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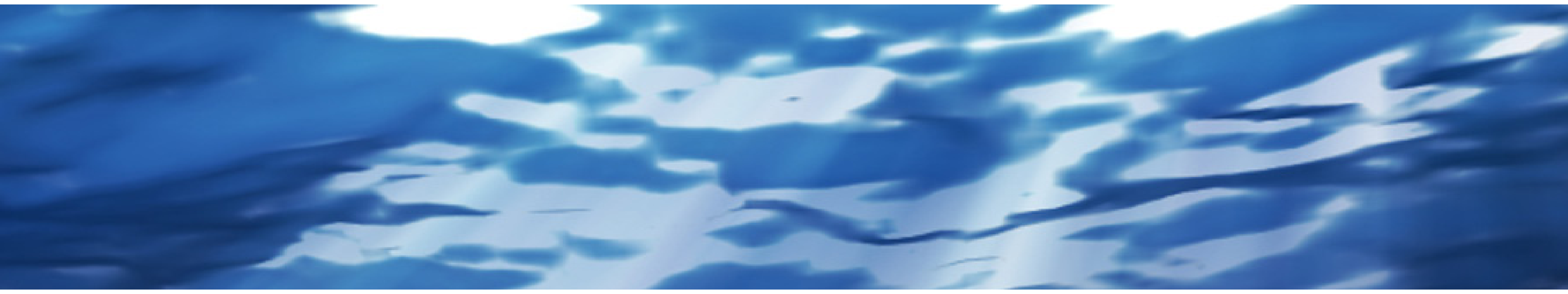
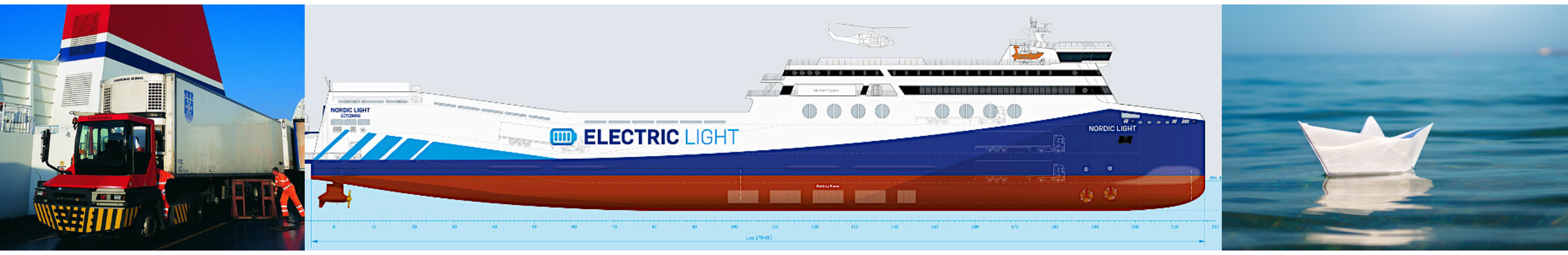


LIGHTHOUSE REPORTS

Lätta elfartyg – Electric Light

Lightweight and electrically propelled Ro-Pax ships



An innovation project carried out within the Swedish Transport Administration's industry program Sustainable Shipping, operated by Lighthouse

TRAFIKVERKET

Electric Light – Lätta elfartyg

Lightweight and electrically propelled Ro-Pax ship

Authors

RISE Research Institutes of Sweden and

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In association with

Stena Rederi AB, Wallenius Marine AB, and ABB Marine

June 2021

This innovation project has run within the Swedish Transport Administration's industry program Sustainable Shipping, operated by Lighthouse

Summary

The objective of this project was to establish an innovative ship concept for a fully electric Ro-Pax ship, which makes use of new technology, especially in the area of electrical propulsion and energy storage. The project also included a risk assessment of the concept and identification of possible follow-up studies of critical design items.

There is a growing demand for all types of shipping to reduce their emissions of greenhouse gases and particles, and also NOx and SOx. Meeting IMO’s emissions objective by 2050 will require large efforts both for energy efficiency measures on existing ships and for new concepts for fossil-free ships. Electrical propulsion for small ships has been discussed for long and many installations are today operational.

This project is an innovation project with participation from industrial partners contributing to the overall goal of sustainable shipping by proposing a ship concept for an electrically powered large Ro-Pax ship for shorter international voyage.

The amount of electric energy estimated to be stored in batteries onboard is approximately 60 MWh. This is ten times more than the current largest marine battery installation.

When it comes to fire safety, it is very important with a holistic approach, including integrity, ventilation, failure detection and fire suppression methods, etc., based on hazard identification. The battery fire safety concept developed in this project constitutes safety requirements guidelines for large ship battery installations and is one of the main results from the conducted risk analysis work. The idea of the presented concept is that it should be applicable for any electrically powered ship and that it could be used as starting point for discussions on IMO harmonized regulations for battery energy storage systems onboard ships.

It can be concluded that a fully electric Ro-Pax ship operating on the route Gothenburg to Frederikshavn is a technically and commercially realistic alternative.

Sammanfattning

Syftet med detta projekt var att skapa ett innovativt fartygskoncept för ett helelektriskt Ro-Pax-fartyg, som använder sig av ny teknik, särskilt inom området elektrisk framdrivning och energilagring. Projektet inkluderade också en riskbedömning av konceptet och identifiering av möjliga uppföljningsstudier av kritiska designdelar.

Kravet ökar på alla typer av sjöfart att minska utsläppen av växthusgaser och partiklar, samt även NOx och SOx. Att uppfylla IMO: s utsläppsmål 2050 kommer att kräva stora insatser avseende såväl energieffektivitetsåtgärder på befintliga fartyg som nya koncept för fossilfria fartyg. Elektrisk framdrivning för små fartyg har diskuterats länge och många installationer är idag i drift.

Detta projekt är ett innovationsprojekt, med brett industriellt deltagande, som bidrar till det övergripande målet för hållbar sjöfart genom att föreslå ett fartygskoncept för ett eldrivet stort Ro-Pax-fartyg för kortare internationell resa.

Mängden elektrisk energi som beräknas lagras i batterier ombord är cirka 60 MWh. Detta är tio gånger mer än den nuvarande största installationen av marina batterier.

När det gäller brandsäkerhet är det mycket viktigt med ett holistiskt tillvägagångssätt, inklusive integritet, ventilation, feldetektering och brandbekämpningsmetoder etc. baserat på riskidentifiering. Konceptet med brandsäkerhet för batterier som utvecklats i detta projekt utgör riktlinjer för säkerhetskrav för stora fartygsbatteriinstallationer och är ett av huvudresultaten från det genomförda riskanalysarbetet. Tanken med det presenterade konceptet är att det ska vara tillämpligt för alla eldrivna fartyg och att det ska kunna användas som utgångspunkt för diskussioner om IMO-harmoniserade regler för batterilagringssystem ombord på fartyg.

En viktig slutsats från projektet är att ett helelektriskt Ro-Pax-fartyg, som går på rutten Göteborg till Frederikshavn, är ett tekniskt och kommersiellt realistiskt alternativ.

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1 Introduction

1.1 Scope

This document is the final report for the innovation project IP2_2019, which is part of the Swedish Transport Administration's industry programme "Sustainable shipping/Hållbar Sjöfart". This program is run by Lighthouse and the project has been conducted by RISE Research Institutes of Sweden and Chalmers University of Technology in cooperation with the industrial partners Stena Rederi AB, Wallenius Marine AB, and ABB Marine AB.

The purpose of the project is to establish an innovative ship concept for a fully electric Ro-Pax ship, which makes use of new technology, especially around electrical propulsion and energy storage. The project also included a risk assessment of the concept and identification of possible follow up studies of critical design items.

1.2 Background with motivation

There is a growing demand for all types of shipping to reduce their emissions of greenhouse gases and particles, and NOx and SOx. Meeting the International Maritime Organization's (IMO's) emissions objective of 50% reduction of greenhouse gases from shipping by 2050 will require large efforts both on energy efficiency measures on existing ships and on developing new concepts for fossil-free ships. Electrical propulsion for smaller ships has been discussed during a longer time and several installations are today operational. A good overview of this subject can be found in ”Elektrifiering av sjöfarten – en nulägesbeskrivning av teknik och marknadsläge inom maritim elektrifiering och analys av behov och möjligheter för elektrifiering i nom sjöfarten", (LIGHT, 2018). However, larger battery installations on ships with longer range is still a research area.

The objective of this project was to establish an innovative ship concept for a fully electric Ro-Pax ship, which makes use of new technology, especially in the area of electrical propulsion and energy storage. The project also included a risk assessment of the concept and identification of possible follow-up studies of critical design items. The ship concept should be fully electric and be able to manage all normal operations without relying on combustion engines. New alternative propulsion systems give possibilities for simplifications in the ship design. As an example, electrification and using batteries for energy storage will decrease the need of machinery and auxiliary sub-systems. The following items have been studied:

- battery as energy storage,
- energy efficiency, and
- optimization of the ship's size with respect to cargo capacity.

Further, redundancy concepts and safety measures have been studied.

1.3 Outline

This final report is structured according to the following:

Chapter 1	is this introductory section.
Chapter 2	gives a description of how the work has been performed.
Chapter 3	summarizes the main conclusions.
Chapter 4	presents the results from the ship design.
Chapter 5	gives the risk analyses and mitigation measures.
Chapter 6	lists proposals on following studies and activities.

1.4 Limitations

This study has chosen a dedicated use case as baseline for the operational requirements leading to a specific conceptual design. Hence, the results are tailored to this use case. Ice conditions have not been considered. However, despite some limitations several design conclusions are generic and can contribute to general conceptual design aspects of fully electric ships. An overall life cycle perspective has not been included.

1.5 Abbreviations

ABL	Above Base Line
AC	Alternating Current
BES	Battery Energy Storage System
BMS	Battery Management System
CO2	Carbon Dioxide
DC	Direct Current
DoD	Depth of Discharge
FE	Finite Element
GHG	Green House Gases
GZ	Metacentric height
HazID	Hazard Identification
HAZOP	Hazard and Operability studies
HVO	Hydrotreated Vegetable Oils
IMO	International Maritime Organization
LEL	Lower Explosion Limit
LM	Lane Meters
LOA	Length Over All
LPP	Length Between Perpendiculars
MGO	Marine Gasoil
MSC	Maritime Safety Committee
NM	Nautical Miles
NOx	Nitrogen Oxides
Pax	Passengers
Ro-Pax	Roll on roll off cargo ship with Passengers
Ro-Ro	Roll on Roll off cargo ship
SMCR	Specified Maximum Continuous Rating
SOC	State-of-Charge
SOLAS	Safety of Life at Sea
SOx	Sulphur Oxides
SRtP	Safe Return to Port
TR	Thermal Runaway
USD	United States Dollar
VCG	Vertical Centre of Gravity
WP	Work Package

2 Method

This project is an innovation project with participation from industrial partners and is contributing to the overall goal of a sustainable shipping by proposing a ship concept for an electrically powered Ro-Pax ship and has addressed the following questions:

- What should an innovative ship concept for an electric powered Ro-Pax ship look like?
- How should propulsion and auxiliary systems be designed for a fully electric powered ship?
- How much lighter can the ship be?
- What will an optimum design for weight, speed, and range look like?
- What risks are introduced with respect to the electrical systems?

To end up with a realistic concept, a real use case has been selected. Based on this, some operational requirements have been set up. This use case and the most important requirements can be summarised as:

- Route: Gothenburg - Frederikshavn, two round trips per day
- Cargo capacity: 3 000 Lane meter and 1 000 Pax
- Assumed start of operation: 2030
- Design speed: 19 knots
- Class: DNV-GL, 1A, Ferry, Battery
- Flag state: Sweden
- Cargo: Trucks, Buses, Cars, Trailers

The use case has been divided into the following operational phases:

- In port in Gothenburg
- Arrival/departure in Gothenburg
- Fairway navigation in and out of Port of Gothenburg
- Open sea transit
- Arrival/departure in Port of Frederikshavn
- In port in Frederikshavn

The design process is illustrated in *Figure 1* below. The innovative design is compared with the design of a conventional ship.

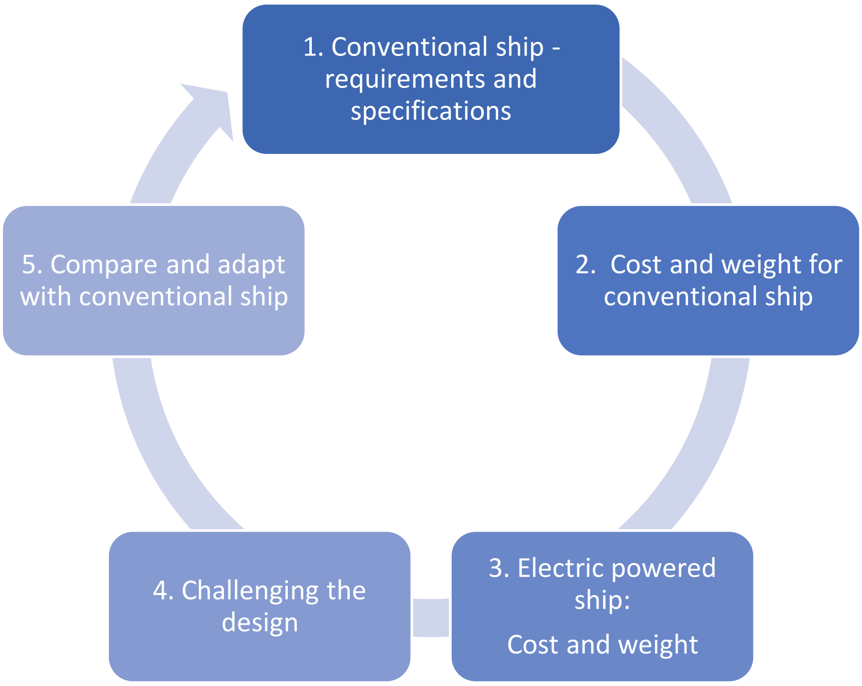


Figure 1. Design process where a conventional ship has been used as reference.

The starting point has been the Stena Trader/Stena Transporter with respect to weight and cost. An innovative design is established to meet the operational requirements. The operational speed is optimized with respect to the range in the particular use case. In *Figure 2* the study logic is depicted with four interrelated work packages.

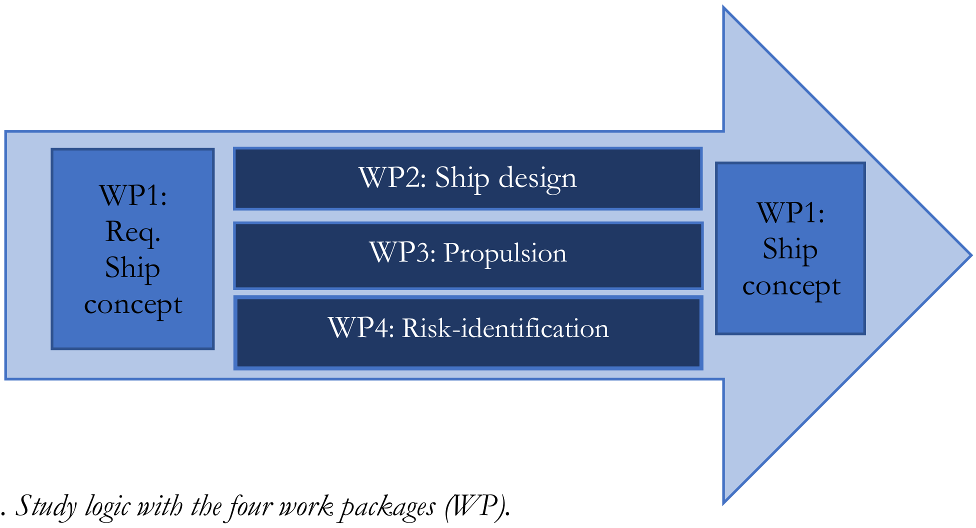


Figure 2. Study logic with the four work packages (WP).

In the first work package, the conceptual design is performed starting from the operational requirements. The conceptual design has a focus on optimizing the cargo capacity with respect to weight, length, and power consumption for the specific range. The conceptual design is taken further in the work packages Ship Design and Propulsion. During the process, as many design parameters as possible have been kept open. This to not disqualify any design alternatives to early in the process. In the end of the project a baseline design is set, the costs are estimated and compared with the reference ship.

One important aspect has been to perform a risk assessment of the design. This assessment started with a hazard identification (HazID) workshop early in the process followed by risk mitigation measures for the most critical identified items. The final conclusions are also including suggestions on future projects, which are addressing the most critical design issues for a fully electrical ship.

3 Conclusions

It can be concluded that a fully electric Ro-Pax ship operating on the route Gothenburg to Frederikshavn is a technically and commercial realistic alternative.

The amount of electric energy to be stored in batteries onboard is approximately 60 MWh. This is 10 times more than the current largest marine battery installation so the design of the ships will constitute a major leap in the development of fully electric ships with a large number of conceptual and detailed design issues to be worked out.

A fully electric ship will be more expensive to build due to the cost of the batteries which will be roughly one third of the costs of the ship. The absence of combustion engines will save some cost and weight but all in all the capex of a fully electric ship can be expected to be approximately 20% more expensive than a conventional ship.

The major benefit is of course the almost complete elimination of emissions from the operation of the ship. In Sweden and Denmark, a very large part of the electricity production is fossil-free. The reduction in GHG emissions can be in the range of 25 000 ton per year, if a conventional diesel driven ship is replaced by a fully electric ship running on fossil free electricity.

The economic performance of a fully electric ship compared to a convectional ship will be completely dependent on the energy cost. Energy costs are volatile and energy cost forecasts are very unreliable. Over the time-period of the project, the prices of oil and electricity have changed dramatically.

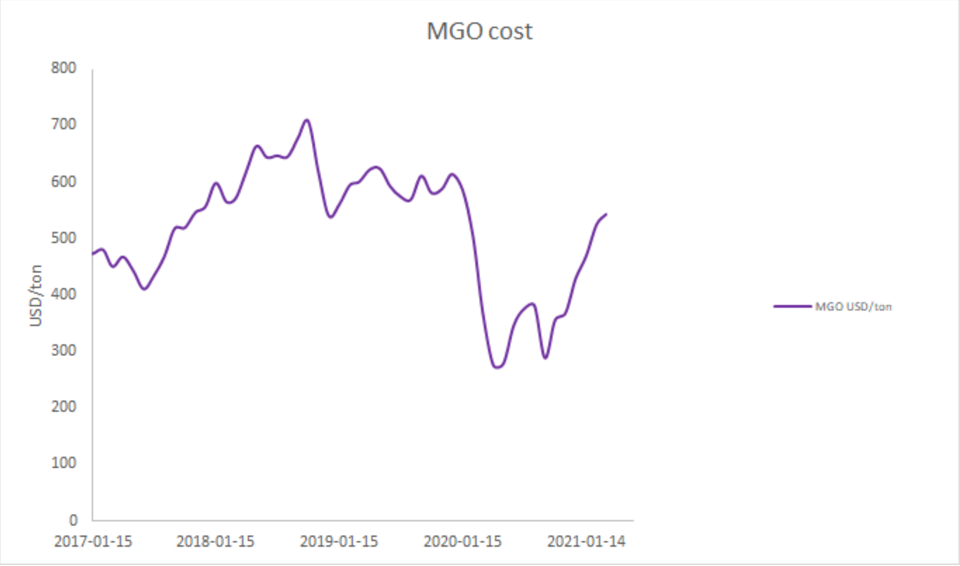


Figure 3. MGO cost variation over the last years USD/ton.

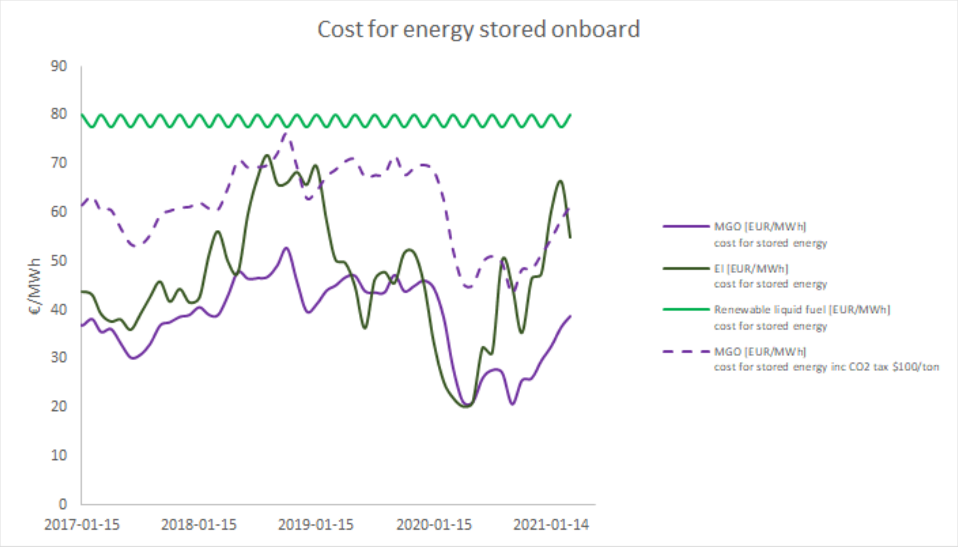


Figure 4. Cost for energy stored onboard €/MWh.

The cost for the energy that is stored onboard is varying over time but there is a correlation between the cost variation of MGO and electricity. The cost of alternative renewable liquid fuel, such as HVO and methanol is not so closely tied to the MGO and electricity costs, but it can be assumed that a renewable liquid fuel will be at least twice as expensive as the fossil fuel. Discussions are ongoing regarding CO2 tax on fossil fuel. When and how a CO2 tax will be applied is very unclear, but it is good to consider it when comparing fossil and fossil-free alternatives. The size of a CO2 tax is also an un-known, but 100 USD/ton CO2 is a reasonable figure to be used for comparison. That number has been assumed and added to the MGO cost as shown by the dashed curves in the graphs.

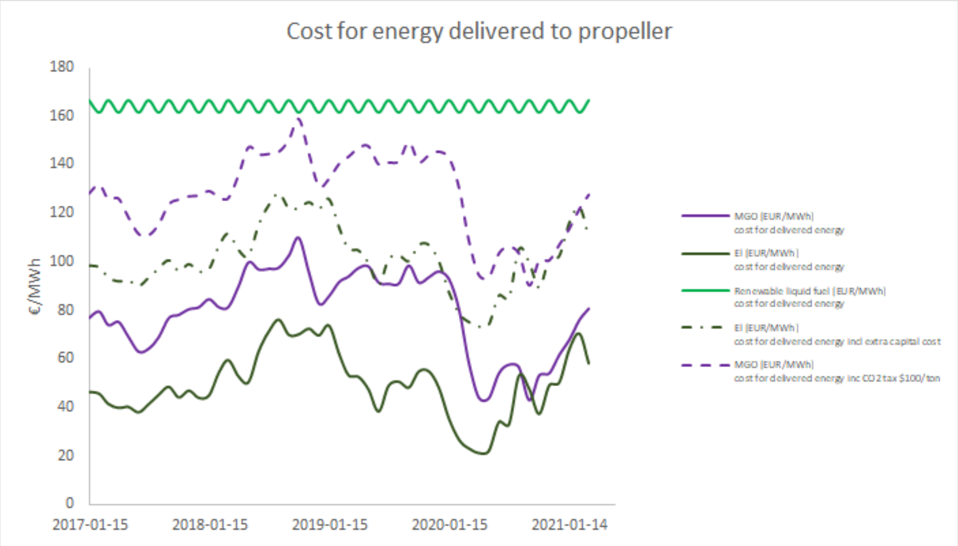


Figure 5. Cost for energy delivered to propeller €/MWh.

The efficiency of the system to convert the stored energy to mechanical energy differs a lot between a conventional diesel installation and a fully electric system. For the conventional system an efficiency of 48% can be assumed compared to 88% for the full electric system. Based on this, it is clear that the energy cost will be much lower for the electric ship in all cases. Even considering the additional investment cost for the fully electric ship (as shown in the above graph by the dash-dotted line), the result from the project indicates that the total cost of operation will not be significantly higher than for a conventional vessel using MGO and more important, it will be lower than any other alternative considering the CO2 emissions.

The project conducted a design of a novel ship concept including a new vehicle deck lay-out utilizing the possibilities a fully electric ship can provide regarding reduction and rearrangement of the machinery compartment. This has resulted in a 15% shorter ship with maintained cargo capacity compared to a conventional ship. The structural design was done according to the DNV design rules assuming "Service Area Restrictions" R3 which were considered representative for the particular use case Gothenburg to Frederikshavn. This fully electric ship will store all the required energy in batteries, which will be a substantial part of the propulsion system installation both in weight and in cost. By removing all combustion engines from the design, a significant number of supporting systems can also be removed or simplified. A novel electric distribution system, pushing the boundaries of DC grid capacity giving an overall electrical system efficiency higher than the AC system at ≈87% and a lower overall weight, has been suggested. The ship concept is illustrated in *Figure 6* below.

Figure 6. Ship concept Electric Light for a fully electrical Ro-Pax ferry.

Regarding battery fire safety, it is very important with a holistic approach, including integrity, ventilation, failure detection and fire suppression methods, etc., based on hazard identification. The battery fire safety concept developed in this project constitutes safety requirements guidelines for large ship battery installations and is one of the main results from the conducted risk analysis work. The idea of the presented concept is that it should be applicable for any electrically powered ship and that it could be used as starting point for discussions on IMO harmonized regulations for battery energy storage systems onboard ships.

An important conclusion related to a specific hazard in ship battery applications is that sea water intrusion in the battery space can be managed. Normal ventilation can most likely handle the generation of electrolysis gases and short circuit protection for high voltage parts of the system ensures that thermal runaway events will be unlikely, since high voltage is needed to cause arcing in salt water.

The design of a fully electric ship with the specified capacities is a huge design undertaking where boundaries of the existing technologies will have to be moved. Three specific areas have been identified where a fully electric ship will mean specifically challenging design tasks where further development project should be initiated:

- **Arrangement of battery banks**

To arrange the large battery bank in the most efficient and safe way is a design task that will require significant resources from all departments of the ship design office. Locations for the battery banks need to be identified that do not steal valuable cargo space but where the considerations regarding safety, cabling/buss-bars, weight distribution, ventilation, maintenance etc. are fulfilled.

- **New technology for efficient heating and cooling**

One consequence of the higher efficiency of a fully electric ship is that less waste energy is available for heating. For a conventional ship, the heat generated from combustion and then removed through the heat of the exhaust gases and cooling water, are of the same magnitude as the mechanical energy generated. This heat energy is easy to recover and is normally enough to cover all heating needs onboard. With the higher efficiency of a fully electric ship, there will not be enough waste heat for the heating needs. The stored electric energy is too precious to use for heating. Heat pump technology needs to be implemented for efficient heating. For cooling of accommodation and crew areas, more efficient solutions will also be needed such as sea water cooling as well as reflective material for windows and solar panels.

- **Charging**

The main bottleneck for introducing fully electric ships is the shore-to-ship charging capacity. The electricity grid and the actual physical ship-to-shore interface need to be upgraded to enable charging powers of 20-30 MW. The principal technology is available, but the challenge will be to involve all relevant stakeholders to develop and implement the technology in a timely manner. Pilot projects should be initiated as soon as possible to establish development teams with participants from ship owners, ports, terminal operators, city planners, electric grid owners, electricity suppliers and equipment suppliers.

4 Ship concept

4.1 General

4.1.1 Design criteria and boundary conditions

The project objective was to design a fully electric Ro-Pax ship with a capacity of approximately 3 000 LM and 1 000 passengers operating two round trips per day between Gothenburg, Sweden and Frederikshavn, Denmark. The route is approximately 50 NM with speed and navigation constrains in the port areas as well as through the archipelago of Gothenburg.

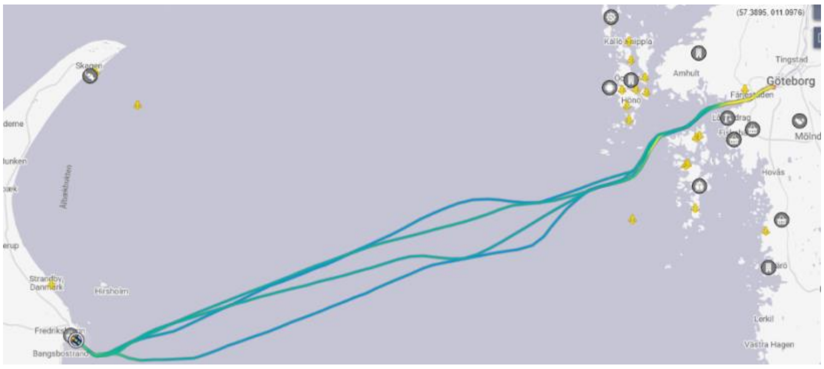


Figure 7. The Route Gothenburg – Frederikshavn.

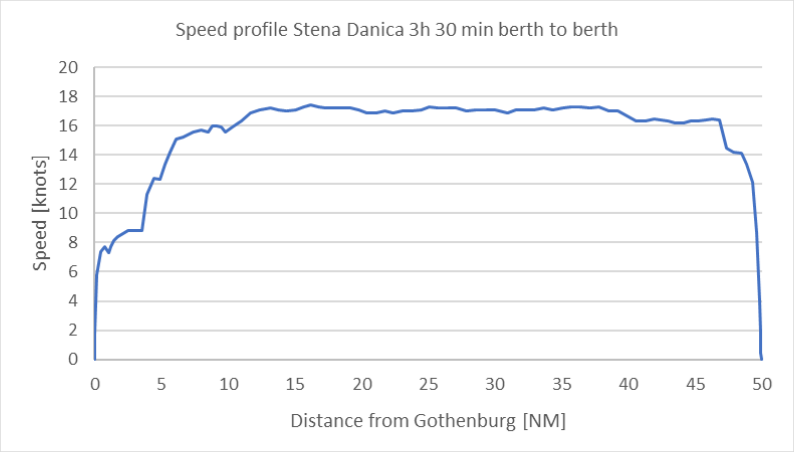


Figure 8. Speed profile Stena Danica 3h 30 min berth to berth.

The all-electric operation needs to provide similar service as todays operation. This means a crossing time of 3 hours and 45 minutes and the turnaround time in port to be less than 1 hour and 30 minutes. The effective charging time for batteries is assumed to be 1 hour at each port.

The route is quite protected from the most frequent adverse weather conditions.

4.1.2 The Electric Light concept

Several different concepts were developed end evaluated. The final concept has the following main particulars.

Table 1. Main particulars final concept.

MAIN PARTICULARS		
LOA	178.4	m
LPP	173.4	m
BEAM	26.7	m
DEPTH TO ENTRY DECK	9.3	m
DESIGN DRAFT	6.0	m
SCANTLING DRAUGHT	6.3	m
LANE METERS	3017	m
PASSENGER CAPACITY	1000	pax
PROPULSION POWER	3×4 MW	MW
PROPULSION SYSTEM	3 x ABB Azipod DO 1250	
DESIGN SPEED AT 85% PROPULSION POWER INCLUDING 10% SEA MARGIN	19	knots
BATTERY STORAGE CAPACITY	61.4	MWh
(OPTIONAL EXTRA CAPACITY)	21.7	MWh
BATTERY SYSTEM	Corvus Blue Whale	
ELECTRIC DISTRIBUTION SYSTEM	DC	
OPERATION RESTRICTIONS:		
SIGNIFICANT WAVE HEIGHT HS <	3.5	m

In the following sections the different concepts for relevant systems will be explained.

- General comparison between a conventional ship and a fully electric ship
- Battery capacity
- Battery storage
- Battery safety
- Charging capacity
- Cargo capacity and handling
- Propulsion system
- Electric distribution
- Ship cost estimate
- Total cost of operation

A general arrangement drawing can be found on the next page.

General arrangement

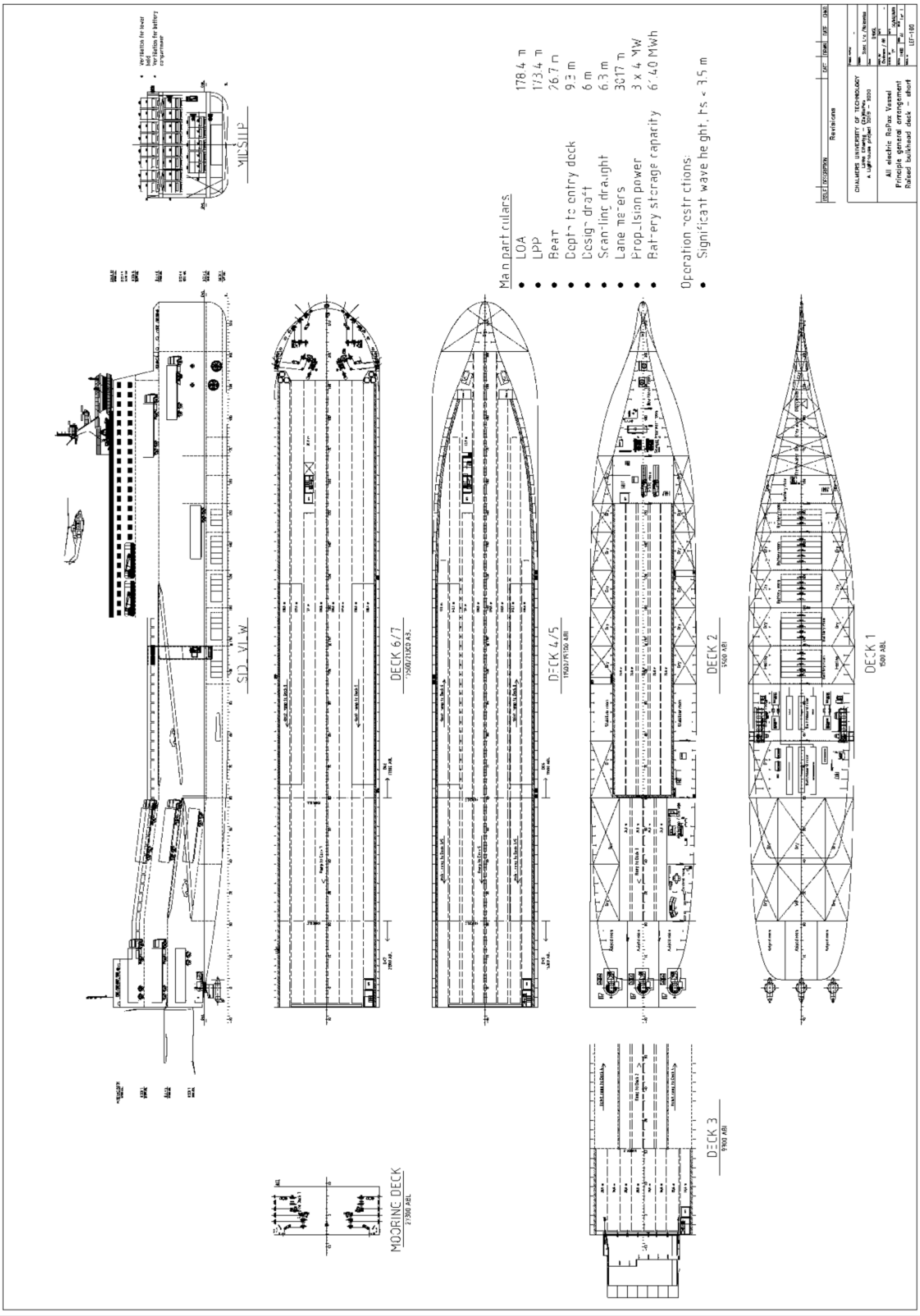


Figure 9 General arrangement Electric Light.

4.1.3 Fully electric ship vs conventional ship

This fully electric ship will store all the required energy in batteries which will be a substantial part of the propulsion system installation both in weight and in cost. By removing all combustion engines from the design, a significant number of supporting systems can also be removed or simplified.

The fully electric ship concept also provides other possibilities when it comes to the arrangement of the propulsion system. By adopting to these, new cargo deck arrangement can be considered which potentially can provide more cargo space for the same main dimensions or reduce the length of the ship but maintaining the same cargo capacity as the reference ship.

In *Table 2* three different designs are compared

1) Conventional Ro-Pax ship, reference ship (Diesel engines)
2) Fully electric ship with maintained main dimensions but with increased cargo capacity, fully electrically powered long ship
3) The final Electric Light design. A fully electric ship with reduced length with maintained cargo capacity.

It can be observed from the table below that if the same main dimensions are kept, the ship's weight will increase somewhat for a fully electric ship. However, considering that no bunker fuel is needed that "steals" deadweight from the conventional ship, the payload capacity will be very similar.

Table 2. Weight comparison between three designs.

		Diesel ref ship	**Fully electric long**	**Fully electric short**
	LOA [m]	212	212	178.4
	Breadth [m]	26.7	26.7	26.6
	Lane meters [m]	3063	3674	3017
SFI		Weight [t]		
2	**STEEL STRUCTURE**	9000	9000	8000
3	**EQUIPMENT FOR CARGO**	660	660	660
4	**SHIP EQUIPMENT**	293	293	293
5	**EQUIPMENT FOR CREW AND PASSENGERS**	1500	1500	1500
6	**MACHINERY MAIN COMPONENTS**	585	173	173
60	DIESEL ENGINES FOR PROPULSION	200		
63	PROPELLERS, TRANSMISSIONS, FOILS			
	2 x Propellers and gearbox	250		
	3 x Azipod DO 1250		150	150
64	BOILERS, STEAM & GAS GENERATORS	50		

65	MOTOR AGG FOR MAIN ELEC. POWER PRODUCTION	80		
66	OTHER AGGR & GEN FOR MAIN & EMER EL PWR PROD.	5		
	Shore connection		5	5
	Propulsion switchboard		18	18
7	**SYSTEMS FOR MACHINERY MAIN COMPONENTS**	190	25	25
70	FUEL SYSTEMS	20		
71	LUBE OIL SYSTEMS	50		
72	COOLING SYSTEMS	50		
73	COMPRESSED AIR SYSTEMS	20		
74	EXHAUST SYSTEMS & AIR INTAKES	40	20	20
75	STEAM, CONDENSATE & FEED WATER SYSTEMS	5		
79	AUTOMATION SYSTEMS FOR MACHINERY	5	5	5
8	**SHIP COMMON SYSTEMS**	325	436	436
80	BLST & BILGE SYSTEMS, GUTTER PIPES OUTSIDE ACCOM	100	100	100
81	FIRE & LIFEBOAT ALARM, FIRE FIGHTING & WASH DOWN SYSTEMS	50	50	50
82	AIR & SOUNDING SYSTEMS FROM TANKS TO DECK	50	50	50
86	ELECTRIC POWER SUPPLY	5	5	5
87	COMMON ELECTRIC DISTRIBUTION SYSTEMS	10	10	10
	Distribution transformer		39	39
	Energy storage switchboard		37	37
	Propulsion switchboard with transformer		35	35
88	ELECTRIC CABLE INSTALLATION	100	100	100
89	ELECTRIC CONSUMER SYSTEMS	10	10	10
9	**SYSTEM FILLINGS**	100	50	50
90	SYSTEM FILLINGS	100	50	50
100	**BATTERY STORAGE 60 MWh** **Corvus blue whale 100 kWh/ton**		600	600
	LIGHTSHIP	**12653**	**12737**	**11737**

The fully electric ship can, by adopting to new conditions, increase the cargo space capacity with approximately 15-20% compared to the conventional ship. If the cargo capacity is to be maintained the length of the ship can be reduced.

Significant differences in performance are the design speed and the operation range. For a conventional ship, it is comparably inexpensive to add propulsion power and bunker fuel capacity to have a good margin or to make the ship more flexible.

A conventional ship will typically be equipped with bunker capacity providing an operation range so it can be re-positioned to any part of the world. This will not be the case for a fully electric ship where the energy storage capacity will be limited to the actual regular operation. Transport from the shipyard to its operation area or change of operation will require assistance.

For a fully electric ship, the energy storage is the most expensive system onboard which means that adding a margin in operation range will be much more expensive than for a conventional ship. The energy stored onboard will also be much higher valued and increased speed will very seldom be a realistic option. For a fully electric ship there is an actual limit for the maximum range where the added energy that is needed to carry one extra battery is higher than the energy content for this battery. This will set the absolute limit for the operation range. For a given ship the limit is dependent on the speed and as always, a lower speed will give a longer operation range. Improved battery technology with higher energy density will also increase the range. A study regarding the theoretically achievable range and limitations is presented in Appendix A: Investigation of achievable range of an electric ship.

Before the theoretical range is reached, practical limitations such as arrangement of battery space, investment cost for the battery and available charging power at the port, will limit the achievable operation range of the ship. The charging power is often the bottleneck that sets the practical limit.

The electric energy that must be charged (kWh) and the charging time (h) decides the charging power (kW). The energy needed for one crossing is dependent on the ship speed, higher speed means more energy, but higher speed also means longer time available at port for charging. How charging power is depending on the ship speed was investigated in the project and is presented in Appendix B: Investigation of required charging power.

4.2 Hull shape

A good hull shape is as important for an electric ship as for any ship. The challenge is to look for an optimum design where all requirements are considered. For given boundary conditions such as length, width, draft, displacement, speed and sea state, an experienced and competent naval architect will, with the help of state-of-the-art design tools, be able to design a very good hull shape that is close to optimum for those given conditions. With fixed main dimensions the difference in calm water resistance between two hulls optimized by two different experienced naval architects should not be significant.

If we allow the main dimensions to be varied, the possibility to find a more optimal hull will increase. The difference in resistance between two hulls with the same cargo intake can vary considerable depending on how the main dimensions are chosen.

The shape of the bow section is also important since it will impact the added resistance in adverse weather. A slender bow gives lower added resistance, but a fuller bow gives more cargo space on deck and better possibilities to arrange bow ramp and bow loading.

For a Ro-Ro ship with stern access, the opening in the transom should be as wide as possible to allow for fast and unobstructed cargo handling. The max width of the decks above waterline are normally maintained all the way to the transom to maximize the cargo space. The cargo spaces and cargo handling requirements mean constraints for a hydrodynamically optimal stern hull shape. Special considerations must also be given to the transom itself whether it should be submerged or not and if a duck tail or interceptor can reduce the resistance.

A parametric study was performed where the length, width and draft were varied. As anticipated, it was shown that a long, narrow ship with high draft and low block coefficient will give the lowest resistance. The maximum length is often limited by the length allowed for a certain port and berth or turning area. The minimum width will be dictated by the stability requirements. The best main dimensions from resistance point of view can normally be derived from:

- Max length given by physical limitations such as port, berth and turning area
- Max draft according to the water depth
- Min width that makes the ship fulfil the stability criteria.

For the Electric Light design the cargo stowage arrangement was improved so that the size of the ship could be reduced but still maintain the same cargo capacity as the reference ship. Since the width could not be reduced due to stability requirements, the length of the ship was reduced to 178.4 m.

The resistance at the service speed was however not significantly changed. The positive effect of reduced friction resistance, due to the reduced wet surface area was offset by increased wave resistance.

4.3 Hull structure

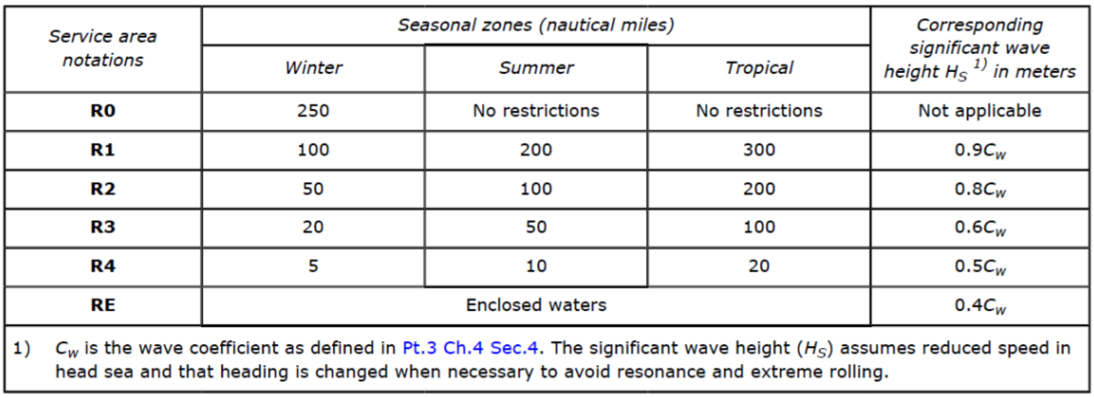
4.3.1 Service area restrictions

Since the operational range of the ship is limited, there is no need to design the ship for unrestricted service considering the conditions on the North Atlantic during the winter period. A more relevant design approach is to consider the conditions for the actual intended operation and apply a service area restriction.

The service area restrictions, representing the maximum distance from nearest port or safe anchorage, are specified in the International Convention on Load Lines by the IMO.

Table 3 shows the various service area notations, which are related to the zones, areas, and seasonal periods as defined in the abovementioned IMO regulations (IMO, 1996).

Table 3. Service area notations



Service area notations	*Seasonal zones (nautical miles)*			*Corresponding significant wave height H_S $^{1)}$ in meters*
	Winter	*Summer*	*Tropical*	
R0	250	No restrictions	No restrictions	Not applicable
R1	100	200	300	$0.9C_w$
R2	50	100	200	$0.8C_w$
R3	20	50	100	$0.6C_w$
R4	5	10	20	$0.5C_w$
RE	Enclosed waters			$0.4C_w$

1) C_w is the wave coefficient as defined in Pt.3 Ch.4 Sec.4. The significant wave height (H_S) assumes reduced speed in head sea and that heading is changed when necessary to avoid resonance and extreme rolling.

In *Table 3*, the wave coefficient C_w is defined in Classification Rules. In this work, we take C_w = 9.75m according to DNVGL (DNVGL, 2017). The service area notation was determined by comparing the historical encountered significant wave heights from 2013 to 2019 for MV Stena Jutlandica along the route between Gothenburg to Frederikshavn, as shown in *Figure 7*. It is found that the maximum encountered wave exceeds the RE and R4 limits as illustrated in the red lines in 10, which implies the R3-restriction should be selected to meet the wave height requirement. This is in line with the seasonal zone requirement of the R3-restriction, for which the seasonal zones are limited to the maximum distance of twenty nautical miles from nearest port or safe anchorage for winter navigation.

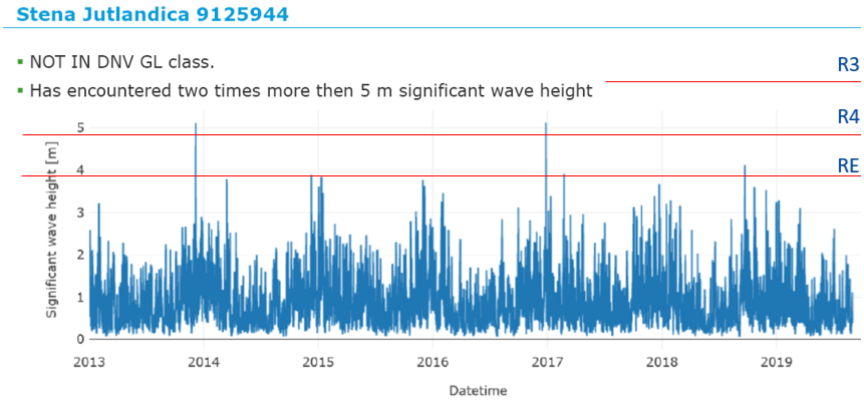


Figure 10. Historic wave data for the route Gothenburg – Frederikshavn from Stena Jutlandica.

4.3.2 Structural design of the mid-ship

The mid-ship section design is the key step for a ship structural design. In this project three variants of the mid-ship section for the Electric Light concept design, which are termed as "Wide", "Long" and "Extra deck" respectively, are proposed. The main dimensions of these concept-designs are listed in

Table 4. The hull dimensions of the existing Stena ferries, Stena Trader and Stena Transporter were comparable with the new design. All the three variants meet the design requirement of at least 3000 lane meters. The drawings of the three mid-ship sections are also illustrated in *Figure 11*, which were created using the computer program *Nauticus Hull* developed by DNVGL (DNVGL, 2020).

Table 4. The main dimensions of the three mid-ship sections.

	"Wide"	**"Long"**	**"Extra deck"**
LOA (meter)	195.3	212.0	170.6
LPP (meter)	184.3	201.0	159.6
Draft (meter)	6.5	6.5	6.5
Breadth B (meter)	29.7	26.7	26.7

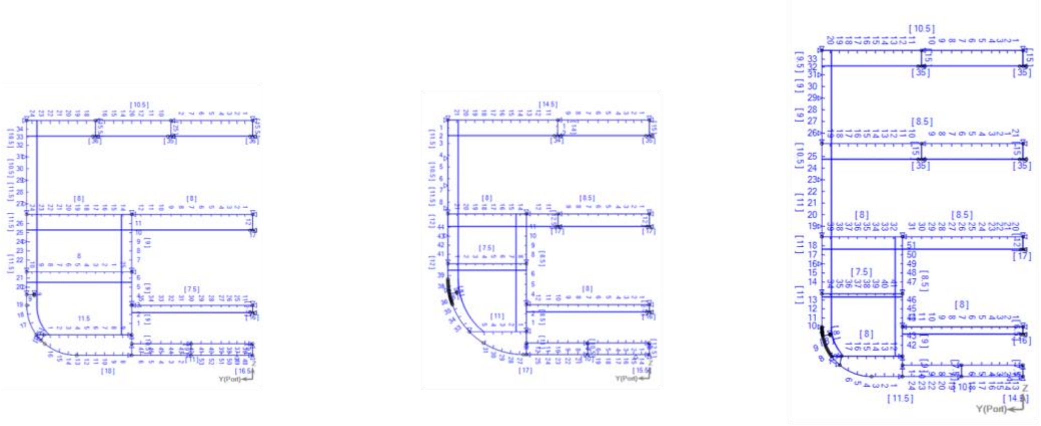


Figure 11. The three mid-ship sections; from the left to the right: the versions of "Wide", "Long", and "Extra deck", respectively.

4.3.3 Weight optimization of the hull

To investigate how much the total hull weight of the new design can be reduced, a conventional simplified weight optimization process was conducted for the three design variants. A reduction of the section areas of the longitudinal members was considered to reduce the hull weight, i.e., the optimization did not include a topology optimization or re-design of the structural parts. The midship cross section areas of the longitudinal members are calculated automatically using *Nauticus Hull*. It is noticeable that all different limiting factors have been considered and are found dominating in the various parts of the cross-sections. The full corrosion marginal of the steel structural members has been included in the calculation using *Nauticus Hull*. For buckling analyses, the full corrosion reductions were considered.

Figure 12 illustrates the limiting factors that dominate the weight optimization process of the various parts of the three design variants. It is found that the hull weights could be reduced by this approach, leading to weight reductions of 8.9%, 4.6% and 9.4% for the "Wide", "Long" and "Extra deck" versions, respectively, in comparison to the original design. It can be recommended in future work to investigate if a weight optimization which also include changes in the topology can reduce the weight further and push the limits for the limiting factors.

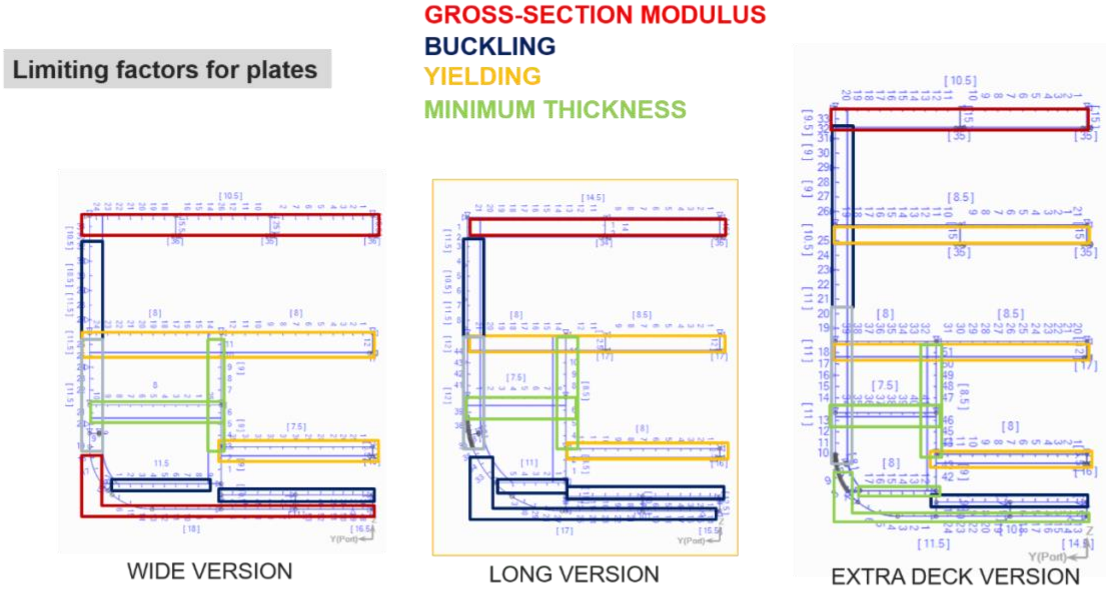


Figure 12 The limiting factors the govern the weight optimization of the three design variants.

4.3.4 FE analyses

In addition to the structural analyses mentioned above, finite element (FE) analyses were utilized as a complementary analysis tool for structural design of the concept ship hull. Because a Ro-Ro ship hull differs significantly from the common ship structural configurations such as those of bulker carriers and tankers, the well-accepted common structural rules cannot be applied directly to Ro-Ro ships. For the similar reason, we need a more sophisticated tool than the formula-based calculation tools such as *Nauticus Hull,* as a complementary tool for structural analysis of Ro-Ro ship. In view of this, the FE models of the mid-ship sections were created using the FE code Sesam-Genie, another computer program developed by DNVGL (DNVGL, 2016a). FE analyses were carried out to ensure that the proposed structural design meets the special strength requirements of Ro-Ro ships.

Figure 13 shows the FE model of the "Long" version of the mid-ship hull; note only half of the mid-ship section was shown. The FE model was created following the DNVGL Class Guideline for Strength analysis of hull structure in Ro-Ro ships (DNVGL, 2016b). This is due to the consideration that for multi deck Ro-Ro ships and car carriers, the primary supporting members and the loads differ considerably from those specified in the main ship class rules. For instance, Ro-Ro ships are characterized by long cargo holds and lacking transverse bulkheads, which makes buckling strength and racking strength more critical for a Ro-Ro ship hull. Following the load cases recommended by the Class guideline (DNVGL, 2016b), additional structural analyses were carried out. The FE analysis results indicate that the proposed structural design gives sufficient buckling strength and the racking strength.

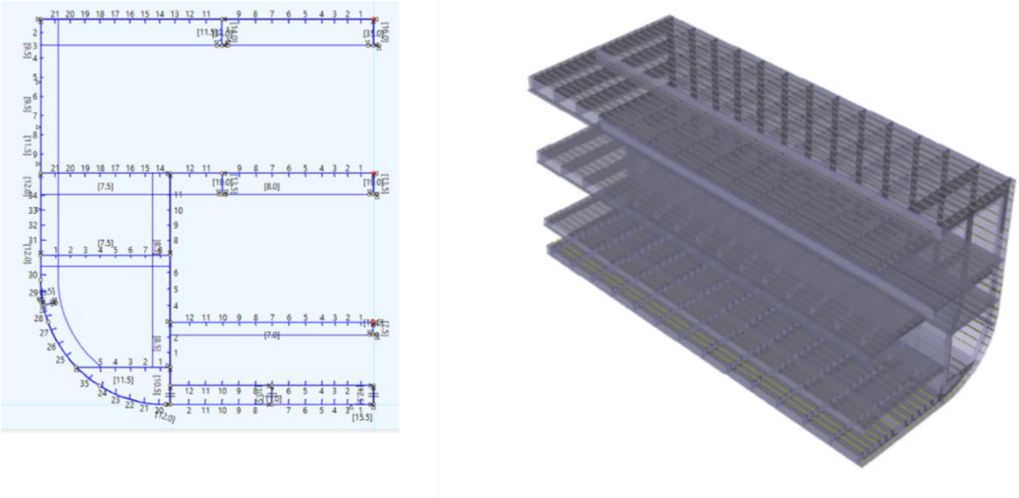


Figure 13. The FE model (right) of the "Long" version

4.4 Cargo space layout

For a fully electric ship, the combustion engines are removed and with them also several supporting systems such as fuel handling and exhaust gas system. Other systems cannot be completely removed but can be significantly reduced in size. Such systems are for example the ventilation and cooling systems. The elimination and reduction of systems provide more freedom to arrange the cargo space and by choosing for example ABB Azipods for propulsion the footprint of the engine room space is further reduced.

The battery arrangement will also impact the cargo space. In order to provide enhanced protection for the batteries, they were not placed in the double bottom but instead in a compartment above the double bottom.

With a double bottom height of 1,500 mm and a tween deck height of the battery compartment of 4 000 mm, the lowest cargo deck was placed at 5 500 mm above base line (ABL) compared to 3 300 mm ABL for the conventional reference ship. Moving cargo higher up is seldom an improvement, but in this case the useful deck area could be increased as a combination of the larger waterplane area, reduced space required for the engine room equipment and the more flexible arrangement of the electric propulsion equipment. Compared to the conventional ship the cargo capacity could be increased with approximately 15%.

The decks were arranged so that the lowest cargo deck also is the entry deck. At the transom the entry deck is position 9 300 mm ABL. At frame 21 (21 800 mm from the transom) the deck is sloped downwards to frame 60 where the sloop reaches the lower flat part of deck at 5 500 mm ABL. The deck above the entry deck is designed to be a watertight bulkhead deck. This has two consequences.

- The stern door/ramp need to be watertight and not only weathertight as on conventional Ro-Pax ships.
- The lower hold has direct access to the stern ramp and the access is independent of the cargo handling on the deck above.

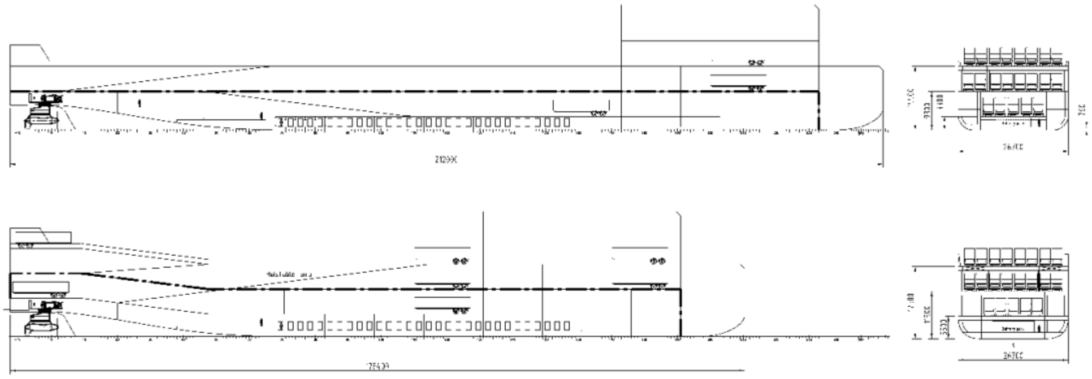


Figure 14. Comparison between conventional cargo deck layout and deck layout with raised bulkhead deck.

4.5 Stability

For the Electric Light design the cargo deck has been moved upwards which means that the vertical centre of gravity for the whole ship moves upwards. Comparing to the conventional reference ship, the Vertical Centre of Gravity (VCG) increases by approximately 300 mm for the lightship and 600 mm for the full load condition. This results in a GMt of 5.56 m at ballast condition and 1.78 m at full load conditions which are reasonable values for a Ro-Pax ship to make it behave well in normal operation.

The ship must fulfil the intact and damage stability criteria. The intact stability is quite straight forward. The ship fulfils all criteria according to 2008 intact stability (IS) code. The GZ_{max} has a value of 1.238 m at 38.2 degrees, and the area under the GZ curve exceeds the requirements with good margin.

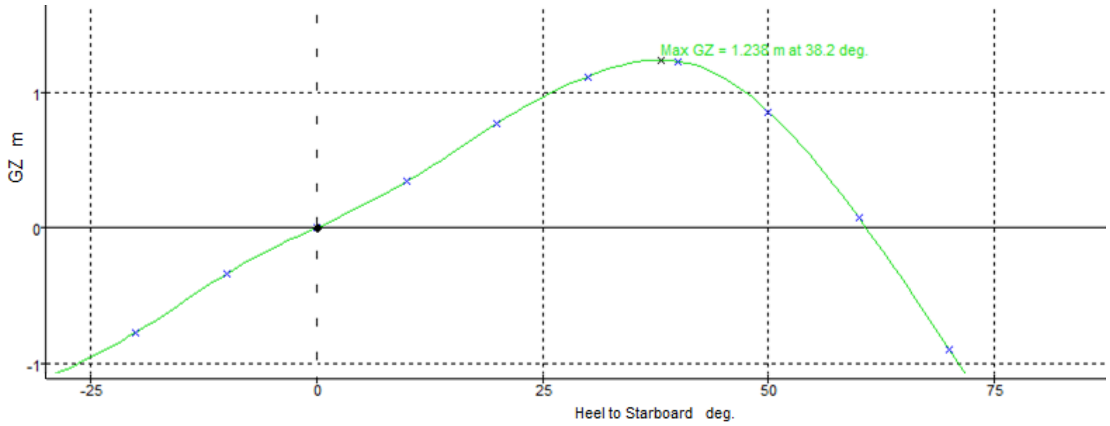


Figure 15. Stability, GZ as a function of heel angle to starboard.

The damage stability is a more complex calculation where a large number of damage cases needs to be assessed. For each case, the probability that the damage occurs and the probability to survive the damage is calculated. This probabilistic approach has been partly used in the history but has now been harmonized and updated. The current rules, MSC.421(98), entered into force in 2020.

According to MSC.421(98) the required subdivision index R, for a ship with 1000 passengers and 50 crew members, is 0.808.

To reach the required index a watertight door is arranged on the lowest cargo deck at the end of the deck slope. Also, the battery system is arranged in several compartments with watertight bulkheads between. Furthermore, cross flooding between void wing tanks is arranged to increase the probability of survivability S_i. This is because the probability to survive in the final equilibrium stage of flooding S_{final}, which is usually the minimum among three survivability category and therefore determine S_i, has an equation relating to the equilibrium heeling angle. By having void wing tanks flooded symmetrically, the heeling angle can be minimized.

The damaged stability calculation gives a result as shown in Table 5. This result is calculated with max 3-zone damage cases. Most of the probability are gained by 1-and 2-zone cases.

Table 5. Damage stability index.

	Attained subdivision index, A	Required subdivision index, R	
Deepest subdivision draught, d_s	0.734	0.727	Pass
Partial subdivision draught, d_p	0.852	0.727	Pass
Light service subdivision draught, d_l	0.962	0.727	Pass
Total subdivision index	0.827	0.808	Pass

4.6 Propulsion

The speed power curve of the ship has been estimated based on the following.

- Data from the reference ship.
- The ShipClean (Tillig, 2020) model where recognised empirical statistical methods are used.
- Hull resistance calculations with the CFD program Shipflow (Flowtech).

The design speed was chosen to 19 knots giving a reasonable margin to the required schedule speed. The meaning of design speed in this context is the speed the ship needs to reach at design draft with 10% added resistance (sea margin) at 85% of the specified maximum continuous rating (SMCR) of the propulsion system.

Table 6. Propulsion power

LOA		m	178.4
LPP		m	173.4
Breadth B		m	26.7
Design draft		m	6
Speed through water (Design speed)		knots	19
		m/s	9.956
Towing resistance at calm water	R_T	kN	575
Effective power	$P_E = R_T \times V$	kW	5 725
Total propulsive efficiency	$\eta_D = \eta_H \times \eta_0 \times \eta_R$		68.1%

Delivered power to propeller	$PD = (RT x V) /\eta_D$	kW	8 406
Shaft efficiency	η_S		98.50%
Brake Power at engine flange (without sea margin)	$P_{B0} = P_D/ \eta_S$	kW	8 534
Sea margin	SM	%	10%
Brake Power (with sea margin)	$P_B = P_D/ \eta_S \times (1 + SM)$	kW	9 388
Engine margin	EM	%	15%
Total required propulsion power		kW	10 796

Table 6 gives that a total propulsion power of approximately 10 800 kW will be required to reach 19 knots at the given conditions. It should be noted that the contract speed is not the normal or most frequent speed the ship will operate at. The schedule speed for the service is between 17 and 18 knots. The hull and the propulsion system should be designed for optimum performance (efficiency) at the most frequent operating condition.

For a fully electric drivetrain concept, two feasible solutions to deliver power to the propellers were evaluated.

Figure 16 Picture with permission from ABB - Azipod DO series

1. electric motors coupled to propellers via straight propeller shafts with conventional rudders,

2. pod propellers, eliminating long propeller shafts and the need for rudders.

The selection between propellers coupled to motors via drive shafts and pods mainly depend on the space constraints of the systems. The pod design offers a much smaller machinery room as compared to having motors within the hull that connect to drive shafts and hence provides more space in the hull for other use. This is due to the packaging of the motor and the directly coupled propellers in pods that protrude out of the hull. While the pods do contribute to additional drag, the stern part of the hull can be given a more optimum shape providing an overall efficiency similar or better than a conventional drivetrain. An added benefit is also the better manoeuvrability provided by the pods eliminating the need for bow thrusters. Three of ABB Azipod DO1250s are selected as the pod units. Each of these units are rated at 4 MW and hence total the required peak power of 12MW together. With a compact and a purpose-built design, they offer a high nominal efficiency of 97%.

4.7 Auxiliary systems

For a conventional ship, the electricity is generated by auxiliary engines driving generators and shaft generators powered by the main engines. A meticulous electricity balance needs to be established to ensure that enough electricity can be produced at all operational conditions at sea, during manoeuvring and at berth. For the fully electric ship the issue is not so much to identify and meet an electricity power demand but more an issue to estimate the total energy needed for auxiliary systems so that this need is included in the dimensioning of the battery capacity. However, for a fully electric ship the auxiliary electric power demand must anyway be considered to ensure that the distribution systems have sufficient distribution capacity.

4.8 Battery storage and safety

For electrical energy storage on board, as an example, lithium-ion battery solution by Canadian company Corvus Energy could be used. Having been designed specifically for marine use, the BlueWhale range of batteries are type approved (Lloyds Register, Bureau Veritas) and class compliant (DNV GL, Lloyds Register, Bureau Veritas, ABS).

The sizing of the battery is determined by the total energy requirement between two full charges and the depth of discharge (DoD). For every trip, considering the different speed restrictions along the route and the auxiliary systems usage, 30 MWh of energy consumption is estimated. The DoD of the cells defines how much of the battery's full capacity is discharged to power a load before being charged up to full again. This parameter has an inversely proportional relation to the lifespan of the battery: the lesser the DoD, the longer the life of the batteries. While lesser DoD seems beneficial for the lifespan, it implies a larger battery installation since the load remains the same. Hence, selection of the right DoD is a trade-off between the lifespan of the batteries and the weight and cost of the batteries to be installed. For this installation, a DoD of 50% is selected.

With the total energy requirement for each trip known, and with a pre decided DoD of 50%, the total energy that needs to be stored can be computed as approximately 60 MWh. The actual energy storage will be an integral multiple of the energy content of the smallest module. The configuration and the true values of the battery voltage and energy content is discussed in the following section.

4.8.1 Configuration

With the DC grid on board designed for nominal 1 000 V, the battery configuration can be designed as follows.

The smallest module has 43 kWh of energy at 80 VDC. For a nominal output voltage of 1 120 V, 14 modules are to be in series (14S). This implies that the energy content of each parallel string is 602 kWh. Having computed the total energy that needs to be stored to be approximately 60 000 kWh, 102 units of the 14S are to be connected in parallel (102P) bringing the total energy to 61 404 kWh.

While 14 modules in series and 102 series strings in parallel is justified theoretically, the practical physical placement of batteries in the hull cannot be 102 parallel rows of strings. For redundancy, the overall battery configuration is divided into 17 racks with each rack comprising of 6 series strings in parallel. Six switchboards, which will be described in chapter 4.9, has three of these racks connected except the last which has only two.

For the battery management system, 8 strings can be monitored by a single unit which implies 13 monitoring units are employed in total.

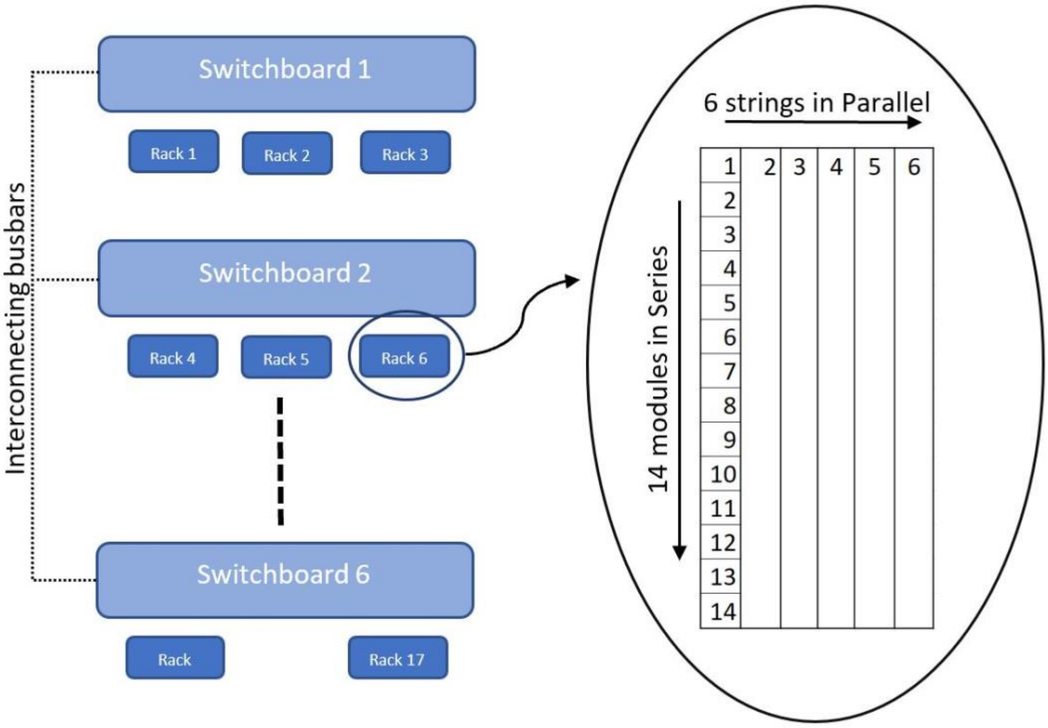


Figure 17. Schematic of the battery configuration and connection to switchboards.

4.8.2 Redundancy in capacity

Regulations dictating conditions for safe return to port (SRtP) in case of emergencies during a voyage are used to design and verify the redundancy in the system. Applicable operational requirements of SRtP distance of 25 NM and a SRtP speed of 5 knots have been based on the 50 NM voyage of the ship.

Under normal operations and speeds, 30 MWh of energy is consumed of the stored 60 MWh per trip. Considering an emergency, covering a distance of 25 NM at 5 knots will consume under 1 MWh of energy and under 1.5 MWh of energy with nominal use of auxiliary units along with propulsion. With a diesel generator set on the upper decks to provide for the essential auxiliary units such as navigation and communication devices, less than 2.5% of the total energy storage in batteries is required for propelling the vessel to safety under SRtP conditions.

The 2.5% that is needed for SRtP physically corresponds to only half a rack of the 17 installed racks as discussed in the previous section. From the risk workshop conducted to evaluate damage and flood conditions, it is established that complete flooding and loss of all installed batteries is extremely unlikely. Regulations imposing relevant IP ratings for the battery cabinets, placement of the racks on a platform, placement of racks in separate Class A compartments that are isolated from each other further minimise risk of complete flooding or propagation of fire that would deem the entire energy storage unusable. Hence, the ship is designed such that there is much more in reserve than what would be needed for a safe return to port in case of emergencies.

4.9 Power distribution

For efficient transmission of power either to the batteries from the shore connections or to the pods from the batteries, a DC grid is proposed as follows. The DC bus bars to which both the source (batteries) and the loads (pods and auxiliaries) are connected are divided into 6 switchboards. Each of these switchboards are interconnected via DC bus bars.

Each switchboard has two power lines feeding it with the charging power. This power is the output of charging transformers that step down the shore connection voltage to the DC grid voltage of ≈1 000 V. Each of these charging power lines then go through a rectifier within the switchboard for conversion to DC. Each switchboard, except one, has three racks of batteries connected to it. The configuration and arrangement of a rack is detailed in chapter 4.8, Configuration. These battery racks supply power to a common DC bus within the switchboard. Since the switchboards are interconnected, the battery racks are also interconnected in effect and hence contributing to redundancy in the system. This is because the interconnection allows for equal load distribution on the battery racks even on complete loss of one or more racks from any switchboard. For protection of the racks from surge or short circuits currents from other faulty racks. The racks are connected to the switchboard busbar via IC modules that offer isolation from faults.

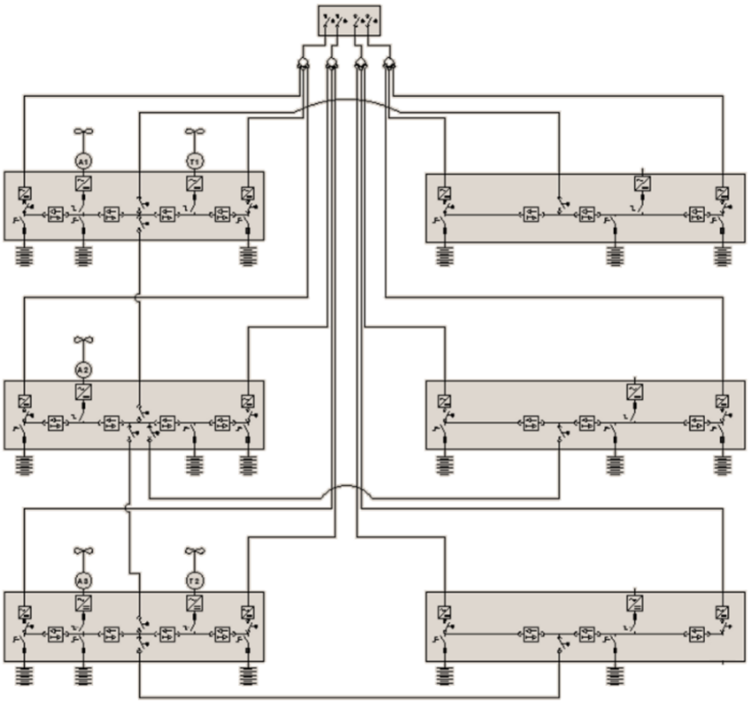


Figure 18. Single line diagram showing the 6 switchboards, interconnecting bus bars, charging inputs and the battery rack connections.

The loads are distributed over the switchboards for ease of control. While three switchboards feed the pods and the thrusters, the other three cater to the auxiliary loads. While any particular load is associated with a particular switchboard, the power driving that load is not just from the battery racks associated with that switchboard owing to interconnection of switchboard.

A 3D schematic of the DC grid with the 6 switchboards, the battery racks, the charging transformers, and the pods is as shown in *Figure 19*. The lines in red represent AC bus bars while the lines in blue represent DC bus bars.

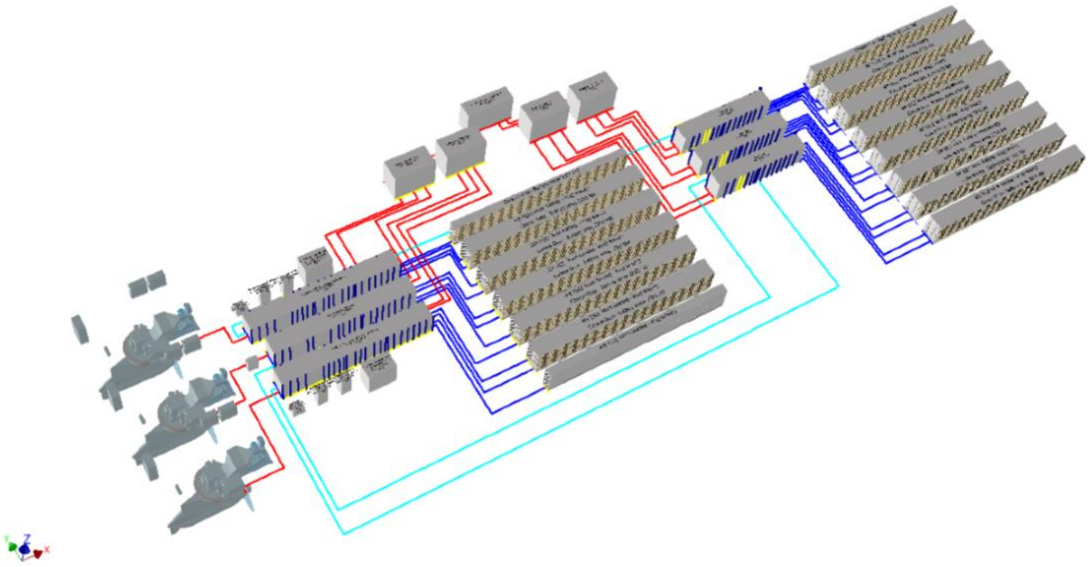


Figure 19. A 3D schematic of the electrical system on board.

4.10 Charging

Charging of battery storages as large as this poses interesting challenges to both ship operators and the design engineers. While keeping up a set schedule, the consumed 30 MWh of energy needs to be replenished in the batteries after every trip.

The cells making up the Corvus Blue Whale modules support a nominal charging rate of 0.5C and hence a total charging power of 30 MW is proposed. This implies one hour of charging after every trip. The cells also support a maximum charging rate of 0.7C corresponding to 42 MW of charging power and a peak charging rate of 1C for no more than 20 minutes which corresponds to 60 MW of charging power. While the cells do support such faster charging options, only 30 MW at 0.5C is proposed for two reasons.

Firstly, 30 MW over an hour is already an abrupt peak load for an unprepared distribution grid. This is ideally undesirable since it affects the load scheduling for the generators. Increasing the charging power only increases this burden on the grid. Secondly, increase in power implies increase in the ratings of all necessary switchgear and connections. This increases the installation costs and possibly the maintenance costs of all related equipment. Hence, 30 MW is a justifiable compromise between the speed of charging and the burden on the grid (assuming the power distribution company is aware and factors in the charging as part of their load schedule) and the cost and ratings of the equipment).

For the physical transfer of power from shore to the ship, two options were considered: plug-in connection and inductive charging. For charging powers as high as 30 MW, inductive charging can be eliminated as a feasible option since technologies transferring only up to 2 or 3 MW have been tested so far.

Plug in solutions, especially when automated, are the most feasible for transferring 30 MW of power. The number of connections can be minimized, and the cable size can be maximized since there will be no manual handling of connectors or cables.

4.11 Next step

The electrical design for a fully electric power ship is challenging. Below two critical design items are identified for further work.

- **Streamlining electrical equipment** - Development of an electrical system purpose designed for a specific power rating and energy consumption rather than a combination of separately designed generic components might prove more efficient on an electric ship such as this.
- **Heat recovery from electrical losses** - Unlike a combustion engine powered ship, the heat losses on an electrical counterpart is significantly lesser and the heat produced is not as localized as in engines making the heat recovery harder. Studies to develop good heat recovery systems from the electrical converters will reduce power used from the batteries for heating of the decks.

5 Risk analysis

In the project, several activities have been performed to identify and analyse risks and safety aspects of battery installations for propulsion of a ship. A background analysis was carried out to identify and summarize current regulations, guidelines, and other relevant safety information. A Hazard Identification (HazID) workshop was held at the beginning of the project, followed up by a "What-if" analysis workshop, focused on a limited number of selected scenarios. As a consequence of the second workshop, there was also further work conducted regarding fire suppression methods as well as on the impact of saltwater on Li-ion batteries. Finally, based on the results from the background analysis and conducted workshops, a battery fire safety concept, constituting guidelines for fire safety requirements, was iteratively developed to be valid for any fully electrically powered ship. These parts carried out in the project are further described below, while the battery fire safety concept is documented in Appendix H.

5.1 Regulations and Guidelines

No international regulations or guidelines concerning risk management of battery storage and installations for electric propulsion have yet been developed by IMO. Several Flag states and classification societies have although published relevant guidelines regarding battery storage for electric propulsion. In Table 7, obtained national guidelines and classification society rules are summarized and compared against each other regarding some critical aspects selected.

Brief information on the referenced standards found in the rules and guidelines included in *Table 7* is presented together with other relevant background information in Appendix C. Note that this compilation was mainly done at the beginning of the project and since this is an area in rapid change, there might exist updated documents that are not covered.

Table 7. Short overview and comparison of different national regulations/guidelines and classification rules regarding battery storage for electric propulsion

	STA (SWE)	NMA (NOR)	DMA (DNK)	MCA (GBR)	DNV GL	BV	LR
Min. number of systems/spaces					2 systems/spaces (SRtP).	2 systems (SRtP).	
Structural integrity			Same as for machinery spaces of category A.		Same as ship structure. Aft of collision bulkhead.	No sea water should be able to enter.	Separate from other spaces. Aft of collision bulkhead.
Fire integrity	Fire protection as for machinery spaces.		As for machinery spaces of category A + A-60 towards high or medium fire risk areas.		As for machinery spaces of category A + add. req. (e.g., A-60 towards machinery spaces and dangerous goods areas).	As for machinery spaces (A-0 between battery spaces).	'A-60' unless negligible fire risk, then 'A-0'. Not contiguous to machinery spaces, main source of power, associated transforming equipment or main switchboard.
Detection	Fire protection as for machinery spaces. CCTV recommended.		Gas detection should be considered in battery space and ducts.	Temperature monitoring (cell level). Feedback from fire-fighting systems to separate space.	Smoke and heat detection, Gas detection (both low and high in the space), Battery alarms.	Explosion risk (gas detection). Fluid leakage from pipes located in the space.	Smoke and heat detection. Alarms are specified for diff. battery system conditions.
Ventilation	"Safe and effective". Automatic fire dampers prescribed.	Air extracted to where it can do no harm. Explosion analysis required.	Independent system.		Emergency exhaust fan and inlet (min. 6 ACPH). EX proof fan. Fitted with means of closing and separate ducting.	No explosive atmosphere. Toxicity should be analysed. Vent. flow and room pressure detection required.	Vent. necessary for extraction of gases. Separate system, external fan motors, and minimise risk of sparking.
Extinguishment	Fire protection as for machinery spaces.		Suitable, fixed, automatic fire-extinguishing system.	Fire-fighting mediums should be able to penetrate battery casings. Possibility of standing water is not allowed.	Fixed total-flooding system; water-based (fresh water for 30 min) or gas (2 charges). Water-based is recommended.	Fixed fire-extinguishing system.	Appropriate water-based fixed fire-fighting system with automatic activation. Other medium than water can be considered.
Ingress protection (IP)				Fire-fighting mediums should be able to penetrate battery casings.	At least IP44. Lower rating can be accepted based on risk evaluation.	IP 2X (<1500 VDC), IP 32 (>1500 VDC).	

Risk analysis should cover	Hazard identification (HazID) and operability analysis (HAZOP).	Safety philosophy considering location of battery spaces, explosion, ventilation, and fire-extinguishing.	In accordance with MSC.1/Circ.1455.	Personnel safety, Environment, Ship operation, (FMEA is recommended).	Safety philosophy considering gas development, fire, explosion, detection, ventilation, and external hazards (e.g., fire and water ingress) + Hazard description (identification and analysis)	Gases (incl. toxicity analysis), Internal hazards (e.g., short circuit, thermal runaway), External hazards (e.g., fire, fluid ingress), Sensor/BMS failure, Cooling and leakage.	FMEA considering, at least, overpressure, fire, explosion, short circuit, mechanical impact, venting of gases, battery rupture, and ingress of water.
Safety testing required	IEC 62619 IEC 62620	Propagation test, Gas analysis.		BS EN 62281 BS EN 62619 BS EN 62620 UN 38.3 (IEC 60529)	IEC 62619 (NMA for propagation) IEC 62620 + add.	NR320, IEC 62619 IEC 62620 IEC 62281 + add. (prototype + onboard).	IEC 62619 IEC 62620 Gas analysis + add.
Other equipment in the battery room		Only equipment associated with the battery system should be placed in the battery room.			No other systems/equipment. No unnecessary piping.	No unnecessary piping.	No unnecessary piping.
Other	Only batteries certified for marine applications, Fixed to ceiling (recommendation).						All safety systems, if not made explicit, should be at least equivalent to those of a machinery space of Category A.

5.2 Hazard Identification Workshop

A hazard identification (HazID) workshop was held in Gothenburg, November 28, 2019. A HazID workshop is a systematic brainstorming session carried out by a multidisciplinary team, to investigate the safety of a specific subject. The participants should mirror the diversity of the subject in the sense that they should possess all the necessary competence to identify potential hazards and safety measures for the specific subject. The focus of this HazID was "risks associated to the electrification concept of a Ro-Pax ship".

5.2.1 Method

A spreadsheet was developed prior to the HazID workshop, to guide the procedure and for documentation of results. Risk areas to consider were decided to include fire and explosion as the main focus, while occupational health, environmental risks, and ship operation also were considered. Initially in the workshop, different parts of the electrical systems that should be discussed separately were identified as:

- the charging system (on shore and ship interface),
- the electrical conversion space,
- the battery space, and
- the propulsion system.

For each of these four system parts, hazards were identified connected to the considered risk areas, such as fire, loss of power, electric shock and release of toxic gases. Causes and critical factors were identified for each hazard along with current safety measures. Thereafter, specific challenges related to each hazard were highlighted together with potential safety measures for each challenge. Along the entire process a list of related comments was created as well.

Most time and focus were put on analysing the battery space, and especially the batteries. Failure of a battery may be the result of:

- external abuse (thermal, mechanical, electrical),
- poor cell design or manufacturing flaws,
- poor battery assembly design or manufacture,
- poor battery electronics design or manufacture, or
- poor support equipment (i.e., battery charging/discharging equipment) design or manufacture.

Integrated safety devices and the BMS (Battery Management System) would protect the battery against many potential failure modes such as overcharge, over-discharge, ambient extreme temperatures (by regulating cooling) and external short circuits (to some degree). However, protection against internal short circuits, mechanical damage, or external fire (or other external high heating source) cannot, in general, be guaranteed. The focus of this workshop was not to identify and analyse internal causes of battery failure, so it was decided to only analyse battery failure due to mechanical damage to the batteries or leakage (e.g., salt water or coolant) that may cause external short circuit, since this is affected by the configuration of the battery space and relate to specific challenges encountered in ships.

Battery failure would potentially result in a thermal runaway (TR), meaning that the heat produced due to exothermic reactions within a battery cell cannot be dissipated fast enough. (A formal definition of thermal runaway used within GTR (Global Technical Regulation on Electric Vehicle Safety (EVS), GTR 20, paragraph 23B.3.3) is when $dT/dt \geq 1$ °C/s and exceeds the maximum operating temperature.) Of course, any hazards potentially resulting from thermal runaway, such as fire, explosion, release of toxic gases and loss of power were included and analysed in the workshop.

5.2.2 Results

The resulting documentation from the hazard identification workshop is presented in Appendix D. Some notable results and discussions from the workshop were:

- The battery system should be designed to sustain roll motion and inclination by a significant safety margin. This will be dimensioned for mechanical damage rather than collision or grounding. In addition, no unnecessary additional or mobile equipment should be stored in the battery space.
- Integrity protection of e.g., IP44 should manage an extinguishing system, but sea water filling will probably cause problems (IP68 is only tested for water pressure at 1 m depth).
- The effect of sea water was discussed: Risk of arch flashes? Amount of gas due to electrolysis? (Read more on the impact of saltwater in Appendix G)
- To what battery system level should a TR be manageable in the design? Fuses should be installed at least between modules to avoid short circuit of larger units.
- In a battery space there are many potential sources of fire, not only the battery cells. What is the design scenario? (Read more on fire suppression in Appendix F)
- Clean up after a fire in the battery space may take considerable time, considering re-ignition/TR risks.
- The ventilation concept and battery safety concept must be thought through with regards to explosion risks and release of toxic gases. (Read more on this in next chapter and in Appendix H)
- Two means of escape should exist from all battery spaces, however, there should be no permanent occupation in battery spaces.
- Important with compartmentalization and redundancy. Safe return to port (SRtP) shall be fulfilled. In addition, separate additional emergency power shall be available further up in the ship if the battery spaces are located below water.
- It is primarily the battery space that introduces new hazards on the ship. For other spaces containing converters, transformers and propulsion system, the overall risks are reduced compared to a conventional machinery space, with combustion engines, boilers, etc.
- Redundancy for the onshore charging station might be critical. However, it was commented that the likelihood that the charging station is down could be compared to the probability of cancelled trips due to bad weather, which probably is higher.
-

5.3 What-If Analysis Workshop

Later in the project, when a more detailed conceptual design was available, a What-if analysis workshop was held online in two sessions November 5 and November 20, 2020. As for the HazID, this workshop could also be described as a systematic brainstorming session carried out by a multidisciplinary team. The main difference from the HazID workshop was that these workshops focused on a limited number of scenarios or events selected based on the output from the HazID, with more time available for analysing and discussing these events, and with a slightly different approach.

5.3.1 Method

A spreadsheet was developed prior to the workshop, to guide the procedure and for documentation of results. The considered scope was decided to include fire, explosion, toxic gases, business continuity and ship design effects on water filling. However, stability issues and electrical risks were not considered. Selected events to be analysed and discussed were:

- What if an internal battery cell failure occurs, leading to thermal runaway?
- What if battery racks are submerged in sea water?
- What if there is a fire in the battery space?

Regarding submerging of battery racks, three scenarios were considered; small water filling, submerging at least the lowest positioned modules, slow complete filling of the battery space, and fast filling, e.g., due to large hull rupture.

For each of the events, possible causes and prevention measures were identified, where both prevention of the cause and prevention of that cause leading to the event were considered. Further, consequences of the events were identified along with risk reduction measures, considering both reduction of the probability and the severity of the consequences. Along with the entire process, a list of related comments was created as well.

Most of the causes and consequences were quantified by letting the experts gathered estimate the probability of the event due to the different causes, the probability of the identified consequences due to the events, and the severity of the consequences. In addition, a second round of estimations was made given the potential prevention measures and risk reduction measures. Four levels were considered for the quantification of the probability and severity, with interpretations of the levels according to Table 8.

Table 8. Interpretation of the probability (P) and severity (S)

	0	1	2	3
P	Practically impossible	Not likely/heard of it	Known to occur	Common
S	Minor service / component replacement (Battery cell-> module)	Major service / material damage OR minor risk of injury (Battery module)	Major repair requiring downtime OR major risk of injury (Battery space)	Loss of propulsion OR risk of fatalities (Complete loss of battery space and likely spread to adjacent spaces)

5.3.2 Results

The resulting documentation from the What-if analysis workshop is presented in Appendix E. The result from the quantification process is summarized in *Table 9*, where also the following notes and explanations are important to consider:

Cell failure

- It was assumed that, even with tested TR propagation protection on cell level, there is always a risk that all parallel connected cells or the complete module becomes involved in a TR. (see the definition of "casualty unit" in the battery fire safety concept in Appendix H)
- The severity estimations presume in this case a separate exhaust gas ventilation system that ventilates TR gases directly from the modules, resulting in maximum '1' in severity if the gases can be handled without risk of fire or explosion (meaning that gas concentrations are kept below LEL).

Submerged in sea water

- Several estimations are marked with an asterisk, meaning that these consequences have been discussed further after the workshop.
    - It is very unlikely with TR due to salt water only (however, it is unclear what the significant corrosion effects can result in).
    - The electrolysis gases can be handled by normal ventilation.
    - Several battery spaces could be affected if the ventilation ducts are connected.

Fire

- The probability of fire spread to batteries was not quantified in the workshop, but it depends on the fire suppression concept, which is described further in Appendix F.

It can be concluded, considering any cause, that cell failure and fire in the battery space are more likely to occur than having battery modules submerged. Salt water might have more severe consequences as indicated by the initial estimations, but the probability of a scenario leading to severe consequences is very low. The consequences are discussed further in Appendix G.

Table 9. Summary of the estimated probabilities (P) and severities (S) with and without consideration to the identified measures (M)

Event	Cause	P	P|M	Consequences	P, S	(P, S)|M
Cell failure -> Thermal runaway	Any cause	2		TR in 1 cell	2, 0	2, 0
	Manufacturing flaws	2	2	TR in parallel cells	1-2, 0	1-2, 0
	Ageing and stress	2	1	TR in module	1-2, 2	1-2, 1
	Missuse	1	0-1			
	Missuse -> stress	2	1			
	Software virus or malfunction					
Battery modules submerged in sea water	Any cause	1		TR	1*, 3	1*, 2
	Grounding or collision	1		Electrolysis gas	1, 3*	
	Extinguishing system using sea water & failure of drainage system	1		Several battery spaces affected	0*, 3	0*, 2
	Explosion in adjacent space	0				
Fire in the battery space (outside battery modules)	Any cause	2		Fire spread to batteries		
	Electrical failure	1				
	Mobile equipment	1				
	Hot works	1				
	Human error incl. arson	2				
	Fire in adjacent space	1				

* initial estimations, but these were discussed further after the workshop.

5.4 Risk Analysis Conclusions

Regarding battery fire safety, it is very important with a holistic approach, including integrity, ventilation, failure detection and fire suppression methods, etc., based on hazard identification. The battery fire safety concept developed in this project, see Appendix H, constitutes safety requirements guidelines for large ship battery installations and is one of the main results from the conducted risk analysis work. The idea of the presented concept is that it should be applicable for any electrically powered ship and that it could be used as starting point for discussions on IMO harmonized regulations for battery energy storage systems onboard ships.

Considered in the battery safety concept is the risk level of the design, which requires several testing activities. For example, thermal runaway propagation tests together with short circuit protection tests will define the "casualty unit", the risk level defined in the concept, and measurement of gas release is fundamental to define the capacity of the ventilation system as well as the design of explosion integrity.

An important conclusion related to a specific hazard in ship battery applications is that sea water intrusion in the battery space can be managed. Normal ventilation can most likely handle the generation of electrolysis gases and short circuit protection for high voltage parts of the system ensures that thermal runaway will be unlikely, since high voltage is needed to cause arcing in salt water (Nembhard, 2019).

Identified in the project were also several areas that need to be studied in greater depths to validate the assumptions made and to further develop the safety concept. Here follows a list of potential future work:

- **Testing of battery immersion into saltwater -** Further testing to validate assumptions regarding the production rate of electrolysis gases in case of battery immersion into saltwater, as well as to confirm that short circuiting is a very unlikely effect. How is this affected by cell capacity, distance between terminals, SOC, voltage, and battery module configuration? How do corrosion effects alter the conditions over time?
- **Detailed study of the ventilation concept -** Study of how different specific ventilation system solutions relate to the battery safety concept. Consideration should be given to capacity, redundancy, ducting, distribution between battery spaces, exhaust ventilation from battery enclosure vs. ventilation from battery space, inlets and outlets, etc., and their influence on risk.
- **Post-fire strategies -** How should a battery space containing potentially flammable gases be purged without using air. How can damaged batteries, in the best way, be removed from the bottom of the ship?
- **Validation of the risk level (“battery casualty unit”) -** Is TR propagation testing on cell level enough or must TR propagation also be tested on a higher level? Study, including testing on battery module level, of the risks of more than one cell to be involved in TR and how this would affect TR propagation in case protection on cell level has been validated. Study of the impact on the general battery fire safety concept.
- **Early detection -** Study of methods for early indication and confirmation of a thermal runaway event.
- **Identification of necessary testing requirements for marine applications -** There is a potential difference in the result from current TR prevention tests (e.g., required in UN38.3 to allow transport of batteries) and similar tests which also verify a safe function of the battery after tests. There is also a question regarding whether abuse testing should be performed with the battery under load, which is generally not done today, and how that might affect the results.
- **IMO harmonized regulations -** Work towards internationally harmonized IMO regulations regarding battery energy storage systems (BESS) onboard ships.
- **Battery fire safety related to collision accidents –** A collision has the potential to cause the battery to burn, which has been proved by Bøe (Bøe, 2017) for electric road vehicles. Designers of electric road vehicles have been considering fire safety due to traffic accidents and identified “safe zones” for electric cars and electric

trucks (Bisschop et. al, 2019). A “safe zone” is the area in the specific electric vehicle where the battery is most unlikely to be damaged in colliding accidents. The “safe zone” idea can be applied to electric ships as well because ship collision is considered as one major ship accident type, particularly for ships operated in coastal areas. To identify a “safe zone” for an electric vessel, numerical analyses are needed to simulate various collision scenarios regarding the bow type of the colliding ship as well as the colliding speeds and angles. In addition, to provide the best protection against battery damages in ship collision accidents, an improved structural design with reinforced compartments might be needed where the battery packs are installed. This is in line with a holistic battery safety concept. Moreover, damage stability that is crucial for Ro/Ro ships can be checked in connection with the collision simulations.

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Appendix A: Investigation of achievable range of an electric ship

The purpose of this part of the study was to investigate the achievable range of an electric ship, depending on the ship speed. Increasing the number of batteries in the ship will increase the available energy to power the ship, but at the same time increase the displacement and thus increase the power demand.

A Ro-Pax ship with main dimensions according to *Table 10*, was used for the study. During the study, the length, beam and draft were kept constant, while the displacement (and hence the block coefficient) increase with increasing battery capacity/ weight. The study was performed with fixed speeds and constant environmental conditions, headwind of 12kn and head waves of 1.8m in height.

Table 10. Main dimensions of the study ship.

Ship type	Ro-Pax
LoA (m)	212
D (m)	6,50
B (m)	26,70
Displacement without batteries (t)	17 362

Figure 20 presents selected results from the study for one desired range (300 NM) and 5 different ship speeds. It can be seen how the displacement increases with the installed battery capacity for all ship speeds. The required battery capacity is found as the intersection between the total power consumption curve for the speed in question and the curve of the available battery capacity. As it is shown, the curves do not intersect for a ship speed of 21 knots, thus a range of 300 NM is not achievable with this ship and 21 knots of ship speed.

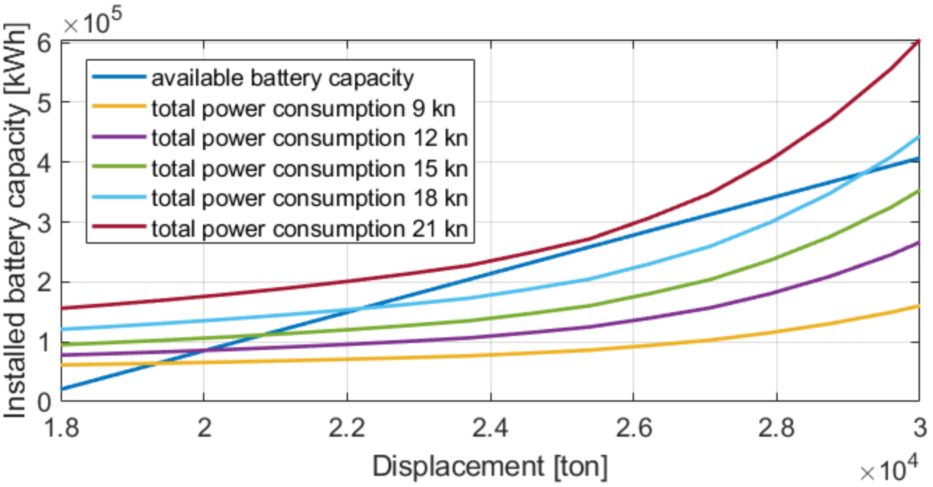

Figure 20. Power consumption and available energy over displacement for a 300 NM range and different ship speeds.

Resulting ranges for different ship speeds are presented in *Table 11*. Naturally, the achievable range decreases with increasing ship speed. With 5 knots of speed, the ship can have a range of up to 1300 NM, which decreases to only 250 NM for 21 knots of speed. For the project, the ship shall cover a route of about 50 NM. According to Table 10, the battery weight and range limit will not be of concern at any speed.

Table 11. Achievable range for 5 different ship speeds.

Speed (knots)	Range (NM)
5	1300
9	900
12	600
15	450
18	350
21	250

Appendix B: Investigation of required charging power

Early in the project it was identified that the required charging power in the harbours can be challenging. Naturally, the required charging power is closely coupled to the ship speed. A higher ship speed will result in shorter travel times and thus more time to charge the batteries in the harbour. However, higher ship speeds also result in higher energy consumption. To get a better understanding of the coupling between ship speed and charging power and to potentially find an optimal speed, a variation study for the ship speed during the journey was performed.

As a first step, the speed profile along the route was defined, which is presented in *Figure 21*. Due to the geography of the route, speeds are limited at both ends of the journey. The only free variable to vary was the speed on the open sea leg.

Figure 21. Route and speed profile definition.

The ship as defined in *Table 10* is used for this study. To estimate the required battery capacity and displacement of the ship a limiting condition was defined, where the ship shall have enough energy to travel along the route. The limiting condition was defined to be 3 m wave height (head waves), 40 knots of wind (headwind) and maximum 12 knots of ship speed. For the example ship, 486 batteries were required, and the total displacement became 21 230 t.

The results of the study are presented in *Figure 22*. It can be seen, how the energy consumption increases with increasing ship speed (red line). However, as presented by the curve of the required charging power (blue curve), the required charging power does not follow this trend. It is shown that there is a minimum of the charging power, in the studied case this is found at about 17 knots. It is also shown that the minimum is rather flat, meaning that the ship speed can be varied between 15.5 – 18 knots without significantly affecting the required charging power. However, the energy consumption was about 15% lower if traveling at 15.5 knots instead of 18 knots.

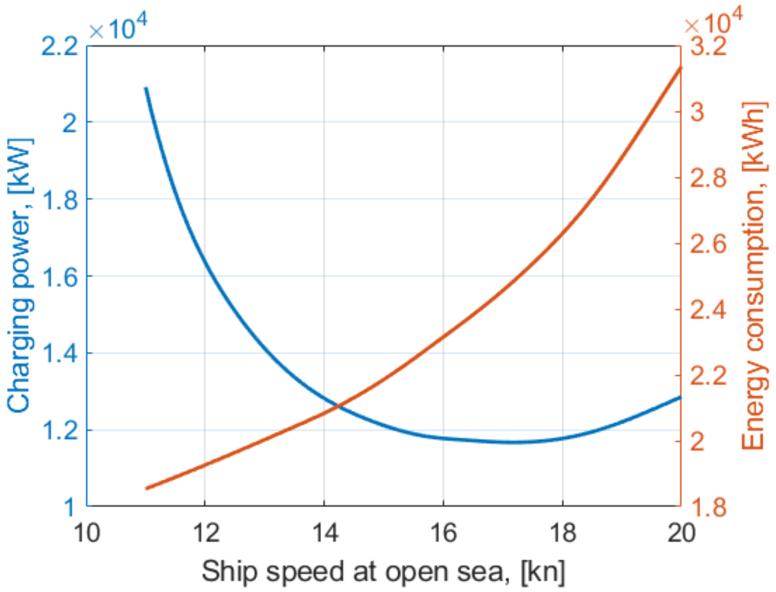

Figure 22 Charging power and energy consumption over the ships speed.

Appendix C: Regulations, Guidelines and State-of-the-art

Regulations and Guidelines

No international regulations or guidelines concerning risk management of battery storage and installations for electric propulsion have yet been developed by IMO (International Maritime Organisation). Only some general regulations related to electrical installations can be found in SOLAS (Safety of Life at Sea):

SOLAS Chapter II-1, Part D "Electrical Installations" has the following general requirement (SOLAS II-1/40.2):

> *The Administration shall take appropriate steps to ensure uniformity in the implementation and application of the provisions of this part in respect of electrical installations.**
>
> * Refer to the recommendations published by the IEC (International Electrotechnical Commission) and, in particular, publication IEC 60092 – Electrical installations in ships.

Furthermore, regulation 45 "Precautions against shock, fire and other hazards of electrical origin" states the following related to batteries:

> *"9.1. Accumulator batteries shall be suitably housed, and compartments used primarily for their accommodation shall be properly constructed and efficiently ventilated."*

Several Flag states and classification societies have although published relevant guidelines regarding battery storage for electric propulsion. Some national guidelines and classification rules were summarized in Chapter 5.1, *Table 7*, and below is a short list of where the information was retrieved from:

- The DNV GL class notations regarding battery and hybrid ships are found in DNV GL Rules for classification, Ships, Part 6, Chapter 2 and DNV GL Class programme, Type approval, Lithium batteries. DNV GL also have comprehensive guideline material to complement the rules; "DNV GL Handbook for Maritime and Offshore Battery Systems" and "In Focus – The Future is Hybrid – A Guide to Use of Batteries in Shipping".
- Bureau Veritas (BV) have a notation on Battery Systems found in BV Rule Note: "Steel ships, Part F, Chapter 11, Section 21".
- Lloyd's Register (LR) have, since July 2020, included requirements on lithium battery system installations in their "Rules and Regulations for the Classification of Ships" (Part 6, Chapter 2, Section 12: Batteries). Before the updated regulations, LR only required the use of a generic risk analysis procedure, with a guidance note of what to consider in the risk analysis; "Battery installations – Key hazards to consider and Lloyd's Register's approach to approval".
- General guidelines for battery and hybrid electrically propulsed ships were published by the STA (Swedish Transport Agency) in 2018: "Transportstyrelsens riktlinjer för batteri- och hybriddrivna fartyg" (TSG 2018-735).

- Guidelines for ships with battery propulsion were published by the NMA (Norwegian Maritime Authority) in 2016: “Guidelines for chemical energy storage - maritime battery systems” (RSV 12-2016).
- The document MSC 97/INF.8 includes the DMA’s (Danish Maritime Authority) guidelines on battery installations.
- Requirements for battery installations were published by the MCA (Maritime and Coastguard Agency, UK) in 2016: “Electrical Installations - Guidance for Safe Design, Installation and Operation of Lithium-ion Batteries” (MGN 550).

It can be noted that the two ForSea electric ferries Aurora and Tycho Brahe operating between Helsingborg-Helsingør are in much identical, where Tycho Brahe was approved by DMA and Aurora was approved by STA.

Referenced Standards

Below is a short description of the different standards referenced in above regulations and guidelines:

- IEC 60092 “Electrical installations in ships”. Extensive document on more than 1 200 pages with general electrical installation requirements.
- IEC 60079 “Explosive atmospheres”. Extensive document on more than 5 300 pages. It includes requirements and information on general equipment, gas detectors, intrinsically safe equipment, a variety of different methods of equipment protection, the classification of areas, material characteristics, and some industry specific standards.
- IEC 60529 “Degrees of protection provided by enclosures (IP Code)”. Classifies and rates the degree of protection provided by mechanical casings and electrical enclosures against intrusion, dust, accidental contact, and water.
- IEC 60533 “Electrical and electronic installations in ships - Electromagnetic compatibility (EMC) - Ships with a metallic hull”. Specifies minimum requirements for emission, immunity and performance criteria regarding EMC of electrical and electronic equipment for ships with metallic hull. It is based on the assumption that the ship is constructed such that metallic hull and structure parts will significantly attenuate electromagnetic disturbance.
- IEC 62281 (BS EN 62281) “Safety of primary and secondary lithium cells and batteries during transport”. Specifies test methods and requirements for lithium cells and batteries to ensure their safety during transport other than for recycling or disposal.
- IEC 62619 and IEC 62620 are referenced for testing of batteries:
    - IEC 62619 (BS EN 62619) “Secondary cells and batteries containing alkaline or other non-acid electrolytes – Safety requirements for secondary lithium cells and batteries, for use in industrial applications”. This standard gives advice on general battery safety considerations (e.g., wiring, venting, measurements, contacts, assembling/design and operating range). It

    includes cell and battery tests (e.g., short circuit, impact, drop, thermal, overcharge/discharge and propagation test).
  - IEC 62620 (BS EN 62620) "Secondary cells and batteries containing alkaline or other non-acid electrolytes – Secondary lithium cells and batteries for use in industrial applications". Tests include cycling and measurements during normal use and information on marking of cells.

- UN Manual of Tests and Criteria Part III, Subsection 38.3. Recommendations on the transport of dangerous goods and specifically for subsection 38.3: lithium metal and lithium-ion batteries.

- MSC.1/Circ.1212 "Guidelines on alternative design and arrangements for SOLAS Chapters II-1 and III", 20/12/2006. Provides a structured approach for the development of AD&A (Alternative Design and Arrangements) studies related to construction and life-saving systems.

- MSC.1/Circ.1455 "Guidelines for the approval of alternatives and equivalents as provided for in various IMO instruments", 18/07/2013. Provides a general approach for the assessment and approval of alternative design and arrangements as well as equivalents in ship design and construction.

IEC 62619, which was published in 2017, is referenced for safety testing in most rules and guidelines. It should be noted that this standard (as for many other standards) is quite vague in many aspects. For example, in the thermal runaway propagation test

- there are no specific requirements on state-of-charge (SOC),
- one can choose to test either on cell level or pack level, and
- the general requirement is that there should be no fire.

"No fire" and "no explosion" are recurring requirements in several standards, while heat generation and ventilation of flammable gases are allowed as long as they do not ignite in the test. Another potential drawback in most test standards is that abuse testing, in general, is conducted without having the battery under load.

A test standard used for energy storage systems (ESS) is UL9540A, which has a more detailed testing specification and requires both small-scale and large-scale testing. NFPA 855 "Standard for the Installation of Stationary Energy Storage Systems", published 2020, has prescriptive requirements for common situations, e.g., small energy systems within buildings, but refers to UL9540A for situations that deviate from the standard.

Another new standard regarding safety of battery storage systems was published in 2020, namely IEC 62933-5-2 "Electrical energy storage (EES) systems Part 5-2: Safety requirements for grid-integrated EES systems - Electrochemical based systems". This is also a relevant reference standard for ships.

State-of-the-art

Battery installations exist on many ships today, for example Norled Ampere, Texelstroom Seaspan Ferries, Scandlines ferries (e.g., Prinsesse Benedikte), CalMac ferries, Vision of the Fjords, etc. In 2020, there were more than 200 ships in operation around the world using batteries for propulsion and about 400 including those under construction. Most of the ships are hybrids, but about 20% are pure electric (DNVGL, n.d.).

Battery spaces

On current ships, a common solution for retrofitting of a battery storage is to place it in a container on top of the ship, e.g., as for Stena Jutlandica and ForSea Aurora. On Aurora, some reinforcement of the structure was needed to manage the weight from the batteries, but there was no difference in the end of the total weight of the ship due to reduction of the amount of diesel carried. For new electric ships it is easier to design and place a battery space anywhere in the ship and for small ferries the only reasonable place is usually in the bottom of the ship.

MSC 97/INF.8 contains "information on the approval of the battery installation on a hybrid ro-ro passenger ship" operating between Germany and Denmark. The ESS of this ship contains 1.5 MWh of battery energy divided on 231 battery modules. Some safety aspects of the document are summarised below:

- There is a separate battery space which fulfil requirements for machinery spaces of category A.
- One side of the room is towards machinery space (A60) and three sides are designed as potential pressure relief valves in order to relieve the pressure if a thermal runaway results in explosion.
- A HazID (hazard identification) analysis showed that fire tests were needed; a test with fire behind an A-60 bulkhead and a propagation test with provoked thermal runaway. The tests showed that such fires did not spread.
- There is a separate ventilation system and emergency extracting system to handle pressure rise from thermal runaway in one module as well as to extract toxic and explosive gases.
- Temperature sensors are used in the ventilation system (the referenced guideline prescribe "gas detection or other suitable system").
- There is a fire sprinkler system with automatic activation. The activation includes both the battery space and adjacent spaces in case of a thermal runaway event.
- The BMS (Battery Management System) gives warning at 40°C, alarm at 42°C and 60°C, and shuts down the system at 65°C. Evacuation alarm is given at 80°C.
- The electrical installation is not Ex classified.

Machinery spaces

Many rules and guidelines prescribe that battery spaces should be categorized as machinery spaces. SOLAS requirements for machinery spaces with regard to fire detection, fire extinguishment and fire integrity include:

- Detectors are required to be activated by heat, smoke or other products of combustion, flame, or any combination of these factors. Detectors that will be activated by factors of incipient fires may be considered, provided that they are no less sensitive than detectors activated by products. Flame detectors shall only be used in addition to smoke or heat detectors (SOLAS II-2/7.4 and the FSS code).

- A fixed gas fire-extinguishing system, or a fixed high-expansion foam fire-extinguishing system, or a fixed water-spraying fire-extinguishing system is required for machinery spaces of category A (SOLAS II-2/10.4). (see further descriptions in Appendix F)
- If the machinery space is larger than 500 m^3, the above total flooding system shall be complemented with an approved type of water-based (or equivalent) local application fire-extinguishing system (SOLAS II-2/10.5.6).
- At least one portable foam applicator unit and a sufficient number of portable fire extinguishers of foam type are required (SOLAS II-2/10.5).
- Fire integrity requirements for machinery spaces are specified in SOLAS Chapter II-2/Regulation 9 *Containment of fire* and depend on the type of ship and on the category of the adjacent space. On displacing passenger ships with more than 36 passengers, machinery spaces should for example be separated from stairways and corridors by A-15 bulkheads and A-30 decks, and from tanks, voids and auxiliary machinery spaces by A-0 bulkheads and decks.

Onshore Energy Storage Systems

The size and layout of battery spaces on electrically powered ships are in much similar to onshore energy storage systems. In the previous chapter, some standards were mentioned that have been developed in recent years for ESS applications (NFPA 855, IEC 62933-5-2, UL9540A). As background, some full-scale tests on ESS were performed by FM Global in 2019, generating interesting data. They conducted fire tests on LFP and NMC battery racks (Ditch & Zeng, 2019). Based on the tests, there are separation distance recommendations between a battery rack of a certain size to non-combustible or combustible adjacent surfaces for spaces with and without sprinkler protection of the ESS, as seen in *Table 12*.

Table 12. Separation distance recommendations based on full-scale tests by FM Global (Ditch & Zeng, 2019)

ESS Capacity Rating		**Sprinkler Protection**		**No Sprinkler**	
		Non-combustibles	Combustibles	Non-combustibles	Combustibles
LFP	31 kWh			<0.9 m	1.2 m
	83 kWh	0.9 m	1.5 m	1.2 m	1.8 m
NMC	47 kWh			1.2 m	1.8 m
	125 kWh	1.8 m	2.7 m	2.4 m	4.0 m

DNV GL gives some information on onshore ESS based on an extensive testing program on cells and modules (Hill, 2017):

- The toxicity of the battery fires was found to be mitigated with ventilation rates common to many occupied spaces.
    - Recommended Ventilation Rate Correlation of 0.2 - 0.32 cfm/Wh (0.34-0.54 m^3/h per Wh).
- DNV GL recommends more stringent criteria such that a single cell failure cannot propagate to adjacent cells.
- For fire extinguishment, a 2-stage system is recommended:
    - Stage 1: If a battery system is designed to limit cell failure cascading, a gas-based fire-suppression system may be considered for the first stage of firefighting, in order to extinguish a single cell fire and prevent flashover in a contained environment.
    - Stage 2: If temperatures continue to rise or if an increasing level of smoke and gas is detected, forced ventilation (of the enclosure containing the batteries) and firefighting using water should be considered to cool the battery system and prevent further propagation of fire.

Appendix D: Documentation from HazID Workshop

The resulting documentation from the hazard identification workshop is presented below compiled in four tables, one for each part of the electrical system.

Battery Space

Event	Cause	Critical factors	Current safety measures	Status	Challenges	Potential safety measures	Comments
Thermal runaway (TR) from mechanical damage	*Grounding/collision	*State-of-charge (SOC)	*TR propagation protection between cells/modules is generally required	Battery room at the bottom	Hull damage causing mechanical damage to the electrical system/batteries and initiating TR	* Moving the battery space further up in the ship * Compartmentalization of the battery space * Increasing the double hull spacing * Stronger double hull * Emergency/SRtP power could be stored separately, not in the bottom of the ship (emergency generators are generally above the water line)	*Consider whether the battery space is in a critical zone in case of collision/grounding. How large part of the battery system is probably affected?
	*Arson (bomb, fire…)	*Design/safety philosophy of the battery system (on cell/module level vs system level)	*Security and accessibility (ISPS Code)		Mobile equipment inside the space shifting and causing mechanical damage to the electrical system and initiating TR	* Structural integrity of the battery racks/cabinets * Operational procedures preventing that equipment stays inside the space.	*Is there any equipment used for handling the batteries (crane, wheeled rack, etc.) inside the battery room? How is it stored? There should be no mobile equipment in the space, and no other systems which are not needed for the batteries or for room protection.
	*Inclination/heel causing shift of battery system (e.g., pack, or module) or mechanical damage from mobile equipment	*System power (see comment***)	*Structural integrity of the battery room		Battery racks shifting/falling over	* Attachment of the battery systems so that they can sustain roll motion and inclination by significant safety margin.	*Most battery systems are not designed to handle TR above module level. To what level should a TR be manageable in the design?
	*Event in adjacent spaces (e.g., explosion in ro-ro space)	*Security and accessibility to the space (arson)			Battery modules falling out from racks due to inclination and roll motion, causing mechanical damage to	* Attachment of the battery systems so that they can sustain roll motion and inclination by significant safety margin.	*Shock forces from a collision/grounding would not be dimensioning for mechanical damage (rather significant heel/roll motion).

					the electrical system and initiating TR		
		*Whether the batteries are placed in the double hull or further up in the ship will affect the potential damages in case of collision/grounding					***With regard to system power, it is the cell/module design and at which level short circuit protection is applied that matters rather than the total system power.
							*Normally, ship systems are designed for handling a 22.5-degree inclination.

Event	Cause	Critical factors	Current safety measures	Status	Challenges	Potential safety measures	Comments
TR from leakage (external short circuit)	*Hull damage (grounding/collision) causing saltwater ingress	*State-of-charge (SOC)	*BMS (electrical isolation fault) and fuses.		Activation of fixed extinguishing system causing flooding or ingress into battery, causing TR	* Increased integrity of battery system. * Compartmentalization to avoid deployment of extinguishing system over all batteries. * Gas fire extinguishing system as a first resort, and water-based system in case initial fire progresses. *Continuous reduced oxygen environment.	*External short circuit of unprotected circuit (no fuse) due to dropped equipment is unlikely unless work within batteries is conducted. *IP44 should manage an extinguishing system.
	*Leakage of coolant liquid	*Placement of fuses (e.g., shortage of a battery pack/string before the fuses in the BMS/string control)	*Integrity of (parts of the) equipment (IP56/65/…), however flooding requires quite significant integrity of all parts.		Sea water filling of compartment	* Increased integrity of all components of battery system. * Fuses between modules to avoid short circuit of battery pack/string.	*IP68 is tested for water pressure at 1 m depth and may not be enough in case of flooding of the bottom compartments. The Corvus Blue Whale battery system have unprotected string connectors at the bottom of the packs, which could imply an early exposure in case of flooding/extinguishing system release and drainage failure.

	*Extinguishing system (leakage or activation)	*Impedance of the liquid/water (potentially causing arch flash)	*Drainage system (same as for all spaces).		Leakage of liquid coolant, causing short circuit, causing TR	Leakage detection.	*Systems exist where the cooling system is designed such that coolant (normally distributed through thin cooling pins) is filling the module in case of TR (emergency cooling) with the purpose to stop propagation of TR. *Sea water filling could potentially generate global TR in case the whole battery system is not integrity protected (more than IP68) as a whole. Common battery systems today are generally not IP classed in all relevant parts. Water immersion might not cause arch flashes but will results in production of large amount of gases. *The potential of arch flashes due to sea water in unprotected circuits should be investigated (tested), but is probably low. Without arch flashes, the sea water will act as an electrical load. Electrolysis of the sea water will produce large amounts of gas, e.g., hydrogen and clorine. It should be tested how much flammable gases are released when a battery cell is submerged in saltwater (due to electrolysis) compared to the amount of flammable gases released due to TR in the cell. *Fresh water gives a significantly lower risk than salt water.
	*Failure in water drainage	*Gas production from electrolysis of sea water (e.g., hydrogen and chlorine gas)	*TR propagation protection between cells/modules is generally required.		Loss of drainage capacity (single point failure?)	Redundant power for drainage	

Event	Cause	Critical factors	Current safety measures	Status	Challenges	Potential safety measures	Comments
Fire	*TR (internal or see above) *Electrical failure in external system	*Availability of combustible materials (cabling, casings, …)	*Fire extinguishing system	High SOC	Limit TR propagation between cells	* Passive protection by distance/insulation/heat dissipation between cells * Active cooling or fire protection (such as CO2, water filling etc.) * Continuous reduced oxygen environment.	*Propagation protection between cells or modules depend on the system design. For example, some systems have active protection and dedicated ventilation, some do not have active systems since passive protection prevent propagation and normal ventilation is supposed to handle venting from one cell (e.g., Corvus Dolphine).
	*Electrical/mechanical failure in brought in mobile equipment	*SOC	*Detection system, BMS	High SOC	Limit fire spread/TR propagation between modules.	* Passive protection by distance/insulation/heat dissipation between modules * Active cooling or fire protection (such as CO2, water filling etc.) * Continuous reduced oxygen environment.	*Cooling of batteries could be done by a cooling liquid or by air
	*Hot works	*Performance of extinguishing system	*Fire integrity of battery, cell//module propagation protection inside battery		Fire protection limiting fire spread between battery racks and from surrounding equipment	* Water-based fire extinguishing system inside space. * Fire integrity of battery space divisions. * Continuous reduced oxygen environment.	*The ventilation and battery safety concept needs to be thought through for different scenarios.
	*Human error (arson, smoking, etc.)	*Safety culture, security/ISPS, accessibility	*Fire integrity of battery room, to/from other spaces		Fire protection limiting fire spread from surrounding spaces	* A-60 towards r-ro space or other high-risk spaces.	*What design scenario should fire safety be based upon? TR in cell/cells/module/packs?
	*Fire in adjacent space (in particular Ro-Ro space above in case BR is located in the bottom)	*Location of battery space *Performance of detection system *Ageing effects on the batteries *Propagation protection inside battery (cell/module)	*Ventilation for battery packs *Ventilation for battery room				*Clean up after a fire is difficult, in particular with consideration to re-ignition/TR risks as well as contamination of the batteries. Cleaning and movement of the batteries may trigger new TRs. It is not inherently safe until batteries have been deenergized. Clean up may take considerable time, days/weeks, which may significantly affect ship operations.
Event	**Cause**	**Critical factors**	**Current safety measures**	**Status**	**Challenges**	**Potential safety measures**	**Comments**

Explosion	* TR (internal or see above) causing venting of flammable gases	*SOC	*Ventilation for battery room		Explosive atmosphere inside battery room	* Gas detection inside battery space (hydrogen, hydrocarbons…), connected to ventilation system (LEL) * Ventilation * EX classification of electrical components	*Determine what the ventilation system should be designed for (venting of a battery cell, module or pack?)
		*TR propagation protection	*Ventilation for battery packs				*Venting of one cell could be manageable with normal compartment ventilation system, depending on cell size.
	* Electrolysis of salt water/mist, generating hydrogen (see above)	*Ventilation	*Detection system, BMS				
	*Arson (bomb, fire…)	*Security and accessibility to the space (arson)	*Security and accessibility (ISPS Code)				
			*Fire extinguishing system				
Event	**Cause**	**Critical factors**	**Current safety measures**	**Status**	**Challenges**	**Potential safety measures**	**Comments**
Release of toxic gases	* TR (internal or see above) causing venting of toxic gases	*Manning of battery room	*Ventilation for battery room *Ventilation for battery packs		Firefighting	* Remote control and feedback from all systems, to allow remote control from a safe space	*Battery room should only be manned during maintenance and patrols
	* Electrolysis of salt water or mist in the room, generating e.g., chlorine gas (see above)	*Feedback from safety systems inside the spaces (detection system, extinguishing system, ventilation system, gas concentrations, etc.) from a safe place	*Detection system, BMS, to give early warning *Fire extinguishing system, to wash down gases		Manning for maintenance or controls/patrols	* Evacuation in two directions, avoiding passing through toxic gases * Normal and/or emergency ventilation system * Gas detection and warnings (BMS)	*Design of room ventilation system based on one cell venting with regard to generation of toxic gases? *In case of air-cooled batteries, this function will more likely dimension the ventilation system capacity.

Event	Cause	Critical factors	Current safety measures	Status	Challenges	Potential safety measures	Comments
Electro Magnetic Fields	Electrical equipment/cables	*Manning and location of passengers *Shielding by steel structures					*No permanent occupation in battery rooms or ro-ro spaces above *DC/AC? Voltage/Current? What are the determining factors for EMF?

Event	Cause	Critical factors	Current safety measures	Status	Challenges	Potential safety measures	Comments
Electric shock							*Follow state-of-the-art safety procedures and arrangements (as used on current ships, where similar magnitude electrical equipment is already common) *Are there any differences compared to current ships? Charging system and connection of shore power?

Event	Cause	Critical factors	Current safety measures	Status	Challenges	Potential safety measures	Comments
Loss of power	TR or other cause	Availability of emergency power			Loss of power due to e.g., TR	* Emergency power by one of the battery rooms (compartmentalization) allowing SRtP (propulsion, steering gear, navigation, …) * Separate emergency power system further up in the ship, allowing safety systems on the ship (except propulsion) for 36 h	

Event	Cause	Critical factors	Current safety measures	Status	Challenges	Potential safety measures	Comments
Personnel getting trapped	*Flooding due to hull damage (grounding/collision) *TR/fire		2 means of escape from all battery spaces		Personnel getting trapped inside the battery room due to fire/venting/flooding…	* 2 means of escape from all battery spaces * Normal and emergency ventilation, separate for all battery spaces	Follow state-of-the-art with regard to watertight doors

Charging System

Event	Cause	Critical factors	Current safety measures	Status	Challenges	Potential safety measures	Comments
Fire	*Electrical fault (see below)						
	*Human error/hot works						
	*Fire in adjacent space						
Event	**Cause**	**Critical factors**	**Current safety measures**	**Status**	**Challenges**	**Potential safety measures**	**Comments**
No power in charging station or power transmission to the ship	*Blackout in municipality power distribution network *Electrical fault (see below) *Mechanical damage, e.g., forklift/truck collision on land, or damage to the onboard shore connection.	*Probability of blackout (see comment) *Electricity management procedures *Location of charging system in relation to vehicle operations	*Shore connectors on both sides of the ship and sufficient cable to feed both connectors. *Physical collision damage protection barriers around charging system building		No possibility for charging the ship	*Redundant charging stations *Redundant supply from electricity distribution network (to the same charging station)	The likelihood that the charging station is down should be compared to the probability of cancelled trips due to bad weather, which probably is higher.

		*Location of onboard shore connection in relation to ship related operations and obstructions. *Mechanical damage to the robot connection			No electricity onboard/blackout onboard.	*Emergency generator onboard *Manual back-up solutions to connect emergency power to shore *Emergency generator on quayside	

Event	Cause	Critical factors	Current safety measures	Status	Challenges	Potential safety measures	Comments
Electric shock							*There are current standards for charging and high voltage/current systems that will be used for charging station setup and work procedures. Reference should be made to these standards to make sure all safety aspects are covered for personnel safety. *Emergency plans/procedures shall be included.

Event	Cause	Critical factors	Current safety measures	Status	Challenges	Potential safety measures	Comments
Electrical fault	*Human error in the connection process/ work procedure. *Failure of the robot connection					* Robotic power connection	There are current standards for charging and high voltage/current systems that will be used for charging station setup and work procedures.
	*Flooding in the charging station *Fault in the shore connection sub-station (transformer failure, breaker failure, etc.)					* Flooding protection of charging station	

Conversion Space

Event	Cause	Critical factors	Current safety measures	Status	Challenges	Potential safety measures	Comments
Fire						Chemical powder hand-held fire extinguishers	*The space includes switchboards, converters and transformers. *The same converters could potentially be used for charging as for discharging the batteries, depending on the distribution system.

Propulsion System

Event	Cause	Critical factors	Current safety measures	Status	Challenges	Potential safety measures	Comments
Fire		Straight shafts or PODs?					*Overall risks are reduced compared to a conventional machinery space since there are no combustion engines, boilers, etc. *The propulsion system could potentially make use of the same conversion space as used for charging the batteries.

Appendix E: Documentation from What-If Analysis Workshop

The resulting documentation from the what-if analysis workshop is presented below.

What if (event)	Possible causes	**Prevention measures** (prevent direct causes and causes leading to event)	Comments	Consequences	**Risk reduction measures** (Lower probability and severity of consequences)	Comments
An internal battery cell failure occurs leading to thermal runaway?	Manufacturing flaws	-	* Difficult to do anything about manufacturing flaws.	Thermal runaway in 1 cell Venting of toxic and flammable gases	Ventilation system (fan) that can handle explosive gases.	* We have prevention ventilation. It should be designed so that the ventilated gases are below LEL. It could also be relevant to have a push fan (instead of suction).
	Ageing/stress	Not use the complete SOC range of the battery (charging/discharging)	* P(E) is also a function of age and quality control.	Thermal runaway in parallel connected cells Venting of toxic and flammable gases	Ventilation system (fan) that can handle explosive gases.	
	Ageing/stress	Quality control	* Stress can also occur due to misuse (e.g., cell/module balancing.)	Thermal runaway in module Venting of toxic and flammable gases	Ventilation system (fan) that can handle explosive gases.	* Assuming that the heat from the parallel connected cells cause a module to TR. This should be tested. A quite high ventilation capacity would be needed to make sure that the ventilated gases are below LEL. S(C)=L was based on that the gases can be handled by the ventilation system.
	Misuse	Quality control of BMS	* Misuse can often be identified by the BMS. * Maintenance can lead to module not being connected to BMS.	Thermal runaway in module Venting of toxic and flammable gases	A higher ventilation capacity	
	Misuse/stress	* Education and training of crew. * There should also be a standard protocol for how to connect, disconnect, and other charging	* It is often the manual operations that cause faults in a system.			

		routines to minimize stress.				
	Software virus or failure causing thermal runaway					
What if (event)	**Possible causes**	**Prevention measures** (prevent direct causes and causes leading to event)	**Comments**	**Consequenses**	**Risk reduction measures** (Lower probability and severety of consequenses)	**Comments**
Sea water submerging battery racks (at least lowest module)?	Hull rupture due to grounding/collision	* Moving the battery space further up in the ship could alter the P(E&Ca) to N. * Increasing the double hull spacing * Stronger double hull * Closure of the ventilation system ducts in case of collision/damage causing water ingress.	*Some consequences may depend on rate of water filling (hull damage vs sprinkler/drainage problem). Collisions on this route are quite common, but still not frequently occurring. Stena has had 2 occurrences in 20 years, and in these cases the penetration depth was less than B/5. Our current ship design has a large void between the battery spaces and the hull. If the ventilation system would be in the side of the ship, even a small collision could imply water ingress.	Complete battery system affected (several battery spaces => loss of propulsion)	* Compartmentalization of the battery space * Emergency/SRtP power could be stored separately, not in the bottom of the ship (emergency generators are generally above the water line)	* The design with 6 battery spaces makes the probability of complete battery system affected very low. * Extinguishing system divided for each battery space makes it unlikely that more spaces would be affected. Small filling (malfunctioning drainage), slow filling, fast filling. * It would probably be reasonable to test what happens if you submerge a module, if the battery space is below the main deck.

	Explosion in adjacent space (e.g., ro-ro space)	-	*The deck separating the battery space from the ro-ro space is very strong. Perhaps an explosion could cause water penetrating the ventilation duct, leading to the battery space.	Water ingress to modules leading to thermal runaway (fuses at module level). Venting of toxic and flammable gases.	* Increased integrity of modules/system (now IP44) * A measure could be to shut down the ventilation system, to stay above the UEL. At least until evacuation of the ship has occurred. * Gas sensors measuring the gas concentration (LEL, UEL). * CO2 system could deplete the oxygen level in the space.	* IP68 is tested for water pressure at 1 m depth. It may be enough to handle water filling by an extinguishing system but not enough in case of flooding of the bottom compartments. * Fuses at module level should disconnect each module (external short circuit). * The batteries should not stand directly on the deck, allowing for some water filling before they are affected.
	Extinguishing system using sea water Last resort or Unintended activation? And failure of the drainage system.	* Increased capacity with fresh water of the Initial response system, allowing more time without salt water. * An additional gas fire extinguishing system to handle fires which are not in the battery system. * Redundant power for drainage	* IP44 should manage an extinguishing system. * The system should only be used as a last resort. * The human factors aspect needs to be considered. * A fire simulation could determine how long a fire could continue without oxygen depletion. * Failure in the drainage system is known to occur.	Gas production from electrolysis of sea water (hydrogen and chlorine gas)	* Gas sensors measuring the gas concentration (LEL, UEL). * CO2 system could deplete the oxygen level in the space. Shut down ventilation system.	* The potential of arch flashes due to sea water in unprotected circuits should be investigated (tested), but is probably low. Without arch flashes, the sea water will act as an electrical load. Electrolysis of the sea water will produce large amounts of gas, e.g., hydrogen and chlorine. It should be tested how much flammable gases are released when a battery cell is submerged in salt water (due to electrolysis) compared to the amount of flammable gases released due to TR in the cell.
Small filling (malfunctioning drainage)		Routines for checking drainage system		Some modules affected. Large volume for gas accumulation (electrolysis).	ATEX classed compartment ventilation to handle explosive gases from electrolysis spreading to the room (can probably not be connected to a heat pump to heat up the ship)	* Separate venting duct should handle TR. * How much hydrogen gas and oxygen gas?? * Electrolysis gases could be released to the space and might not be ventilated by the system connected to the module. * If we produce H2 gases, we need to vent them out. At least unless the consequence of explosion is quantified. * The amount of H2 produced by electrolysis/submerging a module in water needs to be quantified to

						know if the compartment ventilation can ventilate it sufficiently (below LEL).
Slow filling		Routines for checking drainage system	* Risk for water ingress through ventilation system?	All modules affected over time. Volume for gas accumulation smaller and smaller.		* If the cell is fully charged and submerged in salt water, the positive terminal will probably be fully corroded before the energy from the cell is gone, which could lead to TR.
Fast filling			* Mechanical damage large?	All modules affected. Risk of damage due to water wave. Risk of damage to separate venting duct.		* Still low filling rate of modules (IP44)? No room for gas accumulation?

What if (event)	Possible causes	**Prevention measures** (prevent direct causes and causes leading to event)	Comments	Consequences	**Risk reduction measures** (Lower probability and severity of consequences)	Comments
There is a fire in the battery space?	Electrical failure in external system (BMS, battery control system, lighting, ventilation, electric power equipment, switchboard…)	* Transformers which are of "dry type" and less prone to fire ignition could be chosen * The battery space should be as free from other equipment as possible. * ATEX classed exhaust fan.	* The only external equipment (in addition to the batteries) in the space should be the exhaust gas fan and the BMS system. Converters and transformers should not be in the space. Do fans need to be inside the room?	Fire spread to battery racks	* Water-based fire extinguishing system inside space. * Continuous reduced oxygen environment.	* There is a compartment fire suppression system that should handle any fire in the space. * It could be relevant to have a gas fire extinguishing system inside the cabinets etc which are not reachable by a water-based fire extinguishing system. * A water-based system could be used not only to extinguish a fire, but also to cool down the space in case of a fire in an adjacent space (to avoid TR due to heating). * A CO2 system could also be used to flush out potential explosive gases. * It is important that the compartment fire-extinguishing system is not damaging to the electrical systems in the space. * Clean up after a fire is difficult, in particular with consideration to re-ignition/TR risks as well as contamination of the batteries. Cleaning and movement of the batteries may trigger new TRs. It is not inherently safe until batteries have been deenergized. Clean up may take considerable time, days/weeks, which may significantly affect ship operations.
	Electrical/mechanical failure in brought in mobile equipment		* There need to be proper procedures and training in place to handle this hazard.	Thermal runaway in several cells/modules (Venting of toxic and flammable gases) - See TR scenario above.		

	Hot works		* There need to be proper procedures and training in place to handle this hazard.	Fire spread in complete battery room	Compartmentalization of the battery space	* Emergency/SRtP power could be stored separately, not in the bottom of the ship (emergency generators are generally above the water line)
	Human error (arson, smoking, etc.)		* There need to be proper procedures and training in place to handle this hazard.			
	Fire in adjacent space	* Additional thermal insulation. * Routine to not use the batteries in the space directly below the fire (to make sure that they are cooled as much as possible).	* Do we need to consider additional fire insulation for the division between the battery space and the Special Category Space above? * The drencher system will provide good boundary cooling and it is important that there is sufficient power to run it for a long time (what do the regulations require?)			

Appendix F: Fire Suppression in Battery Spaces

Something that makes Li-ion batteries different compared to many other fire hazards is that all the prerequisites needed for fire are available inside the battery; the fuel, the heat, and to some extent even the oxygen. In addition, the heat produced from exothermic reactions, which eventually lead to thermal runaway, can provoke exothermic reactions in the neighbouring cells and so on. This process is independent of combustion/fire of the ventilated gases and propagation will continue as long as the heat produced in a cell is enough to start thermal runaway in the next cell. Of course, a fire may assist propagation and enable heat spread over larger distances.

Another problem is that re-ignition and delayed thermal runaway may occur hours and days after a first damage (Bisschop, Willstrand, Amon, & Rosengren, 2019). As long as there is energy in the batteries, new internal reactions could be triggered (e.g., by small movements, or due to conductive soot particles, liquid, etc.).

Extinguishing systems for battery fire

Thermal runaway in a cell cannot be interrupted, but thermal runaway propagation can be stopped. DNV-GL (Hill, 2017) recommends that "if a battery system is designed to limit cell failure cascading, a gas-based fire suppression system may be considered for the first stage of firefighting, in order to extinguish a single cell fire and prevent flashover in a contained environment." The idea is that a gas fire-extinguishing system should not damage other parts of the battery, as with e.g., water. However, DNV-GL also says that such a system should be combined with a water system.

To stop thermal runaway propagation by a fire-extinguishing system, cooling is essential. However, cooling of battery cells is difficult due to access limitations (densely packed and sealed) (Andersson, o.a., 2018; Willstrand, SLUTRAPPORT - Att hantera brandrisker med Li-jonbatterier i fordon, 2019). There are several different extinguishing agents with cooling ability other than plain water, e.g., F-500 and AVD are both argued to be suitable solutions for li-ion batteries. None of them is an all-purpose solution though.

The access of cooling to battery cells is a challenge. However, note that a total compartment fire-extinguishing system may well be used for the protection of battery spaces with the objective to reduce the probability of fire spread between battery racks or from the battery space to adjacent structures. Of course, there could also be conventional fires in a battery space.

Extinguishing systems required for machinery spaces

As mentioned before, many rules and guidelines prescribe that battery spaces should be protected similar as machinery spaces. For reference, one of the following systems, further defined in the FSS Code, is required for machinery spaces of category A (SOLAS II-2/10.4, 10.5):

- A fixed gas fire-extinguishing system (the FSS Code refers to CO_2, but other gases can be used);
- A fixed high-expansion foam fire-extinguishing system; or
- A fixed pressure water-spraying fire-extinguishing system.

The latter (fixed pressure water-spraying fire-extinguishing system) is a traditional low-pressure sprinkler system. In accordance with the FSS Code, equivalent water-based fire-extinguishing systems (generally high-pressure water mist systems) are also allowed, after performance tests in line with MSC/Circ.1165. In addition, for passenger ships >500 GT and cargo ships >2 000 GT with machinery spaces of category A above 500 m^3, a water-based "local application fire-extinguishing system" is required above certain equipment (see MSC.1/Circ.1387).

Table 13 below list the pros and cons of three common fixed fire-extinguishing system alternatives for machinery spaces (total compartment):

- Fixed pressure water-spraying fire-extinguishing system (referred to as sprinkler);
- Fixed carbon dioxide gas fire-extinguishing system (referred to as CO2); and
- Equivalent high-pressure water-based fire-extinguishing system (referred to as water mist).

The assumed performance objective in a battery spaces would be to prevent fires starting inside the battery space, but outside the actual battery modules, from involving the batteries. It is not expected that any of the systems will prevent a fire from starting in a single battery cell to progress to adjacent cells, but they may have an impact on fire spread from a battery module to adjacent modules. Such a performance objective should always be tested for the specific battery design and installation.

Carbon dioxide (CO_2) systems reduce the oxygen content of the atmosphere to a point where combustion becomes impossible. This requires an agent concentration that is lethal. The system is normally activated by signals from a fire detection system. The earlier the detection of a fire, the earlier the activation of the system, but before activation certain safety and sealing procedures may be required (in particular, ensuring that no personnel is occupying the space). It is assumed that the battery space is normally unoccupied. However, due to the safety aspects, it is recommended that a pre-discharge alarm and a delay time from fire detection to system discharge is applied. It is also recommended that the system can be put into a non-automatic mode when the battery space is occupied, for example during inspection, service, or maintenance and that a disable device is fitted for the system inside the space.

Water-mist fire protection systems can be designed and installed as a deluge system, where all open nozzles discharge water. Such a system is activated by signals from a fire detection system and/or by manual operation. The earlier the detection of a fire, the earlier the activation of the system, and activation can be initiated immediately. However, discharge when the battery space is occupied is not desired, even if it likely does not pose any large hazards to potential occupants. The system may also use automatic nozzles, individually activated by the heat from the fire. For such a system, the fire is likely to be larger upon discharge, and only nozzles exposed to heat will activate.

A traditional sprinkler system may be of deluge type or utilize automatic sprinklers, in line with the descriptions given above. Typically, a larger water flow is used compared to that of a water-mist fire protection system, especially in enclosed spaces.

Table 13. Pros and cons for different total compartment fire protection system alternatives.

Type of system	Pros	Cons
CO2	The agent is distributed in about 60 seconds and acts quickly to extinguish (even small) fires. This may reduce fire damage, leading to less downtime. Carbon dioxide is a suppressant that works well for a wide range of fire hazards, such as electrical rooms, paint booths, power plants, and more. The agent is non-conductive. It is a colourless and odourless agent. When it is released, it leaves no residue behind. This means that there is no clean up necessary which lessens downtime. It does not cause any harm to the environment, as it is already present in air around us. Quantities used in fire suppression systems do not significantly contribute to global warming.	The protected space needs to be evacuated prior activation. The gas is lethal at concentrations well below the design concentration. Typically, carbon dioxide systems are used in non-occupied spaces. Carbon dioxide is heavier than air. Safety aspects, particularly in spaces below the protected space should be regarded. Any ventilation to the protected compartment needs to be shut off and the compartment sealed prior to activation. Overpressure vents are needed. Less effective on deep-seated fires as compared to water-based systems since it does not have a significant cooling effect (more important with early detection)
Water-mist	Provides cooling of hot combustion gases. Provides cooling of hot surfaces and objects. No risk of asphyxiation as with gas fire suppression. Less damage to property than traditional sprinkler and easier to drain/clean up. Environmentally friendly (no additives). Less weight and space requirements as compared to traditional sprinkler systems due to thinner piping. The protected compartment does not need to be airtight. Ventilation may need to be turned off, all dependent on the ventilation rate.	Small, shielded fires may not be fully extinguished. Water is conductive. The system may be connected to the sea water connection for prolonged discharge, but such operation requires flushing of piping and post-inspection of nozzles and nozzle strainers. Water damage, although less water is typically used as compared to traditional sprinkler systems. Run-off (contaminated) water may need to be collected.
Sprinkler	Similar advantages as for water-mist systems, but the cooling of hot combustion gases is often considered lesser, and the cooling of hot surfaces and objects considered better. Larger water droplets mean greater penetration depths to reach the seat of fire and they are less affected by	Similar to those of water-mist, although the water flow rates typically are higher, and the system weight and space requirements are larger. Drainage of water is required, more than for water-mist. Less effective on shielded fires as compared to water-mist.

	ventilation as compared to smaller droplets.	

Appendix G: Impact of saltwater on Li-ion batteries

In both conducted workshops, the impact of saltwater and the probability of submerging the batteries have been discussed. In the HazID workshop, it was identified that sea water intrusion due to grounding must be considered when the battery compartments are positioned at the bottom of the ship. Partly due to this concern, the new ship design was developed where the distance between the bottom hull and the battery compartments was increased. However, in the second workshop it was identified that also water intrusion through the ventilation ducts could happen, potentially affecting several spaces if the ducts are connected. It is therefore important to still consider the possibility of sea water intrusion. The two scenarios are illustrated in *Figure 23* and *Figure 24*.

Another scenario is that sea water is used in the fire-extinguishing system. If, at least, IP44 is used, the water spray should not be able to enter battery enclosures, but if the drainage system fails there is a risk of standing water. Except having routines for when sea water is allowed to be connected to the extinguishing system and required drainage, some important preventive measures are; redundant drainage system and regular inspections of its function, as well as having no batteries standing directly on the deck, which would allow for some water filling before they are affected. Of course, this is important also in case of a minor hull damage.

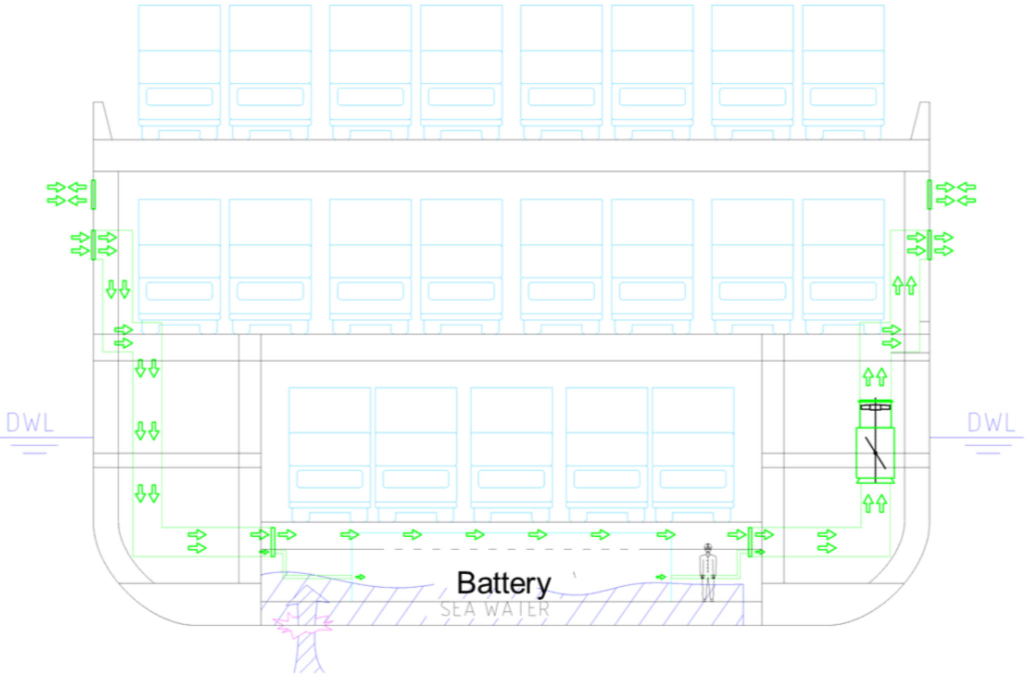

Figure 23. Seawater penetration into the battery compartment in the original ship design due to grounding.

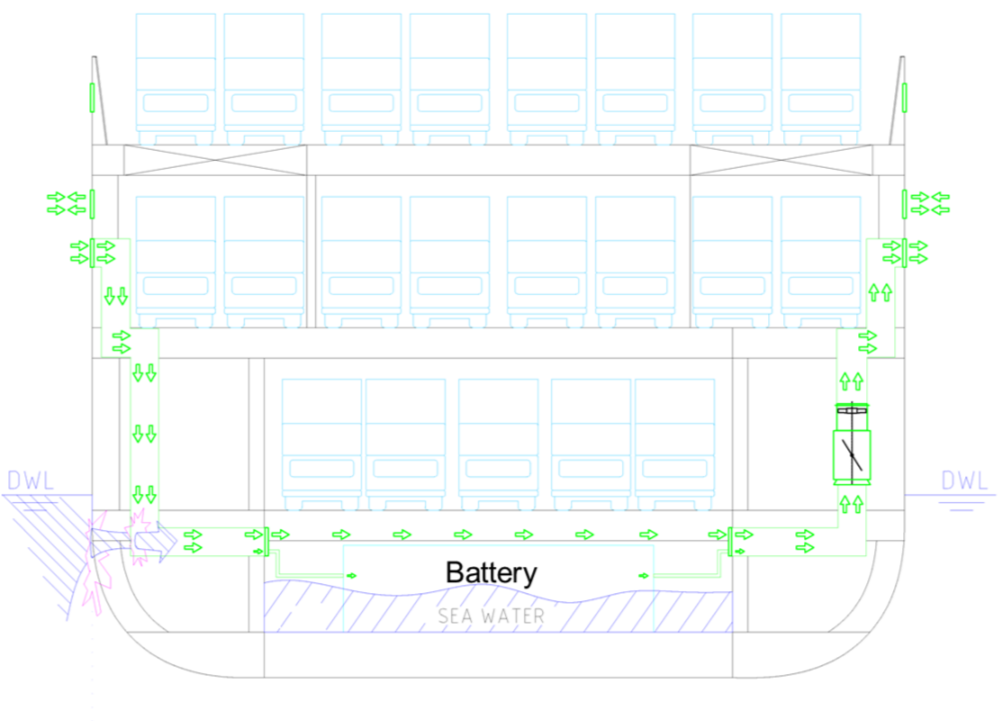

Figure 24. Seawater penetration into the battery compartment in the new ship design with larger safety margin for bottom penetration.

Consequences of sea water intrusion

In case battery modules are submerged into seawater there are two main hazards: production of electrolysis gases and risk of short circuits. The sea water will act as an electrical load and a short circuit is only possible with presence of arch flashes. Contamination of the water could potentially reduce the resistance, but there will also be an increased cooling capacity from the seawater preventing heat build-up in the cells. However, in 3.5wt% NaCl solution arcing may occur at a current discharge density of 90 000 A/m^2 (Nembhard, 2019), which might be the case on battery pack or string level. For example, arcing was observed for a 250 V battery pack when submerged in 2.4wt% solution (Nembhard, 2019). Fuses at least on module level is therefore important for protection against external short circuits on higher level. For battery cells the voltage will be too low for arc flashes and based on experience from putting batteries into saltwater for discharge after abuse testing, the conclusion is that thermal runaway in battery cells due to saltwater is very unlikely.

In addition, it is assumed that occasional single cell failures are managed by the ventilation design. That means that several cells must be shorted at the same time to produce more gases than can be handled by the ventilation. The amount of gases produced during thermal runaway varies between different Li-ion batteries, from about 0.1 l/Wh to several litres (Willstrand, Bisschop, Blomqvist, Temple, & Anderson, 2020), but 0.5 l/Wh is a good estimate (Baird, 2019) (this needs to be tested for every specific battery solution). CO, CO_2, H_2, and different hydrocarbons constitute the largest part of the gases, whereof all except CO_2 are flammable. In general, a lower explosion limit (LEL) of 6% could be considered (Baird, 2019), which means that with a battery module of 43 kWh the estimated total potential volume of a flammable air-gas mixture from that module is 360 m^3. To be handled by 6 acph (air changes per hour), resulting in 4 600 m^3/h with the considered ship design, the minimum total time of release should be 5 min, which cannot be guaranteed if all cells are going into thermal runaway at the same time. As mentioned, this is a very unlikely scenario due to sea water intrusion only, but the numbers are given for comparison to the amount of gases produced due to electrolysis, given below.

The expected scenario if the batteries are submerged in sea water is that electrolysis gases are produced when the battery cells are discharged through the saltwater. The gases produced are primarily hydrogen and oxygen (from the water, H_2O), but also chlorine gas which has a very strong odour (from the salt, NaCl). The chemical reactions occur at the terminals, which could be outside the module enclosure if the water has not reached the cell terminals, resulting in that the produced gas could easier spread in the room.

An estimate of the amount and rate of oxygen and hydrogen produced due to electrolysis can be theoretically calculated based on a few assumptions. Seawater is assumed homogeneous and to have a resistivity 'ρ' of 0.2 Ωm. For a single pouch cell with a nominal voltage of 3.8V, the resistance between the terminals is calculated using the area between the terminals 'a' (product of the length of the terminals and their thickness) and the distance between them 'l' as follows

$$r = \rho \frac{l}{a} \; (ohms)$$

This resistance is then used to calculate the current across the terminals using Ohm's law. For complete discharge of the cell, the approximate time taken is calculated by dividing the capacity of the cell by the discharge current. This is a conservative and vague approximation since ideally as current is discharged, the potential drops which leads to the current dropping further. This approximate time, along with Faraday's constant 'F' of 96485 C/mol can be used to compute the volume of hydrogen and oxygen released during electrolysis. The current discharged 'A' multiplied by the time for its complete discharge 't' gives the total charge in coulombs. This divided by F gives the hydrogen released in mols.

$$Volume = \frac{A * t}{F} \; (mols)$$

To get the volume in litres under STP conditions, the mols are multiplied by 22.4 which is the molar volume of a gas. This value of hydrogen release divided by 2 gives the volume of oxygen released.

$$Volume = Molar\ volume * 22.4 \; (l)$$

Similar calculations can be used with appropriate approximations for different kinds of cells.

Now, assuming a pouch cell with capacity 10 Ah, nominal voltage of 3.8 V, 3 cm distance between terminals, 1 cm length of the terminals and thickness of 2 mm gives, with 0.2 Ωm as the resistivity of sea water, a production rate of H_2 of 0.01 l/h. If that is scaled linearly to 230 modules of 43 kWh each (complete battery room), and assuming 4% LEL for hydrogen, that gives a flammable mixture of about 70 m^3/h that must be ventilated, i.e. easily handled by 6 acph for the battery space. In case the ventilation is shut down there is a possibility that the room is filled up with a flammable mixture only from the H_2 and O_2

produced in the electrolysis process, but with the production rate mentioned above, and assuming all batteries are involved, it would take almost 11 hours to fill up the complete room. In that case it is also a matter of water filling rate since explosion under water is extremely unlikely.

Small-scale tests

Some small-scale tests were performed to validate above theoretical assumptions. A Samsung SDI prismatic cell with capacity 51 Ah and a Panasonic NCR18650B cylindrical cell with capacity 3.2 Ah were submerged in salt water within a pressure vessel, as seen in *Figure 25* for the latter cell. The saltwater contained 3% NaCl, which is about maximum percentage encountered in the Kattegat.

Figure 25. Pressure vessel seen from the inside (left) and outside (right).

For the cylindrical cell, a gas sample was taken from the vessel after about 1 h, and for the prismatic cell, gas samples were taken from the vessel after about 1.5 h and after 3 h, respectively. Agilent 490 Micro GC was used to measure hydrogen content in the gas samples. Voltage and temperature of the cells were measured continuously. Results from the gas analysis and voltage measurements are summarised in *Table 14*, no significant temperature increase was measured for any of the cells.

Table 14. Summary of test results.

	Samsung SDI 51 Ah	Panasonic 18650, 3.2 Ah
H_2 production (l/h)	0.10	0.008
Discharge (V/h)	0.011	0.014

The hydrogen production rate is higher for the prismatic cell, but considering a discharge rate that is 20% lower for the prismatic cell, the difference in hydrogen production rate is reasonable since this corresponds to the difference in capacity given the same discharge time:

$$\frac{(0.011/0.014)\times 51}{3.2} \cong \frac{0.10}{0.008}$$

In addition, for the prismatic cell the size of the terminal was 4×1.8 cm^2 and using the centre-to-centre distance of 11 cm gives a theoretical expected H_2 production rate of 0.11 l/h at 4.1 V, which is quite close to the experimental value measured. Although the production rate is ten times higher for the prismatic cell compared to the theoretical calculations for a pouch cell presented earlier (0.01 l/h), this would for the complete battery room only mean that production rate is doubled, considering the difference in cell capacity (51 Ah compared to 10 Ah).

It was also noted in the tests that the saltwater had a clear corrosive effect, especially on the cylindrical cell, as seen in *Figure 26*. However, from both tests the residual water was heavily contaminated, see *Figure 27*. The water was not further analysed in these tests.

Figure 26. Visible corrosion on the cylindrical cell, but not on the prismatic cell.

Figure 27. The saltwater after tests were finished.

Appendix H: Battery Fire Safety Concept

Below is a draft version of a battery fire safety concept based on the conducted work within this project. These requirements should be valid for any fully electrically powered ship and could be the starting point for discussions on IMO harmonized rules for battery energy storage systems onboard ships.

General battery system requirements

The battery system's thermal runaway (TR) propagation protection and safety concept are connected to the battery space explosion integrity as well as to the battery space ventilation concept, with requirements per below. The battery space ventilation concept and explosion protection are determined by the estimated time of gas release for different scenarios and by the size of the *casualty unit*.

The *casualty unit* is defined as the greatest of:

- the largest unit of parallel connected cells;
- the largest unit (of both parallel and series connected cells) without external short circuit protection; or
- the unit of cells for which TR propagation protection (passive and/or active) has been verified by test.

Depending on the design, cells connected in parallel are more likely to be involved in a TR scenario in case of single cell failure and could reach TR in a much shorter time period (short circuit + heat propagation) compared to cells connected in series (only heat propagation).

An electrical fault (internal or external cause) outside a battery string or battery pack (e.g., connection box, BMS or other control) should not result in a short circuit in the affected batteries.

The battery systems should be installed to sustain roll motion and inclination by significant safety margin.

The battery system should be controlled by a certified (for the intended application) Battery Management System (BMS).

Structural integrity

Structural requirements are divided in the section's compartmentalization, structural fire integrity and explosion integrity.

Energy storage location and compartmentalization

The energy storage should be compartmentalized into at least two fully redundant battery spaces that are not contiguous in any boundary, each allowing (1) an emergency source of electrical power (cf. SOLAS II-1/42) and (2) propulsion back to harbour, in line with SRtP requirements (cf. MSC Res. 325, SOLAS II-2/21 and MSC/Circ.1369). To ensure full redundancy of the spaces, all electrical distribution systems, including cables and other support systems, for each battery space should be completely separated from each other.

Battery spaces should not be located forward of the ship's collision bulkhead (cf. SOLAS II-1/42.1) or less than 780 mm from the shell side, to avoid sea water penetration into the spaces due to collision. In case of sea water penetration into any ventilation duct running along the side of the ship, this should not cause water filling of more than one of the redundant battery spaces. Ventilation ducts from the battery spaces should be positioned to minimize risk of damage in case of collision.

Unless two battery spaces, and associated electrical distribution systems, are separated by at least 10 m in separate watertight compartments and at least one battery space is located above the uppermost continuous deck, an additional emergency source of electrical power should be provided (cf SOLAS II-1/42.1.2).

Structural fire integrity

Battery spaces should be thermally protected with fire integrity as required by SOLAS. Depending on the type of ship (HSC, cargo vessel or passenger ship carrying not more than 36 passengers, or passenger vessel carrying more than 36 passengers), a battery space containing less energy than 100 kWh should be categorized as category B/7/11 and a space containing 100 kWh or more as category A/6/12.

Battery space explosion integrity

The structural explosion integrity determines to what extent an explosion should be manageable by the surrounding structures, including potential pressure relief vents. The explosion integrity must be in balance with the battery design and TR propagation protection and is thus defined by the pressure caused by explosion of the gases released from TR in a complete casualty unit, considering estimated gas release time and ventilation concept as well as encapsulation of batteries. Pressure relief vents and weak structures should be designed considering a worst plausible such scenario.

Battery thermal runaway integrity

It should be strived to achieve TR propagation protection in-between battery cells, which assumes both (1) that there is sufficient distance or other passive protection to stop propagation between cells, and (2) that parallel connected cells have short circuit protection which disconnect them in case of TR in neighbouring cells.

The TR propagation protection should be verified by test. In the tests it is important to not only consider single cell failure but also other failure modes, e.g., leakage of coolant that might affect a larger number of cells at the same time or multiple failure events. A TR propagation test should therefore be performed of the casualty unit even if TR propagation protection in-between cells has been validated for single cell failure. In case TR propagation protection is not achieved at the casualty unit “level” but only for a smaller unit, this will define the design criteria for the fire suppression system(s).

Ventilation

Generic standard ventilation requirements should not be used for the battery space. The ventilation concept for battery spaces depends on several factors. Principally, three types of ventilations should be considered: *basic ventilation*, *preventive ventilation* and *casualty ventilation*. The ventilation from the battery spaces should eject to the outside of the ship considering the gases can be both toxic and flammable. ATEX classification of the battery space is generally not required since this is not possible for the batteries, however it could be applicable for the ventilation system.

Basic ventilation

If the batteries have a separate exhaust gas ventilation system directed from any encapsulation of the batteries, the battery space should have a basic ventilation of 6 acph. Without a separate exhaust gas ventilation system, the ventilation requirements for the battery space are determined by the preventive ventilation and the casualty ventilation as long as these requirements exceed the basic ventilation requirements.

Preventive ventilation

Preventive ventilation should be provided with sufficient capacity to ventilate TR in one single cell. The amount and flow of released gases from TR in one single cell should be determined by an overcharge test. The preventive ventilation should always be active.

Casualty ventilation

In case of a TR, or at the earliest warning of a potential TR emerging, the ventilation should automatically increase to a capacity which is at least sufficient to ventilate TR in the casualty unit.

The amount and flow of released gases from the casualty unit should be determined by worst case scenario test considering the different types of casualty units.

Detection

Smoke detection should be provided in the battery space.

Gas or smoke detection dedicated for the battery installation is required at least by each string or pack and should be connected to the integrated alarm system of the ship. Temperature and voltage are monitored by the BMS, which should give alarms to the integrated alarm system in case of abnormalities and transmit information to a continuously manned central control station.

Early indication of TR should be provided, e.g., by CO detection. Only LEL and cell voltage surveillance is not sufficient. If a separate exhaust gas ventilation system for the batteries exists, gas detection is most suitably positioned in the ventilation extraction.

Early gas detection or other early indication of actual or impending TR event should generate disconnection of the battery module, string or pack (sensor signals should still be active) and activate casualty ventilation. The suppression system should not be connected to the gas detection system, but automatic release of the suppression system may be connected to the BMS temperature sensors.

Feedback from the active systems should be available, by e.g., CCTV or other means.

If liquid cooling is used, leakage detection is required.

Fire suppression

Fixed fire suppression system(s) should be installed with consideration to the battery system design and in agreement with the battery supplier. Some battery suppliers utilize active fire suppression solutions for TR propagation protection, and some utilize only passive protection.

In principle, two types of fire suppression functions are required: *total compartment fire suppression* and *initial response fire suppression*. These functions may be provided by one system, depending on the design of the battery system.

To avoid electrical faults upon activation of the fire suppression system(s), high voltage parts of the electrical system should be:

- protected from water ingress (e.g., switch encapsulated by IP44);
- isolated, if possible, before water suppression system activation; and
- separated, as much as possible, from encapsulated parts of the battery system into which water discharges.

Total compartment fire suppression

The main performance objectives of total compartment fire suppression are:

1. to suppress fires in the battery space, in particular to prevent fires starting inside the battery space, but outside the battery cells, from involving the batteries; and
2. to prevent fire spread to and from the battery space.

Total compartment fire suppression should be provided in each battery space. The system should be sectioned to allow discharge in each battery space separately, but the system should have sufficient capacity to discharge in all contiguous battery spaces. The system medium should be selected with consideration to the battery system, but the starting point should be to use a water-based system designed for machinery spaces of category A.

Automatic activation of the system should be default, but manual release should also be possible. If the batteries are encapsulated by at least IP44 and there is a separate exhaust gas ventilation system for the batteries, the suppression system may be activated by smoke detection. Otherwise, heat detection only should generate automatic compartment fire suppression system activation.

The drainage system should be fully redundant, including e.g., scuppers and pumps.

Initial response fire suppression

The main performance objectives of initial response fire suppression are:

1. to assist prevention of TR propagation from a casualty unit; and
2. to swiftly suppress a fire in the battery space safely in its initial stage.

It should be noted that these functions may be achieved without the need for an initial response fire suppression system.

If the total compartment fire suppression system cannot be activated swiftly and safely with consideration to the batteries, generally if battery strings or battery packs are not in their entirety encapsulated by at least IP44, the initial response fire suppression system should be installed with discharge into the battery space. A performance objective of the system is then to prevent fires starting inside the battery space, but outside the battery cells, from involving the batteries. In case TR propagation from a casualty unit cannot be prevented by only passive means, a performance objective is also to prevent a fire in the battery, involving at least one battery casualty unit, from escalating. This should be verified by test.

If the total compartment fire suppression system can be activated swiftly and safely with consideration to the batteries, generally if battery strings or battery packs in their entirety are encapsulated by at least IP44, the initial response fire suppression system should be installed with discharge directly into the battery encapsulations. The performance objective of the system is then to prevent TR in a casualty unit from propagating. Fires starting outside the battery encapsulations are then handled by the total compartment fire suppression system. Hence, if TR propagation from a casualty unit is prevented by passive means only, no separate system for initial response fire suppression is required. If the BMS or other potential fire sources are part of the encapsulations, it must also be verified that heat propagation from these fire sources are prevented, by passive or in combination with active means.

The system medium should be selected with consideration to the battery system, but the starting point should be to use either fresh water or gas.

A fresh water initial response fire suppression system should have capacity to discharge for at least 20 minutes at maximum capacity.

Risk analysis

A HazID analysis shall be conducted to identify hazards along with safety measures for the specific installation. It is important that identified hazards are documented along with any potential measures that can minimize the risks. Further, the analysis shall identify and address any dependencies affecting different hazards, safety measures or requirements.

The risk analysis shall also contain a document describing how the requirements of this battery fire safety concept are achieved for the specific case.

Required fire safety testing

Summary of required testing:

- TR prevention tests (temperature, vibration, overcharge, over-discharge, short circuit, etc.). It is important to verify safe function after tests (i.e., only UN38.3 tests are not sufficient).
- TR propagation protection test on cell level or/and other chosen level of protection with or without suppression system

→ Determining the size of the casualty unit.

→ TR propagation test on casualty unit level also determines design criteria for the fire suppression system(s)

- Measurement of the amount of gas released during TR from 1 cell and the casualty unit, respectively. It is recommended to also analyse the gas composition.

→ This determines the capacity of the ventilation system and the design of explosion integrity.

- IP classification
- → Verifying high voltage protection from water and suppression media.

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