0 ELBAS – WP0: Introduction and Background

The Danish Maritime Fund –
Project number 2021-039

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0.1 The ELBAS Project

The ELBAS project (Electric Vehicle Fires at Sea: New Technologies and Methods for Suppression, Containment, and Extinguishing of Battery Car Fires Onboard Ships) aims to develop new solutions, training forms and risk assessments that can help improve the fire safety of electric cars on board ferries, as electric cars form an increasing part of the Danish car fleet. The project identified potential solutions and developed mockups for new, near-to-market, effective fire-extinguishing technologies, and firefighting techniques for tackling Electric Vehicle (EV) fires at sea. The conclusions from this project have an emphasis on practical solutions, which are simple, quick, and affordable to implement for Danish ferry and shipping companies.

The ELBAS project ran from October 1st, 2021, until December 31st, 2022. It was made possible thanks to the generous financial support of the Danish Maritime Fund (project number 2021-039.)

0.1.1 Project Stakeholders

This project was completed with the assistance of a wide range of companies focused on the shipping industry. Below is a list of the project stakeholders:

- Project Coordinator: The Danish Institute of Fire and Security Technology (DBI)
- Danish Shipping Companies: DFDS, Scandlines, Molslinjen, and Stena Teknik
- The Danish Maritime Authority (DMA)
- Danish Emergency Services: Danish Emergency Management Agency (Beredskabsstyrelsen) and Danske Beredskaber (in Slagelse municipality)

0.2 Introduction and Background

As an effect from the Danish government's ambitious green transition plan, it is projected that there will be 750,000 electric vehicles (EVs) registered in Denmark by 2030. The increase in EVs on Danish roads is as a major step towards achieving full climate neutrality by 2050. However, while EVs have obvious benefits for decreases in CO_2 emissions from the transportation sector, they present unique and complicated challenges when it comes to fire safety.

After years of having significantly lower sales of EVs compared to Sweden and Norway, Danish sales of EVs are on the rise. In the first half of 2020, EV sales almost doubled from 2019, while sales of internal combustion engine vehicles dropped 31%. Currently, there are approximately 31,900 registered EVs in the Danish car fleet, accounting for 1.2% of personal vehicle transportation.

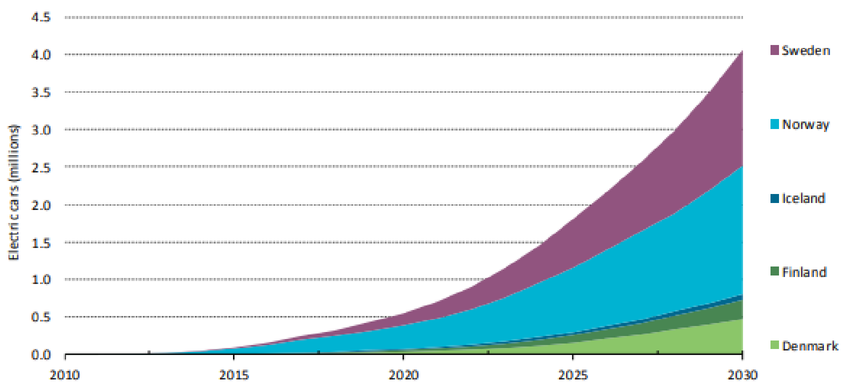

Figure 0.1: Electric vehicle projections in Nordic countries to 2030 [Nordic Energy EV Rapport, 2018]

The policy ambition of Denmark, and the Nordic region overall, to increase the electric car fleet suggests a marked increase in EVs over the coming years. It is projected that 4 million electric cars will be on the road in the region by 2030.

0.3 The Challenge

As more EVs enter the transportation market, issues regarding the containment and extinguishing of battery fires need to be addressed. Battery fires can originate from abuse during regular use, charging treatment, or even thermal abuse exterior to the battery (i.e., a fire originating within the passenger compartment or outside of the vehicle). If the battery is abused to the point of causing an internal short circuit the compromised cell within the battery pack can undergo Thermal Runaway (TR). Sources of abuse range from mechanical abuse (puncture), thermal abuse (overheating), or electrical abuse (under and overcharging) that each can potentially lead to a TR event. Once one cell within the battery pack enters TR a cascade-like process can occur where the cell experiencing TR can propagate to neighboring cells which can result in fire, arc flashing, off gassing, and sometimes explosions.

However, battery fires cannot be extinguished or suppressed using standard fire extinguishers alone and may require vast amounts of water to put out compared to gasoline or diesel engines. Furthermore, there is a risk of batteries reigniting up to 24 hours or more, after extinguishing. Additionally, toxic smoke and soot present a danger to the health of both people and the environment. These factors become compounded risks and hazards during maritime travel, where space is confined, and firefighting equipment and resources are limited.

0.4 The Lithium-ion Battery Inside of an Electric Car

Conventional vehicles often rely on gasoline, diesel, or other fossil fuels for their power source, whereas EVs are powered using a lithium-ion battery (LIB) pack as their powertrain. Firefighting medium and tools have been developed and industry tested when responding to a conventional vehicle fire. Currently, there is not a universal firefighting medium and tools when responding to an EV fire. This skill gap is due to the unique decomposition of LIB packs.

One unique reaction found in the decomposition of LIB cells is the formation of oxygen when the electrodes within the LIB cell decompose. This self-generation of oxygen is one reason that traditional fire extinguishing methods are ineffective against LIB fires. Responding firefighters, not familiar with EV fires, have been humbled by the intensity and tenacity of these fires. The internal chemical reactions within the LIB cells continue to evolve even after all flames emanating from the LIB pack have been extinguished. There have been recorded cases of extinguished EVs reigniting during transport to a secure holding area and even cases of reignition 24 hours after extinguishment. A common practice for shore-side emergency services is to use thermal imaging equipment to monitor hot spots on the failed EV. Since the LIB pack is encased within a protective frame the important aspect of this extended monitoring process is to note any increase in temperature of the neighboring surfaces.

Risk of reignition aside, if a vehicle bursts into flames the priority should be to remove any people inside or around the burning vehicle to safety, prior to fully extinguishing the fire. Extraction tools commonly used by shoreside emergency services, such as hydraulic shears and spreaders, axes, Halligan bar, irons, etc., give professional firefighters the ability to safely extricate trapped passengers. The danger when responding to an incident involving an EV is that high voltage cables can be routed through the vehicle's frame. Without knowledge of the vehicle's construction, firefighters may expose themselves to electrocution hazards.

With more EVs on the roads and an increasing demand for charging stations, both on land and at sea, there is a need for efficient solutions to management of battery fires. While EV fires at sea are a rare occurrence at present, the likelihood of fire related accidents rises as EVs make up a larger share of vehicles in Denmark. This project aims to address this increased risk and improve safety by identifying practical measures and developing training methods for putting out LIB fires at sea.

Although battery safety has improved greatly and Battery Management Systems (BMS) are now found on most newer vehicles, there are still many older vehicles on the roads. Older vehicles are more likely to be poorly maintained or less compatible with new models of charging docks, increasing the potential of technical issues and risk of fire. Battery damage can be hard for drivers to detect, leading to delayed ignition, and human error using charging docks can lead to accidents. Furthermore, the EV industry lacks common standards for design and safety, such as battery placement, which poses an additional obstacle to fire safety and extinguishing efforts. As EV usage is expected to rise in the coming years, so increases the variety of models potentially having their own and differing BMS. This creates new challenges in establishing efficient standardized safety strategies in case of battery fire, both on land and at sea.

0.5 Fire Safety at Sea

Ferries offer the attractive advantage of transport over long distances, saving EV drivers both km driven and downtime for re-charging breaks during the journey. This introduces the new challenge of allowing passengers to be able to recharge their vehicles while on-board. Some ferry companies have chosen not to offer this option for safety reasons, instead only allowing charging while waiting to board in port. Pressure from the EV consumer and manufacturing markets are great, and it is projected that soon charging onboard for EVs will be common practice.

As charging locations become more commonplace and the range between recharging increases, more and more EVs will be traveling around the country and crossing national borders. The Nordic region has the highest number of EVs per capita in the world, and policy across the Nordic countries favor carbon-reduced transportation, resulting in the number of EVs travelling across Denmark likely to significantly increase soon. These journeys will include travel onboard ferries, which offer the additional benefit of reduced driven kilometers and thus further increasing their range between recharging.

However, with this development comes an increased risk of an EV fire onboard maritime transport, which adds additional demands for shipboard firefighting capabilities, both in terms of training and materials. Since EV fires are already considered complicated on land, the requirements for successful fire containment and extinguishing at sea present the need for reviewing, updating and further developing the current standards and methods.

To support the ongoing development of greener transportation, there is a need for both long and short-term solutions to fire safety concerns, particularly those related to maritime transport of EVs. While firefighting services on land are developing specialized protocols and technology for handling battery fires, these types of fires are still a very rare occurrence and rank much lower than other safety concerns at present. However, the implications of a shipboard battery fire are so great that, when they occur, the crew need to be able to react quickly and efficiently. This will increasingly be the case, as we move towards 2030 and the Danish government's goal of 750,000 EVs.

As transportation technologies continue to develop, with future EVs presenting a variety of battery types and different modes of charging, fire safety becomes increasingly complex and requires an agile and forward-thinking approach to meet challenges as they arise, as well as short-term solutions to immediately address potential risks.

0.6 Project Goals and Objectives

The overall goal of the ELBAS project is to identify and present new holistic fire strategies, for fighting EV traction battery fires at sea: This to prevent and manage the increasing potential for such fires onboard ferries, as EVs make up a growing segment of the Danish car fleet. The objective is to prevent both the loss of lives and extensive property damage and support the expansion of electric transportation by preparing for fire safety issues. Another goal is to promote Danish influence on future technology for fire safety, and propose efficient solutions, including training, materials, and equipment for managing battery fires at sea.

The activities conducted in the ELBAS project also work to support the Danish government's goal of greatly increasing the number of EVs in Denmark by 2030, as well as the widespread ambition of an increasingly electric car fleet in the Nordic region, in general. The ELBAS project supports several of the UN Global Goals for Sustainable Development. Namely UN SD Goals 7, 9, and 13. Goal 7 is regarding universal access to renewable energy and marked increase in the use of renewable energy. Goal 9 is regarding the development of reliable infrastructure, supporting sustainable industry and investing in innovation and research. Goal 13 is regarding climate measures to restrict the global temperature spike and strengthen resilience and climate adaptations.

The aim of the ELBAS project is to strengthen the position of Danish stakeholders, the Danish maritime industry, and to break down barriers to the green transition in Denmark, while also contributing to the achievement of the UN's global sustainability goals.

0.7 Project Description

The ELBAS project work has been intensive, focusing on delivering immediate, easily implementable, and relatively inexpensive solutions for Danish ferry companies and the crew onboard. While battery fires aboard ships do not happen often, they pose a significant risk to both people and assets and these risks will only increase as EVs and charging stations become more commonplace.

To reduce the risk of future accidents, fire safety measures and specialized equipment must be able to address these risks. To do so, the project proposes methods and equipment working with local emergency services to transfer and further develop existing knowledge of EV-specific firefighting techniques on land to the maritime sector.

0.7.1 How Should Fires in Electric Vehicles be Handled?

Fires involving LIBs have proven to be a challenge. When a lithium battery ignites, it causes an adverse chain reaction that keeps the fire burning. When thermal runaway occurs, the batteries produce oxygen during the decomposition of the LIB cell's electrodes. This reaction creates a fire feedback loop that makes the use of standard dry-powder and CO_2 extinguishers ineffective.

Until now, there are only two options when tackling such fires:

- Simply let the fire burn until the battery runs out of power and the fire will put itself out.
- Douse the fire with thousands of liters of water, which is far more than what it takes to extinguish any fire from a gasoline or diesel engine.

Neither of these options are particularly feasible on board a ship, where vehicle deck space is limited and confined, and extra weight effecting the stability of the vessel is of concern.

0.7.2 Other Hazards to be Aware of in Electric Vehicle Fires

EV fires present additional challenges to emergency response services as although the ensuing fires can be controlled utilizing normal procedures, there is the possibility of the battery itself reigniting after a short period and all the way up to 24+ hours later.

If punctured, breached, or otherwise damaged, heat can build rapidly inside the compromised battery cells and spread to surrounding cells in a cascade-like process called thermal runaway, which can lead to fire, arc flashing, off gassing, and sometimes explosions.

Firefighters typically also lack proper protective equipment to handle or remove the battery's energized lithium-ion cells, as there is no practical way for first responders to drain the potentially massive amount of energy still trapped in an unstable battery. A vehicle's frame could be energized, but firefighters lacked special tools to test for it.

0.7.3 General Principles of the ship's Fire Main System

The fire main is a system consisting of sea inlet(s), suction piping, fire pumps and a distributed piping system supplying fire hydrants, hoses and nozzles located throughout the vessel. Its purpose is to provide a readily available source of water to any point throughout the vessel which can be used to combat a fire and is considered the backbone of the fire-fighting systems onboard a vessel. Through the fire main system, the firefighter is provided with a reliable and versatile system capable of providing a number of different methods with which to engage a fire.

0.7.4 Fixed Fire Extinguishing Systems

Some fixed fire extinguishing systems are not suitable to control the type of fire seen with EVs, where cooling of the battery pack is key to control thermal runaway (TR).

For example, vehicle decks on ships are normally protected by a fixed firefighting drencher or water mist system. Water is supplied by the fire main system. Such systems are designed and dimensioned for extinguishing fires on vehicle decks covering fixed zones and have nozzles located above the vehicles.

0.7.5 Extinguishing Water may be Poisonous

A problem, however, is the extinguishing and cooling water which is produced when fighting such a fire and storing a burnt-out battery in a water basin.

Analyses from a Swiss study on the subject showed that the chemical contamination of the extinguishing water exceeded the acceptable threshold values for industrial wastewater by a factor of 70; the cooling water is even up to 100 times above threshold values. It is important that this highly contaminated water does not enter a sewage system without proper treatment. While onboard a ship, extinguishing water would either be collected in the bilge system or go directly overboard, in an emergency at sea safety of life and property normally has priority over environmental concerns. Despite this, the potential for contaminated extinguishing water should also be taken into consideration.

0.7.6 Toxic Soot

The soot from an EV fire contains large amounts of cobalt oxide, nickel oxide and manganese oxide. These heavy metals cause severe allergic reactions on unprotected skin. Clean-up after an EV fire is a job for suitably trained personnel donning the appropriate personal protective equipment.

The above factors present an even greater risk when a fire occurs at sea, on board ships where space is confined, and firefighting resources are limited. Danish and international ferry operators are facing these realities today and are interested in having new fires safety challenges with EV fires addressed promptly.

0.8 The Ships

Fire safety on board ships is traditionally covered by IMO regulations[1], Flag state and national requirements, and by classification society rules and notations. For European flagged passenger vessels operating in a domestic trade, are subject to the EU Passenger Ship Directive (2009/45/EC). All three shipping companies and vessels included in the ELBAS project, operate in accordance with all the applicable requirements and current legislation.

To address the issues surrounding EV fire safety onboard ferries, the ELBAS project has investigated three different passenger ship types, which are representative of those in operation by Danish ferry operators.

The three different types of ferries are:

- Overnight Cruise-Ferry – with a totally enclosed vehicle deck, and a retractable car deck
- High-Speed Ferry – two vehicle decks, fully open at stern and opening forward upper car deck
- Ro-Pax Day Ferry – two full height vehicle decks, lower enclosed and upper open at either end

An overnight ferry will typically have hotel style accommodations for passenger and the crew in cabins, and may only have one or two loading and unloading of passengers and on the vehicle deck. While a day ferry typically has many voyages during a day, involving multiple loading and unloading of passengers and on the vehicle deck.

One of each of these ship types, from three different Danish ferry companies was selected. The ships each service different routes of varying distances and vary significantly in age, vessel and crew size, and with three different vehicle deck configurations.

[1] IMO regulations refer to *Ro-ro passenger ship (*which means a passenger ship with ro-ro spaces or special category spaces) and to *High speed passenger craft* (which are passenger ships built subject to the IMO's **HSC Code** - International Code of Safety for High Speed Craft.) For the sake of simplicity, these ship types in the ELBAS project are referred to as Ferries and are further distinguished by the commonly used descriptions of: an Overnight Cruise-Ferry, High-Speed Ferry, and a Ro-Pax Day Ferry. All three ship types have ro-ro cargo spaces, which in the ELBAS project are referred to as *vehicle decks*.

0.8.1 PEARL SEAWAYS: Overnight cruise-ferry

The PEARL SEAWAYS, formerly PEARL OF SCANDINAVIA and originally delivered as ATHENA, is a cruise ferry built in 1989 in Turku, Finland. The ship is Denmark's largest passenger ship with an overnight capacity of 1,832 passengers in 703 cabins. The has PEARL SEAWAYS sailed on DFDS's Copenhagen-Oslo route since 2001, and as of June 2020, her route also includes a stop in Frederikshavn. The overnight voyage between takes approximately 19- hrs.

In November 2010, the ship experienced a fire on the vehicle deck, in an EV left charging (unauthorized) onboard[2]. This was the only known EV fire incident to have occurred onboard a Danish ferry, at present time. Following the fire, the ship was refitted and given its current name.

0.8.2 EXPRESS 4: High-Speed Ferry

The EXPRESS 4 is a high-speed catamaran ferry built in 2018 at the Austal shipyard in Australia. EXPRESS 4 sails the route(s) between Aarhus/Ebeltoft and Odden, Denmark and has a capacity for 1006 passengers. The ship operates on shorter crossings (and does not have overnight accommodation for passengers sailing onboard. Instead, passengers spend time in the ship's lounges, where food and a large seating area are available.

The EXPRESS 4 is the fastest vessel of the ones examined in ELBAS, capable of reaching speeds of 40.5 knots (75 km/h), allowing for multiple journeys during a day, involving multiple loading and unloading of passengers and on the vehicle deck. The types of passengers sailing onboard EXPRESS 4 are typically persons who need a quick route to go from Zealand to Jutland without passing over the island of Fyn.

The EXPRESS 4, unlike the other two vessels investigated by this report, is constructed using aluminum, which potentially makes the ship more vulnerable to the effects of a fire. However, EXPRESS 4 is constructed to, and fully meets, all of the statuary fire safety requirements for such vessels.

0.8.3 COPENHAGEN: Ro-Pax Day Ferry

The COPENHAGEN is a Ro-pax day ferry, completed at the Fayard A/S shipyard in Denmark and was delivered to Scandlines in 2016. A Ro-pax day ferry is a Roll-on/roll-off ship designed to carry wheeled cargo, such as cars, motorcycles, and trucks that can drive on and off the ship on their wheels. The ship sails the Gedser-Rostock ferry route between Denmark and Germany together with her sistership, BERLIN and has a capacity for 1,300 passengers.

The COPENHAGEN has two full height vehicle decks, and is similar to both the PEARL SEAWAYS in the layout of the lower vehicle car deck and to the EXPRESS 4, with the COPENHAGEN’s partially open upper vehicle deck. As a day ferry, the COPENHAGEN does not provide any overnight accommodations onboard for passengers, but the ship has a selection of restaurants allowing passengers to buy food and relax for their approximately 2-hr journey.

The PEARL SEAWAYS, EXPRESS 4 and COPENHAGEN are subject to regular safety inspections, and all are certified in full compliance with the Danish Flag Sate requirements. Each of three ferries was visited during the ELBAS project, and their crews were interviewed regarding onboard fire safety and the challenges of EV

[2] Division for Investigation of Maritime Accidents of the Danish Maritime Authority/ Danish Maritime Accident Investigation Board, “PEARL OF SCANDINAVIA Fire,” pp. 1–14, November 2010.

fires specifically. In addition, the vehicle decks of these ferries were modeled using computational fluid dynamic tools, to preform fire simulations of various fire scenarios.

0.9 Challenges of Shipboard EV fires

Battery fires are complicated fires to extinguish, even for well trained professional full-time land-based firefighters. So, it is to be expected that they are even more so for seafarers, where fires are a rarity. Some of the potential risks and challenges needing to be addressed are:

- The EV itself (battery has risk of thermal runaway, particularly toxic smoke/soot/extinguishing water, creates its own fire with production of oxygen, not much space available for isolation and firefighting making it difficult to access and extinguish)
- Lack of specialized training for shipboard firefighters.
- Lack of effective fire suppression and extinguishing equipment on board.
- Risk of fire spreading from other burning cars or trucks on board.
- Risk of using incorrect, poor quality, or unauthorized charging cables.
- Saltwater environment.

Shore-side emergency services have developed methods and techniques to tackle fires more effectively in EVs. This experience of handling such complex fires can greatly benefit marine firefighters, so an important component of the ELBAS project is to bring together crew members of shipboard fire teams with their counterparts from shore, and to conduct realistic joint firefighting exercises and training with EV fires. This will promote improved and efficient fire strategies and the sharing of best practices and lessons learned from EV fires.

0.10 Research into EV Files

The ELBAS project has been focused on identifying practical and concrete solutions, which can be implemented immediately improving the safety of transporting EV by ship. The identified solutions in ELBAS provide knowledge of which firefighting equipment and fire strategies are most efficient to contain EV fires quickly and effectively.

Several large multi-year R&D projects have been underway addressing fire safety of Ferries, such as the EU Horizon Europe Project LASH FIRE and the German national funded project ALBERO, which have work packages investigating many of these issues. While awaiting results and final conclusions from these multi-year projects, it was felt that stopgap measures were needed which can quickly be put into place, in order to keep the passengers, crew and first responders/shipboard firefighters safe, when faced with added risks, dangers, and complexities of shipboard EV fires. It is the goal of ELBAS to provide this.

This project addresses many of these challenges, examining current practices of tackling battery fires on board ships and developing effective methods and propose solutions. The issue of fire safety should not be a barrier to meeting the increasing market demand and support the green transition.

0.10.1 Project Work Packages

WP1: Interview stakeholders on training methods and competencies. Fact finding from and field study at land-based/shore-side emergency services.

WP2: Screen current technologies and methods both for maritime and on-shore use – present hypotheses and design criteria. Mapping existing methods to suppress and extinguish fires in electrical cars.

WP3: Develop experimental test set-up and conduct tests – combining existing solutions, applying technology from other industries, or trying out completely new solutions. Goal: Present a list of potential solutions.

WP4: Evaluate current drills and training methods, perform specialized training, and identify future training needs.

WP5: Final evaluation, conclusions, and recommendations, including dissemination activities (published articles, presentations at seminars, workshops, and conferences.)

0.11 Project Results

The outcome of the ELBAS project is the development of performance based holistic fire safety strategies for EV battery fires on ferries, focusing on delivering solutions for the Danish maritime sector that are implementable and affordable in the short-term. This was realized, in part, through transfer and further development of existing knowledge of EV-specific firefighting on land to the maritime sector through interdisciplinary cooperation, and in part by original research, experimentation, analysis and evaluation leading to new insights. This two-prong approach provides concrete methods and materials, evaluate, and develop techniques, and identify future needs for firefighting equipment and training.

Furthermore, the project has increased the awareness of the complexity of EV traction battery fire, and the need for both short- and long-term solutions and addressing fire safety issues, which potentially could slow or hinder the fulfilment of government policy goals in the Nordic region. Through a broad involvement of partners, the project focuses on anchoring results and making them immediately useful in the maritime sector. This will help to facilitate safer EV travel across Denmark and throughout Europe, with reduced risk for potential fatalities and property damage.

Finally, the project provides a foundation for stakeholders in the maritime industry in Denmark - and Danish companies manufacturing detection and suppression technologies at the forefront of the development of EV fire safety at sea.