Unit [€]	Number of units	Price [€]
Medium Diesel Engine	32110	2	64220
Generator Set	7594	2	15188
Gearbox	4800	2	9600
Total			89008
Final Initial Cost			1004895

The maintenance cost of both a conventional and an all-electric tugboat with a VRB battery system and their net difference are shown on the next table:

Table 28: Maintenance savings from a VRB battery system.

Maintenance Savings for 1 year	
All-electric Tugboat	
Maintenance Costs Concerning the Battery Pack [€]	12673.15
Maintenance Costs Concerning Other Equipment [€]	19844
Total cost [€]	32517.15
Conventional Tugboat	
Maintenance Costs [€]	37448.92
Total Maintenance Savings [€]	4931.772

Note that the costing for maintenance and installation for both scenarios are thoroughly clarified on APPENDIX B

6.4.3.3 Annual Operation Cost Estimation

The annual cost of operation for both a conventional and an all-electric tugboat as well as their net difference is calculated to be:

Table 29: Operation cost savings.

Fuel Cost Saving for 1 Year	
Days	365
Number of Missions per Day	3
All-electric Tugboat	
Required Energy per Mission [kWh]	867.34
Annual Required Energy [kWh]	918454.22
Price of kWh from the Grid [€/kWh]	0.08259
Total Cost of Electricity [€]	75861.49
Conventional Tugboat	
SFOC of Main Engine Transiting [g/kWh]	233
SFOC of Main Engine idling [g/kWh]	231
SFOC of Main Engine Assisting [g/kWh]	212
SFOC of Auxiliary Engine Hoteling [g/kWh]	217
Fuel Consumption of Main Engine Transiting [tn]	188.19
Fuel Consumption of Main Engine Idling [tn]	37.34
Fuel Consumption of Main Engine Assisting [tn]	233.09
Fuel Consumption of Auxiliary Engine Hoteling [tn]	27.73
Total Fuel Consumption Estimation [tn]	486.35
Price of MDO per ton`	550
Total Cost of fuel [€]	267492
Total Fuel Cost Savings [€]	191631

The investment is going to span in a time period of 20 years, so the future oil and electricity prices must be predicted. Predicting the future price of fuel oil is a difficult task due to the unpredictability of the oil market. With that said all future predictions point to an increase of fuel price from 60% to 400% of its present price until 2040 (U.S. Energy Information Administration, 2018). In the present dissertation an annual 3% steady increase was assumed as a reasonable and conservative estimation. The estimation of electricity prices in Greece was a more difficult task as there was a lack of available sources covering this subject. The fact that new private companies emerged during the last years that took the monopolization from the public sector in addition with political pressure from the EU for the adoption of greener technologies could lead to the rise of electricity's price. At last, an annual steady rise of 1.5% was assumed.

Table 30: Fuel and electricity costs estimation for a 20-year period

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
Price of MDO per ton [€/ton]	550	566.5	583	599.5	616	632.5	649	665.5	682	698.5
Total Cost of fuel [€]	267492.3	275517.1	283541.9	291566.6	299591.4	307616.2	315640.9	323665.7	331690.5	339715.2
Price of kWh from the Grid [€/kWh]	0.0826	0.0838	0.0851	0.0863	0.0875	0.0888	0.09	0.0913	0.0925	0.0937
Total Cost of Electricity [€]	75861.49	76999.32	78137.15	79274.97	80412.8	81550.63	82688.46	83826.28	84964.11	86101.94
Total Fuel Cost Savings [€]	**191630.8**	**198517.8**	**205404.7**	**212291.7**	**219178.6**	**226065.5**	**232952.5**	**239839.4**	**246726.4**	**253613.3**
	Year 11	Year 12	Year 13	Year 14	Year 15	Year 16	Year 17	Year 18	Year 19	Year 20
Price of MDO per ton [€/ton]	715	731.5	748	764.5	781	797.5	814	830.5	847	863.5
Total Cost of fuel [€]	347740	355764.8	363789.5	371814.3	379839.1	387863.9	395888.6	403913.4	411938.2	419962.9
Price of kWh from the Grid [€/kWh]	0.095	0.0962	0.0975	0.0987	0.0999	0.1012	0.1024	0.1037	0.1049	0.1061
Total Cost of Electricity [€]	87239.76	88377.59	89515.42	90653.24	91791.07	92928.9	94066.73	95204.55	96342.38	97480.21
Total Fuel Cost Savings [€]	**260500.2**	**267387.2**	**274274.1**	**281161.1**	**288048**	**294935**	**301821.9**	**308708.8**	**315595.8**	**322482.7**

6.4.3.4 Net Present Value Calculation:

Scenario 1: Li-ion Battery System

Return of investment	Discount Rate 6%	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
Costs	-1895392	-1895392	0	0	0	0	-651695	0	0	0	0	-575025
Savings		0	208511.5	215398.5	222285.4	229172.4	236059.3	242946.2	249833.2	256720.1	263607.1	270494
Residual Value of Investment			0	0	0	0	0	0	0	0	0	0
Net Cash Flow			208511.5	215398.5	222285.4	229172.4	-415636	242946.2	249833.2	256720.1	263607.1	-304531
			Year 11	Year 12	Year 13	Year 14	Year 15	Year 16	Year 17	Year 18	Year 19	Year 20
Costs			0	0	0	0	-460020	0	0	0	0	0
Savings			277380.9	284267.9	291154.8	298041.8	304928.7	311815.7	318702.6	325589.5	332476.5	339363.4
Residual Value of Investment	0		0	0	0	0	0	0	0	0	0	0
Net Cash Flow	1992336		277380.9	284267.9	291154.8	298041.8	-155091	311815.7	318702.6	325589.5	332476.5	339363.4
NPV	96944.08											

As discussed earlier the battery modules must be replaced every 5 years. A decrease of the price of the battery modules was assumed, following the decrease of Li-ion battery prices for other industries such as this of the automotive industry. Although a decrease of 65% is predicted by 2028 (A Strategic Outlook for the Global Lithium-ion Batteries Market to 2028, May 2018) a more conservative approach was considered for this dissertation. The reduction was assumed to be 15% in Year 5, 25% in Year 10 and 40 % in Year 15 of the original price. Lastly, the spent modules was assumed that they would be resold for recycling purposes at 15% of their price according to the year of the transaction.

Scenario 2: Redox Flow Battery System

Return of investment	Discount Rate 6%	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
Costs	-1004895	-1004895	0	0	0	0	0	0	0	0	0	0
Savings		0	196562.6	203449.5	210336.5	217223.4	224110.4	230997.3	237884.2	244771.2	251658.1	258545.1
Residual Value of Investment		0	0	0	0	0	0	0	0	0	0	0
Net Cash Flow			196562.6	203449.5	210336.5	217223.4	224110.4	230997.3	237884.2	244771.2	251658.1	258545.1
			Year 11	Year 12	Year 13	Year 14	Year 15	Year 16	Year 17	Year 18	Year 19	Year 20
Costs			0	0	0	0	0	0	0	0	0	0
Savings			265432	272319	279205.9	286092.8	292979.8	299866.7	306753.7	313640.6	320527.6	327414.5
Residual Value of Investment	0		0	0	0	0	0	0	0	0	0	0
Net Cash Flow	2855308		265432	272319	279205.9	286092.8	292979.8	299866.7	306753.7	313640.6	320527.6	327414.5
NPV	1850413											

The system suggested on the second scenario is much more economical and the fact that the electrolyte has an unlimited cycle life makes it a much more attractive solution for investors, but as discussed earlier does not fit inside the vessel.

As shown above both investments seem to be financially viable, although the first scenario seems to have a very low positive NPV value. This means that if some of the assumptions that were made during this dissertation for the future of battery, fuel or electricity prices are proven to be wrong (i.e. the price of marine batteries doesn't drop as is expected, or the fuel price drops again from external and unpredictable reasons) the investment could easily not be economically feasible. However, European funds available for new green technologies could partially fund such a project making it more attractive for investors.

7 Discussion:

7.1 Conclusions:

From the results presented above the following conclusions can be made:

Scenario 1: Li-ion Battery System

- The battery system can be easily fitted inside the tugboat and more specifically inside the fuel oil tanks in accordance to the new regulations.
- The weight of the battery packs is low which could lead to improved energy consumption while negative effects such as propeller emergence could be easily fixed with ballast water.
- Two independent battery packs are installed to ensure vessel's safety and reliability in accordance to the regulations.
- One battery pack can provide enough energy for the vessel to return safely to its station in case of an emergency.
- The battery modules have a relatively short life expectancy since they must be replaced after 5 years of operation.
- Batterie's price is the biggest expenditure of the retrofit, but also the cost of the rest of the equipment is not negligible.
- Savings from operation and maintenance costs are significant, but the costs of the battery modules that must be replaced every 5 years balances these benefits.
- The investment seems economically feasible, but changes in fuel oil or battery prices could easily make the investment non-viable
- External financial aid, such as European funds, could help to create a more attractive environment for investors.

Scenario 2: Redox Flow Battery System

- The battery system cannot be fitted inside the tugboat. Even though the electrolyte can fit inside the fuel oil tanks, the rest of the battery system is too massive to be housed inside the rest of the available space.
- The total weight of the battery system is high. This could lead to worsen energy consumption and towing efficiency due to higher resistance. Another thing to consider is that the added weight could interfere with the longitudinal strength of the vessel.
- The VFB demonstrates an excellent electrochemical reversibility and virtually an unlimited cycle life. The electrolyte can last throughout the 20 years of the investment without the need of replacement.
- This battery technology needs further improvements in space and weight optimization for it to be a viable solution in the maritime sector; especially for vessels where limited space is a serious issue such as tugboats.
- Battery system's cost is still a significant part of the total cost of the retrofit but is still considerably cheaper than the cost of the first scenario.
- As an investment, the second scenario is much more profitable than the first scenario, if the battery system could be fitted inside the vessel.

- Future improvements on this battery technology could make it a dominant alternative to both fuel oil and Li-ion batteries in the maritime industry.

The environmental benefits of an all-electric tugboat are indisputable. An all-electric tugboat will help in reducing the amount of pollutants emitted locally. The emergence of zero emission vessels will help with the reduction of pollutants and noise, especially in a port city such as this of Piraeus. Another thing to consider is that an all-electric vessel will help in the reduction of carbon footprint as well as the emission of other pollutants nationally. This is because the difference between the annual amount of pollutants produced by on-shore power supply and the amount of pollutants generated by onboard power generation is significant. If Greece focuses in modernizing its infrastructure by incorporating greener energy generation technologies, these benefits could become even greater.

Furthermore, it is concluded that the retrofit of a conventional tugboat into an all-electric battery powered one is not yet feasible. Even though both scenario's NPVs were positive, the battery system proposed in the second scenario could not be fitted inside the vessel while the battery system proposed in the first scenario was too expensive to acquire, balancing out all the economic benefits of its lower operational and maintenance costs. More specifically, even though the NPV of the first scenario was positive, if some of the assumptions made on this dissertation fail to meet reality, the investment could become non-profitable. Future predicted lower Li-ion battery prices or technical innovations in VRB battery technology could make both technologies more competitive.

Finally, it is important to note that even though this study concludes that retrofitting a conventional tugboat into an all-electric battery powered one without external funding is a risky investment at present, the continuous development and improvements of battery technologies during the last years is evident. If this trend continues battery technology in the maritime industry is going to be a very promising solution for the future.

7.2 Further Research:

As discussed above concerning the first scenario presented in this dissertation the high price of the battery modules creates a costly battery system making the investment feasible but risky. It is recommended that a similar study with the same subject to be reexamined in the future when the prices of Li-ion batteries might be lower.

The system proposed in the second scenario seems really promising, but further research in improving energy and power density is needed for the system to be able to fit inside a vessel such as a tugboat where limited space is an issue. Its ability of instant recharging via replacing the spent electrolyte is vital for the marine industry and can potentially become the preferred alternative solution to fuel oil. New studies concerning other types of vessels, where limited space is not that big of an issue, such as passenger and car ferries is recommended. If this battery system proves to be viable for marine applications, specific regulations for the installation, operation and safety of the system must be considered.

All-electric ships are starting to emerge and the trends show that more vessels are going to adopt this technology in the future. Appropriate infrastructure must be installed in the ports in order to accommodate these ships.

Feasibility studies for other type of vessels should be investigated. Some type of vessels to consider are anchor handling tugs, supply ships, firefighters, pilot boats and other vessels that operate in short distances.

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The Maritime Executive: https://www.maritime-executive.com/features/prospects-for-battery-electric-ferryboats

UniEnergy Technologies: http://www.uetechnologies.com

Appendix A: Electrical Load Balance Sheet

This is the electrical load balance sheet as provided by the tugboat's operator.

	Equipment	Efficiency Factor	No. Installed	Installed Power				Idling			Transit			Maneuvering		
				Pov.αποδ		Pov.απορ	Ρεγκατ.	No. in Use	Load Factor	Power	No. in Use	Load Factor	Power	No. in Use	Load Factor	Power
				[Ps]	[kW]	[kW]	[kW]			[kW]			[kW]			[kW]
	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	[13]	[20]	[21]	[22]
	Engine Room Auxiliary Systems															
1	Fuel Oil transfer pump	0.850	1	8.668	6.375	7.500	7.500	0	0.200	0.000	1	0.100	0.750	0	0.000	0.000
2	Fire pump	0.850	2	-	-	(d)	-	-	0.000	-	0	0.000	-	0	0.000	-
3	General service pump	0.850	1	4.623	3.400	4.000	4.000	1	0.900	3.600	1	0.200	0.800	1	0.200	0.800
4	Potable water pump	0.850	2	1.734	1.275	1.500	3.000	2	0.500	1.500	2	0.500	1.500	2	0.500	1.500
5	Sanitary pump	0.850	1	1.734	1.275	1.500	1.500	1	0.400	0.600	1	0.400	0.600	1	0.400	0.600
6	Water Heater	1.000	1	8.158	6.000	6.000	6.000	1	0.500	3.000	1	0.100	0.600	1	0.200	1.200
7	Main engine cooling fan	0.850	2	3.467	2.550	3.000	6.000	2	0.200	1.200	2	0.850	5.100	2	0.850	5.100
8	Engine Room lighting	1.000	20	0.024	0.018	0.018	0.360	20	1.000	0.360	20	1.000	0.360	20	1.000	0.360
								Σ		10.260	Σ		9.710	Σ		9.560
	Ship Auxiliary Systems															
1	Anchor windlass	0.850	1	6.356	4.675	5.500	5.500	0	0.000	0.000	0	0.000	0.000	0	0.000	0.000
2	Strore room lighting	1.000	6	0.024	0.018	0.018	0.108	6	1.000	0.108	6	1.000	0.108	6	1.000	0.108
3	Deck lighting 1	1.000	18	0.024	0.018	0.018	0.324	18	1.000	0.324	18	1.000	0.324	18	1.000	0.324
	Deck lighting 2	1.000	2	0.136	0.100	0.100	0.200	2	1.000	0.200	2	1.000	0.200	2	1.000	0.200
	Deck lighting 3	1.000	2	0.136	0.100	0.100	0.200	2	1.000	0.200	2	1.000	0.200	2	1.000	0.200
	Deck lighting 4	1.000	3	1.360	1.000	1.000	3.000	3	1.000	3.000	3	1.000	3.000	3	1.000	3.000
	Deck lighting 5	1.000	1	1.360	1.000	1.000	1.000	1	1.000	1.000	1	1.000	1.000	1	1.000	1.000
4	Bridge lighting	1.000	8	0.024	0.018	0.018	0.144	8	1.000	0.144	8	1.000	0.144	8	1.000	0.144
5	Air comressor	0.850	1	2.138	1.573	1.850	1.850	1	0.200	0.370	1	0.200	0.370	1	0.200	0.370
6	Stearing gear pump	0.850	2	5.201	3.825	4.500	9.000	0	0.000	0.000	1	0.100	0.450	2	0.200	1.800
7	MARPOL pump	0.850	1	0.393	0.289	0.340	0.340	0	0.000	0.000	1	0.200	0.068	0	0.000	0.000
Electronics																
1	Batery charger	0.850	1	2.589	1.904	2.240	2.240	1	0.200	0.448	1	0.200	0.448	1	0.200	0.448
								Σ		5.794	Σ		6.312	Σ		7.594
	Accomodation Quarters Auxiliary Systems															
1	Accomodation Lighting 1	1.000	26	0.024	0.018	0.018	0.468	26	1.000	0.468	26	1.000	0.468	26	1.000	0.468
	Accomodation Lighting 2	1.000	6	0.020	0.015	0.015	0.090	6	1.000	0.090	6	1.000	0.090	6	1.000	0.090
2	A/C unit	1.000	1	6.118	4.500	4.500	4.500	1	0.750	3.375	1	0.750	3.375	1	0.750	3.375
3	Accomodation quarters ventilation	0.850	1	0.040	0.030	0.035	0.035	1	0.850	0.030	1	0.850	0.030	1	0.850	0.030
4	WC ventilation	0.850	1	0.023	0.017	0.020	0.020	1	0.850	0.017	1	0.850	0.017	1	0.850	0.017
5	Fridge	0.850	1	0.578	0.425	0.500	0.500	1	1.000	0.500	1	1.000	0.500	1	1.000	0.500
6	Electric hob	1.000	1	4.079	3.000	3.000	3.000	1	0.200	0.600	1	0.200	0.600	1	0.200	0.600
7	TV	0.850	1	0.508	0.374	0.440	0.440	1	0.000	0.000	1	0.500	0.220	1	0.500	0.220
8	Public addresor	0.850	1	0.347	0.255	0.300	0.300	1	0.100	0.030	1	0.200	0.060	1	0.200	0.060
								Σ		5.110	Σ		5.360	Σ		5.360
								Total		21.164	**Total**		21.382	**Total**		22.514

Load Facrors				
		Idling	Transit	Maneuvering
Manoeuvering and Propulsion Auxliary Systems				
1	Fuel Oil transfer pump	0	0.1	0
2	Fire pump	0	0	0
3	General service pump	0.9	0.2	0.2
4	Potable water pump	0.5	0.5	0.5
5	Sanitary pump	0.4	0.4	0.4
6	Water Heater	0.5	0.1	0.2
7	Main engine cooling fan	0.2	0.85	0.85
8	Engine Room lighting	1	1	1
Ship Auxiliary Systems				
1	Anchor windlass	0	0	0
2	Strore room lighting	1	1	1
3	Deck lighting	1	1	1
4	Bridge lighting	1	1	1
5	Air comressor	0.2	0.2	0.2
6	Steering gear pump	0	0.1	0.2
7	MARPOL pump	0	0.2	0
8	Batery charger	0.2	0.2	0.2
Accomodation Quarters Auxiliary Systems				
1	Accomodation Lighting	1	1	1
2	A/C unit	0.75	0.75	0.75
3	Accomodation quarters ventilation	0.85	0.85	0.85
4	WC ventilation	0.85	0.85	0.85
5	Fridge	1	1	1
6	Electric hob	0.2	0.2	0.2
7	TV	0	0.5	0.5
8	Public addresor	0.1	0.2	0.2

Appendix B: Costing of the Battery Systems

Scenario 1:

Equipment Costs:

- Battery Modules: 1100 €/module, source: Bakirtzoglou. C (2017), "Techno-economical feasibility study on the retrofit of double-ended Ro/Pax ferries into battery-powered ones", Diploma thesis, NTUA March 2017.
- Battery Management System: 60 % of battery system's cost, source: After consulting with the supervisor.
- Electric Motor: 140 €/kW, source: ABB web site.
- Inverter: 150 €/kW, source: After consulting with the supervisor.
- Gearbox: 12000 €/unit, source: Advance web site.
- Other/Labor: 10% of total cost, source: After consulting with the supervisor.

Maintenance Costs:

All-electric tug:

- Battery Maintenance: 0.5 €/kWh, source: After consulting with the supervisor.
- Other Equipment: 1% of total cost, source: After consulting with the supervisor.

Conventional tug:

- Maintenance of Machinery: 14% of operational costs, source: Marinna Zanne, "Shipping Company Economics: Costs and revenues from running a ship".

Operation Costs:

All-electric tug:

- Cost of Electricity: 0.08259 €/kWh, source: ΔΕΗ επαγγελματικό Τιμολόγιο Γ22.

Conventional tug:

- Cost of MDO: 550 €/ton, source: Ship and Banker web site.

Scenario 2:

Equipment Costs:

- Battery Equipment: 300 €/kWh, source: John f. DeBoever, Vice president of global sales at UET
- Battery Management System: 60 % of battery system's cost, source: After consulting with the supervisor.
- Electric Motor: 140 €/kW, source: ABB web site.
- Inverter: 150 €/kW, source: After consulting with the supervisor.
- Gearbox: 12000 €/unit, source: Advance web site.
- Other/Labor: 10% of total cost, source: After consulting with the supervisor.

Maintenance Costs:

All-electric tug:

- Battery Maintenance: 0.5 €/kWh, source: John f. DeBoever, Vice president of global sales at UET.
- Other Equipment: 1% of total cost, source: After consulting with the supervisor.

Conventional tug:

- Maintenance of Machinery: 14% of operational costs, source: Marinna Zanne, "Shipping Company Economics: Costs and revenues from running a ship".

Operation Costs:

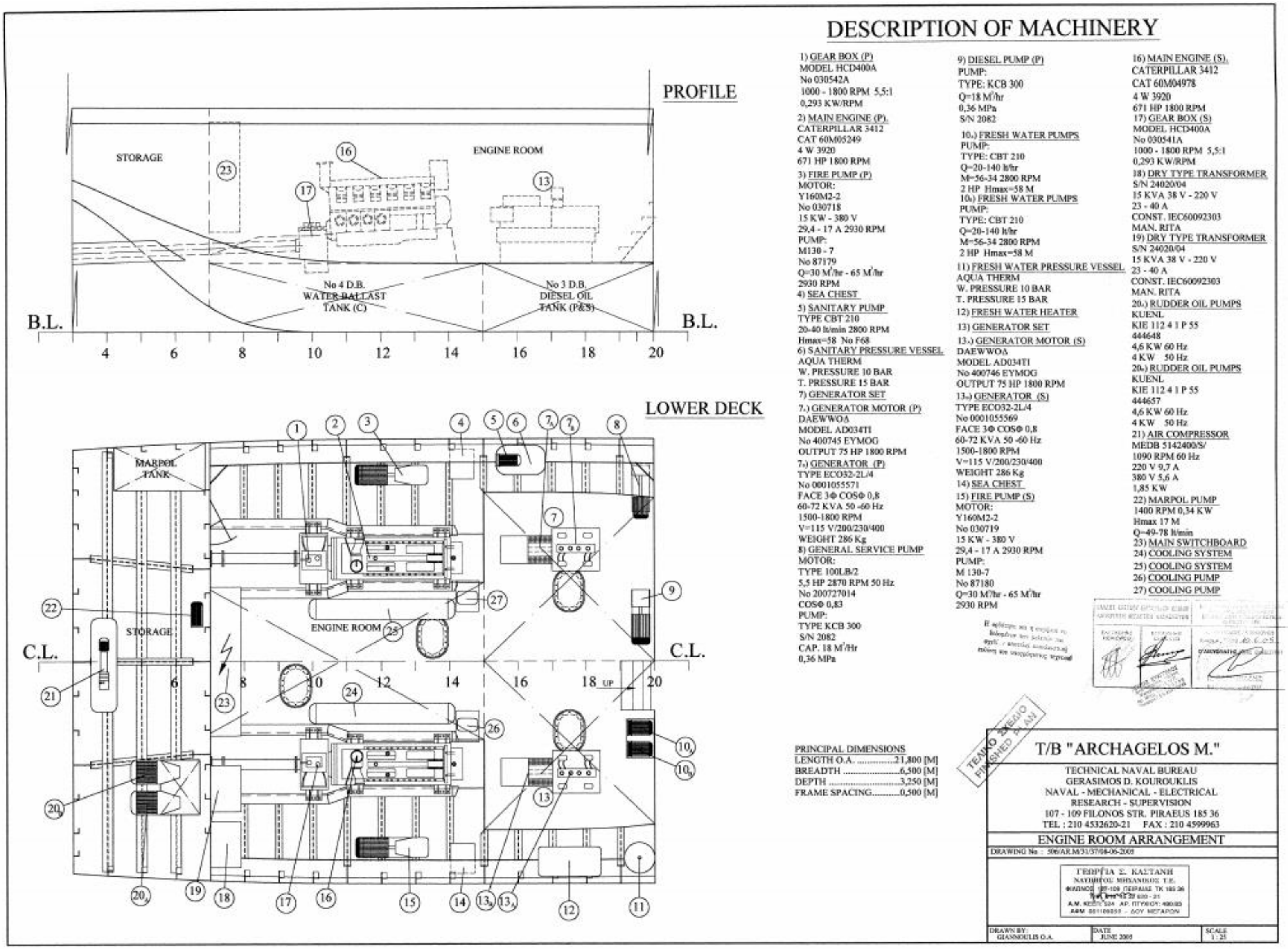
All-electric tug:

- Cost of Electricity: 0.08259 €/kWh, source: ΔΕΗ επαγγελματικό Τιμολόγιο Γ22.

Conventional tug:

- Cost of MDO: 550 €/ton, source: Ship and Banker web site.

Appendix C: Engine Room Arrangement of “Archaggelos”



Appendix D: Line Diagram of “Archaggelos”