

# **Feasibility study of an electrical energy storage in a marine vessel**

Master of Science in Technology Thesis  
University of Turku  
Department of Mechanical and Materials engineering  
Materials engineering

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### **Abstract.**

In this Master's thesis, energy storage solutions were designed for two vessels with long route of operation. The aim was to achieve fuel savings and reduce emissions. The fuel savings resulted from three sources. Firstly, the capacity effect of the battery enables shore power to be utilized at sea. The second factor is peak shaving, where engine runtime and load are optimized in order to have lower specific fuel consumption. The third effect comes from shutting down the engines and providing the hotel load with shore connection when the ship is berthed at port.

In the theoretical part of the thesis, energy storage solutions were presented and a battery was selected as the energy storage for the inspection. Furthermore, varying battery capacities were introduced, and battery usage was briefly reviewed from the point of view of safety, legislation and installation structure. In the case study, two battery types, NMC/LFP and LTO, were selected for closer inspection regarding their application in the vessels from economic and fuel saving perspectives. Two alternative battery capacities were considered. The capacity options were intended for similar kind of use but with differences in engine profile and resulting battery demand. Battery use between different capacities was optimized so that the cycle count would result in 10 year cycle-life for NMC/LFP and 20 year cycle-life for LTO battery.

The results showed that among the options, the smaller capacity NMC/LFP battery was the most economically feasible while still achieving good emission savings. Higher capacity battery would be better for drivability and engines as well as for fuel savings, but at the expense of economic feasibility. Sensitivity analysis showed that for the first vessel, the chosen battery solution would likely be feasible with the fuel price of 1000 €/t when the electricity price is below 15 c/kWh. For the second vessel, the economic feasibility would be more challenging to achieve. With fuel price of 1000 €/t, the electricity price would need to be below 7 c/kWh. Increase in fuel price would improve the economic feasibility, whereas the increase in electricity price and investment cost would impair it.

**Keywords:** energy storage, battery, lithium, ship, peak shaving, emission, economic feasibility

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## Glossary

<b>Term</b>	<b>Definition</b>
Intercalation	Lithium-ions insert between layers in a crystal lattice
Lithiation	The incorporation of lithium into an electrode
Solid electrolyte interface (SEI)	Passive layer formed in the surface of graphite anode
Specific energy	Energy per unit mass (kWh/kg)
Energy density	Energy per unit volume (kWh/l)
Thermal runaway	Faulty process of a battery cell where self-heat generation rises over effective cooling
State of charge (SOC)	The level of charge of an electricity battery relative to its capacity
Depth of discharge (DOD)	The level of discharge of an electricity battery relative to its capacity
Specific fuel consumption (SFC)	The amount of fuel consumed for each unit of energy (g/kWh)

## 1 Introduction

Environmental pollution and fossil fuel consumption have become a common concern in recent times. Energy efficient and environmentally-friendly actions have been introduced and deployed in many fields. The demand of maritime transport has been increasing for decades along with global trades and world population. This has been associated with higher pollution and emission levels. [1] Shipbuilding is coming to the point where the development towards cleaner solutions is necessary. Maritime ship traffic accounts for 3-4% of all EU CO<sub>2</sub> emissions and 11% of transport sector. At the same time maritime transport covers 31% of EU internal and 75% of the external trade in terms of volume and is thus an essential component of transport system and European economy. [2]

International maritime organization (IMO) has set the target to reduce shipping greenhouse gas (GHG) emissions by 50% in 2050 [1]. While EU is committed to reduce shipping GHG emissions by 55% in 2030, and to achieve climate-neutrality in 2050. Current directives in EU don't have a link between taxing the fuels based on energy content or environmental impact, which benefits fossil fuels and contributes against the goals. In addition, the current energy taxation directive (ETD) has exempted the fuels in commercial aviation and maritime transport. [3]

In order to achieve the goals, EU has set the revisioned ETD, emission trading system directive (ETS) and EU taxonomy criteria to put to use presumably in 2023. [3] Updated ETD will categorize the fuels and tax them based on the environmental impact. In addition, the maritime industry would not be fully exempted from the taxes of fossil fuels anymore [3]. ETS directive would introduce a price for GHG emissions. For instance the shipping companies would have to purchase and surrender emission allowances for each ton of CO<sub>2</sub> emissions. [4] EU has also set the FuelEU maritime regulation that requires all vessels of 5,000 GT or higher to start reducing the annual average GHG intensity by 2% of the energy they use. The regulation will come into effect in 2025, and from 2030 onward the annual decreased GHG intensity will be 6% and increased periodically in the future. Alternative fuels infrastructure regulation (AFIR) will also be revisioned in order to improve the availability of the alternative fuels and power supplies in ports. [2]

Upcoming regulations will have a clear influence on maritime industry. It is expected that the shipping will have to undergo global transition to alternative fuels in the future. Also deploying

new technologies in order to increase energy efficiency will be important in reaching the goals. One important approach is to utilize large energy storages onboard the vessel. It will enable several advancements regarding engine use, consumption and performance. The global marine battery market is projected to register a CAGR (compound annual growth rate) of 48.1% from 2020 to 2025 [5]. This Master's thesis is part of a larger project that aims at cutting down fossil fuels consumption and reducing environmental pollution. To progress towards these goals, this thesis concentrates on the implementation of electrical energy storages in the marine vessels.

The thesis consists of two main parts. Chapters 2 and 3 provide a theoretical part, which focuses more generally on the potential propulsion use of energy storages in maritime applications. Addressed topics include utilization of energy storages in different marine situations and applications, and ship requirements on the energy storage. Working principle, materials, types and aging of energy storages are further covered. Chapter 4 contains a case study investigating the application of energy storages in specific marine vessels. It utilizes simulations that are based on actual operational profiles. The main research question regarding the case study is: what would be the most suitable energy storage solution for the case ships with long route of operation when economic feasibility and fuel/emission savings are considered? The study also looks into the potential of utilizing energy and power dense energy storages as a combo for the case ships. Different capacities and types of an energy storage are inspected.

## **2 Fundamentals behind marine energy storage systems**

### **2.1 Energy storage utilization**

The chapter introduces propulsion use cases for an energy storage between different marine applications and situations of ship use – from small customer boats to ferries and further to passenger ships and heavy merchant vessels. The use cases vary between different applications according to the characteristics of the vessel, operation profile of the route and desired personal objectives. In order to address these topics, the operation of ship propulsion is covered first.

#### **2.1.1 Marine powertrain**

The main power in a ship can be provided by with diesel, gas, steam, electric or even nuclear powerplant [6][7]. The power is used to run the propulsion and cover the service load which can be accomplished by with different layouts of the drive. The most conventional types are mechanical- and electrical-drive.

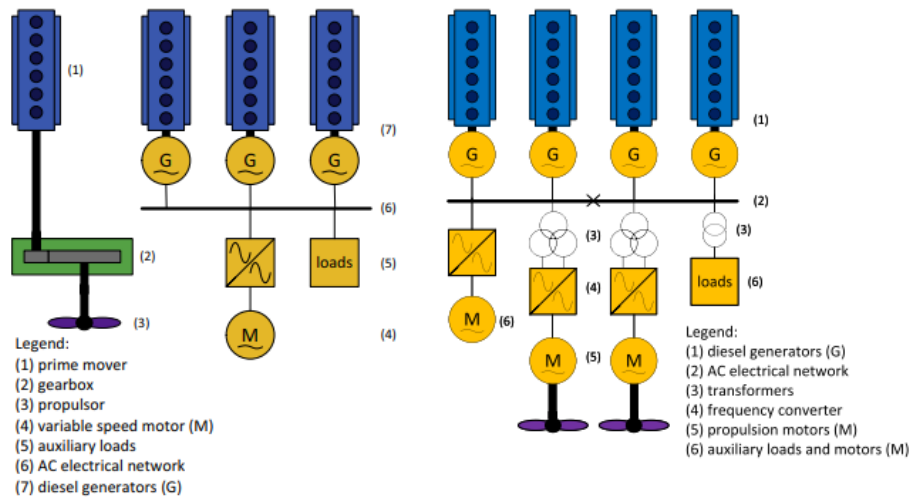
##### **Mechanical-drive**

A ship with mechanical-drive generally uses a diesel engine or gas turbine to move the propeller and a long shaft via mechanical gears. The electric service load is powered by generators. Mechanical drive can provide higher system efficiency than electrical-drive when the power unit can be maintained close to the optimization point. [8] That is mostly achieved by ocean-going merchant vessels with steady power and long distance.

##### **Electrical-drive**

Electrical-driven ship, on the other hand, run the propulsion with electric motors that are powered by propulsion dedicated generators, and the service load is powered by separate generators. Another way is to integrate both generator sets into one main generator unit that covers both propulsion power and service load. [9] The generator motor is generally driven with diesel or gas, due to which electric-drive can sometimes be referred as diesel-electric. In contrast to mechanical-drive, electrical-drive can provide higher system efficiency at low and dynamic loads making it more suitable on many applications. The layouts of mechanical- and electrical-drives can be seen from picture 1.

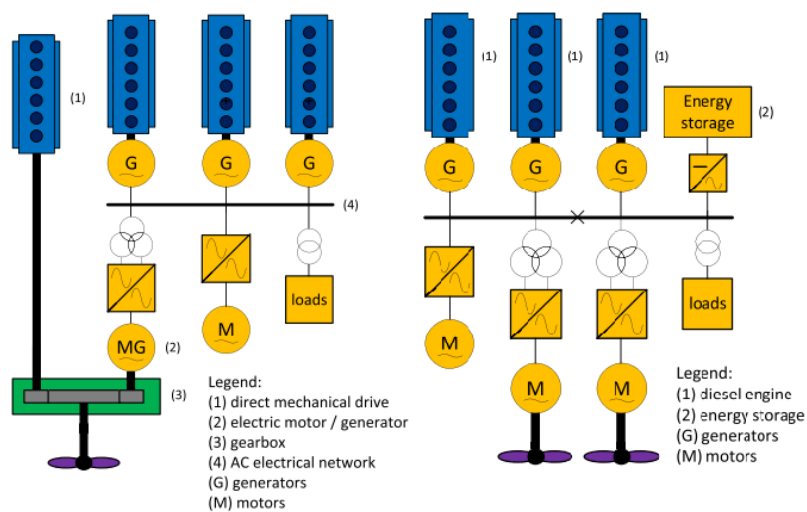




Picture 1. Layouts of mechanical- and electrical-drives. Mechanical-drive on the left, and electrical-drive on the right. Reproduced under CC BY 4.0 license from ref. 10.

## Hybrid-drive

In addition to conventional drives there are at least two different hybrid layouts. Firstly, there is a hybrid propulsion of mechanical- and electrical-drive, where propulsion is powered by both drives while service load is covered only by the electrical-drive as is presented in picture 2. Second possibility is to utilize either mechanical- or electrical-drive with hybrid power supply, where propulsion and service load are powered by two or more different sources. The additional source can be an energy storage such as battery, flywheel, supercapacitor, or potentially fuel cells. In this work, hybrid mostly refers to an electrical-drive with battery energy storage similar to the right side example in picture 2.



Picture 2. Two different hybrid layouts. Hybrid propulsion of mechanical- and electrical-drive on the left, and electrical-drive with energy storage on the right. Reproduced under CC BY 4.0 license from ref. 10.

## Energy storages

There are two ways to utilize energy storages in the powertrain of the vessels: hybrid or all-electric. All-electric vessels do not form any emissions during operation. It can currently be achieved at least with a battery-electric vessel that is completely powered by the battery. As the required capacity of the battery increases mainly according to the distance of the route, only some of the applications with shorter routes can reasonably be fully electrified with current technology [8]. When the routes get longer, the battery applications tend to change from all-electric use towards hybrid solutions. In those larger ocean-going vessels, the development of alternative power options and sustainable fuels comes important in order to reduce emissions.

Future fuel alternatives include bio- and electrofuels such as ammonia or methane that can be produced from biomass or renewable energy and can be turned into methanol [11]. Ammonia and methanol as well as hydrogen can also be utilized with fuel cell, which converts the fuel to electricity with relatively high efficiency of about 50%.

All the non-battery options with fuels and fuel cells have the feature to operate most efficiently at a specific power rating. [12] When the power rating falls the efficiency decreases. An energy storage combined with an electric motor is, however, very efficient under vast range of loads. In transportation, the power requirements fluctuate with numerous variables having an effect. Battery can provide stable powering of non-battery options by buffering the transient power demands while main power units provide steady base load [12]. This increases the efficiency, which relates to lower fuel consumption and further to lower emissions. In addition, potential renewable energy sources to supplement the load are an option. For instance, wind power could save fuel significantly in a long windy voyage [13]. The conclusion is that whatever the powering option will be in the future, battery will be equally compatible with all of the alternatives, and it can ensure a power generation efficiency closer to the peak [12].

In general, a vessel with mechanical propulsion where the electrical load of the vessel is not connected to the main engine, can use a battery to handle the hotel load peaks [14]. This kind of system is generally referred as a semi-hybrid system. Full hybrid system in a conventional mechanical propulsion or diesel electric propulsion vessel can utilize a battery to support both the hotel load and propulsion. In case of full hybrid mechanical propulsion, a battery is included with PTO/PTI (power take off/power take in) system that allows the batteries to support propulsion and propulsion to charge the battery. [8] Full hybrid diesel electric vessel can run

purely with batteries or generator sets, or with a combination of both depending on the situation and hybrid configuration of the ship.

### 2.1.2 The use of an energy storage in different marine operations

In order to utilize batteries on board, it is necessary to identify the use cases from the operation patterns of the vessel. In most cases the conventional pattern includes hoteling, maneuvering and cruising. A hoteling vessel is berthed in port waiting for the cargo and next voyage and is required to cover the hotel load. The plug-in capability at port allows charging a battery and covering the hotel load from external grid. During maneuvering a vessel turns to the direction of travel. Propulsions of the maneuvering vessel operate at low loads meanwhile additional equipment such as thrusters operate at their highest load [15]. Hoteling, maneuvering and cruising at port happen close to the land which is challenging in terms of emissions. Internationally 70% of the emissions happen within 400km of land and emissions may travel hundreds of kilometers inland [16]. The power demand in port or protected areas can be supported by a battery to mitigate emissions or covered completely to ensure zero-emission operations. One option is to charge a battery with generators during the voyage to allow emission-free port stays powered by a battery in case of no shore connected hotel load [8]. Vessels with crane operations are particularly suitable for implementing a battery because of high variation of power demand and capability to be run by electric motors that can utilize regenerative braking [17]. The battery can load the released potential energy when the cargo is lowered and burned on brakes [18].

Cruising relates to every marine application but the dependent use of a battery in a hybrid system comes from an extensive set of different load fluctuation scenarios. The conventional use of a battery in a hybrid system is peak shaving that shaves the load peaks and ensure the engines to operate at more optimal load. Peak shaving can be utilized during regular propulsion use or when performing other functions, such as dynamic positioning or crane operations [19] [12]. Propulsion load during cruising can fluctuate according to some external factors such as adverse weather conditions, waves, ice or regional speed limits. The rapid development and increasing popularity of electric vehicles (EV) have also created the need and opportunity to charge EVs during voyage, which will add another cause of load fluctuation. With dynamic load transition ramps, the steepness of the load transition can be smoothed by a battery to achieve fuel and emission savings, and avoid negative impact on the engines [8]. Very steep load fluctuations can cause high particle emissions [8]. With load leveling during the phase of

low demand, battery can be charged via the excess power from a generator and vice versa the stored energy can be utilized during high demand. The fast load response of a battery can also aid the acceleration [8]. Gas engines specifically have poor load response and can benefit more from a battery.

A battery can also work as a spinning reserve and back up. Usually vessels have multiple generators to ensure redundancy, and they operate at partial load. With a battery installation, there is no need to have operating generator capacity as a spinning reserve when a battery can be used instead as a backup or for the time when a secondary generator is started. [19] Battery installation can lead to a replacement of a generator set. Furthermore, battery powered cruising allows zero-emission and silent sailing, which are increasingly common features especially in the proximity of larger populations [19]. Batteries can also provide range extension without having to refuel.

### 2.1.3 Marine energy storage applications

By dividing the marine applications arbitrarily into ferries, working boats, warships, cruise ships and merchant vessels we can look closer into the current state of battery use associated with vessel types. Ferries obtain the best characteristics to be fully electrified since they traditionally sail relatively short routes with a cyclic routine and possibility for battery charging at shore. Fully electrified ferries come with higher investment costs but the difference can be compensated in 5-8 years, or even faster in the future with potentially lowering battery prices [20]. Operation costs will be much lower during the remainder working life compared to diesel powered ferry, and huge amount of fuel and emissions are saved. An example of a fully electric ferry is Ellen E-ferry, which was the largest of a kind during its deployment in 2019. Ellen is a 59.4 meter long, medium sized ferry operating in Denmark on approximately 40 kilometer roundtrip journey. The main engines are 2x700 kW, and the nominal battery capacity is 4.3 MWh with charge effect of 4 MW. [20]

Workboats such as support vessels, tugboats, icebreakers and fishing boats can utilize a hybrid battery or full electric battery system according to the characteristics of the operation and operation closeness from the port. Compared to large ocean-going vessels, workboats typically have more speed- and task-wise variation in their operation profile. Workboats can benefit from all the previously mentioned marine battery utilization scenarios along with more intrinsic ones. For example, the diesel engines of tugboats might operate only 2% of their life at maximum power which doesn't allow the optimal use for those engines, but offers an opportunity for

battery installation [12]. Support vessel Edda Ferd, in turn, is reported to spend 70 % of its time in dynamic positioning, while having the main purpose in powering a crane with 546 kWh battery [12]. Fishing boats might benefit from silent sailing and low speed operation. Icebreakers generally utilize hybrid systems and can achieve more efficient icebreaking performance in addition to fuel and emission savings [21]. For example a battery hybridization for icebreaker Polaris, estimated by ABB showed that a 4.5 MWh battery installation can achieve fuel and CO<sub>2</sub> savings up to 12% and 46% lower engine running hours [21].

The utilization of energy storages in warships is also growing. U.S. Navy announced their electrification roadmap for 2019-2037 in the naval power & energy report (NPES). The report raises a shift into new weapon requirements and advantages of electrification. The development of directed energy weapons such as stochastic electronic warfare systems and lasers, kinetic energy weapons such as electro-magnetic railguns, or radiated energy systems such as air and missile defense radar, requires a lot from the power system. Legacy systems do not possess the electrical characteristics to withstand the on/off fluctuation or ripple pulsation effects of the advanced technologies resulting in unnecessary thermal and mechanical stresses in generators or diesel/gas turbine engines. Modern power electronics and energy storages among others are pointed out as an advancement. In addition to advanced weapons and sensors, the electrical-drive can provide warfighting improvements such as silent sailing, ability to avoid detection, mobility, reduction in the probability of being hit, recoverability in seaworthiness, information and communication security/cybersecurity just to name a few. [22] Large batteries have been used in submarines for a long time already mainly in submerged operations [23].

Cruise ships generally travel quite long distances with heavy loads. Depending on the parameters, cruise ships have applied hybrid battery applications. In addition to peak shaving and spinning reserve, a hybrid system of a cruise ship benefits from fully electric port operations due to high emission amounts. The world's first hybrid cruise ship MS Roald Amundsen, deployed in 2019, can run 45-60 minutes on batteries of 1.35 MWh in port or protected areas, and can reduce the emissions by 20 % compared to similar size vessel without hybrid capability [24][25]. The operation profiles of cruise ships are however typically relatively difficult for battery utilization, and fuel savings for larger vessels tend to remain below 5% [26]. A case study from MAN energy solutions in 2019 showed that with current technology, the battery application for roll-on/roll-off (ro-ro) shipping with around 220 km journey and 5000 lane meters vessel is feasible by volume and weight. However, the initial cost is over double to traditional solution when considering the lowest cost scenario. The difference becomes even

larger when considering the expected swap of the battery halfway through vessel lifetime. With longer routes, the required weight and volume for the battery would significantly decrease the cargo carrying potential of the vessel. [8]

Other merchant vessels such as tankers, container ships and cargo ships can find similar hybrid applications than cruise ships where the main benefits come from peak shaving and port operations. Large ocean-going merchant vessels with constant load can have higher efficiencies with diesel-mechanic propulsion than diesel-electric [8]. Huge battery installations on such vessels is not currently commercially viable even from the point of view of weight or volume [9]. Emission-driven shift towards electrical-drive propulsion and energy storages in large high demand applications will require vessel design advancements. [8] Smaller-scale merchant vessels have nevertheless found electric propulsion applications and even a fully electric one. Yara Birkeland, the first fully electric container ship travels around 24 km journey between three ports and has a battery pack capacity of around 7-9 MWh [27].

Table 1 presents some battery enabled fuel saving and payback time estimations for specific ship types. The main battery-uses and some particular beneficial factors are also presented. Final values and operations are always eventually case-dependent and the purpose of the table is to give some direction of the battery-utilization for the ship types.

Table 1. Battery potential comparison between ship types. [26][24]

<b>Ship type</b>	<b>Fuel saving potential [%]</b>	<b>Payback time [years]</b>	<b>Main battery function considered</b>	<b>Factors which can maximize benefit</b>
<b>Ferry</b>	Up to 100	< 5	All electric where feasible	High port time, low electricity cost, low distance
<b>Supply vessel</b>	5 – 20	2 – 5	Dynamic positioning, spinning reserve	Low power and energy needs for backup
<b>Fishing vessel</b>	3 – 30+	3 – 7	hybrid load, levelling and spinning reserve	Diesel sizing relative to loads
<b>Tug boat</b>	5 – 15 (100 with all electric)	2 – 8	All electric / many hybrid uses	Detailed analysis of duty cycle
<b>Cruise ship</b>	< 5	Highly variable	Peak shaving	Periodic all-electric use
<b>Deep sea vessel</b>	0 – 14	Highly variable	PTO supplement	Detailed analysis of duty cycle

## 2.2 Energy storage requirements

Energy storages require certain characteristics in order to be a worthwhile installation in marine applications. The key entities of the energy storages involve safety, performance, cost, maintenance and lifetime characteristics. Safety as a whole is the most crucial factor due to marine applications not having as effective escape possibility compared for example to electric vehicles [28]. Energy storage chemistries with different thermal runaways and safety hazards contribute to the required safety precautions generally including a cooling system and a fire extinguishing system [8]. Energy storages with higher safety risks require such compromises to be made safe that the impact on system-level energy density is high [5]. As a fire control precaution, limiting the risk of thermal runaway spreading, the cells are contained in waterproof metal cases and further in racks separated by an air gap. Safety is one of the factors that decreases the marine battery energy density from theoretical values. For instance, the specific energy of Ellen E-ferry of 86 Wh/kg is half compared to Tesla model 3 of 160 Wh/kg even though both use the same battery chemistry. In marine applications there is a real scope towards lower performance chemistries with better safety, and lower need for safety precautions, which can result in similar or even better system-level energy density [5].

Performance characteristics such as specific energy, energy density, specific power, power density, C-rate, depth of discharge, charge/discharge rate, efficiencies, capacity and voltage are all relevant parameters when choosing and building an energy storage in a ship environment. Power requirements for a marine energy storage are very important due to high loads. Peak shaving of fluctuating loads requires high power rates, and working as a spinning reserve requires low time response. Capacity related parameters such as specific energy and energy density often seem to be the key parameters to showcase and compare. They practically determine the driving ranges of electric vehicles due to limited usable space. In marine applications, specific energy doesn't have the same level of importance than in electric vehicles due to lower contribution of battery weight in relation to the vessel [28]. However, capacity-related parameters are generally a limiting factor when considering full-electric applications and future expansion of zero-emission shipping and thus will continue to be a topic of conversation [23]. Energy density is important in the sense that the energy storage fits the vessel and doesn't take too much space from the cargo. In full-electric applications there would be spare space for the energy storage after the removal of at least fuel tanks, fuel processing, air and exhaust trunking, engines and gear box [23]. Reliable technology is also very crucial. Table 2 gives some direction for the requirements of the battery according to the energy, c-rate and

cycles for given ship types. The ratings give some perspective on what kind of battery would be suitable on a certain application. All the requirements are however very dependent on the exact case.

Table 2. Energy storage capacity, C-rate and cycle-life requirements for specific marine applications. [26]

Ship type	Capacity	C-rate	Cycles
Ferry	Nominal	Very high	Very high
Fishing vessel	Nominal	Nominal	Nominal
Tug boat	High	Highly variable	Highly variable
Cruise	Very high	Low	Likely high
Deep sea vessel	Highly variable	Highly variable	Highly variable

Another limiting factor is the lifetime of the energy storage. The lifetime of the battery energy storage can be classified as cycles and calendar years. Cycle aging occurs in charged or discharged state while calendar aging occurs in rest condition and in every degradation process independent of cycling. The chemistry of the battery technology determines the potential lifetime, although use habits and conditions may further degrade it. [29] Batteries are generally considered to be exhausted enough for field of transportation when they have degraded to 80% capacity [12]. The lifetime of the battery energy storage varies a lot depending on chemistry and use, but no battery can currently reach as long calendar lifetime as a new vessel. The lifetime of different chemistries could be a defining factor when calculating the number of times the battery needs to be replaced in new build applications or retrofits. The replacement period ranges from 5 up to 20 years depending on battery chemistry and use profile [19].

The cost of energy storages is also an essential factor in the process. Typically the economic feasibility goes along most of the construction projects. High prices have previously refrained the use of energy storages and naturally continued the use of cheaper means such as diesel. However, dictation of the legislation and directives as well as technological advancements have increased the use of energy storages and further decreased prices [30]. Different energy storages have their specific costs per kWh, but that often is not the only parameter that dictates the initial cost. For example a higher degradation effect of a specific energy storage requires higher excess capacity and thus higher initial cost [31]. The extent of safety characteristics can have an impact on safety precautions and further to initial system-level cost. On top of initial cost comes maintenance, operation and end-of-life costs. Maintenance costs are much lower with batteries



compared to conventional engines. The overall cost is highly impacted on when and if the battery needs to be replaced.

In addition to the characteristics of the battery there are certain ship conditions that should be noticed. The safe temperature range for a battery is typically between 0-60 °C while the optimal temperature mostly is 20-25 °C [32]. The importance of the temperature in regards of battery safety and health is evaluated more precisely in the chapter 3.7.1. The temperature ranges demanded by the battery manufacturer can be quite strict and tight, which is good to take into account. Sea and air temperatures have an impact to the ambient temperature of the battery in the battery room of the ship, which will likely set up the need for thermal management system. Water has much higher specific heat than air, which makes the sea temperature to fluctuate much slower compared to air. The effect and variation of the sea and air temperatures can be quite high at least in colder regions. The temperatures vary according to the weather, location and season. The placement of a battery room in a ship can have a significant influence as well. Closeness to a room or space with highly different or fluctuating temperature is non-favorable. Furthermore, heavy elements such as batteries should generally be positioned lower rather than higher due to balance of the vessel.

### **2.3 Marine rules**

After RMS Titanic collided with an iceberg in 1912, there have been aspirations towards securing safer marine operations. The most notable international convention for the safety of life at sea (SOLAS) was first introduced in 1914. After many updated versions it is often referred as the most important of all international treaties concerning safety. Nowadays IMO managed SOLAS convention sets the minimum standards and requirements for the construction, equipment and operation of all merchant ships. Flag states are accountable to ensure that the ships under their flag obey the requirements by demanding certifications. [33] Certifications can be provided by classification societies. Classification societies have a mission to classify and certify ships in the project phase, under construction or operation. Classifications are issued by the technical standards of personal safety (SOLAS) and pollution (the Marine Pollution convention, MARPOL). [34] In addition to SOLAS and other rules, classification societies can issue their own requirements [32]. Shipowners generally utilize the services of a classification society for it to verify the standards and issue a certificate. Classification of the ship ensures the reliability to shipbuilders, repairers, brokers, flag administrations, insurers and financial community [35]. There are at least 50 marine classification societies in the world. [34]

The major ones include DNV, Lloyd's Register Group (LR), Bureau Veritas (BV) and American Bureau of Shipping (ABS).

The amount of official international regulations for large energy storages in vessels is negligible. For instance SOLAS more vaguely states that the electrical installations need to ensure and maintain the safety of passengers, crew and the ship from electrical hazards [32]. Based on that many classification societies have created more detailed class notations for the use of batteries for example by adding International Electrotechnical Commission (IEC) battery-related standards to the mix. DNV provides cell tests, battery system tests and battery system environment tests, and further provide battery rules, industry guidelines, type approval services and advisory services. DNV divides the battery class notations into battery safety and battery power. [36] BV on the other hand divides them into battery related class notations of battery system, electric hybrid and electric hybrid prepared. The latter relates to vessels that do not include a battery but a later battery conversion is taken into account in the construction. [37] Classifications generally include additional more detailed notations.

Requirements for the notations differ according to the classification society. Short compilation of the basic principles is presented in the following mainly focusing on the rules of DNV and BV. Generally, the battery requirements include specific operating ranges for voltage and temperature [32]. In addition, charge and discharge currents, state of charge and health control are addressed. Furthermore, a sufficient voltage balance between cells needs to be maintained through cell balancing. Controlling and monitoring can be achieved with battery management system (BMS) that is typically required for the certification. Properly designed BMS can prevent a thermal runaway originated from a short circuit, but not if it is originated from mechanical abuse or defect. [32] In addition, there are numerous different requirements in the segments such as accessibility for maintenance, protection, risk analysis, configuration, battery propulsion use, battery hybrid use, certified equipments and tests [38].

Installation-related requirements include battery room, location and safety measure aspects. The battery room needs to locate at aft of the collision bulkheads, and the room space boundaries must constitute of the ship's structure. Battery room should contain only the battery system. Heat sources or fire risk sources in the same space are not allowed. In case of neighboring room containing combustion engines, the walls must have high enough fire rating. [32]

### 3 Energy storage

The traditional role of an energy storage was to store energy and use it later when the demand is higher. Nowadays energy storages have several ways to produce value, whether the use is based on fluctuating electricity price and profit, improving performance characteristics or some other benefit. The utilization of energy storages in marine propulsion use has generally been based on storing shore power and using it at sea in order to save fuel, although there exist many additional beneficial factors as mentioned in chapter 2.

There are many energy storages with different storing mechanisms. Most energy storage types are not applicable for marine environment because of initial cost, available space, power or capacity requirements. This work will focus on battery energy storages that utilize electrochemical storing.

#### 3.1 Working principle of a battery

A battery consists of five main elements. There is a positive cathode electrode that consists of a substrate such as aluminum that is coated with active cathode material. Negative anode electrode consists of a thin film of a substrate such as copper and is further coated with active anode material. The electrolyte is contacted to both electrodes and works as a medium for ion transfer between the electrodes. [39] The electrolyte is usually liquid but there are also polymer, gel and ceramic (solid) electrolytes [40]. In contact with electrolyte there is normally a separator that mechanically blocks the short circuiting by separating the cathode and anode [39]. The separator allows the exchange of ions between the electrodes at the same time preventing the same for electrons [40]. The separator has an optimal size of porosity so that the ion-containing electrolyte reaches the maximum ionic conductivity [41]. The fifth element that completes the structure of a battery is the enclosure such as polymer type pouch, metal can or plastic housing [39].

Batteries can be divided into two classes, primary and secondary, according to the chargeability. Primary batteries are single-use batteries that have to be discarded once they run out of chemical energy and they end up at discharged state. Secondary batteries can be used multiple times through charge-discharge cycles. The amount of cycles preserved depends on materials, chemistry and operating profile. [39] The batteries covered in this work will all be secondary batteries.

The working principle of a rechargeable battery can be divided into two phases, charge and discharge. Since commercial batteries are generally assembled in discharge state, which means that there is no electrochemically stored energy in the battery, we will first look into the charge phase. When external electrical energy supply is connected to the electrodes, electrons will be forced to leave the cathode and proceed externally to the anode. At the same time, ions will move internally across the electrolyte from cathode to anode. Electrical current is used to charge the battery electrochemically. In the discharge phase the process will happen in reverse with the exception that the electrical supply is not needed, but rather the battery is connected to an external load. Electrons will flow spontaneously from anode to cathode externally while transforming stored electrochemical energy into electrical power. Simultaneously, ions will move internally from anode to cathode. [40] The storing and loading of electrochemical energy is possible because of the chemical reactions of oxidation and reduction. In oxidation reaction electrons are donated and in reduction reaction electrons are being accepted. [42] The theoretical cell voltage can be calculated by determining the Gibbs free energy change during the chemical energy release by the electrodes. The voltage will change depending on materials used in a battery. [40]

### **3.2 Battery chemistries**

The materials of cathode, anode and electrolyte determine the characteristics and performance of a battery and therefore enable suitable applications. There are four key material classes: lead-, nickel-, sodium- and lithium-based batteries.

#### **Lead-acid**

Lead based battery refers generally to the lead-acid (PbA) battery that consists of lead dioxide cathode, lead anode and an aqueous sulfuric acid electrolyte. In charge-phase the electrolyte of lead-acid breaks down to hydrogen and oxygen. Those gases leave to atmosphere because of vented design. Ordinary lead-acid needs an addition of water as a regular maintenance, which can be mitigated with a sealed design. With valve regulated design (VRLAB) and absorbed glass mat (AGM), the safety and the need for maintenance can be improved. [42] Lead-acid is the cheapest secondary battery in the market. Other advantages are reliability, recyclability, unlimited material resources and worldwide production. The main disadvantage is low specific energy due to high atomic weight, which makes the battery heavy. [43] Other disadvantage is short cycle life due to active material shedding from the electrode plates and corrosion. Some

marginal development of lead based batteries may happen but the chemistry will always have low theoretical limits. [42]

### **Nickel**

Nickel-based batteries use nickel oxyhydroxide cathode and potassium hydroxide electrolyte. The chemistries differ according to the anode material. Cadmium was used as an anode originally with improved cycle life and energy density over lead-acid. Due to cost and toxicity of cadmium the usage of nickel-cadmium battery is reduced and it has also faced a ban in Europe. Nickel metal hydride has trended to replace nickel cadmium batteries with advantages in decent specific energy and high rate capability. Disadvantages of poor low-temperature performance, cycle-life and high self-degradation however limit the usage. [42]

### **Sodium**

Sodium based batteries can mainly be divided into sodium beta and sodium-ion batteries. Sodium-ion batteries (SIB) are introduced in chapter 3.4.1. Sodium beta batteries generally consist of molten sodium anode and either liquid sulfur or solid metal-chloride cathode. Cathode and anode are being separated by beta-alumina solid electrolyte (BETA). BETA offers similar ionic conductivity as aqueous electrolytes but only at high temperatures. General challenges for beta batteries on top of high operating temperature are low power and fragility. [42]

### **Flow battery**

A bit different approach compared to presented battery types is a flow battery. In a flow battery the energy is stored as an electrolyte. The electrolyte is pumped through the two electrodes while the supplied current polarizes the electrodes. This results in redox reactions that occur in the active species of the electrolyte. The electrolytes locate in external positive and negative tanks which makes flow battery scalable in energy capacity. [44] Other benefits in longevity of the system and low cost also support its usage in electric utility applications. [42] Low specific energy of the flow battery, however, terminates the usage in limited space applications.

The battery chemistries presented briefly above lack some key features that makes them inconvenient for use in ships while better alternatives exist in lithium-ion batteries. Therefore, the work will focus more in detail on lithium-ion battery chemistries below.

### 3.3 Lithium-ion batteries

Lithium-ion batteries (LIB) are currently the dominant battery type in portable electronic devices, while having increasing demand on the electrification of vehicles [40]. The inherent lightness of lithium and the ability to produce high electrochemical potential make lithium-ions very suitable to be utilized in batteries [45]. LIBs can offer high specific energy, high power density, high efficiency and relatively long cycle-life without having to sacrifice too much in almost any performance issue in contrast to other commercial battery chemistries. [42] Lithium-ion batteries include quite many different chemistries. The common factor between them is the charge storing mechanism of lithium-ions that travel back and forth between the electrodes as a consequence of redox-reactions.

#### Anodes

Graphite anodes have gained the standard role in LIBs nowadays [46] Graphite has an intercalation structure where the lithium-ions can fill in between the graphite layers and thus the expansion of graphite during the charge is only about 7% [47]. Carbon-based anodes such as graphite and hard carbon are more stable, less costly and have higher specific capacity than most current alternatives. [42] The weakness of graphite is that it requires more space from a battery than any other component and thus is one capacity limiting factor [47]. Another issue with graphite anode is lithium plating, which can happen when the potential of graphite drops below 0V compared to lithium electrochemical potential ( $\text{Li}^+/\text{Li}$ ) in charging [48]. As a consequence lithium-ions plate out as metallic-lithium on the anode surface and cause capacity loss and safety concerns [42]. Lithium titanate oxide (LTO) is another commercially established anode material with highly increased safety over graphite. [46] LTO is covered more closely in chapter 3.3.3.

The most notable new anode types that are in development phase include silicon (Si), composite alloys, 3d-metal oxides and Sn-based materials. They have higher specific capacities than graphite but they naturally undergo high volume expansion during the addition of lithium, which deteriorates the electrical contact and cyclability. [40] Si has been seen as the most promising one to replace graphite because of abundant, non-toxic and eco-friendly nature with high gravimetric (3579 mAh/g) and volumetric (2194 mAh/cm) capacities as well as good potential of 0.4V vs.  $\text{Li}/\text{Li}^+$  [46]. The average specific capacity of a commercial graphite anode is 330 mAh/g [42]. Si does not obey the intercalation mechanism but instead a conversion mechanism where silicon and lithium atoms compose an alloy with strong bonds that store high

amounts of energy enabling high specific capacity. That results in thinner structure and thus a significant increase in charge speed because ions can reach the anode particles easier and faster. However, the chemical bonds are difficult to break which causes damage, and the expansion of Si during the charge is as high as 300%, which causes stress and decomposition of materials resulting in low cycle-life. Nanostructured silicon particles can prevent the decomposition of particles but it doesn't solve the damage done on the solid electrolyte interface (SEI) layer on the anode surface. Because of poor cyclability, there does not yet exist any commercialized high-volume anodes of Si alone. In 2020, it was stated that 1% of current anode materials mix low amounts of silicon (3-10%) with graphite to improve energy density a bit without significant suffering from the disadvantages of Si. Si anodes remain as the most promising anode material with a target on utilizing even higher and higher amounts of silicon. [47]

There has also been interest for intended use of lithium-metal as an anode since it could potentially increase the gravimetric and volumetric energies of graphite by 35% and 50%, respectively [49]. The chemistry has a theoretical capacity of 3860 mAh/g. The main challenges are interfacial resistance and formation of dendrites that can result in short circuit and safety problems. [50]

## **Cathodes**

Lithium-ion cathodes have currently more variety than the anodes. The three classes of lithium-ion cathode oxide structures are layered, spinel and polyanion. The first layered cathode was lithium cobalt oxide (LCO) that was commercialized in 1990s. In the beginning it was paired with hard carbon anode but later with graphite to give an increase in specific energy. High cost and toxicity of cobalt as well as limited capacity of LCO have driven the substitution of cobalt with Ni, Mn and Al. This has led to the generation of new layered chemistries with reduced cobalt content, of which nickel cobalt aluminium (NCA) and nickel manganese cobalt (NMC) are the two most valid and popular. [42]

Layered oxide structures have good electronic conductivity, energy density, cycle life and wide range of different chemistry compositions. The biggest downside on top of high cost is safety. The cost is heavily influenced by cobalt prices and amount of nickel. Safety concerns are relatively high due to oxygen formed under extreme conditions such as high voltage, high temperature, or energy content, where the reaction can happen with the dissolution or electrolyte. The process is typically highly exothermic and the electrolyte is flammable with

oxygen, which can lead to fires and explosions. However, NCA and NMC cathodes can provide somewhat safer usage than other layered cathodes. [42]

The second class of cathode oxides is spinel structure with stable three-dimensional form. High electrical and lithium-ion conductivity provides quicker charge-discharge and good reversibility when compared with layered LCO. The spectrum of spinel cathodes is considerably smaller than for layered cathode structures. The only spinel lithium oxides known are formed with titanium, vanadium and manganese. Spinel vanadium cathode undergoes some structural changes in use and thus does not have relevant usage as a cathode. The same conclusion is to be made for titanium that only has 1.5 V voltage. [51] Titanium ( $\text{Li}_2\text{TiO}_3$ ) however, is used as a spinel anode material that forms a competitive LTO battery [52]. Lithium manganese oxide ( $\text{LiMn}_2\text{O}_4$ ) comes as one of the most suitable spinel cathode material and it has advantages in cost and safety in contrast to layered cathodes [51][42]. The lower cost comes from manganese being cheaper compared to cobalt. Safety is improved in comparison to layered cathodes by the structure that releases lower amounts of oxygen and heat under abusive conditions. [42] The open spinel structure for Li-ion intercalation offers high power and efficiency [42]. The issues with  $\text{LiMn}_2\text{O}_4$  are the dissolution of manganese from the lattice into the electrolyte and its migration to the anode. The dissolution will degrade the cathode and the migration poisons the anode, which results in capacity and longevity issues. [51] Therefore, the spinel manganese cathode is not that relevant in the competition with other lithium-ion chemistries.

The third class of polyanion oxides involve phosphates, sulfates and silicates. It is a versatile group including more materials than layered or spinel oxides. The most attention for lithium-containing polyanion cathodes has mainly culminated towards the olivine structured lithium iron phosphate ( $\text{LiFePO}_4$ ). The electronic conductivity of polyanion oxides is poor so they need to be synthesized as small particles and coated with carbon, which increases production cost, causes performance inconsistencies and reduces the volumetric energy density. Polyanions, however, have many advantages in high thermal stability, impressive safety, cost and high charge-discharge rate. The oxygen of polyanion cathode is covalently bonded to P, S or Si which improves the stability and safety. Polyanion cathodes generally utilize abundant transition metals that are more sustainable than layered or spinel cathodes. Polyanion and layered cathodes can also be used as base for sodium-ion cathodes. [51]



## Electrolytes

The main purpose of the electrolyte is to move ions freely between electrodes. Additionally, it is required for not conducting electricity to avoid self-discharge, to have high transference number, to have thermal and electrochemical stability in typical operation ranges, to have chemical compatibility with other components as well as low toxicity and cost. [53] The reduction of the electrolyte at the carbonaceous anode forms the SEI layer during the first few cycles. SEI layer improves the long-term stability and prevents further reduction of the electrolyte. However, SEI layer causes some capacity loss and difficulties for ion transport properties. [42]

LIB electrolytes can be either liquid, polymer or gel [54]. Mostly used liquid electrolytes consist of lithium salt, organic solvent and some possible additives. The most used salts are  $\text{LiClO}_4$ ,  $\text{LiBF}_4$ ,  $\text{LiTf}$  and  $\text{LiPF}_6$ .  $\text{LiPF}_6$  was the first to overcome the industry requirements and has maintained the position as the most used salt.  $\text{LiPF}_6$  has very high conductivity and it can form relatively stable SEI layer. However, it suffers from instability outside of 2.5 V - 4.2 V, thermal instability when above  $70^\circ\text{C}$ , and traces and side reactions with toxic and caustic products. It also has challenging and expensive synthetization. LIBs use mostly liquid organic carbonate solvents such as a mix of ethylene carbonate and ethyl methyl carbonate. Mixes provide higher conductivity and temperature range, and some carbonates can not even be used alone. Organic solvents, however, are flammable and cause significant safety issues. Some issues can be mitigated by using additives. [53] Manufactures generally utilize their secret additives in order to enhance certain characteristics. The development towards non-flammable electrolytes has mainly involved research on valuable additives, non-organic ionic liquids and solid electrolytes. [54]

### 3.3.1 Lithium Nickel Manganese Cobalt Oxide

The name NMC comes from the materials included in the cathode: nickel, manganese and cobalt. Reported compositions of NMC are at least (NMC111), (NMC442), (NMC532), (NMC622) and (NMC811) where the numbers reflects the amounts of materials in percents [55]. The first three have been the main compositions for LIBs, and the last two are probably going to be used more in the automotive industry in the future due to higher specific energy and lower cost [56]. The use of nickel increases the initial discharge capacity while causing capacity loss with cycling. It could also impair battery performance by causing thermal-induced phase transitions. The addition of manganese increases thermal stability and safety but decreases the

discharge capacity. Cobalt decreases the capacity but improves the lithium-ion kinetics to achieve better rate for capacity. Higher cobalt content also increases the cost of the battery. [55][57] Generally, NMC batteries use graphite as the anode.

NMC battery is one of the most successful LIBs due to good overall performance characteristics in most of the categories [56]. It also is the most popular battery chemistry in marine applications [5]. NMC battery has an advantage in high specific energy of 250 Wh/kg [58]. High-energy NMCs have indicated as high as ~900 Wh/kg specific energy potential but the chemistry differs from the current NMC quite a lot and its cycling stability requires further development before possible deployment [56]. NMC also has good cycle-life of 1000-2000 cycles compared to other non-lithium-based batteries as well as to NCA but in the context of other LIBs it is average. [52]

The challenges mainly relate to safety and the use of cobalt. While safety has been improved to a reasonable level, NMC still has intrinsic problems with thermal stability. Low thermal runaway can lead to a fire if the cell undergoes rapid increase in the temperature. In addition, the use of cobalt is problematic due to expensive cost and limited availability. It has also raised ethical concerns on its chain of supply. [5] The decreased use of cobalt has nevertheless been an improvement from LCO to NMC, and also the future forecasts more nickel-heavy NMCs [45]. That would increase the specific energy and, thus, the capacity of the battery but it would worsen the stability by the decrease in thermal runaway [59].

### 3.3.2 Lithium Iron Phosphate Oxide

LFP battery generally consists of  $\text{LiFePO}_4$  cathode and graphite anode [52]. LFP battery is a lower voltage LIB but has many advantages over NMC/NCA batteries, which makes it one of the main contenders for layered batteries. Increasingly popular LFP does not contain problematic cobalt at all. It is a bit safer intrinsically and offers better thermal stability compared to NMC. These characteristics are due to oxygen being tightly bonded with strong covalent bonds to P, S or Si, and also because carbon coated polyanion particles at the cathode have structural integrity allowing it to sustain high charge [51]. The high power ability of LFP lowers the internal resistance during a normal operation which results in lower self heating and decreased risk for thermal runaway [47].

LFP has better cycle-life because of lower operation voltage that minimizes the electrolyte oxidation at the cathode. [47] The cycle life of LFP is around 2000 cycles [52]. The cost of LFP

cathode materials is lower because of the cheaper price of iron compared to cobalt and nickel. It is highly likely that the difference might continue to increase in the future due to shortages of nickel and cobalt. [47]

The main disadvantage of LFP is poor electronic conductivity and lower density of polyanions. As a result, the specific energy (180 Wh/kg) and the energy density are lower compared to NMC. However, there has been cell-to-pack level packing advances for polyanions. For example, BYD has announced a blade battery that has cells equally long as the pack which increases the cell-to-pack efficiency by 40% resulting in similar specific energy and even higher energy density than NMC. [58] Furthermore, slightly better safety when comparing to layered LIBs allows the LFP batteries to run with simpler cooling systems, which lowers the weight, cost of the pack and battery management complexity [47].

### 3.3.3 Lithium Titanate Oxide

The LTO battery, unlike other LIBs, gets its name from the anode material lithium titanate oxide. Replacing graphite with LTO results in improved thermal, aging and also some electrical properties of the cell. The spinel LTO structure has low specific energy and high lithiation/delithiation potential of 1.55V, which results in low overall cell-voltage and low energy density. [60] High working potential, however, does not form a SEI layer on the LTO anode. Furthermore, during lithiation/delithiation the structure of LTO doesn't strain. These qualities improve the thermal and mechanical properties. The thermodynamical stability of LTO also lowers the risk for lithium plating and exfoliation making the battery very safe. In addition LTO is highly stable at low and high temperatures, which also leads to very high cycle-life and high rate operations. [59] The cycle-life of 15,000 – 60,000 is considerably better than cycle-life of graphite anode (500-4000 cycles). Rate capability is high and LTO can offer similar charge and discharge current rates while the charge rate of graphite is significantly lower compared to its discharge rate. [60]

The biggest disadvantages are the low specific energy and high specific cost. Low energy properties result in higher space requirements and higher weight of the battery. In marine application that can be detrimental. LTO batteries however are often used in ferries that can highly benefit from high cycle-life and fast charging at short shore stays. High specific cost of LTO compared to NMC and LFP can be mitigated by taking into account the eventual cost. An LTO battery doesn't need to be highly oversized, and it also has the ability to stay in operation for a period that would require at least one battery replacement with NMC or LFP chemistries.

### 3.4 Emerging battery chemistries

Current lithium-ion batteries are approaching the characteristic limits they can achieve. In order to meet the current challenges with emissions and increasing demand of electricity, batteries are required to develop in performance characteristics but also in environmental sustainability. The transformation will require utilization of new materials and techniques. This chapter looks into the potential emerging battery chemistries.

#### 3.4.1 Sodium-ion batteries

The working principle of sodium-ion batteries (SIB) is rather similar than in lithium-ion batteries. The battery components, electrical energy storage mechanism and intercalation chemistry are alike. [61] Sodiated layer transition metal oxides, organic compounds and phosphates have been considered as cathode materials, while transition metal oxides (and sulfides), carbonaceous materials, intermetallic and organic compounds have been studied as anodes. There has also been recent development in anode-free sodium-ion batteries. [62]

One of the main driving factors for SIBs is the availability of sodium. Sodium resources on earth are much higher (2.83%) compared to lithium (0.01%) and are more evenly distributed. Sodium is also cheaper than lithium and have brighter estimates for price development in the future. [63] Lower cost of SIBs is also affected by using Al foil current collectors instead of Cu. Furthermore, the suitability of LIB production line to SIB is going to help in financing the deployment of SIBs in the future. SIBs also have better safety, at least at the cathode and even at high charge state. Sodium cells can achieve high rate performance due to quick diffusion of sodium-ions in the solid phase. The performance of SIB can possibly be further improved because of high amount of sodium transition metal compounds compared to lithium ones.

The challenges and weaknesses for SIBs include somewhat lower voltages compared to LIB. The ionic radius of sodium-ion (1.02 Å) is larger than that of lithium-ion (0.76 Å) which causes simultaneous change of structure during the ion insertion and extraction possibly resulting in capacity fade and worse cycle-life. [61] The larger sodium-ions are also heavier. The specific energies of the first commercialized SIBs are clearly lower than for current LIBs, around 100 – 160 kWh/kg [61][64].

Sodium-ion batteries could potentially provide a cheaper alternative for lithium-ions but they do not have the characteristics to dominate over LIBs. Extensive development of sodium-ion

batteries is needed to reach the level of LIBs in safety, cost and rate performance, which are notable features in marine applications. When considering the defaults, SIBs presumably will not offer major improvement in the transition to emerging batteries in the marine applications without some radical breakthroughs.

### 3.4.2 Lithium-sulfur

Lithium-sulfur (Li-S) battery consist of lithium-metal anode and sulfur cathode. Lithium-metal as an anode has been considered as one of the best anode materials in next-generation batteries. It has the highest theoretical specific capacity of 3860 mA/g and the lowest potential of -3.04 V. [65] Lithium-metal anodes however come with many safety and long-term operation concerns. Sulfur has low molecular weight and as a cathode it can achieve very high energy densities. But with low electrical conductivity, sulfur has the necessity for carbon supports which limits the theoretical specific energy. Sulfur is nevertheless cost-effective and sustainable due to its high availability. [42]

The theoretical specific energy for Li-S is 2500 Wh/kg. Many prototypes with specific energies around 300-600 Wh/kg have been developed in recent years, which already is clear upgrade compared to the specific energies of LIBs. However, there has not yet been any commercialized products. The main challenges in cathode side have been the dissolutions and shuttle effect of lithium polysulfides (LiPS) resulting in lower Coulombic efficiency and capacity fade. The repeating volume expansion of even 80% of sulfur in lithiation leads to weak cycle-life. Poor conductivities of sulfur and lithium sulfide limit the kinetics of electrons and ions resulting in lower specific capacity. On the anode side, the lithium dendrites consume the SEI layer and further lithium metal and electrolyte and potentially even penetrate the separator leading to internal short circuits and safety concerns. The side reactions between polysulfides and lithium can lower the cycle-life and Coulombic efficiency. Also the volume change of lithium metal can, after repetitive stripping and plating, lead to dead lithium layer making the SEI layer unstable, and further lower the Coulombic efficiency. [65]

While having much higher specific energies, LiS chemistries can not improve the volumetric energy density to be an advantage compared to NMCs. When considering that and other aspects such as safety and cycle-life, it is unlikely that LiS battery development could provide major advancements in marine applications. [5]

### 3.4.3 Metal-air batteries

Metal-air battery consist of a metal anode and an external air-breathing cathode. The metal anode needs to have good electrochemical equivalence. At least lithium, sodium, aluminum, magnesium, zinc, iron and tin have been studied as anode materials. From those, lithium-air has got the most attention because of the highest theoretical specific energy of 3458 Wh/kg, and 950 Wh/kg in practise. [66][5] The simplified working principle is such that on discharge metallic anode and oxygen are combined to produce metal oxides and on charge the reduction of metal oxides create metal back to the anode [42].

Metal-air technologies differ mostly by the type of electrolyte that can be either aqueous or non-aqueous depending on the metal anode composed. At least Zn, Al, Mg and Fe generally have aqueous electrolyte, but their surface needs to be passivated because of the instability in aqueous media. On the other hand, Li, K and Na for example are too reactive in aqueous media and consequently they are used with non-aqueous electrolytes. They can work in aqueous electrolytes as well if they are protected by ionic conductive film but the procedure is very complicated and expensive. Both types have their challenges but non-aqueous metal-air batteries have not yet found suitable electrolytes because the common ones decompose in the presence of oxidative products. Depending on materials used there are different challenges such as charge-discharge performance, cycle-life and stability. [67]

Yanguang Li and Jun Lu believe that Zn-air could be a short-term solution replacing LIBs but the longer-term solution could eventually come from non-aqueous metal-air batteries with higher specific energies. Some challenges for Zn-air include optimization of the cathode structure and air catalyst to enhance discharge performance and cycling stability. Solutions are also needed for the corrosion, deposition and dissolution of the anode metal to improve cycle-life. Poor energy efficiency of 60% originating from the high potential of air-cathode is also a developmental area. [67]

The future metal-air batteries with high specific energies could still lack on power performance because of the naturally slow reduction reaction of the oxygen. For the marine applications metal-air batteries could be suitable solution in the future mainly due to high specific energy and low cost. However, some time estimates for applying lithium-air batteries are 15-20 years. [5] The deployment of metal-air batteries at least in the higher power maritime applications can be even longer [12]. Alternatively, the metal-air battery might need to be supplemented with a higher power energy storage. [5]

### 3.4.4 Solid-state batteries

Solid-state battery means that the electrodes as well as the electrolyte are solid. There are many different materials studied for the use as solid electrolyte. At least solid polymers and ceramics such as sulfides, phosphates and oxides have been researched. [49]

Solid electrolyte has many advantages over liquid electrolyte. Solid structure enhances the stability and safety at least in three ways. 1. There is no risk for leakage in case of damage because of the solid structure, 2. solid electrolytes use nonflammable components, which causes that, 3. solid-state battery does not have the same volatility in case of high temperature fast charge and discharge. In addition, the ability of solid electrolyte to work as a separator, thin solid electrolyte structure, and the potential of removing safety components can result in more size-efficient structure and further enhance the capacity by increasing the amount of active material. Furthermore, a solid-state battery would be lighter when all liquid is replaced with solid electrolyte. [68][49]

Solid-state electrolyte could be a potential modification for next-generation LIBs. The performance would be improved with the deployment of lithium-metal anode over graphite anode. [68] The problems of dendrite formation and side reactions when using lithium-metal as an anode exist in most liquid electrolytes. Stable solid-state electrolytes could potentially be able to mitigate these negative factors. However, the knowledge on transport and kinetics of ions between lithium and solid electrolyte interfaces are still a work in progress. Clear interpretations of safety concerns and the need for safety procedures can not yet be expressed. [69] Besides to safety, solid electrolytes would in theory result in higher energy density, cycle-life and generally more diverse use of LIBs. Solid-state batteries could be produced in different shapes. Manufacturing batteries with solid-state electrolytes would also be cheaper without the difficult packaging of flammable liquid electrolytes. [68]

Solid-state batteries could enhance the specific energy up to 75% compared to the state of the art LIBs. In marine applications, the increase could be even higher due to the removal or reduction of fire risk and cooling requirements. System-level specific energy could even triple within 10 years. [5]

### 3.5 Supercapacitor

General capacitor consists of two conducting electrodes with an insulating dielectric material in between. When connected to a supply, opposite charges emerge at the surfaces of both electrodes. The dielectric material keeps the charges separated from where the electric field is produced which makes it possible to store energy. [70] Supercapacitor differs from the general capacitor by using an electrolyte that enables charge/discharge cycles. The electrodes of supercapacitors are usually conductive, porous and have large surface area to maximize the capacity. Materials used for electrodes include at least activated carbon, conducting polymers, metal oxides, carbon nanotubes and graphene. As electrolytes, both liquids and solids are used. [71]

Supercapacitors can be divided into three groups based on the energy storage mechanism. There are electric double layer capacitors (EDLC), pseudocapacitors and hybrid electrochemical capacitors. EDLC stores the charge via the electrostatic relations of ions at the electrolyte/electrode interface. Pseudocapacitors gain the storing ability via electrochemical oxidation-reduction reactions and molecule bonds. Hybrid electrochemical capacitor consist of both electrostatic and electrochemical electrodes. [72][73] Supercapacitors can be considered to have features somewhere between a battery and a capacitor.

The properties of a supercapacitor depend on the mechanism used. EDLC type supercapacitor that utilizes dielectric layer to store charge has clear advantages on power density, durability and cyclability. Pseudocapacitor has higher energy density but lower stability, discharge rate and charge efficiency. EDLC supercapacitors represent the majority of the commercial market. [72][73] Main advantages of supercapacitors are high specific power of up to 10,000 W/kg and cycle-life of up to 1 million. Disadvantages include high cost of 10,000 \$/kWh and low specific energy of 1-30 Wh/kg (EDLC 6 Wh/kg) [73][74].

Supercapacitors are used in applications where high power and short response time are needed, especially in uninterruptible power supplies (UPS), memory backups, energy harvesting systems and automotive industry. [73] Supercapacitors could also be utilized for particular working processes in maritime industry where power demands are high. Though, the capacity might be too low to manage efficient use of supercapacitors for supporting propulsion. At least one fully electrified ferry with a supercapacitor is working in a river in France [75]. It was the first fully electrified vessel without a battery. Key reasons for utilizing supercapacitor were



brief charge time of only 4 minutes, short route of operation of only 7 minutes and high recharge amount of 28 per day resulting in 7000 recharges in a year. [75]

The case study of this thesis (chapter 4) will take a look into the potential use of a supercapacitor in a hybrid electrical-drive vessel composed with a battery. Supercapacitor with high cycle-life could have the ability to support the battery, for example, to avoid deep cycles in very high power situations, to reduce the degradation of the battery, and to decrease the sizing factor of the battery.

### 3.6 Battery comparison

In this chapter, lithium-ion chemistries NMC, LFP and LTO are compared by the performance characteristics, safety and materials sustainability.

#### 3.6.1 Performance

Performance characteristics of different lithium-ion batteries based on the cathode material have been combined to the table 3. Similarly, the characteristic values are summarized for different anode materials in table 4.

Table 3. Performance characteristics of the battery chemistries according to the cathode materials. [59]

	<b>LCO</b>	<b>LMO</b>	<b>NCA</b>	<b>NMC</b>	<b>LFP</b>	<b>LiS</b>
<b>Cell voltage [V]</b>	3.7	3.8	3.7	3.7	~3.5	2.1
<b>Theoretical capacity [Ah/kg]</b>	274	296	-	-	168	1675
<b>Practical capacity [Ah/kg]</b>	~140	~120	~190	~160	-	~1300
<b>Specific energy [Wh/kg]</b>	90 - 180	160	140 – 250 <sup>[58]</sup>	180 – 250 <sup>[58]</sup>	80 – 180 <sup>[58]</sup>	~150
<b>Energy density [Wh/L]</b>	220 - 350	270	-	-	-	< 400
<b>Specific power [W/kg]</b>	760	1800	High	Fair	High	-
<b>Cycle-life</b>	~1000	>1000	Fair	1000 - 2000	>4000	-
<b>Cost</b>	High	Low	High	High	Fair	-

Table 4. Performance characteristics of the anode materials. [59]

	<b>Graphite</b>	<b>Hard carbon</b>	<b>LTO</b>	<b>Metal oxides</b>	<b>Tin composite</b>	<b>Silicon alloy</b>	<b>Li metal</b>
<b>Potential vs. Li/Lit+ [V]</b>	0.05 - 0.2	0.1 – 0.7	1.56	0.05 – 0.6	0.05 – 0.6	0.05 – 0.6	0
<b>Theoretical capacity [Ah/kg]</b>	372	-	175	-	~1000	4000	3860
<b>Specific capacity [Ah/kg]</b>	~350	~200	~170	~750	~600	-	-
<b>Specific power [W/kg]</b>	Medium	Good	Very good	Good	Good	Good	Bad
<b>Cycle-life</b>	Good	Medium	Very good	Bad	Bad	Bad	Bad
<b>State of the art</b>	Com mercial	Com mercial	Com mercial	Mid-term	Mid-term	Long-term	-
<b>Price</b>	Good	Medium	Medium	Medium	Very good	Very good	Good

### 3.6.2 Safety

Safety of the energy storage is very diverse topic including the knowledge for risks and triggers in varying situations and environments, which contributes to regulations and rules. Risks can be divided into thermal, chemical, electrical and kinetical actions whereas general triggers include manufacturing errors, flawed development, mismatched battery, misuse or abuse [59]. The focus on this subchapter is to cover material-dependent safety aspects. It is important to take into account that there are many material-independent factors too, that are outside of the scope of this thesis.

LIBs are relatively safe in the operational window intended for them. Triggers can cause the operation to go outside of that window. Main hazards happen when the temperature is outside of the safe range and cell components get to react directly with each other and free up chemical energy. As a result, uncontrollable energy is released, which converts into heat and increase the temperature of the cell. At some critical temperature, which is dependent on the materials, the chemical reactions of the cell components begin, followed by possible thermal runaway that could lead to fires and explosions. [59]

The critical temperature for exothermic reactions for NMC111 is 306°C. With higher nickel-content the thermal stability reduces, and the temperature decreases so that NMC811 has a critical temperature of 232°C. The heat release for the respective chemistries are 512.5 J/g and 904.8 J/g. LFP in comparison has slightly better critical temperature with 250-360°C and much lower heat release of 147 J/g. [76] Figure 1 illustrates the self heating rates for NMC and LFP.

Exothermic reactions are more unlikely to happen for LFP battery, but even if they happen, the severity is much lower [58]. LFP can sustain high charge better and allows oxygen release only at higher temperatures [51]. Energy density is another influencer on safety. Higher energy density contributes to higher temperatures when the energy is uncontrollably released resulting in increased safety risks [59]. Higher energy density also increases the possibility of an incident in a cell to spread out to nearby cells and to reach thermal runaway in much wider capacity [31]. This further increases the safety risks involved in NMC batteries that have higher energy density compared to LFP.

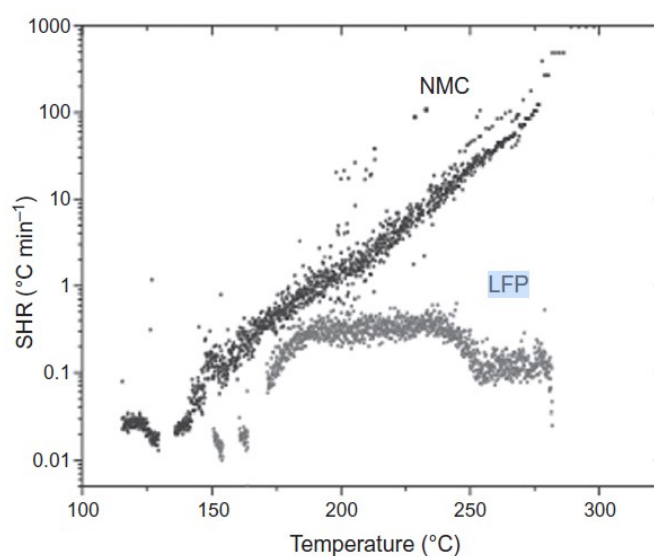


Figure 1. Self heating rates in a function of temperature for NMC and LFP battery. Reprinted from ref. 59, Elsevier Books, Klaus Brandt and Jurgen Garche, *Electrochemical Power Sources: Fundamentals, Systems, and Applications*, Chapter 7: Sources of risks and their effects, Page 188, Copyright (2019), with permissions from Elsevier.

Different tests and statistics show the better safety of LFP in practice. The battery penetration test with nail for ten-cell LFP showed very low temperature increase with the peak at 79°C, whereas for seven-cell NMC, the test caused fires in every cell with the peak at 549°C [77]. In other test, LFP and NMC cells were triggered for thermal runaway with a heater resulting in 2.9 times higher rate for heat release and 3 times higher toxic CO release for NMC [78]. The difference in safety incident occurrences between NMC and LFP was showed quite clearly in a report from China regarding EV safety: 86% of the incidents between May and July in 2019 happened for NMC batteries and 7% for LFP [79]. However, the distribution of the battery chemistries of electric vehicles in China for that period is not reported.

Better safety in this case contributes to two things. Firstly, the hazards are more unlikely to happen in the first place and if they will happen, the consequences are going to be less severe. Secondly, it decreases the need for safety precautions, which will in theory result in lower total cost, and free up some space. However, a question appears whether the safety difference is large enough to have a real impact in a ship environment where safety is the first priority and there must not be a room for error. In this case LFP has lower probability for hazards and severity but still the safety precautions are needed for the worst-case scenario, including fire and explosion.

While LFP batteries are approved for maritime use, there are not much literature on maritime safety precautions for the chemistry. Verma et al. approaches the subject by looking at the EV industry specifically in China where LFP batteries have risen to popularity. The slighter safety precautions of LFP batteries can lead closer to the system-level specific energies of NMC. It is also assumed that the high safety requirements of maritime industry will close the specific energy gap more between NMC and LFP meaning that the safety precautions can be mitigated even more in the ships than in cars because the safety precaution bar is so high initially for NMC. [5]

The comparison of LTO and graphite in terms of safety is highly favorable for LTO due to high operating voltage and crystal structure. During lithiation, the structure of LTO undergoes zero-strain behavior where the structure is transformed to rock salt which causes very low cell volume change of 0.2%. The comparison to graphite expansion of 7-10% is notable. Zero-strain behavior provides almost immutable dimension of the lattice, which contributes to high thermal and mechanical stability. Another major factor compared to graphite is the absence of SEI layer due to high operating voltage, which ensures thermodynamical stability in common electrolytes, and far lower risk for lithium plating. Another aspect in favor of LTO is the lower energy density compared to graphite which also contributes to lower safety risk.

### 3.6.3 Material sustainability

Battery materials have different characteristics of supply depending on, for example, extraction methods, deposit locations and political situations. Reserves, demand and recyclability of material sets up the boundaries for supply. This subchapter analyses the sustainability of NMC, LFP and LTO batteries by evaluating the risks of supply and risks of cost from the material point of view. Main cathode materials of LFP and NMC are presented first and afterwards a study of supply risks is introduced.

All of the chemistries mentioned above, NMC, LFP and LTO, contain lithium. Resources of lithium mainly locate in three countries in South America, Chile, Argentina and Bolivia. Other main producers are China and Australia. In South America, lithium is extracted from brines to form lithium carbonate and can further be processed into lithium hydroxide. Australia, that is the largest producer of commercial lithium, extracts lithium from hard rock deposits. China, on the other hand, can utilize both brine and hard rock deposits. Extracting lithium from hard rock allows processing directly into lithium hydroxide which lowers the cost compared to brine extraction. [80] While lithium hydroxide generally has been the more expensive one compared to lithium carbonate, during the year of 2021 this got reversed due to increased demand of LFP batteries that are usually produced with lithium carbonate [81]. According to U.S. Geological Survey 2022, lithium mine reserves worldwide are 22 Mt and resources about 89 Mt. Worldwide production was 82,500 t in 2020 and 100,000 t in 2021. [82] Lithium resources are expected to last long enough time to cover the electrification of vehicles if recycling operations and mining difficulties can be improved. For example in Bolivia, despite having the largest resources, succeeding in commercially viable lithium production has been complicated due to poor infrastructure, quality of ore and political climate. The price of lithium decreased during 2018-2020 because the increased production did not meet with the demand. [80] However, since then lithium price has increased over 400% [83]. Specifically, the demand for cheaper brine mined lithium has increased [84]. Increased price is a result from, at least, high EV demand, labour shortages due to global pandemic and supply chain, and possibly geopolitical tensions [83]. The price of lithium might stabilize in the future if lithium mining becomes more widely economically feasible [84].

Cobalt is mainly mined in the Democratic Republic of Congo (DRC) with China and Canada coming as the second and third [80]. DRC has almost half of the reserves in the world and is estimated to produce about 70% of the supply of cobalt. The significant role of DRC in the cobalt industry has impaired the reputation of cobalt after the raised concerns of the artisanal miners and child labors in unformalized operations. However, there are operations in place to try to enhance the mining conditions. [85] 70% of the production of cobalt comes as a co-product of copper mining and 20% as by-product of nickel mining [80]. By-product nature and political concerns are the highest risks in cobalt supply.

Nickel production is slowly moving from Russia and Canada to Australia, Indonesia, Philippines, Brazil and New Caledonia [86]. Most of the nickel resources (60%) are found in lateritic ores while most of the production comes from sulfide deposits. Nickel resources are

estimated to be almost 300 Mt and recycling rate is 57 %. Most of the nickel is used in the production of stainless steel. [87] While the usage of nickel in battery industry was only around 1 % in 2017, it is estimated to increase to over 20 % in 2025 due to increasing demand in EVs [80].

Iron is one of the most abundant elements in earth, which is contained in over 300 different minerals. Most of the iron is used in the production of steel. While the resources are high with identified iron content of 99 000 Mt and estimated total of 340 000 Mt, the usage of iron is high as well. In 2009 it was stated that 95 % of metals used in modern industry were iron. The most important resources locate in Australia, Russia, India, China, Brazil and Ukraine. According to Larona et al. the iron supply will increase nine-fold between years 2000 – 2070 with secondary supply from recycling surpassing the primary production by 2033 [88].

Helbig et al. conducted a research on battery materials regarding potential supply risks. The materials were studied based on the risks of supply reduction, demand increase, concentration in the world and political risk. Figure 2. presents the different indicators that were used as a basis for the study. [89]

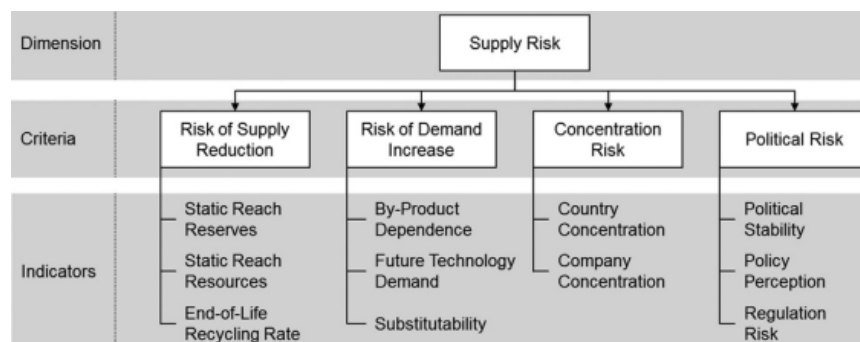


Figure 2. Supply risk criterias and indicators. Reprinted from ref. 89, Journal of Cleaner Production, Christoph Helbig et al. Supply risks associated with lithium-ion battery materials, Page 279, Copyright (2018), with permissions from Elsevier.

Researched materials included Li, Al, Ti, Mn, Fe, Co, Ni, Cu, C and P. According to the study, iron and nickel lack the most in reserves and resources. However, future increases in demand possibly change the view. Both by-product dependency and future technology demand are the highest for lithium and cobalt. Furthermore, recyclability is practically nonexistent for lithium, titanium, graphite and phosphorous which advances the running out of resources. It also needs to be noted that iron has the highest recycling rate of 67%. [89]

While it is stated that manganese and phosphorous have the most unique properties and they are the most difficult to substitute in applications, bigger surprise is that lithium is graded as the easiest to replace from the materials considered in this study. [89] There certainly are other active materials to replace lithium from the general point of view, but when only batteries are considered, replacing is very unlikely to happen in the market as long as that causes performance setbacks since lithium has the best overall characteristics for batteries with today's technology.

Concentration risk reflects the spreading out of the material production in country and company level. Regarding the concentration, graphite appeared to have the most difficult situation due to the production being mainly in China [89]. That also relates to graphite having high political risk along with cobalt [89]. The scores of supply risks for the given materials are calculated for each indicator and the results can be seen from the figure 3.

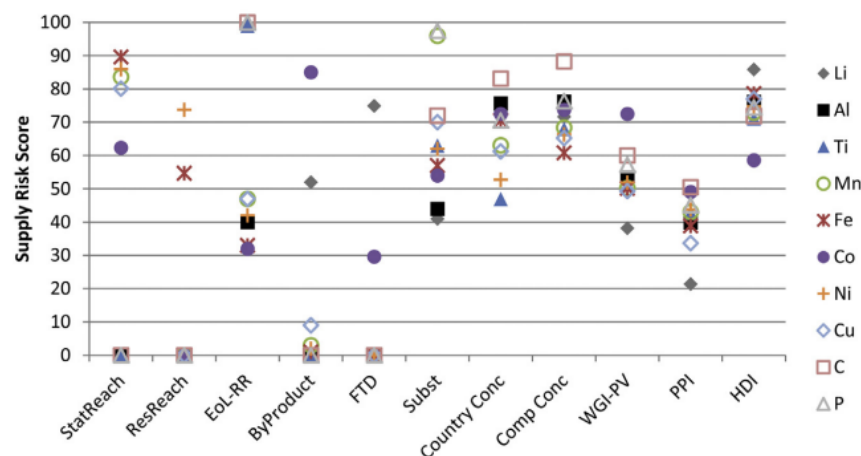


Figure 3. Supply risk values of different materials for specific indicators presented in figure 2. Reprinted from ref. 89, Journal of Cleaner Production, Christoph Helbig et al. Supply risks associated with lithium-ion battery materials, Page 280, Copyright (2018), with permissions from Elsevier.

Figure 4. shows the risk assessment for the materials. Lithium and cobalt received the highest overall supply risk score of 54, followed by manganese, phosphorous, graphite and nickel around 52, copper at 47, titanium and iron at 43 and aluminum at 39. [89]

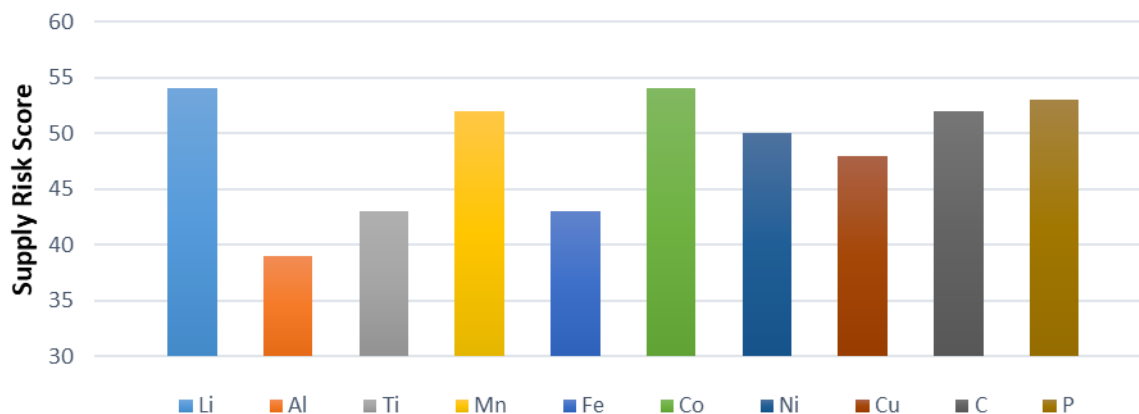


Figure 4. Risk scores for the specific materials. Reproduced from ref. 90, Journal of Cleaner Production, Christoph Helbig et al. Corrigendum to “Supply risks associated with lithium-ion battery materials”, Page 899, Copyright (2018), with permissions from Elsevier.

Materials are divided according to the battery types as follows:

NMC            Li, C, Al, Cu, Mn, Co, Ni, P

LFP            Li, C, Al, Cu, Fe, P

LTO            Li, Al, Ti (Fe, P with LFP cathode)

Figure 5 shows the risk scores for NMC, LFP and LTO batteries with equal indicator weighting. Results are presented with three different material weightings: arithmetic mean weights the risks of each material equally, whereas in mass and cost share risks are weighted according to the mass or cost of the materials. NMC-C chemistry possesses the highest risks of supply in every category. LFP battery has clearly lower supply risk compared to NMC. Graphite as an anode involves more supply risks than LTO by the arithmetic mean, which is a consequence of graphite having higher risks of supply compared to titanium. If considered from mass share the difference is even higher. However, with cost weighting, LTO becomes more riskier than graphite. [89]



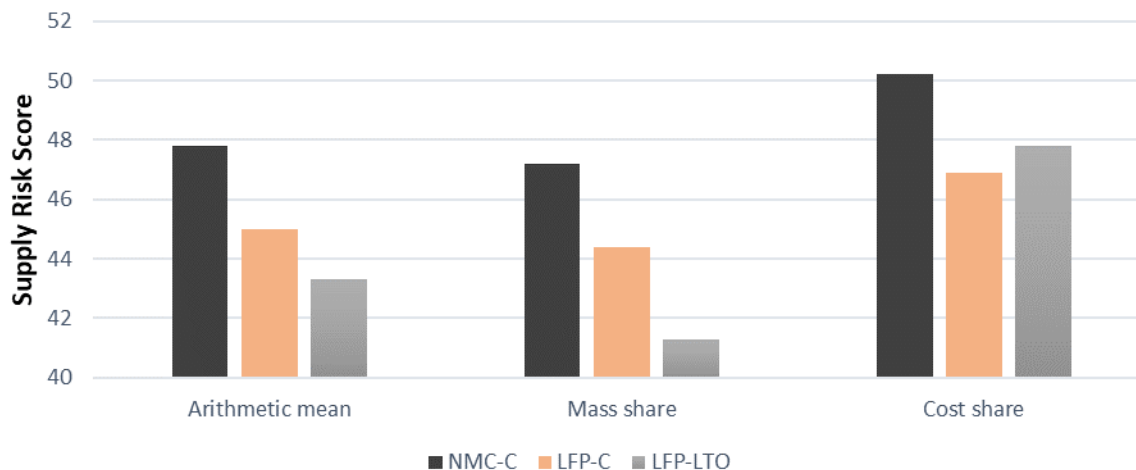


Figure 5. Risk scores for the specific battery types. Reproduced from ref. 90, Journal of Cleaner Production, Christoph Helbig et al. Corrigendum to “Supply risks associated with lithium-ion battery materials”, Page 902, Copyright (2018), with permissions from Elsevier.

If the impact of supply risks is considered in the context of cost forecast, it can be assumed that every indicator from figure 2 can have an influence. It is difficult to weight the priorities between different indicators when whichever of them can end up defining the direction of the cost in the volatile and sometimes hard to predict market. However, the results of the study show that the volatility towards rising prices is more likely for the materials of NMC when compared to LFP. By comparing the current prices of the materials, it can be stated that NMC is currently more expensive material-wise. For example the price of cobalt is over 350 times more expensive than iron [80]. The study also casts a shadow over lithium. Lithium side by side with cobalt were the most prone to non-favorable disadvantages and thus affected by cost volatility. Despite the disadvantages related to supply risks in general, lithium remains difficult to replace in the battery industry. More likely, LIBs are going to get alternatives for some applications from different active materials such as sodium. Risk-based lithium price increase should speed up the development for substituting materials.

### 3.7 Cell structure

#### 3.7.1 Cell types

Battery cells are divided generally into three categories according to the structure and shape. There are cylindrical, pouch and prismatic cells. Cylindrical structure provides high specific energy, good stack pressure performance and internal pressure tolerance, easy manufacturing, good cycle-life, low cost and high mechanical stability due to very durable package that is

difficult to damage [39][91]. The package is usually produced from steel, nickel-coated steel or aluminum [39]. Cylindrical structure can also provide some safety features that the alternatives cannot provide. Cylindrical structured cells are mainly produced in standard sizes where 18650 (18 mm diameter and 65 mm length) has commonly been the most successful. [39] Cylindrical cells have found applications at least in aerospace, aviation and military use, as well as in portable devices such as power tools, laptops, e-bikes and medical devices and instruments [39][91]. The usage in the EV industry has mainly culminated around Tesla who began to utilize 18650 cylindrical cells in their cars [39]. Later, Tesla has announced to be shifting also towards 21700 and 46800 structures that have higher energy density [76][92].

Pouch cell, also referred as polymer cell, utilize a soft polymer case that is very lightweight and flexible to produce in different size variations and unique solutions. Pouch cell offers high energy density that can achieve 90-95% packaging efficiency. Soft case design allows swelling for the whole pouch cell. Where-as some swelling due to gases is normal, extreme swelling is a concern and can cause the case or electric board to crack. Swelling needs to be taken into account in stacking by not putting the cells on top of each other but rather side by side or by having some space between cells [91]. The form factor of pouch cells makes it more difficult to predict and adjust some venting and safety measures [39]. Pouch cells are used at least in military, automotive and consumer applications such as drones that use high load currents [91].

Prismatic cells are rectangular and use plastic, steel or aluminum case. [39] Prismatic cells are offered at least in layered, wound and flattened structure designs, from which the layered structure utilizes space the best. Prismatic cells are also flexible to produce into different sizes but have generally higher production cost. Prismatic cells are also available in large format, which reduces the amount of packing material and delivers rather good capacities. Large cells have found applications in hybrid and electric powertrains while smaller cells in mobile phones and tablets. [91]

### 3.7.2 Module configuration

Generally, a battery pack consist of multiple modules and modules of multiple cells. However, there are innovations such as cell to pack that was mentioned earlier for LFP battery. Cells are connected in a series parallel combination to reach certain current and voltage characteristics for the battery. Series connections increase the voltage while parallel connections increase the current. [9]

Maritime battery modules generally consist of a certain number of cells that are first connected in parallel and those are further connected in series to achieve a given voltage [14]. Specifically, LIBs are naturally installed in that order because they are a voltage-base system that goes well with parallel connections. In addition, this connection order simplifies the pack protection voltage control. For comparison, NiCd packs more commonly utilize series connections that are then paralleled. The abbreviation used for describing the connection is, for example, 3s3p, where 3 parallel cells have been connected into a series of 3. [93] Series before parallel and parallel before series configurations are generally a tradeoff between complex wiring to balance and measure the cell voltages versus cell premature failures and fault tolerance. Large scale battery systems often utilize combinations of nested parallel and series connections determined by cost, fault tolerance, complexity and safety. [42] Complete modules are commonly connected in series to form a battery string to obtain system-level voltage. Eventually, the strings are connected in parallel to achieve the desired capacity. [14]

### 3.7.3 Cell sizing

Cell-level sizing is a diverse topic where finding the most potential option depends on the application and desired characteristics. Different cell sizes are commonly achieved by changing the sizes of the cell components, which affects many key characteristics of the cell.

Higher thickness of the positive electrode contributes to higher amount of active material and increases the energy density and capacity of the cell. However, higher energy density and capacity is a tradeoff to lower power density in this case. While optimizing the cell electrodes into desired parameters, it is important that the negative electrode is somewhat larger in order to avoid the generation of lithium dendrites. Suitable capacity ratio between the negative and the positive electrode is 1.1-1.2. [94]

Thicker electrode contributes also to various performance and safety concerns. Heat generation of the battery can be divided into reversible heat that is caused by entropy change in cell reactions, and irreversible heat caused by polarization heat or ohmic heat. Polarization heat is caused by the deviation of the working potential while ohmic heat originates from the transportation resistance of lithium-ion during the reaction processes. Thicker electrode increases both polarization and ohmic heat resulting in higher total heat generation rate, higher temperature of the cell and higher internal resistance. In addition, there is increased possibility for uneven electrochemical reactions. [94] It needs to be noted that even if safety can be improved with thinner electrode, which allows a smaller cell, the influence of packaging is vice

versa. Denser packing of the cell leaves less room for the volume changes of the electrodes causing mechanical stress and vulnerability for damages and short circuits. [59]

Changing the volume fraction of the active material has the same consequences than changing the thickness of the electrode. Enhancing the volume fraction of the active material increases the lithium-ion intercalation/deintercalation resulting in capacity and energy density increase. However, the consequent disadvantages include uneven temperature response, higher internal resistance, and decrease in power density. [94]

On the other hand, particle size is a parameter that can improve both energy density and power density together. Smaller particle size causes shorter lithium-ion intercalation/deintercalation distance and lower solid-phase diffusion polarization, which mainly results in lower heat generation rate, and higher energy and power density. [94] Another factor affecting the electrode parameters is the porosity. Porous electrode materials can provide shorter diffusion paths and provide higher power and current rate capabilities. There are many examples of porous electrodes having higher specific energies compared to bulk electrodes. However, volumetric capacity is naturally lower with porous electrode due to lower amount of active material. [95]

The importance of energy density in the EV market increases the development and availability of high energy density large lithium-ion cells resulting in lower cost and higher performance, which is expected to increase their usage also in marine applications. [5] On the contrary in ships, power density and safety generally comes as more important parameters than energy density, which would favour smaller cells. In terms of safety, higher number of smaller cells could be better than lower number of larger cells [5]. The relation of cell volume to the amount of combustion energy released in the event of LIB catching fire appears to be even higher than the effect of different specific energy of the cathode material [59]. Since the incidents of LIBs mostly start from one cell, it is better to decrease the severity of the consequences by a smaller cell size even though that leads to more cells and thus higher chance for an incident [5].

In all-electric marine applications, battery pack is generally larger in relation to the size of the vessel and the required power is more easily achieved. However, in hybrid applications, where the battery pack is respectively smaller, power requirements come more important. With a larger pack that has more cells the power requirements tend to come more naturally than with a smaller battery pack where power cells are recommended if high power is required. Hybrid use or other application with high power demand increase the importance of cell-level sizing

factors with thinner and porous cell electrodes. In general, when the size of the battery pack decreases, the more important the characteristics of the cell become.

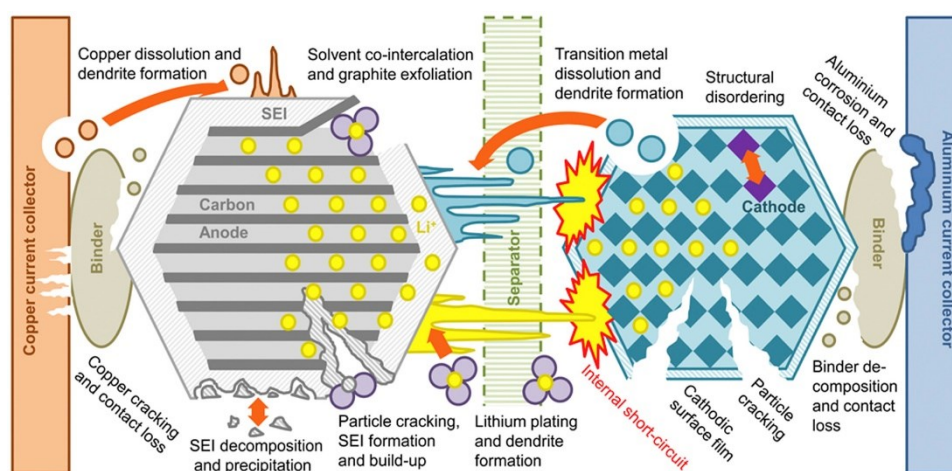
### **3.8 Battery aging**

Battery has the shortest lifetime out of the major components of the marine powertrain system, and it usually requires a replacement over the lifetime of the vessel. The degradation of the battery performance is caused by aging that results from the complicated interplay of chemical and physical mechanisms causing capacity decrease and cell resistance increase [48]. Aging does not play as important role on smaller consumer electronics as on electrification of transportation where large batteries compose a significant economic and environmental impact [48]. In order to optimize the utilization of the battery in terms of economic feasibility, degrading effects of the battery should be taken into account. Optimal sizing of a battery in regard to appropriate use can decrease overall costs. [96] The aging mechanisms typically include side reactions at the interface of an electrode and electrolyte, structural degradation of the active material and degradation of the non-active components. The effects from these mechanisms include loss of lithium inventory, loss of active material and higher impedance. [48] The main reasons behind them are presented below.

The formation of the SEI layer during the first cycles is the main origin for the cell degradation. Minimal growth of the SEI is typically anticipated when new active material surfaces emerge to contact with the electrolyte. Such occasions include cracks caused by anode volume change or dissolved cathode transition metal ions that reduce to the anode surface. Those transition metal ions further increase the electrical conductivity and thus the growth of the layer, the loss of cyclable lithium and resistance increase. Excessive growth of the layer can block the operation of the separator and limit diffusion. [48] The growth can also cause gaseous electrolyte decomposition products that inactivate some parts of the cell [97].

The deposition of the metallic lithium on the surface of the graphite instead of intercalating is another major reason for aging mechanisms. Non-optimal charging conditions and aging of cells further promote lithium plating. It causes capacity and power fade because metallic lithium does not strip during discharge, and because the metallic lithium forms its own SEI layer. Additionally, lithium plating brings about safety risks of lower onset temperature of self heating in thermal runaway, and a chance of penetrating the separator that follows a short circuit.

In addition to SEI layer and lithium plating, mechanical changes and stresses during cycling can fracture particles which leads to the deterioration of electrical contacts and eventually the loss of electrode active material. [48] Positive electrode forms cathode electrolyte interface (CEI) similar to anode forms SEI layer. CEI is however significantly thinner and does not fully passivate the surface [98]. The growth of SEI and CEI, as well as other side reactions on the surfaces of both electrodes consume electrolyte resulting in electrolyte aging and drying which further increase ohmic resistance [97]. Electrode composite can also degrade as a consequence of continued volume change. Contact losses between particles and current collectors also impair the performance by capacity loss and resistance increase. Corrosion of the current collector is also possible. The addition of silicon into graphite can likewise increase the degradation due to high volume change and side reactions. [48] Picture 3 illustrates the aging mechanisms.



Picture 3. Battery aging mechanisms showcased between different battery components. Reproduced under CC BY 4.0 license from ref. 99.

It is important to notice that most of the above mentioned causes are related to the graphite anode. In comparison, LTO anode does not suffer from volume expansion driven mechanical damages, formation of SEI or lithium deposition. Instead, some gas is formed from the reactions with the electrolyte. The degradation effects on LTO are thus much lower. [48]

Some of the earlier mentioned mechanisms deteriorate the performance of a battery inevitably. However, some of them are activated or further affected by use conditions such as cycling/storing temperature, depth of discharge, state of charge range, current density and voltage limits [48]. The following subchapters presents the effects from these conditions.

### 3.8.1 Temperature effect

High and low temperatures affect the battery in different ways. High temperatures increase the rate of electrochemical reactions and thus elevate the performance and capacity [100]. However, prolonged cycling at high temperatures have a side-effect of degrading the lifetime of the battery operation and storage performance. [48] Elevated temperatures similarly increase the rate of parasitic side reactions, material exfoliation and battery deformations, and thereby age the cell [101]. Significant impact can arise for the stability of SEI layer that starts to decompose at 60 – 80 °C. SEI layer components may undergo a transformation from organic to inorganic products as a consequence of high temperature. Inorganic products reduce the ionic conductivity of the SEI layer, which increases the impedance of the cell. Furthermore, the problematic dissolution of the transition metal ions to the anode surface is accelerated. [48]

Lower temperature, on the other hand, contributes to higher internal resistance and slower reaction rates and thus decreases the temporary capacity and power [102][100]. In cold weather it can be difficult for a battery to maintain the demand. In terms of degradation, the reaction rates between electrode and electrolyte decrease, which slows down the aging effects such as the growth of passivating layers, phase changes and transition metal dissolution [48]. Similarly, self-discharge gets slower, which further contributes to more efficient storing at cooler temperatures. Figure 6 presents the calendar aging for varying temperatures, recommending LIBs to be stored below room temperature [103]. For cyclic aging, the main problem with lower temperatures comes with charging. Lithium intercalation kinetics and diffusion rate reduce in lower temperatures, which can make the lithium deposition to the anode surface more favorable over intercalation. [104] Commonly, temperatures below 0 °C significantly increase the probability of lithium plating when charged. The phenomenon can also occur in higher temperatures if charging is prolonged. Furthermore, the cell design and the properties of the graphite electrode may increase the threshold temperature for lithium plating. [48]

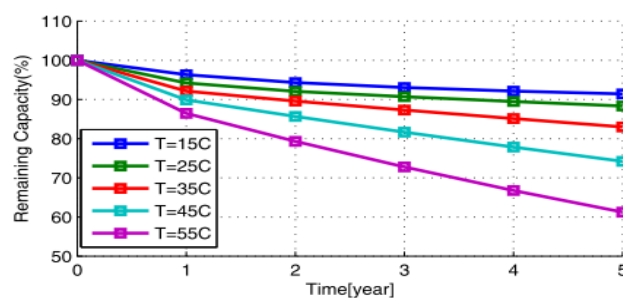


Figure 6. Calendar aging in terms of different temperatures at 50% state of charge. [103] © 2016 IEEE

Yao Wu et al. compared cycle-aging performances in three different temperatures: 10 °C, 25 °C and 40 °C. Results can be seen from figure 7. From these temperatures, 25 °C showed the least capacity fade and maintained the longest service life. Cycling at higher temperatures showed faster aging in terms of cycles and shorter service life compared to cooler temperatures. [105]

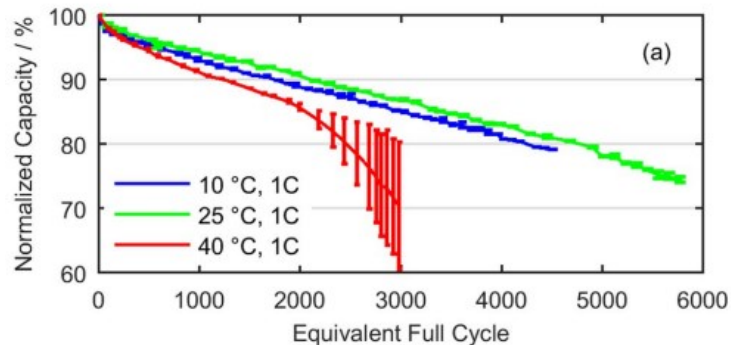


Figure 7. LIB cycle aging at temperatures of 10 °C, 25 °C and 40 °C. Reproduced under CC BY 4.0 license from ref. 105.

Another study found that the temperature has the strongest impact on the lifetime of the battery. At high temperatures (45 °C), the lifetime is basically affected by temperature only. At medium (20 °C) and low (0 °C) temperatures, the operation parameters of charge and current rate also have significant influence. [106]

### 3.8.2 DOD and SOC

High depth of discharge (DOD) generally provides more sufficient runtime of the battery. Meaning that the whole capacity of the battery can be utilized and there is no need to charge that often. High runtime with high DOD however degrades the battery and shortens the service life.

High DOD increases the pressure on negative electrodes causing damage and accelerating capacity loss [102]. Overdischarge can result in the corrosion of the metallic current collector [48]. To prolong battery service time, very deep and full discharges should be avoided during cycling. Low discharges, on the other hand, contribute to insufficient battery runtime [102].

High state of charge (SOC) and specifically overcharge contributes to lithium deposition [48]. It can also shorten battery life by accelerating the SEI growth. Some lithium batteries may go



through structural changes and stresses caused by high SOC in the same way as high DOD, resulting in capacity loss. [102]

Figure 8 illustrates the capacity fade during the storage of a battery with 60, 80 and 100% SOC at 25 °C for 10 years. It is clear that the capacity fade during storing increases with higher SOC. Maintaining SOC values in the mid-range is recommended for storing LIBs [102].

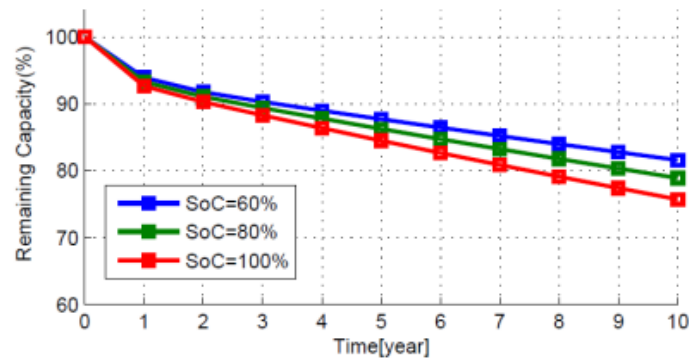


Figure 8. 10 year capacity fade at different SOC values at 25 °C. [103] © 2016 IEEE

The same study contained also a dynamic stress test for cells in mixed SOC ranges. Figure 9 presents the cyclic degradations for the SOC ranges. A notable result is that all three ranges that start from 100% degrade rapidly within the first couple of hundred cycles. From the alternative ranges, 75-65% managed to have the longest service life, however the runtime is only 10% of the capacity. 75-25% delivers the highest energy of 150 000 energy units, whereas, for instance, the range of 82-25% delivers 120 000 energy units. The highest runtime is achieved with 100-25%, which also degrades the fastest. Balancing between sufficient runtime and longer service life generally depends on the use profile of the application.

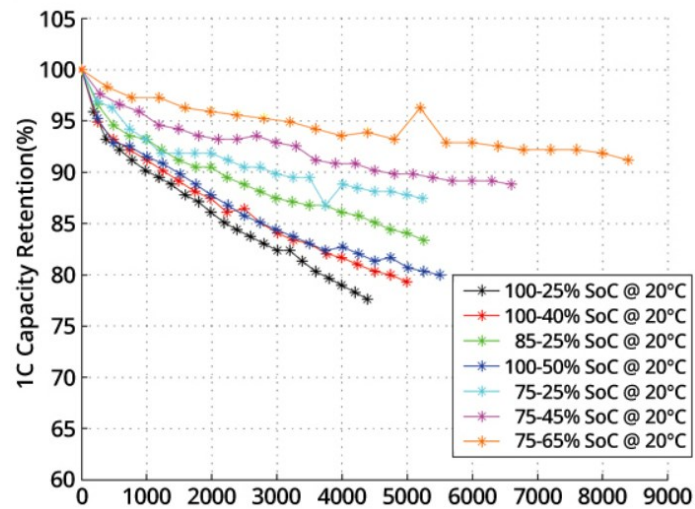


Figure 9. Cyclic aging with different bandwidths of charge and discharge cycles at 20 °C. [103] © 2016 IEEE

The degrading effect from the operation charge cycles can be easily noticed in portable consumer devices such as mobile phones that are designed to have maximum runtime with low cost. As a result, almost the whole capacity of the battery is allowed to be utilized, which often leads to relatively fast capacity fade. Marine batteries, however, are designed in industry standards to last longer. The key difference comes from oversizing the battery by the amount of expected capacity fade during the desired service life [31]. This allows the battery to be used in the mid charge ranges while maintaining practical runtime. The process leads to slower and unnoticeable aging, until the excess capacity is faded. Thereafter, the battery aging continues for the whole remaining energy capacity in a similar manner as in a new mobile phone battery.

### 3.8.3 Operating current rate

High current rate (C-rate) in battery operation increases internal resistance, irreversible capacity loss and available energy loss as well as causes safety issues. High C-rate speeds up the movement of lithium-ions that consequently accumulate on the anode surface causing lithium plating. [103] The mechanical stresses of the structure and electrode particles are also increased by higher C-rates [107]. In addition, high current rates also increase energy loss as part of the energy is transformed into heat as a consequence of increased internal resistance. The heat can increase the internal temperature of the battery accelerating its degradation. [103]

## 4 Case studies

The case studies examine the economic feasibility of installing different battery solutions into case ships that have long route of operation. There are two separate cases with different ships. The cases include simulations of the operation profiles, battery comparison and selection in terms of size and type, economic feasibility, and sensitivity of the result to changing conditions.

Battery type selection has been done between NMC/LFP and LTO. NMC and LFP chemistries haven't been reviewed separately since they have quite similar qualities, at least when compared to LTO. Also due to the difficulty of receiving accurate information from the ship battery packs, or information that would made justice for cell level characteristics between the chemistries.

### 4.1 Operation profile

The power distribution over the engines during a roundtrip route between two ports were given for the case ships. The data was used to form an operation profile that shows the original engine profile as the power demand.

Profiles were used to analyze the potential of battery usage. Since the route is quite long and power requirements are high, the capacity effect of the battery alone is not going to save fuel enough to be economically feasible. The additional advantage from using the battery for peak shaving was considered and the overall battery effect in terms of fuel savings was calculated. The presence of the battery makes it possible to reduce engine runtime since there is no need to have multiple engines running on low power simultaneously because the battery can provide power during sudden shifts. The decreased amount of running engines causes the remaining engines to run more optimally with higher power which results in lower specific fuel consumption (SFC). The overall battery effect includes both peak shaving that makes the difference in specific consumption, and battery capacity effect where shore power can be utilized at sea.

In order to calculate fuel savings, more optimal power profiles of the engines were simulated. Simulations were done for power data averaged over 3 minute segments. For every segment, an optimal number of engines and the percentage of engine load were determined based on the original power data. Although the simulations were done for 3 minute segments, the data was thereafter modified back into seconds and all the following calculations have been done with the most accurate data in seconds.

Simulated profiles were tried to keep as steady as possible, but in case of major changes in power, the simulations follow the original power profile. Engines were simulated to run around 60-90% engine loads to ensure lower fuel consumption. The engines originally ran between 10-90% of the maximum power.

Battery provided power could then be calculated from the difference of the simulated and original engine power profiles. Battery is charged when the power of the engines exceed the demand during the journey, and discharged when the load demand exceeds the engine power. The load variation intended for the battery was to evaluate required capacity, maximum power and cycle-life of the battery

Another important factor affecting the simulations was the state of charge behavior of the battery. The extent of the battery use depends on SOC of the battery, which influences the simulated engine use. When the battery SOC approach certain thresholds, the engine profile needs to be shifted in order to preserve the battery state. Battery levels were kept approximately between 80% and 30% SOC. Battery is charged to 80% during the stays at port.

## **4.2 Case 1**

### **4.2.1 Engine simulations**

Simulations were done for two different drive-profiles. In simulation 1, the engine line follows the demand more closely, which causes lower power and capacity requirements for the battery. The downside is that the profile of the engines might be more challenging to achieve in practice. Simulation 2 is more straightforward, simpler and achievable. It has also fewer amounts of engine starts compared to the simulation 1. However, simulation 2 is more tiring for the battery. In addition, for both simulations two battery types of NMC/LFP and LTO were considered.

Resulting engine loads from the simulations can be seen from figure 10. The figure illustrates improved engine load with simulated profiles compared to the original profile. Simulations have increased the portion of the engine loads that are over 80% by over 30%.

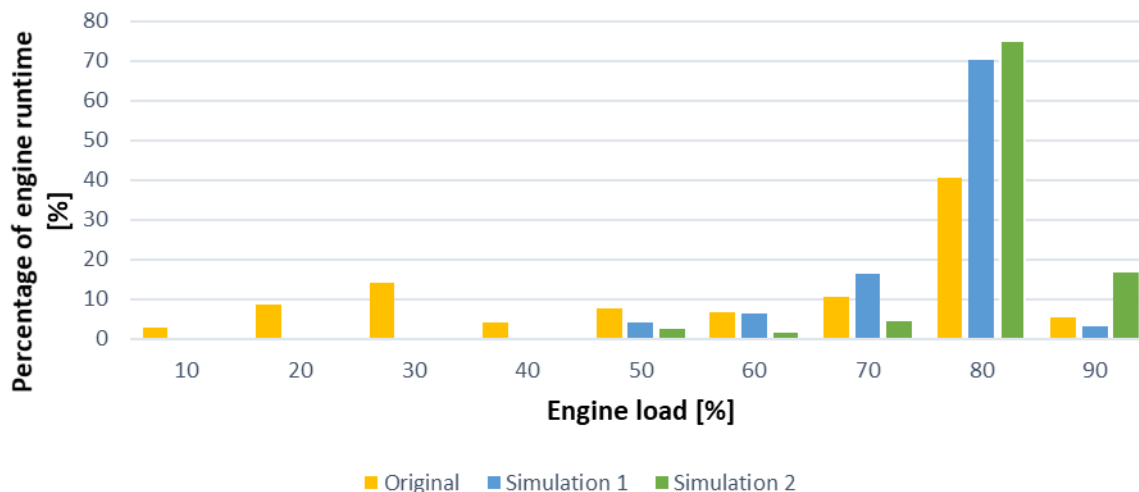


Figure 10. The difference in engine use between original data and simulations 1 & 2.

#### 4.2.2 Battery effect

Powers required from the battery can be calculated from the subtraction of simulated and original engine profiles. The main differences between the two simulations occur in specific segments that are ran with different amount of engines; simulation 1 runs with multiple engines whereas simulation 2 runs continuously with 1 engine, which causes higher demand for the battery. Simulations with different power profiles require different battery capacities in order to maintain similar cycle-life. Simulation 2 battery is sized with 67% higher capacity than the battery of simulation 1. As the main differences in the simulations comes from specific segments, the engine use is most of the time similar between the simulations.

Figure 11 shows the distribution of powers in terms of C-rate. Most of the powers in both simulations can be provided with 0,5 C-rate. In order to cover all peak powers, the power requirement is 2 C-rate for simulation 1 and 1,5 C-rate for simulation 2. However, those peak powers happen so rarely that they are considered insignificant. Therefore, the power requirements are set to 1,5 C-rate for simulation 1, and 1 C-rate for simulation 2.

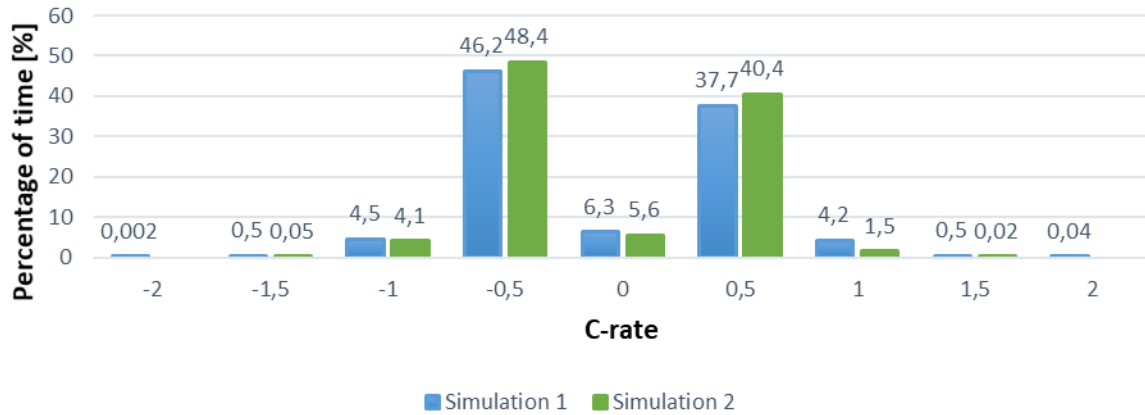


Figure 11. Distribution of battery use between different C-rates for the simulations.

Desired lifetime of the battery in operation in this case is 10 years for the NMC/LFP chemistry and 20 years for LTO. Batteries were sized in the simulations so that the amount of cycles would match desired cycle-life. Calculating the number of cycles to predict cycle-life is challenging because of numerous amounts of micro cycles. In addition, there are many more variables affecting the life as has been reviewed in 3.8. Calculation method was however uniform across the case studies. Figure 12 shows the fluctuating battery levels for the simulations.



Figure 12. Fluctuating battery levels for the simulations.

One of the motivations for the study was to consider whether it would be feasible to install two different type energy storages that have advantages in either capacity or power. They are called the main battery and the second battery in this chapter, respectively. In this case, when the main battery is sized to last 10 years (LTO 20 years), the capacity will be high enough to cover

powers with 1-1.5 C-rates. That can be accomplished with regular battery that has an advantage in providing good capacity, such as NMC or LFP battery. Although the C-rate needs to be from a higher end to cover every single peak.

The capacity is the limiting factor in every scenario because the power requirements stay low enough. The different battery options are presented in table 5. If the power demand would be higher, having a second battery sized by the power could be potentially more feasible. In the simulation 1 with NMC/LFP battery the sizing factor comes the closest to being “power”.

Table 5. Summary of the battery options for different scenarios.

	<b>Simulation1</b> <b>NMC/LFP</b>	<b>Simulation1</b> <b>LTO</b>	<b>Simulation2</b> <b>NMC/LFP</b>	<b>Simulation2</b> <b>LTO</b>
<b>C-rate</b>	1,5	1,5	1	1
<b>Sized by</b>	Capacity	Capacity	Capacity	Capacity
<b>Lifetime</b>	10 y	20 y	10 y	20 y

One potential way for the second battery to become feasible in this case would be if the main battery with lower C-rate was much cheaper compared to the 1-1,5 C-rate battery. If we consider having simulation 1 with NMC/LFP as the main battery with C-rate of 0,7 and a second battery to provide excess power, the power distribution would be as in figure 13. The figure shows the powers in required C-rates as a percentage of operation time separately for main and second battery. The red columns illustrate the second battery that would be used in the situations where the power goes beyond the power capability of the main battery. Only about 5% of the time the second battery would be needed to cover excess powers.

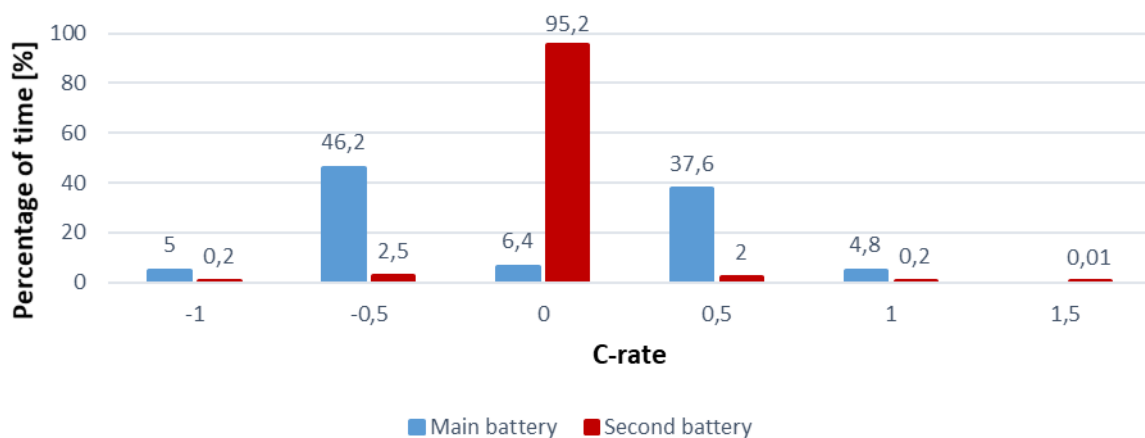


Figure 13. Power distribution between an energy battery and a power battery.

The second battery is considered to be either a supercapacitor or a high power LTO battery since they have good power and cycle-life capabilities. In this examination, the supercapacitor would be sized by the highest peak energy multiplied by 2 because the powers can be either charge or discharge. The capacity of the LTO power battery would be selected similarly but with some oversizing because of lower characteristic cycle-life compared to supercapacitor. The cost estimation for both scenarios is presented in table 6.

Table 6. Cost estimation for the supercapacitor and LTO power battery as the second battery.

	Size	Price	Cost
<b>Supercapacitor</b>	242 kWh	10 000 €/kWh <sup>[74]</sup>	2,4 M
<b>LTO battery</b>	500 kWh	1 000 €/kWh <sup>[52]</sup>	0,5 M

Using high power LTO battery as the second battery as a combo beside the main battery could be feasible if the main battery with 0,7 C-rate was 0,5 M€ cheaper than the main battery with C-rate of 1-1.5. Supercapacitor however seems to be much more expensive here because of two things; the peaks contain too much energy and they happen quite rarely to match well with the characteristics of supercapacitor.

The cycle-life with and without a second battery is illustrated in figure 14. The difference in battery levels is quite small which indicates that by utilizing the main battery as a combo would not result in any major improvements in cycle-life in this exact case. As a result, it is obvious that the powers are not high enough that utilizing a second battery would be justified in this case.

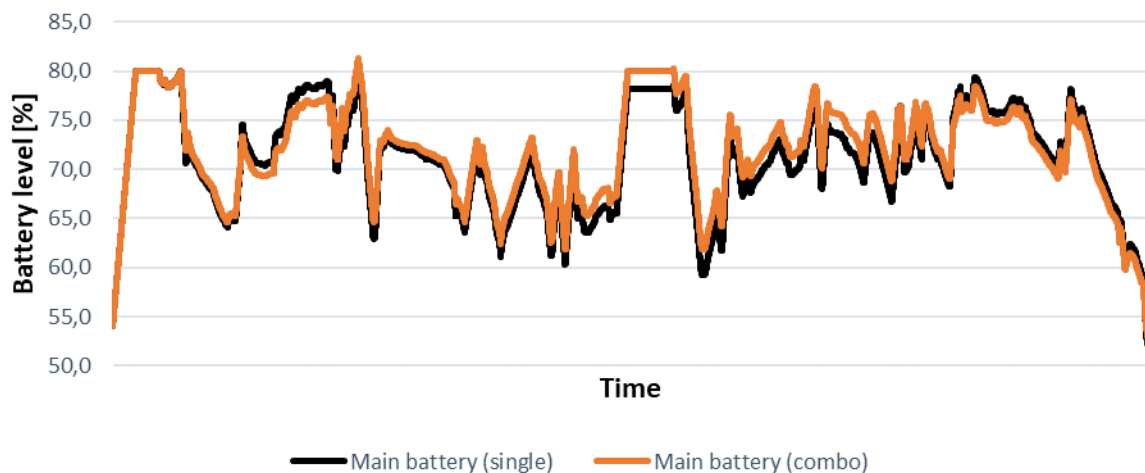


Figure 14. The difference in battery levels between an energy battery used as a single battery and alongside with a power battery.



### 4.2.3 Consumption

The real fuel consumption values for the original operation profile were given. In order to calculate fuel savings for the simulated profiles, the fuel consumption for the simulations needed to be calculated. Using the theoretical SFC numbers would have been possible but the margin of error might have been higher. In addition, the theoretical SFC was not given for the case 2 ship. Therefore, the executed method was to calculate a new SFC based on the given consumption and power values. Since the number of used engines varies between the original and simulated profiles, the SFC was determined separately for each number of engines used. It also seemed to give the most accurate result.

Saved fuel consumptions can be seen from the figure 15. Simulation 1 reached 4,4% fuel saving and in simulation 2 the saving was 5,7%. Since the batteries are being charged at the ports, the shore connection could be used also to provide the hotel load for the duration of the port stay. That would save engine runtime and increase the fuel savings to 6,2% and 7,6% for the simulations.

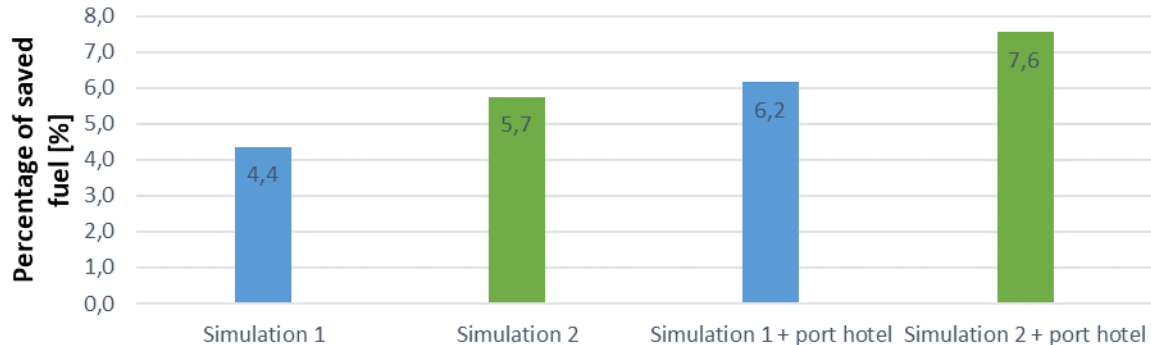


Figure 15. Fuel savings of simulations 1 & 2 with and without a shore connected hotel load.

### 4.2.4 Economic feasibility

#### Cost estimation

The distribution of the initial system cost was formed. An energy storage cost characterization report [108] was used as a base. The costs were divided into battery pack, power conversion, balance of plant, and construction and commission. Due to ship environment, the battery pack

cost was increased by 60%, and construction and commission by 20%. Cost distribution can be seen from table 7 for NMC/LFP chemistry. LTO scenario is considered in the parenthesis.

Table 7. Initial battery system cost distribution.

	Battery pack	Power conversion	Balance of plant	Construction and commission
Price [€/kWh]	400 (1000)			120
Price [€/kW]		200	77	

### Payback time

The payback times were calculated by dividing the initial costs by the yearly subtraction of saved fuel cost and electricity cost according to the following equation:

$$T_{payback} = \frac{C_{initial\ system}}{C_{yearly\ saved\ fuel} - C_{yearly\ electricity}}$$

Electricity is used at ports to charge the battery and provide the hotel load. The prices for fuel and electricity used in the calculations were 1250 €/t and 15 c/kWh, respectively. CO<sub>2</sub> savings might also create economical value in the future in marine sector but in these calculations that was not taken into account. In addition, battery value after the life at operation was not considered.

Because NMC/LFP chemistry batteries were sized for 10 years and LTO for 20 years, NMC/LFP is also calculated for 20 years period for comparison. In that case, the overall cost is increased by the cost of a battery renewal with 30% decreased cost and some installation costs. Resulting payback times are presented in figure 16, where 20 year payback times are shown as darker columns and 10 year paybacks as lighter. Based on the results, it would be more feasible to have NMC/LFP chemistry sized for 10 years than LTO for 20 years. The main reason is that when you have the initially more expensive LTO battery bought for 20 years you do not get the benefit from the potentially decreasing prices. Economically the most feasible option would be the smaller simulation 1 NMC/LFP battery. However, the resulting payback values will change according to the moving parameters of system costs, electricity price, fuel cost and battery cycles.

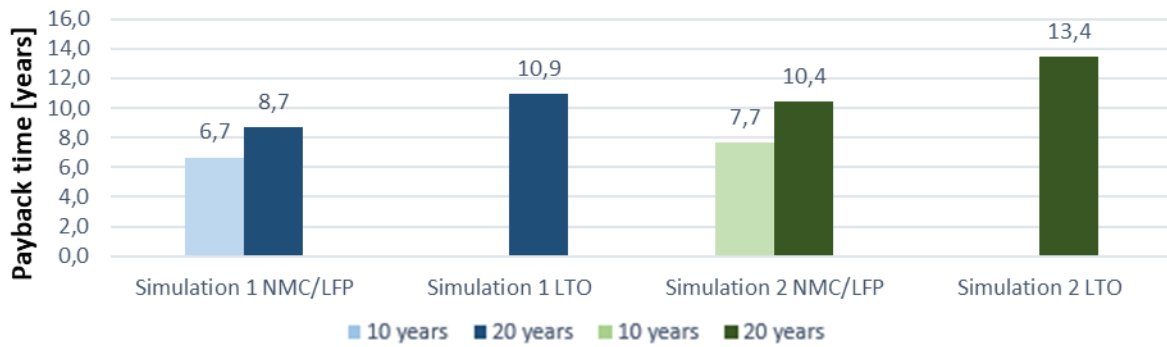


Figure 16. Payback times for different battery options in terms of size and chemistry in 10 and 20 year scenario.

### Sensitivity analysis

The economic feasibility of the smaller NMC/LFP battery was further analyzed with electricity cost, fuel price and total investment cost as moving parameters. Results are presented according to the payback time in figure 17. In figure, the fuel price is indicated with different colors and total investment cost with different lines. Investment cost varies between 800 and 1200 €/kWh. The figure 17 has a highlighted line for 10 year payback since the battery is estimated to last 10 years. Every scenario below that line is considered to be economically feasible. As a rule of thumb it can be summarized that if the fuel price is 1000 €/t, the electricity price needs to be below 15 c/kWh. Increase in fuel price improves the feasibility whereas the increase in electricity price and investment cost impair it.

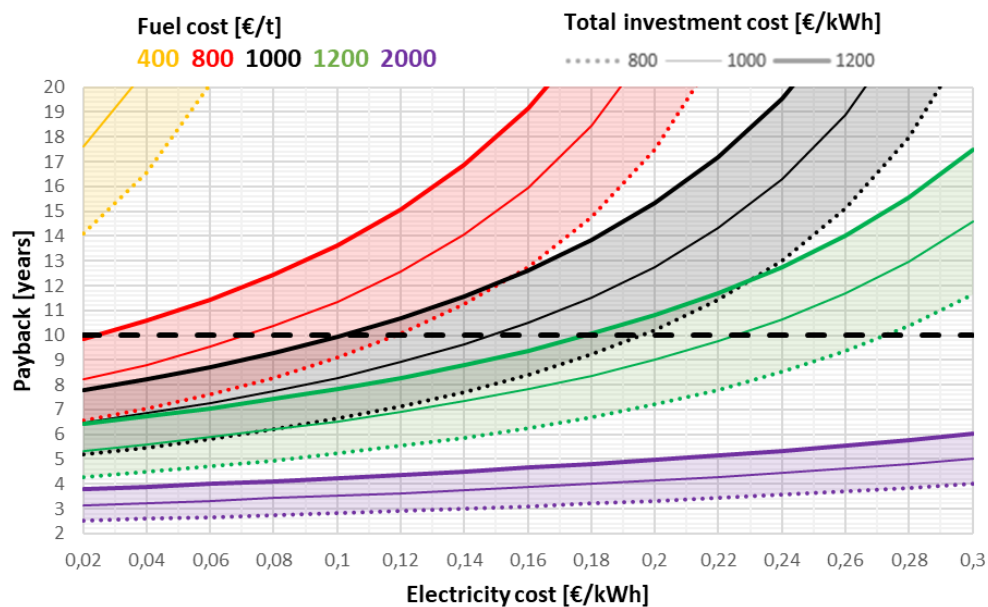


Figure 17. Payback times as a function of electricity cost for varying fuel and investment costs.

## 4.3 Case 2

### 4.3.1 Engine simulations

In case 2, the simulations were done similarly to the case 1 but using case 2 ship original data as the starting point. Two simulations illustrate different driving profiles for the engines to improve specific consumption. Simulation 1 follows the original operation profile a bit more precisely than the simulation 2. The resulting engine loads for the simulations are presented in figure 18.

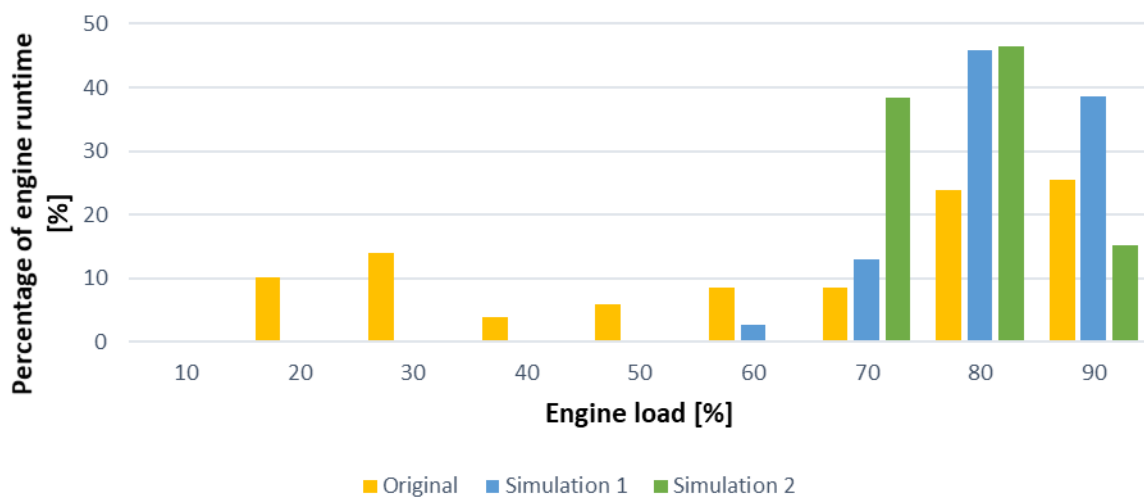


Figure 18. The difference in engine use between original and simulations 1 & 2.

### 4.3.2 Battery effect

Peak powers are slightly lower with for simulations in case 2 than in case 1. The power baseline of the simulations in case 2 is much steadier than in case 1 because of the difference in original engine powers. Case 2 simulations are sized with exactly the same battery capacities as case 1: simulation 2 battery has 67% higher capacity compared to simulation 1.

Power distribution in terms of C-rate for the simulations can be seen from figure 19. The power requirements are quite similar compared to case 1. Based on the figure, C-rate values would be set to 1,5 C-rate for simulation 1, and 1 C-rate for simulation 2.

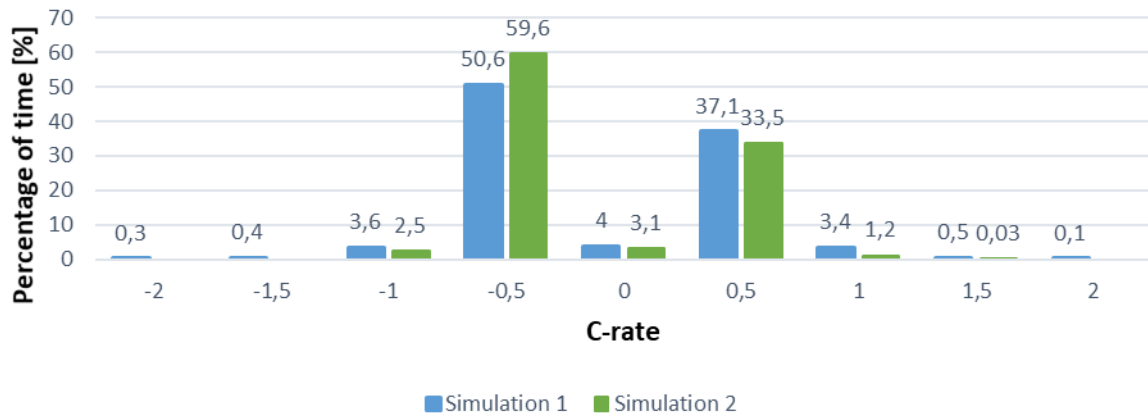


Figure 19. Distribution of battery use between different C-rates.

Since the power requirements are similar than in case 1, it is clear that the sizing factor for the cases is done by the capacity. Therefore gaining economic feasibility by utilizing a second battery is unlikely. The results for the examination regarding a second battery would be similar than in case 1, and thus are not presented.

The battery effect is simulated so that the desired lifetime in operation is 10 years for the NMC/LFP and 20 years for the LTO battery likewise in case 1. Resulting battery levels for the simulations can be seen from figure 20.

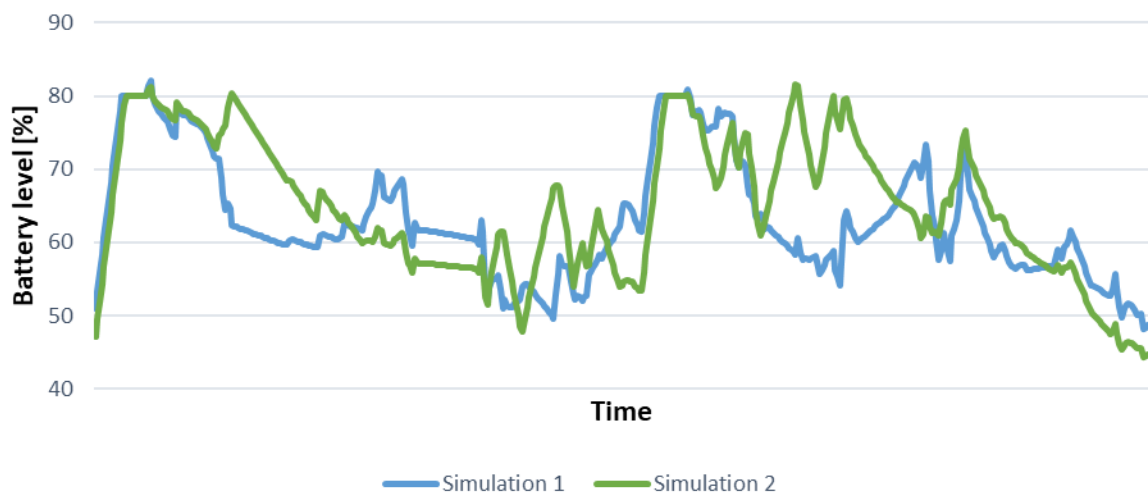


Figure 20. Fluctuating battery levels for the simulations.

### 4.3.3 Consumption

The specific consumption was calculated for different number of engines for case 2 ship in order to calculate the fuel consumption of the simulations. Specific consumption differences between the different number of engines turned out to be smaller compared to case 1, which means that the effect of peak shaving and resulting fuel savings are lower. The fuel savings for case 2 are presented in figure 21. Simulation 1 and 2 resulted in 3,3 % and 4,1 % fuel savings, respectively. Shore connected hotel load increased the savings to 5,4 % and 6,2 %.

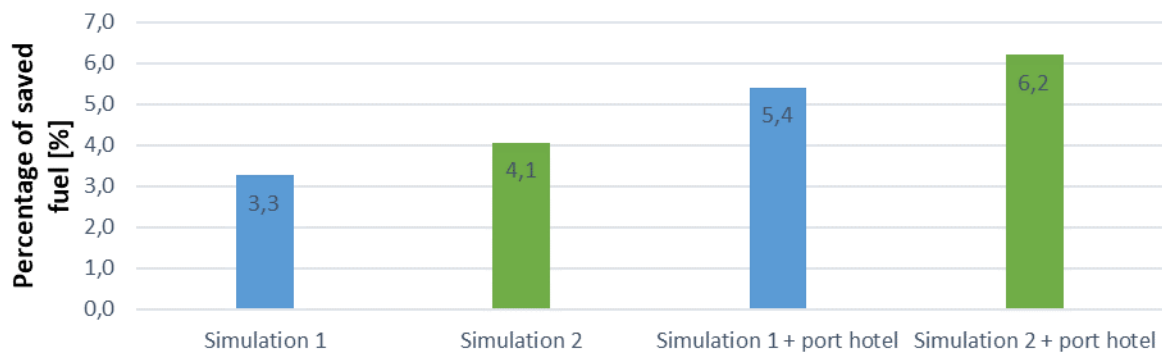


Figure 21. Fuel savings of simulations 1 & 2 with and without a shore connected hotel load.

### 4.3.4 Economic feasibility

#### Cost estimation

The cost distribution of the case 2 is similar with table 7. Since power and capacity requirements were the same for the cases, the cost estimations are equal between cases.

#### Payback time

Payback times of the battery scenarios are presented in figure 22. The prices for fuel and electricity used in the calculations were 1250 €/t and 15 c/kWh, respectively. From the 10 year lifetime options the simulation 1 NMC/LFP battery just reached 10 year payback time. Simulation 2 battery has over 10 year payback time. When compared for 20 year payback times, the NMC/LFP simulation 1 battery stays as the best option, when the second battery pack is estimated to decrease 30% in price. In case 2, the second best option would be the LTO battery of simulation 1 unlike in case 1 where the second best option was the NMC/LFP battery of simulation 2.

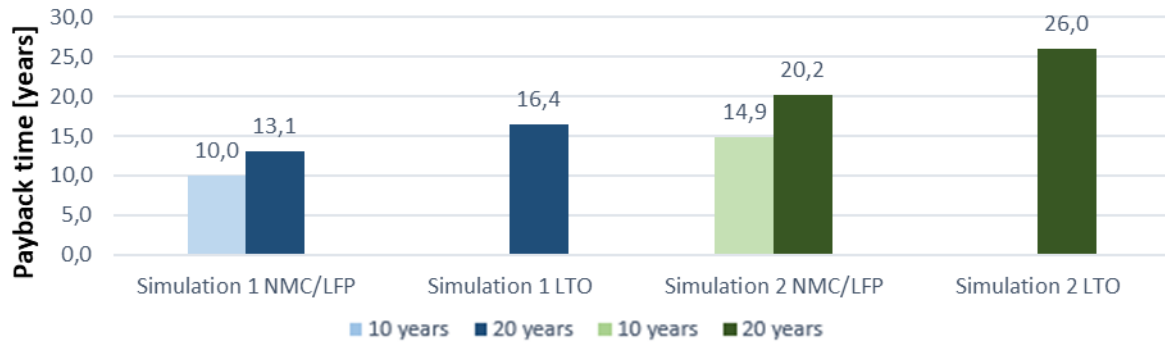


Figure 22. Payback times for different battery options in terms of size and chemistry in 10 and 20 year scenario.

### Sensitivity analysis

The sensitivity of payback time was analyzed similarly than for case 1. Moving parameters were electricity-, fuel- and total investment costs. The results are plotted in figure 23. Economic feasibility is more easily achievable in case 1 than in case 2, because of the higher fuel savings. That makes the profitability of the case 2 ship slightly more vulnerable to changes in fuel and electricity prices. Case 2 would be economically feasible with over 1000 €/t fuel price if the electricity cost is lower than 7 c/kWh. Same conclusion was made for the case 1 but with below 15 c/kWh electricity price. Since economic feasibility in case 2 ship is more challenging, one potential outcome could be to only utilize the shore connection in ports, and deploy the battery once the EU taxation directives begin to increase the value of saved fuel and emission in order to make the battery solution more economically feasible.

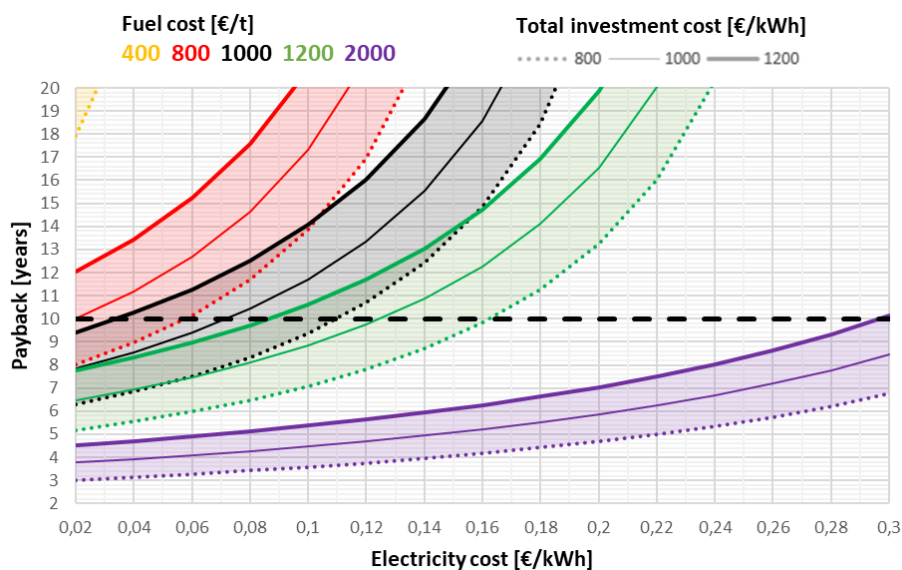


Figure 23. Payback times as a function of electricity cost for varying fuel and investment costs.

## 5 Conclusions

Battery energy storages were found to be valuable in many marine applications. Especially ferries and smaller vessels create the most obvious economic and consumptive benefit. Installing battery solutions on long-distance ships is, however, more challenging, and deploying them with batteries can not straightaway be considered profitable. Every ship is different and battery solutions have to be considered separately for each case.

A battery solution needs to be suitable for desired type and operation of the ship. In addition, the installation needs to follow certain marine rules. The battery requirements of the ship environment relate mainly to safety and performance. The most notable topics include the probability of safety concern and the severity of safety risk as well as power capability, capacity, lifetime and cost of the battery. The most suitable battery chemistries for ships are currently NMC, LFP and LTO lithium-ion batteries.

The case study of the thesis relates to battery solutions of ships with long route of operation. Batteries were used mainly for peak shaving where the engine use was simulated for optimal specific fuel consumption. For both case ships the most optimal battery solution was the smaller NMC/LFP battery. The comparison was done for two different capacities, and for NMC/LFP and LTO lithium-ion battery chemistries. Case 1 ship achieved higher fuel saving of 6,2% compared to case 2 ship with 5,4%. The fuel saving effect came from three sources: peak shaving, battery provided energy and shore connected hotel load during port stays. The main reason behind unequal fuel savings between the cases was different specific fuel consumption profile of the ship engines, which resulted in case 1 ship to gain more advantage from peak shaving effect. In addition, the power of hotel load was different. Based on these reasons, the battery solution of case 1 ship ended up being more economically feasible. The study also showed that utilizing a second battery with high power capabilities would not be needed in these cases because the powers could be covered with regular main battery with C-rate of 2. Second battery was still considered with 0,7 C-rated main battery but it was not found to bring any significant benefits.

With recent fuel and electricity price fluctuations, the sensitivity of economic feasibility was analyzed. Case 1 ended up holding up better unfavorable price changes. Case 2 would just barely be feasible if prices are somewhat favorable. The case studies did not take into account taxation of fuels or emissions, which will likely happen in the future. These changes will



improve the economic feasibility of the battery installations. Until now, the battery installations are mostly culminated into the philosophy of economic profitability but in the future with upcoming EU directives, the justification is potentially going more towards actual fuel and emission savings.

Potential future research regarding the case could concentrate on taking into account the eventual fuel and emission taxation and calculate the impact it would have for the economic feasibility. Another factor to include in the analysis is the value the battery possesses after the life at operation in the field of transportation. After that, the battery would still be suitable for many applications with lower safety and performance characteristics. The sale value of the battery would further increase the economic feasibility of the original case. Another future research could include the life cycle assessment for the battery solutions; what is the total carbon footprint for the lifespan of the battery? How much is consumed for mining, fabrication and eventual end of life disposal of the battery compared to the saved emission benefit during the life at operation?

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