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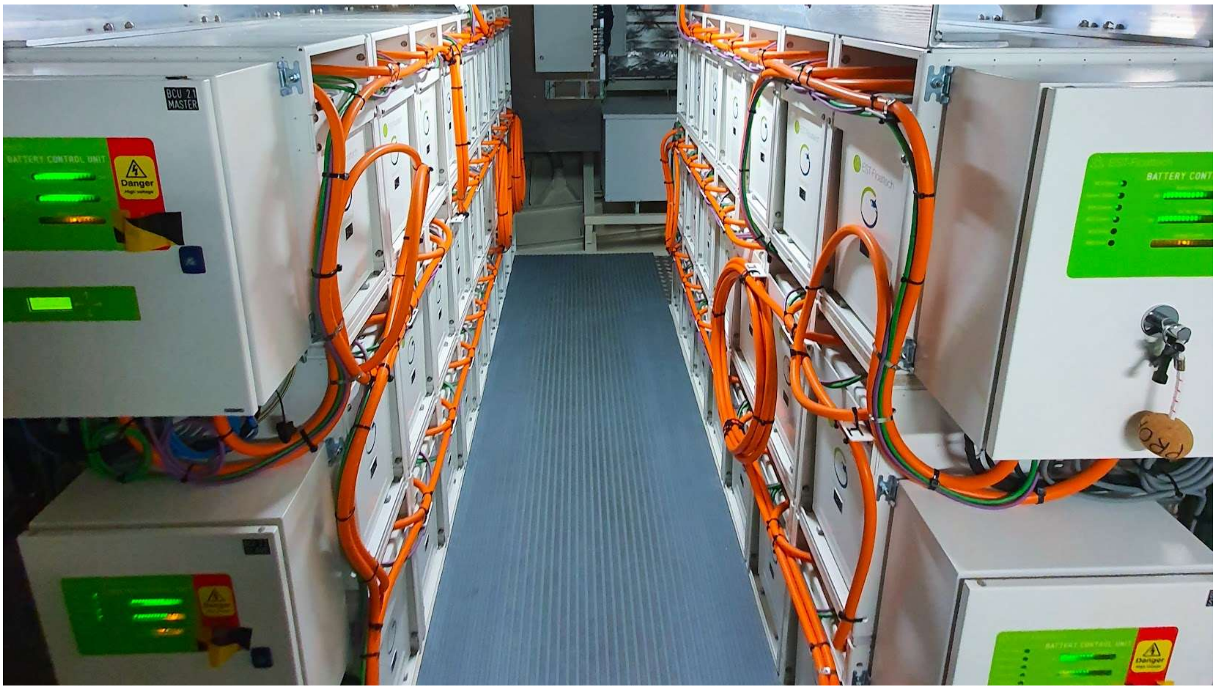


# How is Electrification Affecting the Onboard Fire Safety?

## An investigation on ships using lithium-ion batteries for ship propulsion

Bachelor thesis for Marine Engineering Program

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Cover:
A battery module onboard a hybrid-ferry. Taken by authors with permission.

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# PREFACE

This bachelor thesis was written in the spring of 2022 as the final part of a four-year long education at the marine engineering program, at Chalmers University of Technology. The authors of the report were André Niklasson and Dennis Allerth. Both of us would like to thank our supervisor, Johan Eliasson, for his wholehearted commitment and support. Moreover, librarian Liza Nordfeldt and examinator Martin Larsson are sincerely thanked for their feedback and helpfulness throughout this work. Lastly, a special thank you to all the participants who agreed to be interviewed, and for providing the essential information on which this report could be written. Thank you all!

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# SAMMANDRAG (in Swedish)

Sjöfarten är under förändring, då redare rör sig bort från fossila bränslen mot mer miljövänliga energibärare. En utav dessa energibärare är litium-jon-batteriet, som erbjuder utmärkt växthusgas-reducering och energieffektivitet. Dock kommer litium-jon-batteriet med en orosfaktor, nämligen dess brandsäkerhet. När litium-jon-batteriet brinner så uppför det sig annorlunda än en vanlig brand, då den producerar sitt eget syre och avger explosiva och giftiga gaser. Detta gör dem svåra att hantera. Trots detta så erbjuder den internationella konventionen om säkerhet till sjöss inga specifika regulationer angående brandsäkerheten ombord fartyg som använder litium-jon-batterier till framdrivning. Denna studie undersöker hur olika fartyg i Skandinavien som använder sig utav litium-jon-batterier till framdrivning har anpassat sig angående brandsäkerheten. Den undersöker även hur deras generella känsla är angående deras förmåga att hantera en litium-jon-brand. Studien grundar sig i kvalitativa intervjuer med sex olika svaranden i närområdet till Göteborg.

Inte allt för överraskande så har fartygen anpassat sig liknande om man ser till hur långt reglerna sträcker sig. Det är när reglerna blir mer generella man kan se olika lösningar. Vissa av de svarandes lösningar hade varit väldigt fördelaktiga ombord andra fartyg, vilket pekar mot det faktum att det är viktigt att fartygen delar med sig utav sin kunskap fram till dess att regelverken är mer kompletta. Sedan så kan inte tydliga regler skapas utan operativ erfarenhet, vilket ytterligare trycker på nödvändigheten att fartyg och redare delar sina erfarenheter och innovationer sinsemellan. De svarandes uppfattningar angående deras förmåga att hantera en litium-jon-batteribrand beror mer på deras kunskap än vad det gör på vilka system och metoder de använder ombord. Författarna fann att det är viktigt att informationen som fås från tillverkarna under batteriinstallationen delges effektivt till resten av besättningen, då detta kommer vara den enda informationskällan till det skeppsspecifika systemet. Dock bör detta kombineras med relevant teoretisk kunskap. Det är viktigt att hålla kunskapen uppdaterad då denna teknologi snabbt utvecklas.

**Nyckelord:** Batteri, Fartyg, Brand, Framdrivning, Elektrifiering, Säkerhet, Litium-jon

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# ABSTRACT

The shipping industry is in an era of change as shipowners move away from fossil fuels toward more environmentally friendly energy carriers. One of these energy carriers is the lithium-ion battery, which provides great GHG-reduction and energy efficiency. However, using lithium-ion batteries comes with a great concern, namely the fire hazard. A lithium-ion battery fire behaves differently from an ordinary fire, due to them producing their own oxygen, and creating explosive and toxic off-gases. This can make them difficult to handle. Despite this, the international convention of the safety of lives at sea proposes no specific regulations regarding the fire safety onboard ships using lithium-ion batteries for their propulsion. This study investigates how different ships in Scandinavia have adapted in forms of fire safety, due to them using lithium-ion batteries for propulsion. Also, it investigates the general feelings about their capabilities of handling a lithium-ion battery fire. The study is based on qualitative interviews with six different respondents in close proximity to Gothenburg.

Not too surprising, the ships have adapted in similar manners as far as the regulations stretch. It is when regulations become more general that different adaptations present themselves. Some of the respondents' solutions to battery fire safety would be greatly beneficial to other ships, which points to a necessity of sharing their knowledge until regulatory works become more complete. Also, clear regulations cannot be set until there is sufficient operational experience, which further presses on the importance of sharing experiences and innovations between ships and shipowners. The respondents' feelings about their capabilities to handle a lithium-ion battery fire relates more to their knowledge regarding lithium-ion batteries, rather than which systems and methods they use onboard. The authors found it important that the information received from the manufacturers during the battery installation is properly passed down to the rest of the crew, as this will be the only information source to the ship specific system. However, it should be combined with relevant theoretical knowledge. It is important to keep the theoretical knowledge up to date, as this is still a new technology under rapid development.

**Keywords:** Battery, Ship, Fire, Propulsion, Electrification, Safety, Lithium-ion

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# ACRONYMS AND TERMINOLOGY

| | |
|---|---|
| BMS | Battery Management System |
| CCTV | Closed-circuit Television |
| $CO_2$ | Carbon Dioxide |
| DF | Dual Fuel |
| DO | Diesel Oil |
| DP | Dynamic Positioning |
| DPV | Dynamic Positioning Vessel |
| ECA | Emission Controlled Area |
| ECR | Engine Control Room |
| EMS | Energy Management System |
| EV | Electric Vehicle |
| FAME | Fatty-Acid Methyl Esters |
| GHG | Green House Gas |
| GT | Gross Tonnage |
| GWP | Global Warming Potential |
| HF | Hydrogen Fluoride |
| HFO | Heavy Fuel Oil |
| HMI | Human Machine Interface |
| HVO | Hydrotreated Vegetable Oil |
| IMO | International Maritime Organization |
| kW | Kilo Watts |
| LCA | Life Cycle Assessment |
| LFP | Lithium Iron Phosphate |
| LNG | Liquid Natural Gas |
| M/V | Marine Vessel |
| MARPOL | Prevention of the Pollution from Ships |
| MED | Marine Equipment Directive |
| NMC | Nickel Manganese Cobalt Oxide |
| $NO_x$ | Nitrogen Oxides |
| PM | Particulate Matter |
| PSSA | Particularly Sensitive Sea Areas |
| EU | European Union |
| RISE | Research Institutes of Sweden |
| Ro-Pax | Roll On Roll Off + Passenger |
| Ro-Ro | Roll On Roll Off |
| SCBA | Self-Contained Breathing Apparatus |
| SDG | Sustainable Development Goals |
| SOLAS | Safety of Life at Sea |
| $SO_x$ | Sulfur Oxides |
| UN | United Nations |
| VDC | Volt Direct Current |
| Wh/L | Watthour per liter (energy density) |

# 1. INTRODUCTION

Today the shipping industry is a large contributor to negative environmental impacts. Emissions to the air such as Carbon Dioxide ($CO_2$), Nitrous Oxide ($NO_x$), Sulfur Oxide ($SO_x$), Particulate Matter (PM), and methane pose a great threat to the environment and to human health (Gray et al., 2021). To counter this, several international regulatory bodies have adopted rules and regulations to reduce stated emissions. One of them is the International Maritime Organization (IMO). They are an organ under the United Nations (UN) with the responsibility for all matters regarding shipping such as safety, security, and pollution (IMO, 2019). In 2018, the IMO agreed to reduce greenhouse gas (GHG) emissions by 50% to the year of 2050 (Joung et al., 2020). They will achieve this through their international conventions, which are treaties between flag states and consists of international laws and regulations. The convention that handles the pollution from shipping is named the International Convention for the Prevention of Pollution from Ships (MARPOL). To reduce previously stated emissions, the MARPOL-convention enforces a great deal of the regulations that affects the shipping industry. In January 2020, the sulfur directive was introduced through the convention. This drastically limited the amount of sulfur that is allowed in marine fuel.

The regulatory bodies and strict regulations are huge drivers pushing the shipping industry towards a greener approach when building new vessels and fleets. To reach the international goals, there is a need for more environmentally friendly energy carriers with low environmental impact to the air and sea. One energy carrier that have risen in popularity over the last couple of years is the lithium-ion battery (Chin et al., 2021). This high energy density battery has exploded in popularity in the automotive industry and have spurred the shipping industry to adapt the technology into ship propulsion systems and energy storage systems. Lithium-ion batteries are used both in hybrid ships, where the batteries work in parallel with combustion engines, as well as fully electrified ships. Although the technology is new in the shipping industry, there are a lot of benefits to the usage of battery powered ships over the conventional internal combustion engine. Foremost, there is huge Greenhouse Gas (GHG) and negative emissions reduction potential in using batteries (Jeong et al., 2020). It also requires less maintenance and produces fewer vibrations which results in a calmer environment both for the crew and the marine population according to Chin and colleagues. When used in hybrid propulsion systems the batteries enable less load fluctuation in the combustion engines and takes care of high loads (peak shaving) to limit the engine stress (Geertsma et al., 2017).

However, the usage of lithium-ion batteries comes with a great safety concern. In 2010, two people were killed in the “UPS airlines flight 6 crash” due to a pallet of lithium-ion batteries auto igniting onboard the plane (Gardner, 2018). The phenomena known as thermal runaway, which is the rapid increase in heat leading to a fire or explosion, is a constantly present danger for lithium-ion batteries. Despite extensive research, resulting in efficient systems to prevent thermal runaway, the risk still exists. In a maritime application the risk of the batteries getting exposed to vibrations or humidity for example, the danger of thermal runaway is even more present according to Gardner. Moreover, a vessel requires several and large batteries which would make the outcome even more disastrous if thermal runaway happens. Considering that in a maritime setting, people are working close to the batteries with no means of escape, makes the need for effective extinguishing systems and well-established procedures for lithium-ion battery fires essential.

## 1.1 Background to the Investigation

Using Lithium-ion batteries for propulsion is a new, but at the same time rapidly increasing technology within the shipping industry (DNV, 2022). The technology proposes new challenges onboard ships, for example, there might be a need for new system designs and special training (Anwar et al., 2020). One challenge that comes with the application of lithium-ion batteries is the fire hazard. A battery fire behaves differently from that of an ordinary fire and can be difficult to handle (Ghiji et al., 2020) (Helgesen, 2019). Using batteries will require special fire suppression-and extinguishing systems, and procedures. Despite this, the International Convention of the Safety of Lives at Sea (SOLAS), proposes no specific regulations regarding fire safety measures onboard ships using batteries for propulsion (DNV, 2018, p. 14).

## 1.2 Aim of the Study

The aim of this report is to investigate how the electrification is affecting the fire safety onboard a vessel that uses batteries for ship propulsion. This will be achieved through qualitative interviews with relevant persons who possess knowledge and experience about onboard systems and procedures where lithium-ion batteries are used for propulsion. The investigation is inspired from the suggestion in the bachelor thesis of Jonathan Gullbring and Anja Pandic who wrote about electrification of short sea shipping in Scandinavia (Gullbring & Pandic, 2020). As recommendations for future research, they are suggesting marine engineers to investigate the changing of the engine room through the development of electric operations.

## 1.3 Research Questions

These following research questions regard how the fire safety is being affected when ships are using lithium-ion batteries for their propulsion. They will be answered in this report.

- In what way have different ships adapted to this new battery technology?
- What is the opinion about the capabilities to handle a lithium-ion fire?

## 1.4 Delimitations

Since the shipping industry is a global apparatus with a vast network of regulations and different ship designs, the investigation will be limited to the ships operating in Scandinavian waters. Scandinavia provides the densest maritime traffic regarding vessels using lithium-ion batteries for ship propulsion (DNV, 2022). By focusing on Scandinavia and especially Sweden it will enable enough interviews to establish results about how the onboard fire safety is changing with the usage of batteries for ship propulsion. Current Covid restrictions might pose difficulties regarding field trips abroad, but by focusing on vessels in close proximity to Gothenburg, it might be a possibility. Furthermore, the report will not include all classification societies and their regulations regarding battery installations. The report will only include the regulating bodies of which the respondents are subjected to.

# 2. BACKGROUND

This chapter is to provide the reader the origin of the lithium-ion battery and why it is such a great candidate as an alternative fuel in the shipping industry. The scope in this chapter regards environmental incitements to electrification, as well as a brief historical background of the lithium-ion battery.

## 2.1 Environmental Drivers

To combat the climate crisis there is a need for regulating bodies who can enforce laws and regulations on major contributors to negative environmental impacts. The shipping industry is one large contributor to global warming and pollutants to the air and sea (Anwar et al., 2020). The following part will cover some of the largest regulatory bodies that affect the shipping industry regarding decarbonization and the pursuit for alternative energy sources.

### 2.1.1 United Nations

In 2015 the UN adopted the Paris Agreement (United Nations, n.d.-a). The agreement is an international legally binding treaty that aims to limit the global warming by at least 1,5 degrees Celsius compared to preindustrial levels. Moreover, the UN also launched their sustainable development agenda in 2015 (United Nations, n.d.-b). The phrase sustainable development was first ever coined in the Brundtland Report. It described sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (United Nations, 1987, p. 15). The sustainable development agenda consists of seventeen global goals (see figure 1) called the sustainable development goals (SDGs) which aims to end poverty, protect the planet, and improve the lives and prospects of everyone, everywhere according to the UN.

**Figure 1**

*United Nations 17 Sustainable Development Goals.*


*Note.* This was retrieved from United Nations. (2020). According to their guidelines for the use of the SDG logo.

### 2.1.2 International Maritime Organization

The international maritime organization is a specialized agency under the UN (IMO, 2019). IMO is composed of 174 member states who together are responsible for all matters regarding safety, security, and pollution prevention in the shipping industry. The focus of the IMO is to enforce laws on the shipping industry through international conventions, which are legally binding treaties for flag states that have ratified the convention. Today, IMO claims that their conventions apply to more than 98% of the world merchant shipping tonnage. This makes IMO the single most important international body when it comes to making the shipping industry shift towards a greener apparatus. In 2018, IMO adopted a new initial strategi for reducing GHG-emissions in response to the Paris Agreement (Joung et al., 2020). The strategi involves the reduction of GHG-emissions by 50% at 2050 compared to 2008.

### 2.1.3 MARPOL and the Sulfur Directive

The MARPOL-convention is the convention through which IMO imposes legislations on the shipping industry to further the environment. MARPOL is the international convention for the prevention of pollution from ships, and it was created to do just that. In January 2020, a new directive was added to the convention (Gray et al., 2021). It is called the sulfur directive and it limits the total allowed sulfur content in marine fuels to 0,5%. Furthermore, in enforced Emissions Control Areas (ECAs), which consists of Particularly Sensitive Sea Areas (PSSAs), it is limited to a maximum of 0,1% according to Grey and authors.

### 2.1.4 European Union

In response to the IMO GHG-emission reduction strategy and the Paris Agreement, the European Union (EU) have devised a decarbonization plan of their own (Joung et al., 2020). Their goal is to reduce GHG-emissions from ships with less than 80% in the year of 2025 compared to 1990. Furthermore, EU have stated it one of their top priorities for Europe to become carbon neutral, and resource efficient by the year of 2050 (European Union, n.d.).

## 2.2 The Pursuit for Alternative Fuels

The Heavy Fuel Oil (HFO) and the Diesel Oil (DO) have been the fuels of choice in the maritime sector since the internal combustion engine was introduced to the shipping industry. The conventional fuels are providing a high energy density which is great for merchant ships who might have to spend several weeks at sea without the possibility of refueling. These fossil fuels also have a well-established refueling infrastructure worldwide which makes them a good choice as an energy carrier for a large vessel. However, when considering the environmental aspect of HFO and DO there are a lot of negative emissions originating from the fossil fuels. The IMO estimates that the shipping sector is emitting 2.8% of the world's total $CO_2$ emissions (Gray et al., 2021). Furthermore, the shipping industry emits 1.4 metric tons of PM, approximately 13% of the global $SO_x$, and approximately 15% of the world's total $NO_x$. These pollutants have a large negative impact on the environment, and on human health, and to reach the global goals regarding pollutions to the air and sea, there is a pressing need for alternative fuels in the maritime sector. Gray and colleagues are arguing that future marine fuels should have the following characteristics:

- High energy density (MJ/L) and specific energy (MJ/kg) to minimize fuel volume and mass and allow for long-distance travel

- Produce low levels of local emissions ($SO_x$, $NO_x$, and PM), to ensure compliance with IMO ECA regulations

- Low energy costs (€ /MWh), to ensure cost competitiveness with low-quality residual fossil fuels

- Low lifecycle GHG emissions ($gCO_2e/MJ$), to meet the IMO goal of reducing emissions from shipping by 50% by 2050

- Scalability, to ensure that large volumes of fuel are available at the quantities required of the shipping sector

- Widespread bunkering infrastructure, to ensure vessels can refuel at ports around the world

- Compatibility with existing infrastructure, to allow for decarbonization of current vessels and future potential retrofit projects. (Gray et al., 2021, p. 5)

Because of new and strict legislations, the shipping industry have entered an innovative era. There is still no alternative fuel that is proved the best compared to others and manufacturers are racing each other in developing new technological breakthroughs regarding alternative fuels. One popular fuel that has been around since the 1970s is the liquid natural gas (LNG). Gray et al states that using LNG as a fuel can reduce $SO_x$ emissions by 90%, $NO_x$ emissions by 80%, and it emits significantly less PM in comparison to conventional HFO fuel. Alcohols such as ethanol and methanol have also been proven to be good potential future energy carriers. By the means of retrofitting existing ships, the engines can be rebuilt into multi-fuel engines still working with the diesel cycle but with more environmentally friendly fuels. In 2015, Stena Germania, a Swedish flagged Ro-Pax vessel converted their engines into methanol and reduced $SO_x$ and PM by 90%, and reduced $NO_x$ by 60% (Stena Line, 2021). Furthermore, Gray et al (2021) implies that "there is potential for the use of diesel-like biofuels, such as hydrotreated vegetable oils (HVO), fatty-acid methyl esters (FAME), and Fischer-Tropsch diesel to be used in current marine engines with little to no engine or bunkering modifications" (p. 5). Moreover, prospects include energy carriers such as ammonia and hydrogen in the future, and there are many more.

### 2.2.1 Lithium-ion Batteries as an Alternative Fuel

One alternative fuel that has absolutely exploded in popularity in the automotive industry over the last couple of years is the battery, namely the lithium-ion battery. The lithium-ion battery provides a much higher energy density in a smaller package compared to the conventional lead-acid battery (Cummins, n.d.). This makes it a great energy carrier in automobiles. Shu et al., (2021) states that in 2019, the number of light Electric Vehicles (EVs) globally reached 2,264,400 units, which is 9% higher than in 2018. Today almost all major car manufacturers are providing models with hybrid or all electric drivelines. The trend is that the automotive industry is moving towards a future without the use of fossil fuels for propulsion. In Sweden there is even a motion in the parliament to ban the selling of new cars which are using fossil fuels for propulsion by the year of 2030 (Nilsson, 2017).

The proven working application of lithium-ion batteries in automotive vehicles have caught the interest of the shipping sector as well (Geertsma et al., 2017). In the shipping industry, the very first fully electrified ferry, M/V Ampere, started its operation in May 2015 (Ship Technology, 2015). She is an 80-meter-long and 21-meter-wide car ferry able to carry 120 cars and 360 passengers. Every day she ferries cars and people 5.7 km between villages of Lavik and Oppendal in Norway. The ship has an installed capacity of 1,040 kW deriving from lithium-ion batteries (Chin et al., 2021). The batteries power the onboard LED lighting, solar panels, heating, ventilation, air conditioning and propulsion system. When at shore the ship recharges its lithium-ion batteries during the 10 minutes of unloading and loading. Ship technology writes that during this time, she is powered by 260 kW batteries which are located at the shores on both sides of the travel route. According to Chin and authors, the ship broke new ground in the shipping industry and influenced many other countries and ship owners to join the electrification franchise.

Electrification of marine vessels does come with difficulties, however. There are large economical and technical aspects that needs consideration when it comes to electrification. Before converting an existing vessel or building a new one with batteries for propulsion, there is a need for an established infrastructure with shore connections and charging stations, which requires high initial investment costs (Chin et al., 2021). Furthermore, the crew will require special training revolving around the new technology, and time to familiarize with the equipment (Anwar et al., 2020). Anwar and authors also explain that there is a problem with the voyage distance of fully electric ferries. Therefore, today the fully electric ferries are limited to ones operating in small areas with short traveling distances. Moreover, the foremost reason for using lithium-ion batteries, which is reducing GHG emissions, gets countered by the sheer weight of the battery packs, which requires alternative materials over steel for the ship's construction, like carbon fiber per example. In M/V Amperes case, the weight of its lithium-ion batteries is ten tons, and to balance this out the hull is completely composed out of aluminum (Ship Technology, 2015). Lastly, Anwar et al (2020) states that "in the context of legal challenges, energy regulations, e.g., taxes and ferry construction, are not supportive enough to shift the paradigm towards green energy. In many EU countries, green energy is taxed while hydro-carbon fuels are exempt from taxes. (p. 2)

Despite the challenges regarding the usage of batteries for ship propulsion, the technology is constantly increasing. In the 2021 the total number of vessels operating with battery technology for propulsion in the world peaked at 387 (DNV, 2022). The main part of these vessels consists of ferries (Chin et al., 2021). Chin and authors write that "ferries have the highest number, as they are designed for the same short route daily and travel through already polluted harbors" (p. 25). This is obviously something that makes ferries the most common vessel that uses batteries for ship propulsion. They have an edge over other types of vessels since they can recharge their batteries at both sides of the travel route during loading and unloading of cars and passengers. Furthermore, Chin and colleagues explain that after ferries, the most common vessel type to use batteries for propulsion is the offshore supply vessel. These types of vessels partake in operations that puts a lot of stress on the engine. Using batteries as a hybrid solution can provide a more stable engine load as the batteries handle peak demand and keep the engine load from fluctuating too much. The technology of using batteries for propulsion is spreading to all vessel types, however. There are cruise ships, yachts, tugboats and even cargo ships that uses the technology. There is even a fully electrified, autonomous and zero emission container feeder called Yara Birkeland that will start commercial operation in 2022 (Yara International ASA, 2021).

### 2.2.2 GHG-emissions

Using batteries for propulsion is regarded as one of the most credible options in the marine industry in the pursuit of decarbonization, due to its potential of achieving zero emissions during operation (Jeong et al., 2020). However, there are negative emissions to the environment which are contributed to the manufacturing of batteries. Also, whether the batteries are charged with the power generated from renewable or fossil energy sources provides significant differences in emissions. To establish a holistic view of the GHG-emissions of ships using batteries for propulsion, Jeong, and colleagues conducted a case study on a fully electrified Ro-Ro ship in South Korea. This holistic approach to GHG-emissions included emissions from the production stage, transport stage, and ultimately the operational stage. They carried out a Life Cycle Assessment (LCA), which was determined to 30 years, on both their case ship and on a similar vessel with a conventional internal combustion engine, operating on diesel oil.

In their study, they found that operating on batteries reduced the Global Warming Potential (GWP) by 35.7% over the diesel oil. Jeong and authors explain that high environmental impacts are associated with the power generation and transportation. Furthermore, they found that the Acidification Potential of batteries where 77.6% less than the conventional combustion engine. The Eutrophication Potential where 87.8% less, and the Photochemical Ozone Creation Potential where 77.2% less than the combustion engine. Jeong and authors are addressing the energy production stage as the key part in GHG-emissions regarding ships running on batteries for propulsion. In South Korea most of the power grid relies on coal and natural gas as energy sources (Jeong et al., 2020, p. 9). Jeong and colleagues argue that there is need for more renewable energy sources in South Korea to achieve the 2050 IMO goal in reducing GHG-emissions from ships by at least 50%. They conclude that countries relying heavily on renewable energy sources will benefit from electrification of ships whilst countries relying heavily on fossil energy sources will not gain much in GWP reduction over the ship's life cycle.

## 2.3 History of Lithium-ion Batteries

In the 1850s, Lead-acid was the first battery that, by introducing a reversed current, could recharge unlike the previous disposable batteries which were permanently drained once the chemical reaction was spent (Jiang & Song, 2022). This led to the possibility of using batteries in a completely new way. A few years later, in the 1880s, the first ever dry cell battery, Zink-carbon was introduced. It was more physical and chemical robust due to not using a liquid as electrolyte between the positive anode and the negative cathode compared to Lead-acid which are usually filled with an aqueous electrolyte solution containing sulfuric acid ($H_2SO_4$) (University Of Concordia, 2016). This was the first step of getting the batteries smaller and more light weight. The introduction of dry cell batteries made it possible to use the batteries in a more portable environment since the batteries did not require to stand in an upright position. For example, this led to the invention of the first ever handheld flashlight in the 1890s (Energizer, n.d.).

During the early 1900s the technology rushed in terms of new innovations and in the late 1970s, the big buzzword where portable, cordless, and wireless (Yoshino, 2012). Although, the already existing rechargeable batteries were developing their effectivity, none of these could compare with Akira Yoshino's future Nobel Prize award winning innovation. In the 1980s, the chemist and engineer, Yoshino started to search for an entirely new chemical composition for a completely different kind of battery (The Nobel Foundation, 2019). He started experimenting with lithium cobalt oxide as the cathode and once energized it released lithium-ions, but there were no effective ways of absorbing and storing this energy. However, there was another material that was developed at another laboratory of Asahi Kasei named VGCF which had the carbon structure Yoshino was looking for. He started experimenting with it and found it to perform extremely well as an anode. Yoshino found when he investigated that if he used the same aqueous electrolyte solution as Lead-acid batteries, the battery was limited to 1.5 volt per cell which did not improve the energy density, watt hour per liter, (Wh/L) anything compared with the already established battery technologies (Yoshino, 2012). But when he tried a nonaqueous electrolyte it was possible to have the current above 3.7 volts, which results in almost 2.5 times higher compared with other rechargeable battery types having a limit of 1.5 volt. A higher voltage for each individual battery cell resulted in higher energy density (Wh/L). This meant the lithium-ion battery was now the most compact and energy dense battery. This made it easier to design and fit inside portable electronics.

Akiro Yoshino decided to license patent the lithium-ion battery. This meant that every third-party manufacturer who paid a royalty got permission to use the newly developed technology, and this allowed the knowledge to be spread rapidly around the world. Since Sony Corporation commercialized the lithium-ion battery in 1991, most of our daily used electronics are today powered by these batteries as an energy source. This accounts for electric tools, drones, energy storage parks, and at the time of this report, all well renowned electrical car manufacturers use lithium-ion batteries.

# 3. THEORY

This chapter will provide the reader with information to easier follow the result and discussion. After this chapter the reader will understand the working principle of a lithium-ion battery. Moreover, it will address the safety issues revolving lithium-ion batteries, and some existing solutions to the issues. Different propulsion systems using batteries in maritime settings will be explained, some accidents will be covered, and existing regulations will be introduced. Lastly, it will cover the electrified vessels trafficking Scandinavian waters.

## 3.1 Propulsion Systems

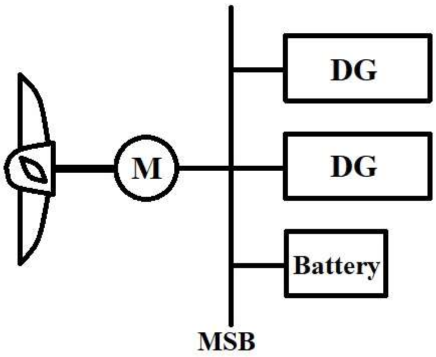
As covered previously there is a need for more energy efficient propulsion technologies to reduce negative environmental emissions from shipping. Using batteries for propulsion is a great solution regarding this. However, ships today are subjected to a wide range of operating scenarios (Geertsma et al., 2017). Geertsma and authors explain that:

> While the pressure to reduce fuel consumption and emissions has increased, the operating profile of ships has become increasingly diverse: offshore vessels perform numerous tasks, such as transit and critical dynamic positioning (DP) operations; heavy crane vessels, such as the *Pioneering Spirit*, exhibit an increased capacity and complexity for diverse offshore operations; naval ships perform traditional patrol operations in open sea, but are also deployed in littoral operations; and tugs require full bollard pull when towing and require limited power during transit or standby. (p. 32)

Because of this, ships get subjected to different needs in forms of propulsion technologies, and that has led to different propulsion design layouts for ships using batteries for propulsion according to Geertsma and colleagues. A ship with short travelling distances and the possibilities for plug-in charging can benefit from a fully electric propulsion system depending on whether there is renewable- or fossil energy sources used for charging (Jeong et al., 2020). For an ocean-going vessel however, a fully electrified solution might not be beneficial due to the lack of ports and charging opportunities. However, Geertsma et al argues that by means of hybrid propulsion with lithium-ion batteries, there is still fuel and emissions reduction potential. A common way of designing a ships electrical grid is with power supply from generators running in parallel with batteries (see figure 2). By designing the electrical grid this way, the batteries can provide power during peak load, when the generators are working at operating points with low efficiency, and they can take over the propulsion completely, providing minimal pollution and vibrations according to Geertsma et al. The batteries can be recharged by the generators when they operate in operating points with high efficiency and thus reducing emissions to the air from $CO_2$, $NO_x$, $SO_x$, etc. Or they can be recharged via shore supply, when possible, to further reduce fuel consumption and emissions. The batteries can also work as a back-up source if a black-out occurs which makes this solution especially fitting on a DP class vessel. However, Geertsma and authors are pointing out that this propulsion system requires smart control systems to enable the batteries to charge and discharge at the right time when running in parallel with the generators. This to provide optimal efficiency and minimum wear on the generators.

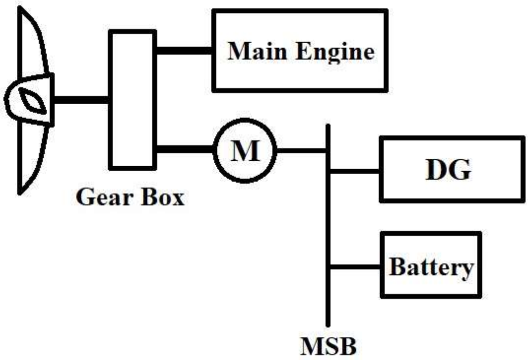
Another typical design is to provide power through a direct mechanical drive in combination with an electric motor powered by a hybrid electrical grid (see figure 3). Geertsma and authors explain that by this design, the mechanical drive can propel the ship at high speeds with high efficiency, and at the same time charging the batteries and powering electrical loads. At low speeds, the main engine can be shut of, and the propulsion and electrical loads relies on the generators and batteries.

**Figure 2**
*Diesel Generators in parallell with a battery pack.*




*Note.* Main Switchboard (MSB), Diesel Generator (DG), Electrical Motor (M)

**Figure 3**
*Main Engine in parallel with an electrical motor.*




*Note.* Main Switchboard (MSB), Diesel Generator (DG), Electrical Motor (M)

## 3.2 Working Principle of the Lithium-ion Battery

This is an advanced technology that takes advantage of freely moving lithium-ions as its electrochemistry. The battery has four main components:

**Anode**

The anode stores lithium and releases lithium-ions during discharge. The most used material is graphite due to its high negative potential (Ghiji et al., 2020).

**Cathode**

The cathode stores lithium and releases lithium-ions while charging. The composition can differ between different types of lithium-ion batteries. The most used maritime batteries contain an electrolyte composed of Nickel Manganese Cobalt Oxide (NMC) and Lithium Iron Phosphate (LFP) (Helgesen, 2019).

**Electrolyte**

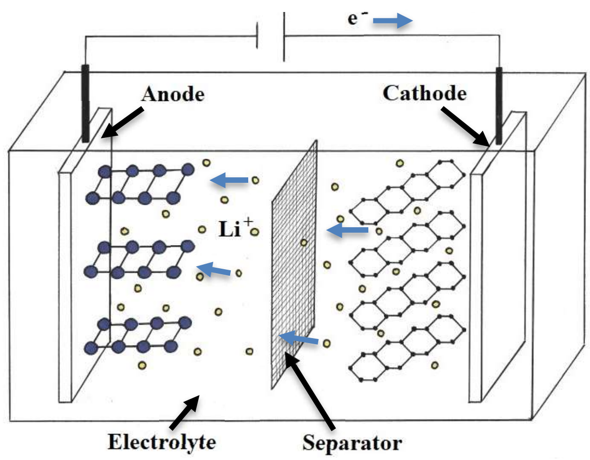
The electrolyte is a conductive substance that acts as a transporter for the lithium-ions to be able to move between the two sides. The typical electrolyte consists of a flammable carbonate-based organic solvent (Ghiji et al., 2020). However, the composition or material choice for this substance differ depending on the anode/cathode materials and operating condition.

**Separator**

Lastly, one of the most important components to ensure safety is the separator, which is a micro-permeable membrane that physically separates the anode and the cathode to prevent any electrical short circuits between them (Orendorff, 2012). Only lithium-ions are small enough to penetrate the micro-permeable membrane, therefore it blocks the electrons from travelling inside the battery which would cause a short circuit inside the battery. The material selection differs between battery types to fit their needs (Arora & Zhang, 2004). But when the lithium-ion battery consists of an organic electrolyte, a microporous film is the mostly used material. Aurora and Zhang (2004) give the example, "batteries that are characterized by small internal resistance and consume little power require separators that are highly porous and thin, but the need for adequate physical strength may require that they be thick" (p. 4422).

**Figure 4**

*Lithium-ion battery while discharging,*




*Note.* Black arrows show the components while the blue, shows which direction the lithium-ions and the electrons are traveling during discharge.

Lithium-ion batteries use the advantages of metals ability to lose electrons. This phenomenon calls electrochemical potential and because of lithium only contain one valence electron which is the electron in the outermost region of atoms. Therefore, lithium has the highest ability of losing electrons and this makes it very reactive. In its pure form it even reacts with water and generates a highly flammable hydrogen gas (Lisbona & Snee, 2011). But when lithium is a part of a metal oxide it is stable and will not try to lose its valence electron. Therefore, the cathode in lithium-ion batteries consist of a metal oxide where the lithium atom remains stable (Clean Energy Institute, n.d.). While in the anode uses the exact opposite of getting the lithium atom stable. Hence, it uses a material where the lithium atom is unable to bind to anything which makes it want to reject the valence electron and therefore unstable. In this case, graphite has been chosen due to its structure where all carbon atoms are already taken. Now, when there are two sides, one where the lithium atom wants to reject one of its electrons and one side where the atom wants to be stable there must be something that separates these two sides apart from each other. This is where the electrolyte and the separator come in and separates these two sides where only lithium-ions can pass though the material and not their electron. When the battery is fully charged the anode is full of unstable lithium atoms that really wants to reject one of their electrons. They will stay there until a connection is made between the positive and negative connection on the batteries. When a connection has been made this generates a flow of electrons and the electrons are allowed to travel though the cable to the metal oxide where it merges and neutralizes with the lithium-ion that got there through the electrolyte. The stable lithium atom stays in the cathode until the next charging in the reversed process.

## 3.3 Safety Issues

Despite all the benefits of using lithium-ion batteries in terms of emissions, there is one major flaw that needs to be mentioned, namely the fire safety aspect. The high cell voltage, high energy density and the long-life cycle come with their compromises. As described, a micro-permeable membrane is used to separate the two sides, the cathode, and the anode from each other. This membrane is very sensitive, and if it would rupture, the risk is very high that there is an internal short circuit. This releases a large amount of energy and can result in fire or even an explosion (Zhang et al., 2020). When a lithium-ion battery is heated up, it can start an internal heat-releasing reaction called thermal runaway. During this process, oxygen releases from the active cathode materials as well as toxic and explosive off-gases (Helgesen, 2019). Zhang and authors explain that this phenomenon can occur because of two different reasons. Firstly, and most unlikely, spontaneous failure. Secondly, and more likely, because of human abuse. Moreover, they break down human abuse into three different types of abuse scenarios:

**Mechanical Abuse**

This occurs due to harsh conditions when the battery is exposed to external forces causing deformation, penetration, or vibration on the battery cell. This causes the casing and separator to rupture which leads to an internal short circuit and starts an exothermic reaction. Chen et al. (2021) says that “numerous battery ignition cases are caused by mechanical abuse (mainly collisions) in electric vehicles every year” (p. 86).

**Electrical Abuse**

There are three different types of electrical abuses. External short circuit, over-discharge, and over-charging (Helgesen, 2019). According to Chen et al. (2021), over-discharge and external short circuiting does not result in an instant which makes these not as dangerous as the last-mentioned type. Over-charging, on the other hand, is one of the most frequently observed reasons for lithium-ion battery safety accidents. The batteries consist of thousands of parallel- and serial connected cells. All these cells have their own properties where they are charged and discharged at different speeds. Because of this, some cells may have higher voltage than others, which may lead to some cells becoming over-charged. Chen and authors explain this in four stages. During stage I, the electrolyte starts to decompose near the cathode, resulting in a slowly increasing temperature (Chen et al., 2021). Stage II occurs when the battery exceeds 1.2 volts above the normally fully charged voltage. During this stage, side reactions start which causes oxygen to be released within the battery. In stage III, the battery starts to swell, and the temperature rises even quicker. Lastly, in stage IV, the battery casing ruptures because of the swell and the separator breaks down. This causes the lithium-ion battery to start its exothermic chain reaction due to an internal short circuit, the same way as in mechanical abuse.

**Thermal Abuse**

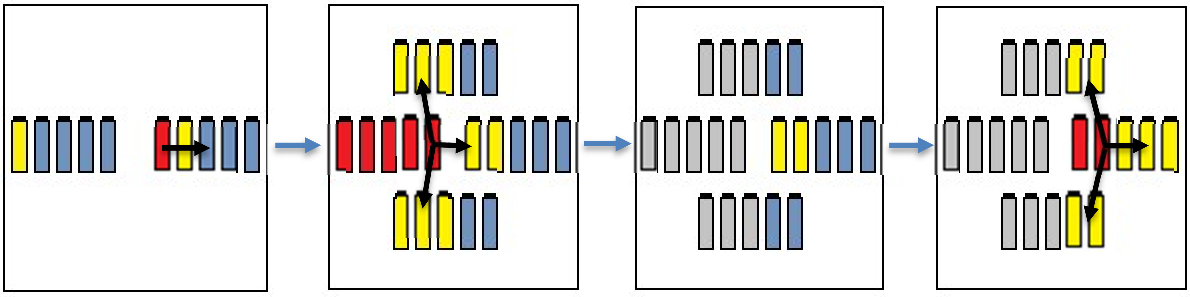
External heating will generate a large amount of heat inside the battery which makes the solid electrolyte to decompose which then advances to an internal short circuiting inside the cell. Then it continuous its exothermic reaction in the same way as over-charging stage I-IV.

### 3.3.1 Fire Suppression Challenges

Something that all these types of abuses have in common is that they end up in an extreme heat-release reaction, thermal runaway. The lithium-ion battery systems used in larger applications consists of thousands of cells. Therefore, when there is thermal runaway in a single cell it heats up and initiates thermal runaway in adjacent cells causing fire in the whole battery system (Ghiji et al., 2020). Because it is difficult to access and effectively cool down all cells, the probability of reignitions is extremely high even if the suppression succeeds (see figure 5). Therefore, the battery needs continuous cooling to prevent any further spread and the possibility of reignition.

**Figure 5**

Shows heat distribution during thermal runaway and how it can re-ignite.



*Note.* In the first step, the heat is spreading between the cells causing thermal runaway. Step two, heat starts to spread between modules. Step three, successful suppression but two cells are still hot. Step four, the exothermic reaction continuous to spread.

Other challenges are because of lithium-ion batteries ability to produce its own oxygen during the thermal runaway process, making it nearly impossible to inert the ambient air. Oxygen, one of the third elements necessary for a fire to exist.

Det Norske Veritas (DNV) have done a report named “technical reference for Li-ion battery explosion risk and fire suppression partner group”. This was made together with Norwegian, Danish and US maritime authorities, battery manufacturers, system integrators, suppliers of fire extinguishing systems, shipyards, and shipowners (Helgesen, 2019). Their report describes the risks involved when using lithium-ion batteries for maritime use and test results from different extinguishing methods. These results are later summarized in advantages and disadvantages for each method. The different extinguishing methods from DNV’s report are presented below.

**Direct Injection of Foam**

Fire suppression tests showed that direct injection of foam had the best performance compared to all other tested methods. When the batteries are installed without a dedicated battery room this method is especially appealing. Furthermore, this method where the most sufficient of preventing module-to-module fire. Because of the capability of flooding the entire module over a longer time.

**High Pressure Water Mist**

This method resulted in good heat reduction and works well for protecting the batteries from external heat. But it also works good regarding gas absorption and decreasing gas temperature.

**NOVEC**

This method gave very efficient results in extinguish the battery flames but showed poorer results regarding heat reduction. Another downside is that when there is a battery fire it releases a lot of toxic and explosive gases and because of that, there must be sufficient ventilation to minimize the risks. But for the NOVEC gas to work the ventilation needs to be closed.

**Sprinklers**

Sprinkler systems showed the same result in heat reduction as the High-Pressure Water Mist. But there is a risk associated with water-based fire suppression. Water could displace gas into pockets with high concentration which means that the explosion risk is becoming more critical with sprinkler. As well as water have the unwanted potential of short-circuiting other cells.

**Aerosols**

One extinguishing agent that is not presented in the DNV report is Aerosols. This extinguishing agent comes in a solid compound and when it activates it transforms into a rapidly expanding fire extinguishing gas (FirePro, n.d.). It suppresses the fire through the release of large microparticles that surround the flame and inhibits the chain reaction in the flame on a molecular level. However, in 2017, DNV GL did similar tests including aerosols (Hill, 2017). The results showed that aerosols extinguished the flame in the same way as water. But, due to lack of thermal mass, aerosols showed poorer result in thermal conductivity which restricted the ability to cool it as effectively as water. Therefore, DNV GL recommends in their report that "gas-based systems be backed up by water-based suppression when cooling becomes a necessity, in combination with cascading protections in the modules and systems" (Hill, 2017, p. 37).

### 3.3.2 Toxic Gases

One dangerous aspect of a battery fire is the release of toxic gases (Willstrand et al., 2020). Protection due to these toxic gases is achievable through the usage of Self-Contained Breathing Apparatuses (SCBA) since most of them are hazardous only through inhalation. However, one toxic substance called Hydrogen Fluoride (HF) is currently a particularly hot topic when it comes to lithium-ion battery fires according to Willstrand and colleagues. The issue with HF when compared to other toxic substances is its ability to penetrate skin and tissue. The substance then causes a poisonous effect by affecting the levels of calcium, potassium, and magnesium in the blood. However, a more recent study concluded that in a smoke diving scenario, there are no studies that show that HF in a gaseous state would have any serious effects through skin uptake (Burgén et al., 2022). Nevertheless, it is important to consider that one aspect of HF is that the HF production from a battery fire may increase when applying water. Burgén and authors emphasize that there is need for more research about this phenomenon.

## 3.4 Battery Management System (BMS)

One of the most important systems to ensure safety and the possibility to prevent an eventual battery fire is the BMS. This system can be divided into three different parts, energy management, protection system, and thermal management (Chin et al., 2021). The last mentioned are monitoring all the cells inside the battery packs with the aim of preventing a thermal runaway. The BMS ensure that the batteries condition is within their safety and operational limits. Such as, temperature, voltage and current. For example, if the temperature in one cell increases an alarm is triggered followed by a complete mechanical disconnection if the temperature continuous to increase above the limits. It is critical that this system is powered up all the time to ensure the batteries safety and to get the possibility to discover a fault in an early stage.

## 3.5 Accidents

With a growing fleet of electric vehicles worldwide, eventually something will go wrong (Huang et al., 2021). Huang and colleagues determine that approximately 0.9-1.2 out of every 10,000 electric vehicles in China catches fire. China is the world's largest electric vehicle market with a reported stock of 3.8 million vehicles in 2019 (Shu et al., 2021). This equation results in several fires every year. Electric vehicles catching fire is not only subjected to China, however. Recently, a car carrying vessel, Felicity Ace, caught fire in the middle of the Atlantic Ocean (ABC news, 2022). The shipment included about 4,000 vehicles some of which were electric. Even though the origin of the fire could not be pinpointed to the electric vehicles the captain of the ship, Cabeças, states that "the lithium-ion batteries in the electric vehicles on board are keeping the fire alive". Luckily, none of the crew members got harmed in the disaster.

Another reported incident is the explosion of a storage facility in Arizona in 2019 (HJ Mai, 2019). The result was four hospitalized fire fighters, two of which were severely injured (Zalosh et al., 2021). In 2010, a horrible accident occurred with the UPS airlines flight 6 plane crash (Gardner, 2018). Gardner explains that the crash was caused by a cargo pallet containing lithium-ion batteries which self-ignited onboard the aircraft. Two people were killed in the calamity.

A highly relevant accident regarding this study took place in Norway, in October 2019. During an overhaul of the cooling plates inside the battery modules onboard the Ro-Pax ferry M/F Ytterøyningen, one of the gaskets got twisted and started to leak. The leaking cooling water came into contact with the electrical components in the lower part of the module and therefore, caused a short circuit between the positive and the negative side. This caused the cells to overheat, resulting in a thermal runaway. Both NOVEC and saltwater sprinkler systems were used to extinguish the fire which lasted for about four hours (Corvus Energy, 2020). 12 hours after the initial event, there was an explosion in the switchboard room, adjacent to the battery room. However, the root cause of the explosion is still under investigation. During the whole event, the ship was running on diesel engines with the batteries not in use and disconnected from the ships alarm system. Shortly after the accident, the Norwegian Maritime Authority, Sjøfartsdirektoratet sent out a recommendation letter to all vessels with a battery installation to carry out a new risk assessment of the dangers related to unwanted incidents in the battery systems. Also, the battery manufacturer, Corvus Energy sent out an issue warning "Important Communique regarding Ytterøyningen Battery Fire", to the ships with similar systems and their immediate actions/recommendations were:

1. Do not sail without communication between EMS and the packs (BMS). Keeping the packs powered up will maintain this communication link. An unpowered pack cannot communicate important system data (faults, warnings, temperatures and voltages) to the EMS/bridge. Ensure that current ESS parameters are showing at the EMS interface. This is a verification of the communication link.

2. If a gas release, thermal runaway situation or fire in the battery room is suspected:
   - Do not power down the battery equipment.
   - Contact Corvus Energy 24/7 Technical Support.
   - See contingency document: 1007814 Guidance Note: Assessment and Response After a Thermal Event involving Orca ESS. (Corvus Energy, 2019, p. 1)

Furthermore, Corvus Energy explains that in the current regulations it is only minimum class level requirements that there shall be isolation between the modules to prevent thermal runaway to spread between the adjacent modules (Corvus Energy, 2020). They further explain that they implemented thermal runaway isolation on cell level in all of their products to limit the extent of a fire.

## 3.6 Safety Actions in the Automotive Industry

The automotive industry takes another approach when it comes to safety. There is a significant difference in the view on safety and what is considered a safe solution. ISO 26262 is an international safety standard for road vehicles with a maximum weight of 3,500 kg (International Organization for Standardization [ISO], 2018). This standard demand that vehicle manufacturers must design their vehicle so if a cell ruptures and starts its thermal runaway, the vehicle must warn 5 minutes before there is a hazardous environment inside the passenger space (Huang et al., 2021). Hence, it shall be at least a 5-minute gap between the first cell ruptures and a full battery fire. Within these five minutes the driver shall be able to stop the car in a safe way and all passengers shall be able to get to a safe distance from the vehicle before the battery catches fire. This solution of a safety standard would not be suitable for maritime use. Hence there is not possible for the crew to get in a safe distance when they are on board the ship.

## 3.7 Safety Regulations in Shipping

All ships are compelled with following certain standards and regulations (Bisschop et al., 2021). The international convention of the Safety of Lives at Sea (SOLAS) is an international treaty between flag states with the objective of specifying minimum safety standards regarding a ship's construction, equipment, and operation (IMO, n.d.-a). IMO states that "Shipping is perhaps the most international of all the world's great industries - and one of the most dangerous. It has always been recognized that the best way of improving safety at sea is by developing international regulations that are followed by all shipping nations" (IMO, n.d.-b).

### 3.7.1 Classification Societies

Despite the dangers revolving around the lithium-ion battery, SOLAS does not provide any specific regulations for ships using these energy carriers for propulsion (DNV, 2018, p. 14)(Bisschop et al., 2021). However, in addition to SOLAS regulations, classification societies can choose to have their own regulations if they are of equal or better level of safety. A classification society is issued by a flag state to ensure ship safety regarding construction and operations (IACS, n.d.). They achieve this by developing their own rules, which are compliant with international regulations, and making sure the ships subjected to their society complies with them. At the time of this report, there are more than 50 classification societies (Marine Insight, n.d.). These classification societies have created additional safety standards for ships using batteries for its propulsion, fully or hybrid solutions. These standards cover the battery system and its spaces and applies to arrangements, ventilation, fire integrity, fire detection, fire extinguishing, risk assessment documentation, installation, and commissioning (DNV, 2018). Below are two of the largest classification societies which are developing standards regarding large battery installations at sea.

**Det Norske Veritas**

According to DNV, the battery spaces shall be positioned in a safe way to prohibit any deformation during collision. Therefore, the battery pack shall be positioned aft of the collision bulkhead (DNV, 2018). Furthermore, the battery space shall not contain any essential systems or even pipes and cables for the propulsion or steering. To prevent loss of propulsion or steering in case of a battery related incident such as thermal runaway. But also, no other heat sources or high fire risk objects. In case of a fully electric propulsion, the systems power capacity shall consist of two independent storage systems. Furthermore, the standard determines how the ventilation should be designed to have certain properties. DNV (2018) writes in their additional class notations that, the ventilation system must be mechanical and separated from the rest of the ship's other ventilation systems. Followed by independent temperature sensors in addition to the temperature sensors included in the battery packs. Also, the ventilation shall be possible to locally adjust in case of the remote or automatic control failures.

They also describe how the battery spaces fire integrity shall be defined as a machinery space. Therefore, they go by the same SOLAS regulations as a machinery space when it comes to structural fire protection, i.e., the battery spaces shall be enclosed by A-0 bulkhead or A-60 fire integrity bulkhead accordingly to table 9.3 in SOLAS Ch. II-2 Reg. 9.2.2.4. When it comes to fire detection, the battery space shall be monitored by conventional smoke detectors. The classification societies fire extinguishing method for suppression lithium-ion battery fires is by having the possibility of having a total-flooding system in the battery space. DNV (2018) clarifies that:

> As there are no established test criteria or approved fire extinguishing systems for battery spaces/protection of battery installations in accordance with SOLAS, 2000 HSC Code or the FSS Code, a water based extinguishing system is recommended due to its inherent heat absorbing capabilities. (p. 22)

Moreover, the ship shall be fitted with an Energy Management System (EMS). A surveillance system that monitors the ships battery energy, power, and supply duration (Chin et al., 2021). The EMS shall be able to limit and remotely monitor a couple of parameters to ensure the batteries safety during operation and charging.

**Lloyd's Register**

Firstly, Lloyd's Register (LR) only required that the shipowner do a risk analysis procedure, according to their guidance notes in case of a battery installation (Bisschop et al., 2021). But since July 2020, LR has included specific requirements on lithium-ion battery system installations. They provide a minimum list of alarms that the BMS shall give as well as fixed detectors that provides the operators with an early identification of a fire or thermal runaway. Moreover, they explain that "the fixed firefighting system is to be suitable for heat removal, boundary cooling and/or extinguishing for the duration that the heat and/or gas release is present" (Bisschop et al., 2021, p. 30). Therefore, LR recommends the same fixed extinguishing system as DNV, a water-based agent. They further explain that if another agent other than water has been chosen, the extinguishing agent shall have equivalent characteristics on a battery fire.

### 3.7.2 Swedish Transport Agency

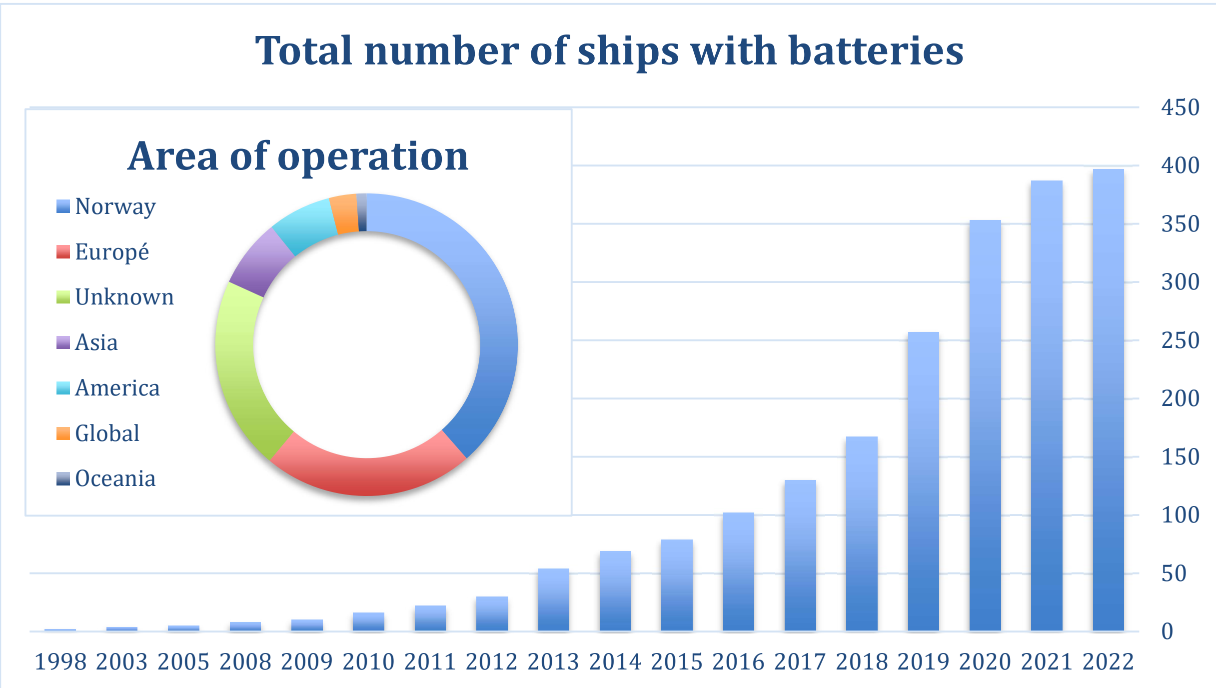
Ships travelling in inland waterways are not subjected to the regulations provided by SOLAS (Bisschop et al., 2021). Instead, they are subjected to national regulations issued by the flag state authorities. In Sweden it is the transport agency who dictates the standards for these ships. Ships using lithium-ion batteries for propulsion will have to comply with their guidelines for "battery and hybrid electrically propelled ships" (Saeed et al., 2021). In the report the Swedish Transport Agency suggest that a risk analysis regarding the battery installation should be conducted. Moreover, they recommend the shipowner to study a handful reports and guidelines. These include the DNV classification rules, and their report as described earlier in the theory.

## 3.8 Ships in Scandinavia with Battery Propulsion

The European economy is highly dependent on its ferry traffic. Approximately 70% of all the worlds journeys can be attributed to Europe and its 900 ferries (Anwar et al., 2020). As stated previously in the background, electrification of ferries can be very beneficial which makes Europe a likely candidate for using batteries for ship propulsion. This is especially true for Scandinavia, where the countries rely heavily on renewable energy sources (Svenska Kraftnät, n.d.). In fact, Scandinavia provides the densest maritime traffic where ships use batteries (DNV, 2022). Norway can be seen as the front runner when it comes to electrification. At the time of writing 210 of all 397 vessels in the world that uses batteries for propulsion can be found in Norway. According to Corvus Energy, Norway's goal is to have all their ferries electric by 2025 (Corvus Energy, n.d.).

**Figure 6**

*Statistics of the number of electrical and hybrid ships and their area of operation.*




*Note.* This statistic was retrieved from DNVs Alternative Fuel Insight. DNV. (2022). Alternative Fuels Insight. https://afi.dnv.com/Statistics?repId=3

# 4. METHOD

For the method, the authors of this report wanted to collect knowledge about how the onboard fire safety is changing due to ships using lithium-ion batteries for propulsion, preferably from an onboard point of view. It was determined that the best way of achieving this is through people who possess relevant knowledge and experience about onboard systems that include these batteries. Therefore, a qualitative interview method was chosen, as suggested by Denscombe (Denscombe, 2018). Moreover, the interviews were conducted as personal and semi-structured. The method used also considered the seven states of Kvale, as described by Jan Trost (Trost, 2010). Before the interviews began, a literary review was conducted through relevant databases to gain a greater knowledge about the usage of lithium-ion batteries for ship propulsion.

## 4.1 Literature Review

The literature review was performed by searching and reading previous research, and the review was conducted by using different databases. When choosing articles, it was important that they were of relevance. Firstly, the keyword lithium-ion batteries were used. Secondly, by stringing it together with the keyword environment and ship or vessel, the search was narrowed down to articles relevant for the background regarding environmental issues. The same method was used for the whole background and theory. Since the report regards new technology, up to date articles were of priority. Furthermore, some of the interviewees shared new reports and documents that had not been published yet.

The databases were the following:

- *Alternative Fuel Insight*
- *Chalmers Library*
- *DNV*
- *Google Scholar*
- *Mendeley*
- *ScienceDirect*
- *Web of Science*

The keywords that were used:

- *Alternative Fuels*
- *Environment*
- *Extinguishing Methods*
- *Fire*
- *Lithium-ion Batteries*
- *Safety*
- *Ship*
- *Thermal Runaway*
- *Vessel*

## 4.2 Selection of Respondents

Respondents were primarily targeted in proximity to Gothenburg where the authors of the report were working. Furthermore, the authors were striving to meet in person with the respondents, preferably onboard in the form of field trips. However, all respondents were given the possibility of interviews through online meetings, telephone, or email in addition to personal meetings. The authors were hoping that by providing more interview alternatives, more respondents would agree to interviews. Out of ten requested interviews, six agreed to be interviewed. Additionally, the authors strived to come into contact with the crew who had the onboard fire responsibility. This usually falls upon the engine department and the engineers. Participant C represent a smaller vessel with not engineers onboard and hence the fire responsibility falls upon the captain. Due notice is also to be taken regarding participant F, who is not representing a specific vessel. Instead, they have been involved in various projects regarding battery installations on ships. The interviewees are presented in the table below:

**Table 1**

*Shows the position, type of vessel, and what kind of propulsion method.*

| | Interviewee's | Type of Vessel | Propulsion |
|---|---|---|---|
| **A** | Senior Chief Engineer & Safety Inspector | Ro-Pax Ferry | Hybrid |
| **B** | First Engineer | Offshore Supply Ship | Hybrid |
| **C** | Captain | Passenger Ferry | Hybrid |
| **D** | Senior Chief Engineer | Ro-Pax Ferry | Hybrid |
| **E** | Chief Engineer | Offshore Supply Ship | Hybrid |
| **F** | Project Manager, Fire Safety | N/A | N/A |

*Note.* This information was retrieved during the interviews.

## 4.3 Interviews

The chosen method consisted of personal and semi-structured interviews. Furthermore, the interviews were conducted in Swedish. The reasoning behind the method choice derives from the authors desire to collect information about certain topics regarding fire safety onboard ships using lithium-ion batteries for propulsion, but at the same time letting the interviewed person provide new perspectives. By conducting the interviews in a semi-structured manner, information about the specified topics could still be collected and at the same time letting the interviewed persons relay their knowledge without any limitations. All interviewees agreed to be recorded.

**Table 2**

*Shows what type of interview and when it was conducted.*

| Interview | Type of Interview | Date |
|---|---|---|
| **A** | Person – to – Person | 2nd February 2022 |
| **B** | Person – to – Person | 10th Mars 2022 |
| **C** | Person – to – Person | 22nd Mars 2022 |
| **D** | Microsoft Teams | 29th Mars 2022 |
| **E** | Email | 5th April 2022 |
| **F** | Person – to – Person | 7th April 2022 |

*Note.* This information was inserted after each interview.

## 4.4 Interview Topics

With the knowledge gathered from the literary review questions regarding fire safety were prepared. These are the topics which were discussed during each interview:

- Fire prevention
- Fire extinguishing
- Fire drills
- Special training/education about battery safety
- Regulations
- Benefits in fire safety when using batteries

## 4.5 Ethics

Since the method was interviewed-based due regard was paid to the ethics revolving around them. The authors wanted the interviewed persons to have full insight about their rights and the purpose of the interview. The respondents were given information about the authors, the purpose of the study, and some background about the project. Moreover, they were given the interview questions and all their rights associated with the interview. Everything was summarized in a form of consent which were provided already when the authors reached out, requesting an interview. The form was a standard template provided by Chalmers University of Technology, specifically made for qualitative interviews. The template was altered to better suit the project (see appendix 1). This form was also discussed before each interview with the participants, and they then signed before starting.

## 4.6 Transcription, Processing, and Analysis

All interviews were transcribed and processed before results were established. The transcription part of the method was very tedious, so the authors divided the workload. However, after a complete transcription both authors listened to the recording and read the transcription carefully. After transcription the data was processed. The information was sorted under the previously stated topics. Information about fire prevention methods was sorted under fire prevention, and information about fire extinguishing systems was sorted under fire extinguishing, and so on. This way provided an overview of the information when all interviews were put in relation with each other. Before the results were produced, all of the summaries were printed out and placed next to each other. After this, the authors highlighted the similarities and differences under each topic between the interviewees. Everything that was not of relevance for the aim of the report were sorted out. Topic after topic, the highlighted sections were compared and produced as a result.

# 5. RESULTS

The results are presented according to the topics discussed in each interview. Lastly some other aspects are presented, as provided by the interviewees. These relate more to the general feelings of the interviewees, regarding battery fire safety. As a result of the semi-structured interviews, this information is not directly associable with the discussion topics, but important, nevertheless.

**Fire Prevention**

All ships in this investigation had similar solutions on how they were equipped to prevent a lithium-ion battery fire. All participants were equipped with BMS-systems together with conventional alarm systems like heat and smoke detectors inside their battery compartments. The BMS-systems had different temperatures at which they would disconnect automatically. Participant A explained the following about their BMS-system, "the system is designed to provide itself with power and enable operators to easily disconnect it from the grid, but still keep all safety functions alive". Furthermore, the battery compartments were made of A-60 bulkheads to protect the batteries from external heat. The compartments however, differed in their positioning. Participant C had the batteries placed within the engine room at the bottom level of the ship. Participant A had a container placed furthest astern and participant D had two containers at the top of the ship. The two supply ships, B and E, had their battery compartments installed on weather deck, close to the accommodation. All ships except B and E had possibilities of visual monitoring in the battery compartments with CCTV. The ship lacking this possibility did however plan on installing a glass window on the entrance door. The participants also explained that the battery compartments should always be closed.

Moreover, they all had a ventilation system in the battery compartment that was isolated from the rest of the ships ventilation system. This to keep the temperatures at desirable levels. All ships had air cooled batteries, except for participant D, which used de-ionized water too cool the batteries. Four of the ships, A, B, C, and D, were also equipped with thermal runaway pipes, which are pipes directly connected to the battery modules, to evacuate the toxic and explosive gases without releasing any into the battery compartment. Three of the participants also mentioned procedures on how to position the vessel so that off-gases would steer clear of the accommodation, in the event of a battery fire. This was also emphasized by participant F as an important aspect.

Additionally, the ships have adapted different solutions on how to protect their batteries from external heat sources. Two ships, C and E, had NOVEC systems, and two ships, A and D, used Aerosols. These systems could be released without causing damage to the batteries but still cool the compartment and keep the batteries cooled. In addition, participant A and D had a fixed sprinkler system installed on the outside of their battery containers, to protect them from external heat sources. All ships except participant C, did however have the possibility of external cooling by water, with the use of hoses or cannons.

**Fire Extinguishing**

The interviewees had adapted different solutions regarding their fixed extinguishing systems. The system of each participant is presented in the table below.

**Table 3**

*Shows what kind of fixed extinguishing system each participant had onboard.*

| Interview | Type of Fixed Extinguishing System |
|---|---|
| **A** | Aerosols |
| **B** | High Pressure Water Mist |
| **C** | NOVEC and Sprinkler |
| **D** | Aerosols and Sprinkler |
| **E** | NOVEC and Sprinkler |

*Note.* This information was retrieved during the interview.

Participant A explained that they had challenges with finding a Marine Equipment Directive (MED) approved extinguishing agent at the time of their conversion to hybrid propulsion. Therefore, they conducted a risk analysis together with the flag state authorities, their classification society, relevant persons from the shipping company, and the battery manufacturer. During this risk analysis, they concluded that adding water to batteries might accelerate the heat spreading between the battery cells. This is why they have disregarded water as an extinguishing agent. Participant A further explain that their aerosol system will not harm the equipment, only smother the fire, which enables anyone in the crew to activate it if they suspect a fire inside the battery container.

Participant B has opted for a water based extinguishing system as recommended by their classification society. They do however express some discomfort with the fact that they only have water to use in the event of a fire.

Participant C uses a NOVEC-system as their primary extinguishing system. On top of this, in coalition with the local fire department, they decided to install a fixed sprinkler system so they can flood the battery space if the fire would escalate.

Participant D has opted for a combination of aerosols and sprinklers. They explain that the aerosols are not capable of handling a thermal runaway. It is only installed to be used for keeping the batteries cooled and protected from external fires, such as a cable fire or other electrical equipment. Furthermore, they say that a single battery module shall be able to go through a thermal runaway, without affecting the adjacent battery modules. During tests of their system, it showed that if there is circulation on the cooling water the battery cell will increase to about 800 degrees Celsius. But the reaction will calm down quickly as long there is circulation. Therefore, it is only if the temperature would spread between modules, that they would activate the sprinkler system. The sprinkler system is a last resort solution since it will destroy the batteries.

Participant E uses a similar solution as participant C. The NOVEC is supposed to smother the fire, and if it does not work, they will activate the sprinkler system.

Of all the interviewees, none had the intention of going inside the battery compartments to fight the fire. Participant A explained that it would require very specific circumstances, per example if a colleague would be passed out inside. Instead, the interviewees rely fully on their fixed extinguishing systems.

### Fire Drills

All participants had in common that they regularly conducted fire drills where the crew familiarize themselves with the extinguishing systems and how to activate them. All ships except one also described procedures on how to cool the battery compartments from the outside. They also hold meetings where they discuss different scenarios that could happen in a potential battery fire. All passenger ships in the study, A, C, and D, had intentions to receive external assistance from the local fire department if a battery fire would break out. Furthermore, participant D explained that they perform a fire drill once per year, together with the Swedish fire department. The two supply ships, however, did not express any similar intentions. Moreover, participants A, B, and C, also discuss how to position the vessels to evacuate the smoke accumulated from a battery fire away from the accommodation.

### Special Training/Education about Battery Safety

Participant A, C, D, and E, had in common that they got information from the battery manufacturer during the installation of the system. The information is then spread internally to the new crew. Throughout, PowerPoints, operational manuals etc. Participant B however, said that no one in the engine crew had received any of this information. They further explained that the crew that had partaken in the battery installation might have received additional information, but they are uncertain. Participant D explains that they exchange information about battery fire safety, when they are having fire drills together with the Swedish fire department. They also explain that they conducted thermal runaway tests on a test facility before choosing which battery to use and that everybody in the engine crew have taken part of basic information about the automation system, alarm limits, and the battery theory. Participant F point out the importance of having sufficient knowledge about battery theory. This is crucial for making the right decisions on how to attack a battery fire. When to activate which extinguishing system etc. Battery theory is possible to study from external sources such as RISE, but to have sufficient knowledge about the ship specific battery system, it is of utmost importance that the crew partaking in the battery installation, pass on the information received to the rest of the crew.

### Regulations

**Table 4**

*Shows which regulating body each ship followed.*

| Interview | Regulating Body |
|---|---|
| **A** | Lloyd's Register |
| **B** | DNV |
| **C** | Swedish Transport Agency |
| **D** | Lloyd's Register |
| **E** | DNV |

*Note.* This information was provided before the interviews by their company's websites.

The two supply vessels have used the DNVs guidelines for their battery installations. Participants A, and D, have conducted risk analyses together with Lloyd's and developed their own standards. At the time they converted to battery hybrid propulsion, there were no clear regulations or guidelines to follow. Participant C is a smaller ferry classified for inland waterways, but they have also used DNVs guidelines for battery installations. Participant F explain that the regulations regarding battery installations of today are not yet complete. They believe DNV has come furthest in their guidelines. Furthermore, they explain that IMO are working on adopting international regulations through SOLAS. Participant F also explain that it is only natural for regulations to differ at initial stages of development, since it requires operational experience before international rules can be determined.

**Benefits in Fire Safety when using Batteries**

Participant A explains that the positioning of their battery compartment is lowering the risk of a fire spreading because it is far from other flammable materials. In comparison with the thermal spreading in a steel ship due to a large oil fire. Participant D said that there is a lower risk of oil fires the less you use the diesel engines, and that you avoid a lot of high pressures. Participant B said that their general feeling about battery propulsion is that it feels safer because it is easier to monitor and prevent a fire to break out in the first place, compared to a traditional propulsion system with a diesel engine. But if there is both a diesel engine and a battery installation onboard, they cannot see any advantages of this, because it is one more system that is a fire hazard. This was emphasized by participant F, who also believed that until we stop using fossil fuels completely there will be an additional fire hazard onboard. They did also argue however, that a fully electric vessel would be a lot cleaner and would not have the same extent of oil mist and leakages as a conventional machinery, which can easily ignite. They further explain that their belief is that a pool fire is much worse than a burning battery, since it might spread across an open deck, and this is much harder to control than a battery with a fixed position. Participant C and E did not provide any thoughts about benefits in fire safety when using batteries for propulsion.

**Other Aspects Provided by Interviewees**

Some of the participants express concern regarding their firefighting suits. Participant A addressed their standard issue firefighting suits as having insufficient protection towards the toxic off-gases. They further explained that there were appropriate firefighting suits being used ashore during lithium-ion battery firefighting. The problem, however, is that marine firefighting suits need to be MED-approved, and the shore-used firefighting suits do not have this approval at sea. Participant B also express discomfort revolving off-gases from battery fires, and they had chemical suits onboard, to be used over the firefighting suits for extra protection. However, these suits had the main purpose to be used against cargo fires and are not specially designed for battery fires. Of all the interviewees, only participant B had additional suit protection regarding lithium-ion battery firefighting. Interestingly, participant D did not regard their lack of additional protection as a problem and referred to a recent report released by RISE. Participant F also refer to the same report, but they point out that the report is focusing on battery fires in electric vehicles, in which case standard issue firefighting suits are sufficient. Nevertheless, if a lithium-ion battery fire would origin in a larger battery installation, in a closed space, like that on a ship, participant F urges extra caution.

Moreover, participant A and B expressed a relief in their choice of using air instead of water to keep the batteries at a satisfactory temperature. Especially Participant B, because they had the same batteries installed as M/F Ytterøyningen but with air instead of water and therefore felt safer that the same accident would not occur on their ship. However, participant D was satisfied with their choice of using de-ionized water as their cooling media because of the high performance and the ability to keep the batteries at a precise temperature, and therefore minimizing the batteries aging process. In addition, participant D explained that tests had shown that as long as there was circulation on the cooling water, the batteries could go through a thermal runaway without spreading across adjacent modules.

During the interviews, all participants expressed that they have faith that their BMS are working properly and if there would be an abnormality the system will alarm accordingly. Participant F explain that the battery manufacturing industry put a lot of resources in the development of battery cells and keeping the batteries from catching fire in the first place. This is because the cell level of batteries is the same regardless the installation and is hence beneficial to all industries. However, all participants did not have the same faith in their capabilities if an actual battery fire would occur. Participants A and D both share a strong belief that they are capable of keeping a lithium-ion battery fire in check until they get further assistance from the local fire department ashore. The other interviewees expressed uncertainties about their possibilities of handling a fire outbreak. Participant B explain that during their fire drills it is clear that they do not possess sufficient knowledge about battery fires. Participant C explain that they do not know exactly what would happen if a battery fire would escalate. Participant E said that they are not sure if they can handle a battery fire like they can a normal oil fire.

Furthermore, participant F addressed the problem that can arise when one becomes too accustomed to certain risks. When you get exposed to certain risks every day, there is a risk that people start to overlook the problem instead of solving it. Participant F gave an example about a person who connect refrigerant trailers on a daily basis. This person continues to do this despite sparks appearing at every connection. The same guy said that they would never accept electric cars to charge onboard the ferries because of the fire safety. This addresses the problem that people are willing to take risks that they are used to. This is a question of maturity. It shall be knowledge that makes you feel safe, not accept the risks you are used to.

# 6. DISCUSSION

In this study we wanted to find out how the fire safety is affected with the usage of lithium-ion batteries. Before the study, we did however not possess a lot of knowledge regarding lithium-ion batteries, and especially not how they are being used in maritime settings. The original idea was to find out how the pioneer ships have adapted and why they have adapted that way. We wanted to discover similarities and differences between ships and get a general understanding of the crew's knowledge and their feelings regarding their safety onboard. These energy carriers are new and provide hazards that many persons have not experienced before (Gardner, 2018). This includes us authors as well, and it was important for us to keep this in focus throughout the investigation. Therefore, we believed it was important to collect as much information as possible about equipment, procedures, and regulations. We know now that the scope of our investigation might have been too broad, as the results we have presented are for the most part general, and not so much in-depth. Nevertheless, we believe that we have discovered findings that are interesting, and that are pressing on the fact that using lithium-ion batteries for propulsion is still a very new technology and that there are still knowledge-gaps that needs to be filled.

## 6.1 Interviews

**Fire Prevention**

At first, we see that all battery installations were similar to each other even if they were of different manufacturers. This include their BMS, alarm systems, ventilation, and isolation. However, these are also aspects that are regulated by the classification societies (DNV, 2018). One important finding throughout the investigation that is not regulated is how different ships have opted for visual monitoring inside the battery compartments. We regard the usage of CCTV as particularly important since all ships have stated that they have no intention of entering the battery space as long there is no crew member passed out inside, or if there is an obvious external fire in a cable or on the carpet etc. Instead, they intend to keep the battery space isolated, monitor through their BMS, and let their fixed systems take care of a battery fire. As we see it, B and E might struggle with these procedures due to their lack of visual monitoring. Of course, it is possible to distinguish a battery fire from an external fire by looking at the temperatures in the BMS as described by Chin et al (2021). But in a stressed-out situation like an onboard fire, our theory is that people tend to not think rational and therefore, an external fire can easily be mistaken as a battery fire. That means, if the decisions made are not correct and swift, a small external fire could easily escalate to a full-scale battery fire. Also, installing a glass window as participant B suggests, might affect the A-60 isolation which is something their classification society DNV regulates (DNV, 2018).

The positioning of the battery compartments does vary quite a bit, but after a few field trips to different ships we can see that they have solved the issue as best they can. Several of the participants have not always been propelled by batteries, and as Anwar and authors (2020) write, the installations are heavy, so that might be a reason to the different solutions. Moreover, we think that the participants using thermal runaway pipes have a great solution, following the philosophy of keeping a safe distance from battery fires, and venting out toxic and explosive gases which can be very dangerous according to Willstrand et al (2020), and Helgesen (2019). We also want to put extra focus on the solution of participants A and D, who have the possibility of external cooling, and at the same time keeping a safe distance. This is a relatively cheap and easy solution that we believe all shipowners should acknowledge if applicable. Using fire hoses for external cooling will require the crew to focus on this, instead of the actual fire. Also, donning fire suits take some time. Activating a fixed sprinkler is much quicker.

**Fire Extinguishing**

The different extinguishing systems and methods of the participants brought up very interesting questions to us. It was very interesting to see that only one ship has disregarded water as a fixed extinguishing system. According to participant A, their risk analysis using water might pose more dangers than being helpful. This is strengthened by DNVs report on sprinkler systems (Helgesen, 2019). At the same time DNV themselves recommend a water based extinguishing system as back-up to a gaseous one, like aerosols (DNV, 2018). This is the solution of participant D, who even argued that only using aerosols will not be able to handle a battery fire. So clearly, there are conflicting opinions. What is correct is beyond our grasp, but there is obviously need for more knowledge and research on the subject.

Participant B on the other hand have opted for a single water-based extinguishing system, and they even express discomfort regarding this. We as authors can understand that discomfort, as using a water-based system will most likely destroy the battery installation according to our interviewees who use water. So, for participant B to try and extinguish a fire within the battery space without damaging the batteries, they would need to physically enter with portable extinguishing equipment. With the solutions of either using only gaseous extinguishing, or water extinguishing in mind, our opinion is that the ships with the most appropriate extinguishing systems are those with both options. By this they can release the gas without too much consideration of harming the batteries, and hopefully catching a fire at an early stage. If this would not work, they can use water as a last resort. As participant F explains, water is an infinite resource on a ship as long as the pumping equipment work, and it has a good cooling effect as DNVs report conclude (Helgesen, 2019). Lastly, we found it to be very interesting that none of the participants have opted for a direct injection of foam, which is supposed to be the best solution according to DNV (2018).

**Fire Drills**

Since battery fires are a relatively new scenario to the marine industry (Gardner, 2018). Because of this, we expected them to have specific procedures and regular drills to prepare the crew for this. This proved to be the case when we talked to our participants. Also, we have to acknowledge the fact that the batteries are restricted to a small compartment, which makes the need for practicing smoke diving somewhat obsolete. Instead, the result was good system knowledge, and a lot of tabletop discussions. Extra regard is to be taken if the idea is to keep the fire in check until local authorities can assist, or if it is to take care of the fire without further assistance from shore. The supply vessels might not have the opportunity to receive shore-based assistance, and because of this we believe it is of extra importance that they have thorough drills. And for the ships with the intention of receiving shore-based assistance, it is important that they train together with the local fire department like participant D.

Moreover, two of the participants explained how they shall carefully monitor the adjacent module temperatures and as long the temperature does not spread on the adjacent cells, they are not going to start their water-based extinguishing system. We have found that there are different ways to look at it. There are some potential risks, either you start the system and extinguish the fire at an early stage, but you also destroy the rest of the batteries. Then there is the risk of waiting too long, and therefore risking the fire to spread further, which results in a severe fire that becomes even more difficult to extinguish (Ghiji et al, 2020). We do not know if there are clear instructions on what temperatures the fixed extinguishing system is meant to be activated. If not, it is possible, as previously mentioned, that irrational decisions could be made in these types of stressed-out situations.

**Special Training/Education about Battery Safety**

In this part we want to highlight the fact that all systems vary, and that they are in several cases ship specific (Geertsma et al, 2017). This puts great pressure on the persons involved in the battery installations, that they get proper introductory education about the ship specific battery systems, from the manufacturers and shipbuilders. After the ship is built, it seems to be these persons who gets the responsibility of further educating the crew and new employees. According to us, the participants who were the most educated were those who had been involved already in the installation process. They were very confident and could provide thorough answers to all of our questions. On the other hand, participant B who had not received any additional education about their ship specific battery installation, radiated a lot of insecurity about their fire safety precautions.

Nevertheless, there are possibilities of collecting theoretical information about battery fire safety from external sources, in contrary to ship specific fire safety. From our study we can see that the persons with more knowledge feel safer and capable, and thus we regard theoretical knowledge about batteries just as important. It is easy to monitor cell temperatures but when the values start to become abnormal it might be difficult to determine the cause without proper knowledge. To understand the phenomena thermal abuse as described by Chen et al (2021), might help making the right decisions if temperatures are irregular. At the same time, many of the studies about battery fires are specific to electric vehicles for example and might not be directly applicable to a maritime setting. Per example, participant D argued that the HF gases from a burning battery will not penetrate standard issue firefighting equipment and thus they do not need any special suits and referred to RISEs report about this (Burgén et al, 2022). However, this report is conducted with electric vehicle batteries. On a ship, the battery installation is much larger, closed within a compartment, and will produce much more off-gases. Considering the conclusion by Willstrand and colleagues, that adding water to a lithium-ion fire will increase the HF production, applying water to a battery fire at sea might have different characteristics than that of an electric vehicle. We propose that these aspects should be kept in mind when collecting information from external sources and forums.

**Regulations**

This part of the investigation really showed us authors that using batteries for propulsion is something new to the marine industry. As far as the regulations go, the ships use similar solutions for fire safety (DNV, 2018) (Bisschop et al., 2021). But in the areas not covered by the classification societies, they have adopted different solutions. It was interesting to us that participants A and D, who have the same classification societies have conducted their separate risk analyses and come up with different extinguishing systems. According to us, this is proof that there are knowledge-gaps about optimal fire safety solutions. However, these participants use different battery manufacturers and cooling systems which might be a reason to the conflicting ideas. We do agree with participant F, that the regulatory work is not yet complete. In our experience, introducing new international regulations at sea is a slow-moving process. Usually, the regulations will change after a major calamity have occurred. At the same time, international regulations cannot be set before it is certain what should be prohibited and allowed, and this requires operational experience. By that, we think that it will take a while before we see an international convention on lithium-ion battery safety. In the meantime, ships should spread their knowledge between them, as several of them have come up with great solutions on their own.

**Benefits in Fire Safety when using Batteries**

The general feeling from our participants about this was obvious. They believed that a battery propelled ships would be less prone to a fire accident due to it being easier to monitor and control. But we have to keep in mind that they were all serving onboard hybrid ships or have been working with hybrid ships (Geertsma et al, 2017). There have not been many battery fires at sea, regarding larger installations, and there are not many fully electrified vessels yet (DNV, 2022). So, this is only hypothetical opinions. But our own opinion is that we agree with our interviewees for now.

**Other Aspects Provided by Interviewees**

This part follows the same line as previous topics with conflicting ideas between the interviewees. It was very interesting, and a bit alarming, that one participant regarded their lack of additional protective suits as a serious concern, while another participant did not even see it as a problem. Moreover, it was a bit surprising that only one participant had taken extra precautions with the usage of chemical suits over their firefighting suits. It is worth to notice that participant B was also the one who expressed most insecurities about their battery installation, which might be a reason for their extra care. We also want to highlight that all participants who used air-cooled batteries were happy about not having water-cooled batteries. In contrary, participant D were happy about having water-cooled batteries, since their superior cooling capabilities. It is hard to point at a concrete reason for these different opinions, but since M/F Ytterøyningen used water-cooled batteries which caused the thermal runaway, people might regard them as dangerous (Corvus Energy, 2020). Technical systems tend to come with pros and cons, and this is surely one of those systems. Furthermore, the ship using water-cooled batteries had high electrical loads during charge and discharge which required optimal cooling. The ships using air cooled batteries did not have the same high electrical loads.

Also in this segment, there were clear connections in the participants knowledge and how their general feeling was when it comes to the batteries fire safety. The ones with a greater understanding of the system could see much more advantages of having this system in comparison with participants B and C, as both of them expressed uncertainties on how to manage the situation regarding a potential battery fire. As we see it, more knowledge leads to feeling more secure. We also want to highlight what participant F said about the tendency to neglect risks after growing accustomed to them. It is important that you feel safe because of knowledge and not because of the fact that you do not care anymore.

## 6.2 Method Discussion

As this was the first time for us using scientific methods to collect information, we had to do a lot of studying before starting off. Our literary review was essential because neither of us had any extensive knowledge about battery installations onboard ships. Thankfully, we had basic knowledge about how to use key words in the scientific databases to collect relevant sources. With the help of tools provided by our university to evaluate sources, we believe that we conducted a decent literary review and provided a good background and theory. This was later confirmed to us when we began our interviews, as it was easy to follow the discussions by our interviewees. Because our topic is a very new technology that is under constant development, some of the reports we thought were up to date were actually not as we later got newer reports from one of our interviewees that had not yet been published. This shows that there is a risk that we might have missed other information that have not been published or have not been accessible through our databases. Furthermore, we had to add to our theory successively, because the interviews opened up new aspects that we had not thought about. This serves as proof that our literary review was far from perfect.

Our main method, the interviews, was something that neither of us have ever done. It required several weeks of studying our literature on semi-structured interviews before we could start off. The two books, Trost (2010), and Denscombe (2018), helped us from the planning stage down to the presentation of the results. Since our knowledge about batteries for propulsion was limited at the beginning of this investigation, we decided the interview topics to cover as many areas as possible within fire safety. If we would do this investigation all over, it could easily be divided into more in-depth investigations within each of our topics. Nevertheless, we set out to get a general view of the battery fire safety onboard, and this is something we have succeeded with.

At the beginning we aimed to come in contact with passenger ferries only. However, quite early in the process of finding interviews we noticed that it was extremely hard to come in contact with the crew onboard, through the shipping companies. Therefore, we had to expand our scope, but even then, we had difficulties to establish interviews on our own. All of our interviews except one were established either through our supervisor, examinator, or through other interviewees. Three of our respondents did not even reply to our emails. Luckily, there were upsides of choosing an interview method also. We got to conduct three field trips to different ships, and these field trips made it possible to get an even better understanding of the battery installations. A lot of the knowledge we possess now would not be possible without them.

Another aspect of conducting the interviews on site, was the advantage of a better interaction between us, and the interviewee through person-to-person interviews. This opened up for better conversations, with the possibility of follow-up questions. We found these types of interviews to be of much more in-depth, in comparison with the interview conducted through email, which only scraped on surface. Lastly, we have to acknowledge the fact that all of our interviews were conducted with representatives on leading positions. When it comes to system knowledge of the battery installations, we regard our method of choice as the optimal one. However, one of our research questions regarded how the general feelings about the possibilities of handling a lithium-ion fire onboard were. For this, we might have gotten different replies from other positions onboard the ships. It might have been better to conduct a quantitative interview method for this. However, it is hard to determine a person feeling without a person-to-person interaction. So, we still believe that our results regarding this are relevant, even if the pool of respondents was limited.

## 6.3 Reliability

According to Trost, there can be issues when it comes to qualitative studies and interviews regarding reliability and validity. This was an important aspect for us throughout the study. There is always a risk of getting different data on different occasions with interview-based data collection. We did our best to stay consistent throughout our interviews. We kept our own opinions out of the discussions and when uncertainties appeared around some information, we asked the participants to further explain so we could understand exactly what the participants meant.

## 6.4 Validity

The articles that have been used in this study have all been peer-reviewed which strengthens the validity. Furthermore, we focused on persons with the onboard fire responsibility which according to us deems the validity of our sources to be high.

# 7. CONCLUSION

At first, we can conclude that as far as the regulations cover, our ships have adapted in similar manners. It is when regulations become more general that we see different adaptations. One reason is that ships and their propulsion systems differ across different areas of operations. Another reason is due to the knowledge-gaps in the shipping industry, and the fact that some of the ships were pioneers within the field at the time of their hybridization. One thing that points to the fact that the technology is under constant development, was that some of the participants possessed a lot of knowledge but still had conflicting opinions. One positive aspect was that most of the participants had read about the earlier accident, M/F Ytterøyningen, and understood the importance of never running without the BMS online. This indicates that information can be spread between ships efficiently. However, until international regulations are established regarding lithium-ion battery fire safety, which will require further operational experience, it would be beneficial for the shipping industry if the different solutions onboard were publicly available for shipowners and the onboard crew, not only when accidents occur. A lot of our participants had come up with great solutions that would improve the fire safety onboard other ships, CCTV, and outside sprinklers etc.

Secondly, we can conclude that the general feeling about capabilities to handle a lithium-ion battery fire relates more to the level of knowledge the crew possesses, rather than which systems and methods they have onboard. We press on the importance of properly passing down the information received from the manufacturers about the ship specific battery installations. This is a key part of feeling capable and should be combined with theoretical knowledge about lithium-ion batteries. We also want to urge some caution when collecting information on lithium-ion batteries. It is important to distinguish between larger battery installations and smaller shore-based ones, and in which environment they have been tested. Also, since the rapid development of regulations and batteries, the relevance of the information can quickly become outdated.

## 7.1 Recommendations for Further Research

- How can theoretical education about lithium-ion batteries be introduced in maritime education?
- What environmental impacts will a lithium-ion battery fire at sea have, due to using water as an extinguishing agent?
- Are special suits required when fighting a lithium-ion battery fire at sea, due to the HF off-gases?

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# APPENDIX 1

**Interview Questions**

The questions that were sent out together with the form of consent are presented below:

- Which methods are used to prevent a battery fire?
- Which methods are being used to extinguish a potential battery fire?
- Do you conduct any special drills around battery fires?
- Do the crew onboard take part in any special training in fire safe regarding battery installations?
- Which regulations are the vessel subjected to?
- Do you see any advantages with the fire safety if you compare with a traditional propulsion method?

**Form of Consent**

The ethical rules that all of the participants agreed on are presented below:

- I have read the information about participating in the study and am aware of how the data collection is performed and the estimated time it takes.
- I have had the opportunity to ask questions regarding the study and have them answered beforehand.
- I participate in this study completely voluntarily and have been informed about why I have been asked and what the purpose of my participation is.
- I am aware that I can cancel my participation at any time during the study without having to give a reason for this.
- I give this consent provided that no one other than the student/-s / supervisor / researchers associated with the study will take part of the collected material.
- I am aware that the study is completely anonymous and collected data will be reported without connection to person, vessel, or company / shipping company.

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