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BATTERY SYSTEM INTEGRATION AS RETROFIT

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The purpose of this thesis was to do concept review of battery technology and give information to design and calculate battery system integration as retrofit in to world's largest cruise ships. This thesis was assigned by Foreship Ltd, to extend the company's design expertise. Idea came from new marine emissions directives and legislations, which forces cruise industry to develop new ways to reduce emissions.

The biggest obstacle is the energy density of batteries, they use up lot of space which is very limited in a cruise ship. Therefore, it is not possible to use batteries for full length of the voyage. For example, use only the system for a limited time in the port area. Batteries can be used also in parallel with combustion engines, to increase fuel efficiency and low emissions.

Thesis was done in the view of electrical design. Battery calculation was done with Foreship Ltd's own calculation methods. In purpose to able to design and provide expertise in battery systems.

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Tämän opinnäytetyön aiheena oli tutkia akkuteknologiaa ja miten suunnittella akkujärjestelmä jälkiasennuksena maailman suurimpiin risteilyaluksiin. Opinnäytetyö tehtiin Foreship Oy:lle kehittämään yhtiön suunnitteluosaamista. Idea tähän työhön on lähtöisin uusista laivateollisuutta koskevista päästörajoituksista ja määräyksistä. Uudet rajoitukset ja määräykset ajavat laivateollisuutta kehittämään uusia teknologioita, joilla pyritään vähentämään päästöjä.

Suurin este akkujärjestelmän käytölle on akkujen energiatiheys. Akkujärjestelmät vievät paljon tilaa, jota on hyvin rajoitetusti risteilijöissä. Akkujärjestelmää ei ole mahdollista käyttää koko risteilyä, vaan vain esimerkiksi satama-alueella. Akkuja voidaan myös käyttää rinnakkain polttomoottoreiden kanssa parantamaan polttoainetehokkuutta ja vähentämään päästöjä.

Työ tehtiin ensisijaisesti sähkösuunnittelun näkökulmasta. Akkujen mitoittamiseen käytettiin Foreship Oy:n omia laskentatapoja. Tarkoituksena on osata suunnittella, ja näin myös tarjota, isoja akkujärjestelmiä.

CONTENTS

1 INTRODUCTION

New marine emission directives and legislations force cruise industry to develop new ways to cut emissions in the port area. This can be done by using fuels that are more environmentally friendly, for example liquefied natural gas (LNG) or using batteries in parallel with combustion engines. One interesting and increasing new technology is the Fuel Cells.

Typically, a cruise ship has over 100 systems that needs electricity which is produced mainly by combustion engines, this obviously generates lots of emissions. Biggest consumer is the propulsion system. In this thesis, I am going to design battery system that could operate as the complete power plant and to cut down fuel consumption from the combustion engines.

There are already batteries that supports uninterruptible power supply (UPS) in all cruise ships, that maintains the electrical supply to essential items, including emergency lighting, communications, navigational equipment and automation system for possible power failure of main electrical supply. This new battery system would be much bigger than UPS system, because it’s design to run the complete power plant.

When the space and the payback period is limited, best way to design battery system is to use it as redundant power source to combustion engines or enabling zero emissions in the port area. When optimal number of combustion engines is used at same time as battery system, it enables higher fuel efficiency and lower emissions. Furthermore, when batteries are used in propulsion system it not only lowers emissions, but also increases system stability and robustness. The bigger, the battery sales volume is, the lower the price of battery systems will be. This enables bigger and more advanced battery systems in the future.

2 FORESHIP LTD.

Foreship limited company (Ltd), founded 2002 in Finland. Foreship Ltd is an independent, privately owned naval architect and marine engineering company with more than 90 professionals in Finland, Estonia and United States of America. (Foreship www-pages 2017)

Foreship Ltd, is the leading cruise ship newbuilding consultant and conversion specialist, typical customers are world's largest cruise ship owners as well as passenger, cargo and offshore shipowners, leading shipyards and maritime suppliers, but also smaller ferries, RoRo vessels and cargo ships. (Foreship www-pages 2017)

Approximately half of the projects are conversions, retrofits and upgrades. Including preliminary studies and sketches through the complete design process all the way to on-site support, supervision and project management during the construction phase. (Foreship www-pages 2017)

2.1 Cruise Ships

Taking sea voyage with cruise ship is more popular than ever. According to news article in Forbes, last year there were around 26 million cruise passengers around the world. In this year, the number is increasing to over 27 million passengers (Micallef J V, 2018). This pushes shipyards to build new cruise ships even faster to cope with the demand. There are many cruise brands that are owned by cruise companies. Taking their passengers around world to different cities and selling from 2-3-day trips to even around world experiences. Carnival Corporation has the highest net revenue of the market in 2018 and has nine cruise brands. Second biggest is Royal Caribbean Cruises with three cruise brands. Other big cruise lines are Norwegian Cruise Line, Mediterranean Shipping Company S.A. Cruises (MSC Cruises) and Tourism Union International Cruises (TUI Cruises). Market share can be seen from next figure (Figure 1). (Cruisemarketwatch www-pages 2018)

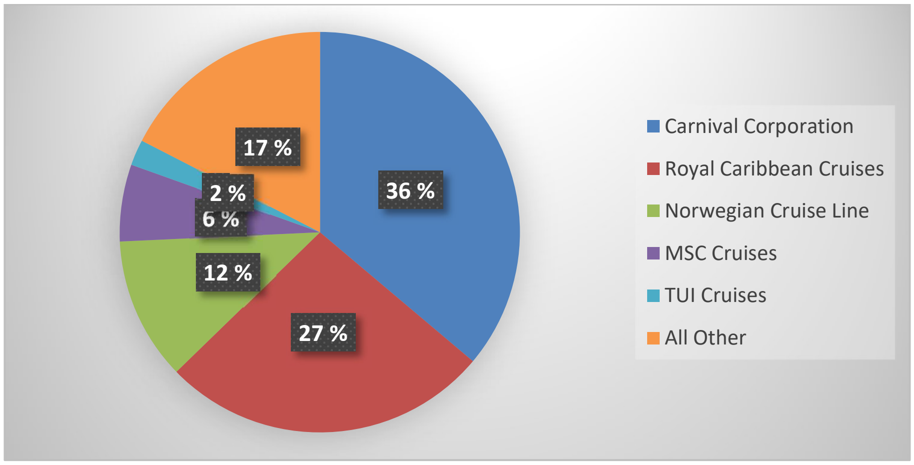
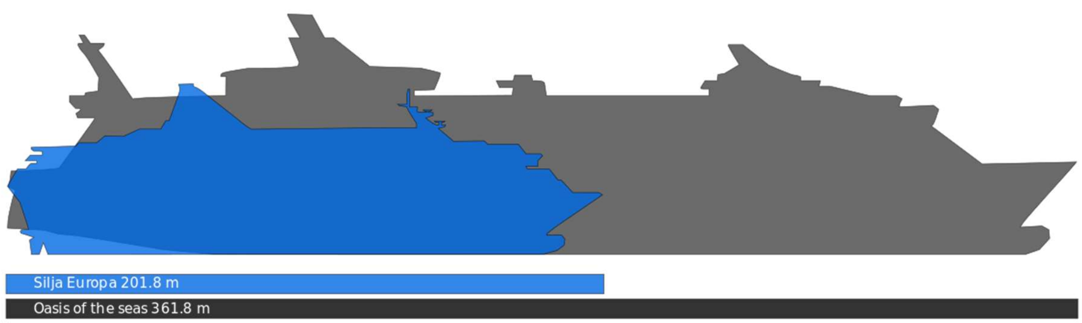


Figure 1. Cruise line market share per net revenue in 2018 (Cruisemarketwatch www-pages 2018).

The size of cruise ships is from 50 000 gross tonnages (GT) up to 200 000 GT and even bigger cruise ships are planned to be built. Making up to 18 decks and length of over 350 meters (m). There are also smaller luxury cruise ships and yacht from 2 000 GT up to 16 000 GT and length from 70 m to 180 m. These smaller cruise ships and yachts are more suitable for battery-driven propulsion systems. Mainly because of the smaller power demand that can be dealt with present energy density of batteries. As comparison, M/S Silja Europa is biggest cruise ferry in Baltic Sea, size of 59 914 GT and 201,8 meters long (Picture 1) (Meyerwerft www-pages 2018).



Picture 1. M/S Silja Europa and M/S Oasis of the Seas comparison 2009. (Wikipedia www-pages 2009)

Nowadays the environmental friendliness is the priority number one and it has also big attention in these cruise lines. Newer cruise ships uses already different kind of technology in propulsion system to lower the emissions. However, on existing ships there are plenty that can be done. Cruise ships have typically four to six combustion engines that generates power for the cruise ship. Usually they are diesel-based motors, generating lots of emissions (Carbon dioxide). One way is to use different kind of fuel, that produces lower amount of emissions. LNG is one of them, using natural gas in combustion engines. This needs motors that use different kind of technology. There are also new technologies, such as Fuel Cells and higher density batteries being developed. Next step could be to use only battery system when entering and departing the port or at least to cut down usage of all the combustion engines.

2.2 SOLAS and IMO

Few years after RMS Titanic famous collision to iceberg in 1912, there have been organizations and international conventions to secure safety measurements of international ships, Safety of Life at Sea (SOLAS) and International Maritime Organization (IMO). SOLAS convention concentrates to specify minimum standards for ship building and first version was adopted in 1914 to latest one in 1974, this SOLAS 1974 convention has been updated numerous times to fit in today's ship building and sailing. Flag States are responsible that under their flag sailing ships fulfills these standards and classification societies gives certificates that proofs that these actions have been done. When cruise ship is visiting United States (US) ports and having US passengers, cruise ships has to fulfill US own regulations for maritime. These regulations are United States Coast Guard, United States Coast Guard Initial Control Verification Exam and United States Public Health Service. (Imo www-pages 2018)

IMO was founded at 1948, after noticing that best way improving safety is by developing international regulation. Nowadays, it is a specialized agency of the United Nations and having 174 Member States. IMO's main aspects are maritime safety, traffic, carriage of dangerous goods and pollution from ships. Main aspects can be divided to four different level of detail: conventions (SOLAS), codes (requirements for ship types, equipment and materials), resolutions (more detailed and clarified requirements) and circulars (more detailed requirements, unified interpretations, testing methods and guidelines). These regulations are also fulfilled by classification societies. The next chapter will look those regulations more closely. The next figure shows hierarchy of regulating ships (Figure 2). (Imo www-pages 2018 and Räsänen J-E IMO, 2018)

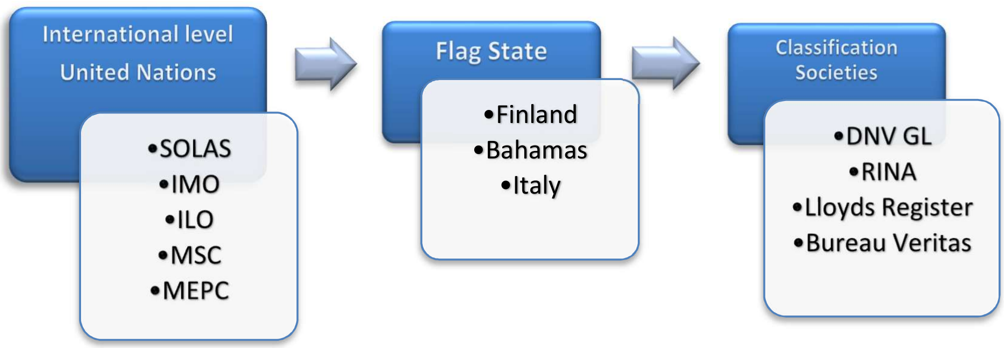


Figure 2. Hierarchy of regulating ships.

2.3 Classification societies

Every new ship or ship that is already in service, must hold a valid certificate to prove that engineering and construction work observes regulations and international conventions. Classifications and certificates are given from valid companies, such as Det Norske Veritas and Germanischer Lloyd (DNV GL), Registro Italiano Navale (RINA), Lloyd's Register Group Limited (LR) and Bureau Veritas Quality International (BVQI). These global companies provide technical assurance and other services to all shipyards to fulfill given regulations from previous conventions and standards mentioned in the previous chapter. The goal of the regulation is to safeguard life, property and the environment. Concentrating mainly on structures, machinery, piping, control and electrical systems. (Imo www-pages 2018 and Räsänen J-E IMO, 2018)

Every classification society has similar requirements for engineering. DNV GL has good handbook for battery systems and rules for classification ships, that’s why their classifications are used in this thesis. Handbook is called “DNV GL Handbook for Maritime and Offshore Battery Systems” and rules of classification are from “Part 6 Additional class notations, Chapter 2 Propulsion, power generation and auxiliary systems " (DNVGL-RU-SHIP Pt.6 Ch.2). Handbook has class rules for vessels having batteries larger than 50 kWh. DNVGL-RU-SHIP Pt.6 Ch.2 has more specific rules for battery room and are quite similar to handbook. What this handbook consists of and its' implications for this conversion work will be discussed later. (DNV GL www-pages 2018)

2.4 Abbreviations

AC	Alternative Current
Aft	Rear of the ship
BMS	Battery Management System
BOL	Beginning of Life, battery systems maximum usage when the system is new.
Bridge	The room or platform from which the ship can be commanded.
DC	Direct Current
EMS	Energy Management System
EOL	End of Life, battery systems maximum usage when the system need of replacement.
ESS	Energy Storage System, batteries arranged in series and parallel for energy content and voltage.
Forward	Forward area of the ship
GT	Gross Tonnage
Hotel Load	Electrical load of the human occupancy, such as air conditioning and lighting, analogous to the features of a hotel.
Hz	Frequency, unit of frequency is the hertz (Hz). One hertz means that an event repeats once per second.
ILO	International Labour Organization, sets labour standards, develop policies and devise programmes promoting decent work for all women and men.
kg	Kilograms
LNG	Liquefied Natural Gas
m	Meter. Base unit in metric system.
MEPC	Marine Environment Protection Committee, addresses environmental issues under IMO.

MSC	Maritime Safety Committee, highest technical body of the IMO.
PMS	Power Management System
SOC	State Of Charge (%), reflects the charge of the battery.
SOH	State Of Health, reflects the general condition of the battery. This can be energy capacity or internal resistance.
UPS	Uninterruptible Power Supply
V	Difference in electric potential between two points.
kV	Difference in electric potential between two points. 10^3 V.
W	Watt. Unit of power. 1V × 1A = 1W
Wh	Watt hour, measure of total energy and it refers to the amount of energy over period time. 1 W for one hour.
kWh	kilowatt hour, measure of total energy and it refers to the amount of energy over period time. 10^3 W for one hour.
MWh	Megawatt hour, measure of total energy and it refers to the amount of energy over period time. 10^6 W for one hour.

3 CONVERSION

In this conversion work, all the regulations and classifications are regulated by the DNV GL. “DNV GL Handbook for Maritime and Offshore Battery Systems”. This handbook gives requirements for vessels that have batteries larger than 50 kWh, including battery space and locations, system topologies and battery safety considerations. DNV GL’s rules are used as classification guideline. “Part 6 Additional class notations, Chapter 2 Propulsion, power generation and auxiliary systems", this guideline specifies more the regulations for class rules in battery notation. (DNV GL Handbook 2016 & DNV GL Part 6 chapter 2 2018)

This “Class Rules” consist of two class notations, Battery (Safety) and Battery (Power). The Battery (Safety) includes all vessels where the system is used as an additional source of power and is not used as propulsion power. Vessels that use the battery power as propulsion power during normal operation or as a redundant source of power for main and/or additional, class notation is noted as Battery (Power). In this conversion the class notation will be Battery (Power) because in this conversion, battery system will be is used as propulsion power or as a redundant source of power depending on scenario that we are going to choose. (DNV GL Handbook 2016, 7)

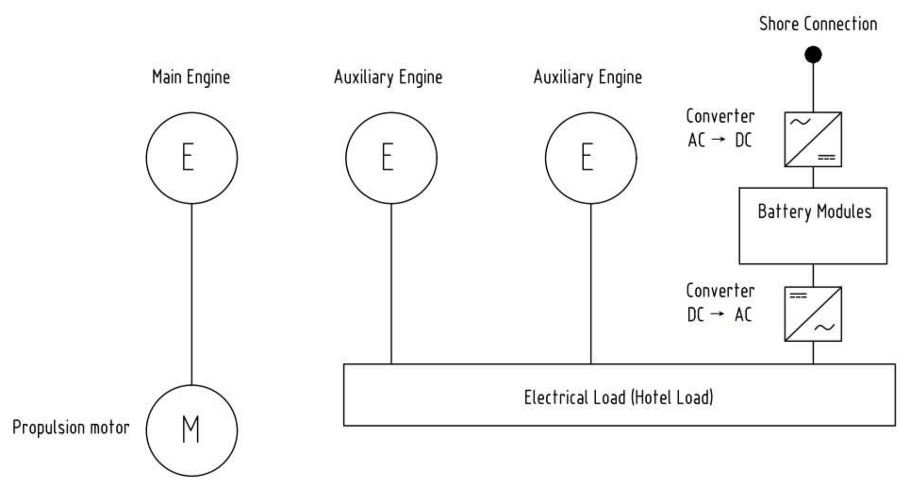
Typically, cruise ship has four to six combustion engines. Divided to aft and forward engine rooms, supplying main switchboards that can be either 6,6kV or 11kV and 50Hz or 60Hz. After that, these main switchboards supply low voltage main switchboards that are 690V and 440/230V, 50Hz or 60Hz via transformers. Low voltage main switchboards are also divided to aft and forward. Emergency network is supplied from the emergency generator. Emergency network is also divided to main switchboards and low voltage main switchboards in aft and forward.

Complete power plant, including propulsion system is supplied from main switchboards. Low voltage main switchboard supplies low-power systems like lighting, catering equipment and sockets on the public/crew areas. Emergency generator supplies emergency lighting, safety systems and other vital equipment for ship controlling.

In this case, propulsion system consists of two propulsion motors that has maximum power demand of approximately 14MW each. They are supplied via propulsion converters from main 11kV switchboard. Purpose is to use battery system to supply these propulsion motors when entering and departing the port.

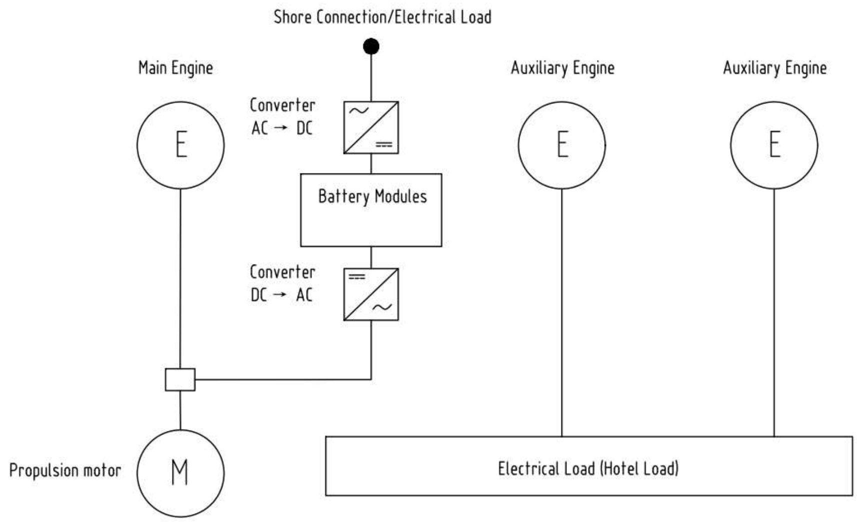
3.1 System Topologies

Nowadays, when battery-based assemblies are used for propulsion system more and more, the ways to do it are also increasing. Therefore, there are different topologies to do it. Typically, main combustion engine is used to produce power for propulsion system. The battery system is added in parallel to auxiliary combustion engines to produce electricity for hotel load. (Picture 2). (DNV GL Handbook 2016, 19)



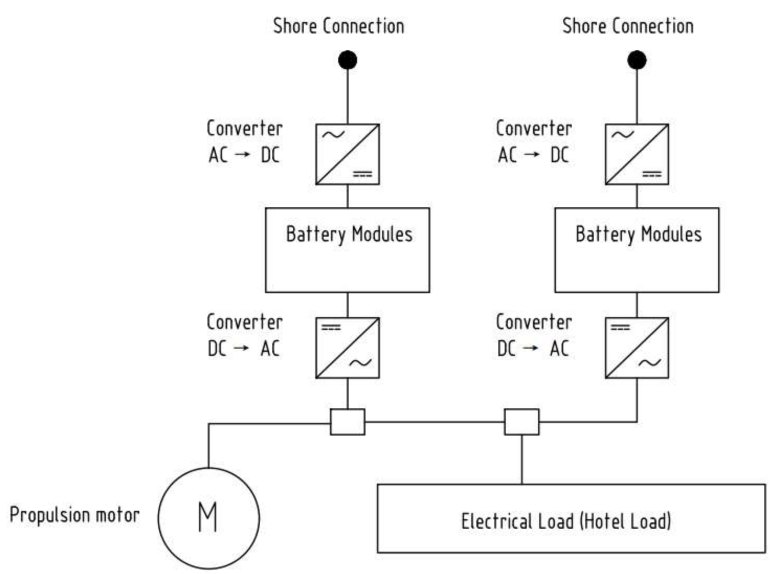
Picture 2. Mechanical propulsion, battery system in parallel with auxiliary engines to produce power for electrical load. (DNV GL Handbook 2016, 19)

In hybrid system, batteries are integrated in a power system that produce power for propulsion system. This way ship can use only main combustion engine or only battery system to operate on the sea or in the port. It’s even possible to use them in parallel, to take advantage of high-powered combustion engine, stable and peak shaving battery system or taking advance of zero emission operation when entering port. Batteries can be charged in voyage or in the port with shore connection. Auxiliary combustion engines generate power for electrical load. (Picture 3). (DNV GL Handbook 2016, 19)



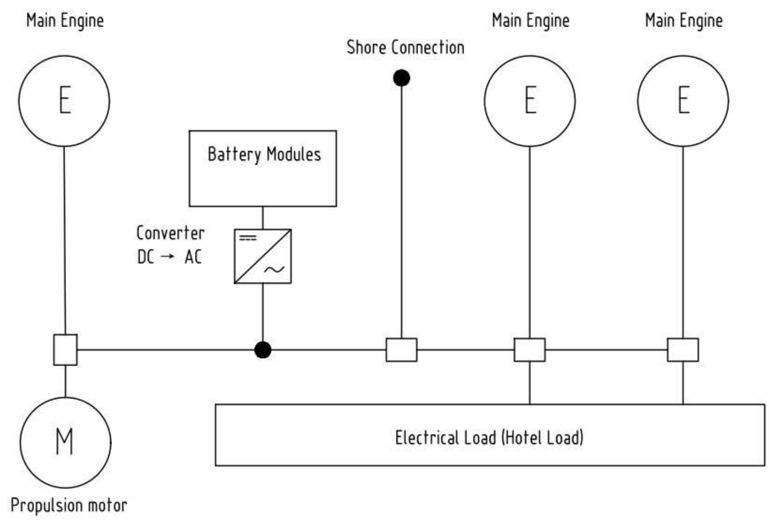
Picture 3. Hybrid system, where battery system is used parallel with main combustion engine. Auxiliary combustion engines powers electrical load. (DNV GL Handbook 2016, 19)

Purely battery-driven vessels need to be charged in the port, due to not having any combustion engines on board to generate power to battery system. This method is common in ferries, when the route and stopping time is always the same. To prevent power failures and accidents resulting from that, two independent battery systems are installed. (Picture 4). (DNV GL Handbook 2016, 19)



Picture 4. Battery system produce power for both, propulsion system and electrical load. (DNV GL Handbook 2016, 19)

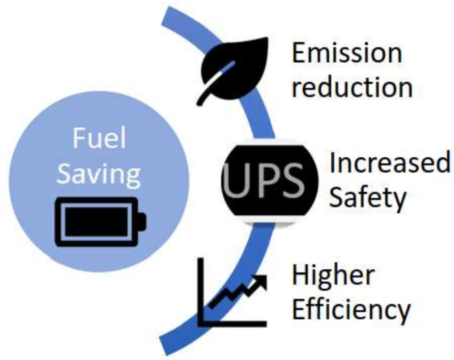
In this particular case, battery system is used as parallel to main combustion engine. Enabling to use only battery system or the main combustion engine to provide power for propulsion system. Power for electrical load is produced with main combustion engines or in the port batteries can be used as auxiliary power source for electrical load. Batteries can be charged in the port or in during sea voyage. (Picture 5).



Picture 5. Battery system is used for propulsion system and for electrical load.

3.2 Scenarios

In the case, there are possibility of four different scenarios how to use battery system when arriving and departing the port, depending on being “zero emission port call” or “one engine operation port call”. Normally cruise ship is using combustion engine(s) during the arrival and departure. The target is to cut emissions as much as possible and make system last long enough to make it profitable. The profitability of the scenarios is based on the how and when the system is charged again, how often the batteries are used, size of the system and investment; how much it will cost and how fast it will pay back. These benefit’s can be seen from picture below (Picture 6).



Picture 6. Battery system's benefits. (Räsänen J-E, 2018)

When doing zero emission port call, only batteries on-board will be used when arriving and departing the port. Depending on weather conditions, combustion engines may be required. Charging is done by electrical shore connection or during sea voyage. Whether it's profitable or not to do charging in the port or during voyage, depends on electricity price. Electricity price range first half in 2018 in Europe for non-household consumers (consumption between 500 and 2000 MWh) was from 0,06€ per kWh to 0,15€ per kWh with taxes (Europa www-pages 2019). One engine operation port call, battery system is used in addition to a main combustion engine when arriving and departing the port. Batteries will work as peak load shaving for desired time during entry and in departure. Battery charging is done during ship operation at the sea or via shore connection.

This work uses two different periods of time that ship uses in port area, A and B. In scenario one, zero emission operation. Combustion engine(s) are shut down and battery system is being used for A hour(s) before the ship is moored and when departing. Batteries are charged at the port. Scenario two, zero emission operation. Battery system is used for B hour(s) when arriving and departing. Battery system is being charged at the port and slowly during voyage. Scenario three, maximum operating time in zero emissions when limiting battery size to 10 MWh. In scenario four, one engine operation. Operating with one diesel engine and assisted by a battery system. Charging of the batteries when ships is in operation.

3.3 Battery space

In the DNV GL Handbook, definition for battery space is “Physical installation space including walls, floor, ceiling and all functions and components which contribute to keep the battery system in the defined space at a specified set of environmental conditions” (DNV GL Handbook 2016, 18). The key point is to separate Energy Storage System (ESS) from ship’s propulsion and from all other systems that can affect the controlling of the ship. To make it as safe as possible to the environment and the system itself.

The location of the battery system is the most challenging part of the project, especially when the system is integrated as a retrofit, because there are so many requirements to consider. Structure in different cruise ships are mainly same to each other. Similar potable water and fuel tanks are required, depending on where they are located and how big they are, they may be replaced for a battery space. In this case, there are four possible spaces where to assemble ESS. Easiest way to retrofit ESS is to modify existing fuel tanks and/or potable water tanks. Frequency converters, transformers and air ventilation physical size increases according to size of ESS. That needs to take in notice in when designing battery room, where every electrical equipment needs to be fit along with the batteries.

First alternative location for ESS is where existing heavy fuel oil (HFO) tanks are fitted, where the fuel oil tanks needs to be removed. Removing these HFO tanks was not ideal, even though we are adding battery system for additional propulsion power, we still need to make sure that cruise ship can be controlled with combustion engines in any situation. Alternative two, void space. There is no need to remove anything, but it is deliberately left to be void space. It is typically part of structure and stability studies shall be done to ensure that it would be possible to use chosen void space. Alternative three and the most suitable space for ESS to be retrofitted, is a big existing potable water tank, around 100m^3. The potable water tank can be removed, considering the overall ship design and when all emergency scenarios are considered. Alternative four, small potable water tank. Potable water tank is around 30m^3 and can easily be replaced due to size of it. Space would be ideal for peak load shaving system but not for zero emission port call which is our priority. Chosen space shall fulfill SOLAS 12 category requirements.

3.4 Electrical safety systems

Electrical safety systems take care of all possible risks, that have been evaluated in safety assessments. The safety assessment is for passengers, crew and for the construction itself. It needs to be done when ship is being built and ensured every time when something is done to any system the ship is depending on. Depending on the type of battery chemistry, these safety assessments are in general: gas development risk, fire risk, explosion risk, submersion risk (salt and fresh water), necessary detection and alarm systems, loss of propulsion or auxiliary power for essential or important services. Emergency shutdown for disconnection of battery system needs to be provided. There are also possible electrical failures inside the battery (cell) and in the system, as internal and external circuits. All the safety assessments mentioned in this chapter shall be documented properly. Figure below shows what safety measures are in the battery room and in the battery module (Figure 3). (DNV GL Handbook 2016, 29 & DNV GL Part 6 chapter 2. 2018, 26)

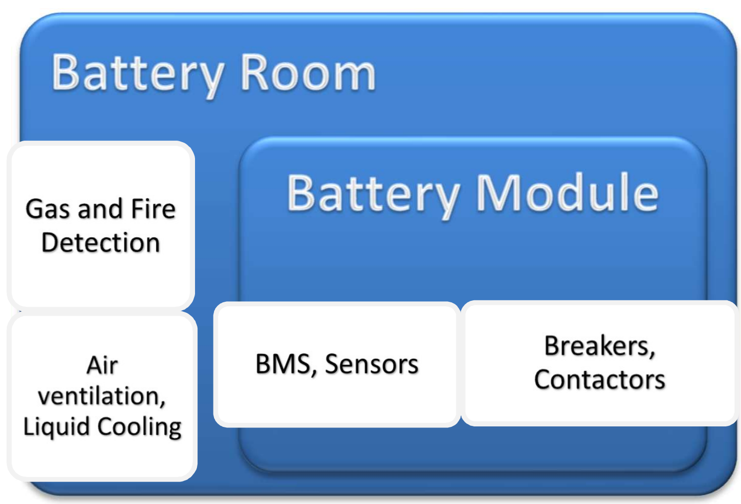


Figure 3. Safety measures in the battery room and in the battery module.

3.4.1 External safety

External safety means failures and risk that are taken care with system that are outside the battery module. For example, room temperature, oxygen that react with toxic gases, fire from outside and submersions risks. Overheating can be considered as one of the notable risks in battery system. Overheating is consequences of poor cooling and ventilation system and when occurred it can also generate toxic gases that can be flammable.

Gas development risk consist of toxic, flammable and corrosive gasses. They are taken care of by ventilation system. More details to this Heating, Ventilation, and Air Conditioning (HVAC) system is in chapter 5.7. The main aspect for the ventilation system is to control battery space's temperature, minimizing risk of overheating, and furthermore to extend battery life in optimal temperature and provide fresh air for crew in the room. When fire is occurred in the room, air ventilation exhaust oxygen from the room to prevent and extinguish fire/explosion. This system should be monitored from the control station, to follow up the temperature of battery space and in battery cell, along with indication of ventilation. Local control is also required, to prevent any failure in the remote or automatic control system. Independent air ventilation system is required even if the battery system is water cooled. (DNV GL Handbook 2016, 49)

Smoke/fire detection and water-based fixed fire extinguishing system needs to be installed in the battery space to prevent and manage fire and explosion risk. Water extinguishing system not only extinguish the fire but also cool down the cells to prevent thermal runaway. Battery space's alarm system gives individual or group-wise indication to cruise ship's main alarm system and it alarms before abnormal condition is occurred. Following battery failures will give an alarm: high cell temperature, over and under voltage, battery shutdown, unbalanced cell voltage, tripping of battery breakers/contactor and other safety protection functions. (DNV GL Handbook 2016, 49 & DNV GL Part 6 chapter 2. 2018, 21-22)

3.4.2 Internal safety

Almost all above risk are consequences of failures inside the battery system. Therefore, monitoring systems voltage, current and cell temperature with proper appliances and software's is important. Closer look on these monitoring systems that takes care of above-mentioned risks will be taken in the chapter 4.3.

4 BATTERY SYSTEM

As said in DNV GL Handbook "Main priorities for a battery system for maritime applications are safety, reliability and sufficient life for the system to be economically feasible. All components in the battery systems must be of good quality to secure a safe and reliable system throughout the system's lifetime. The integration and testing of the complete battery system is of similar importance as the quality of its single components. --" (DNV GL Handbook 2016, 28).

4.1 Battery Technology

The key factors when selecting cell chemistry for battery system are energy density, longevity, consistency and safety. In general, when selecting power source for specific vehicle, the main aspect is how much energy it can carry comparing to size of it. Energy density in cell chemistry, is the amount of energy stored per unit mass, Wh/kg. Longevity is how long it takes to battery system to discharge from 100% to 0%. Consistency, how stable is the discharge. For safety is how the system can be cooled, what is thermal runaway for selected battery chemistry, voltage stability and how fires can be extinguished.

Battery consist of one or more cells that are connected in series or parallel. A "cell" is one basic electrochemical unit that produces energy. Electricity is produced in chemical reaction, between positive and negative terminals (anode and cathode). When charged, ions travel through a separator from positive electrode to negative electrode. This electric energy can be consumed by a load between the terminals, then ions travel opposite direction. In this conversion, we are going to use secondary batteries, because they are rechargeable. Main difference between batteries is its internal content. Batteries can have same voltage but be physically different sizes. When increasing voltage, batteries are lined up in a series of rows and when increasing current, batteries are line in a series of columns. (Batteryuniversity www-pages 2018)

Lead acid battery is oldest rechargeable battery and is used in cost-effective appliances. Charge time is much longer than in lithium batteries and it must be always stored in charged state making it unstable. Lead acid battery longevity suffers in high voltage and has low energy density what is most important in this conversion. Next chapter takes a look through different lithium-based batteries and what type is used in this conversion. (Batteryuniversity www-pages 2018)

4.1.1 Lithium Batteries

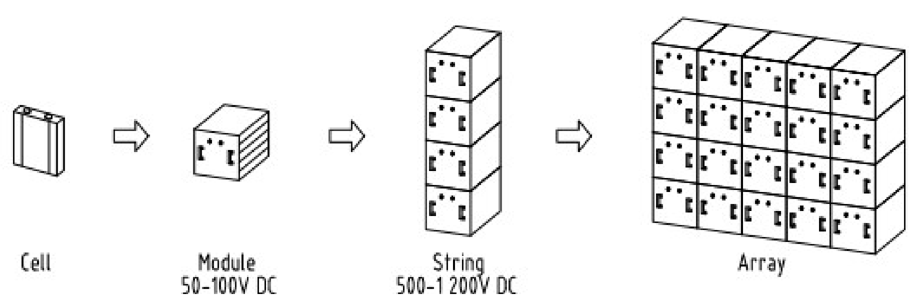
For now, lithium-ion based batteries are fastest growing, studied and most used in commercial appliances. Besides, it is one of the lightest metals, giving the largest energy density for weight. Having significant electrochemical potential comparing to lead-acid, nickel–cadmium or nickel–metal hydride batteries. Most used and potential lithium-based batteries are Lithium Nickel Manganese Cobalt oxide (Li-NMC), Lithium Iron Phosphate (Li-LFP) and Lithium Titanite Oxide (Li-LTO). Ideal temperature in battery room for lithium-based batteries is 20-25ºC. (Räsänen J-E, 2017)

Depending on mixtures of chemistries, it is possible to get batteries with different kinds of charge and discharge rates (C-rate, 1C rate means that 1Ah battery gives 1A for one hour). The higher the C-rate, the faster it will be charged or discharged. Depending on that, batteries can have short or high number of cycles and it’s effecting to lifetime expectation. It’s important to compare these aspects and select right mixtures of chemistries to right operation. Cruise ships have big propulsion systems and like in this case, focus is on batteries that have higher C-rate, dropping the life time quite low. When having high C-rate, heat generated in the cells is also higher, making the cooling very important. For example, Li-NMC can be liquid cooled. (Räsänen J-E, 2017 & Batteryuniversity www-pages 2018)

Li-LFP has little bit lower energy density and has same life cycle rate than Li-NMC. Biggest difference to other types is that it is typically shaped in cylinder shape, like alkaline-batteries. Due that, Li-LFP have worse heat transfer and lower energy-space efficiency. Li-LFP doesn’t have thermal runaway point. Li-LTO has multiple times better life cycle and half energy density than Li-NMC, but costs more. It has also high discharge C-rate. Depending on usage of the batteries they can be manufactured in different shapes, pouch, cylindrical or in prismatic shape. After comparing these different battery chemistries, best choice for this case is Li-NMC and it is assumed that selected manufacturer will use pouch shape to maximize energy storing. (Batteryuniversity www-pages 2018)

4.2 Battery Energy Storage System

Cell is smallest unit in Battery Energy Storage System (BESS), therefore cells are connected in series (modules) to produce needed voltage 50-100V DC. These modules are connected in bigger series called strings voltage of 500-1 200V DC and several strings are connected in parallel (array) to produce needed energy, in this case in the MWh scale. In selected location for BESS, there are room for 11 modules in series. Picture below shows how the BESS can be assembled from the cell to full array (Picture 7). For needed energy, maximum number of strings are in parallel according to given space in the room. Arrangement is depending on battery system supplier, because every supplier has different design to fit modules and strings. To protect these modules and series, there are fuses and contactors to give protection that are selected to match with current and voltage. Battery system generates DC electricity, therefore converters are needed to change DC to AC, depending on what propulsion system uses.



Picture 7. BESS, from cell to full array.

Depending on the space and investment, it’s recommended to maximize number of modules. Because batteries lose capacity over time, depending on how often system is used and how stable the temperature has kept. Average capacity lost is around 1-1,5%

in calenderer year, that’s why battery systems are oversized comparing to realistic needs. Average life time of battery system is 8-10 years. (Räsänen J-E, 2018)

4.3 Battery management system

Any data from the battery system is processed via a Battery Management System (BMS) ensuring smooth and safe usage of battery system. This data can be over-voltage, under-voltage, over-current and temperature. Many possible failures can be avoided monitoring these values, but there are also internal risks inside the battery, that can only be handled with precise battery design when manufacturing and assembling these systems. BMS transmits calculated data from battery system forward to Energy Management System (EMS) or Power Management System (PMS). For example, State Of Charge (SOC) and State Of Health (SOH). Depending on system load, operational criteria, battery status and given input variable from personnel, then EMS or PMS make’s decision on what the power generating system should do. These data and made decision are shown also to crew in digital or analog monitors by the EMS. (DNV GL Handbook 2016, 37)

4.4 Energy demand

Cruise ship generates electricity via main and auxiliary engines to power propulsion system (including thrusters) and hotel load. Hotel load consist of all lightings, sockets, audio and catering equipment. Basically, all used electricity that passenger and crew member use in daily basis. In this case, cruise ship uses three of four diesel generators when arriving to port, powering the hotel load and propulsion system. Typically, hotel load consumption is quite high, because all the systems that it consists of, are on almost all the time.

In this case, hotel load is around 7 MW and propulsion demand is 4 MW when arriving to port. Propulsion power demand decreases when getting closer. When moored, power demand is zero. In departure, energy demand for hotel load is the same 7 MW and the propulsion power demand is little larger than when arriving to port, from zero to 4 MW. Demand increases faster to get cruise ship moving. Ship is moored in the port for nine hours. Hotel load stays same all the time. (Figure 4).

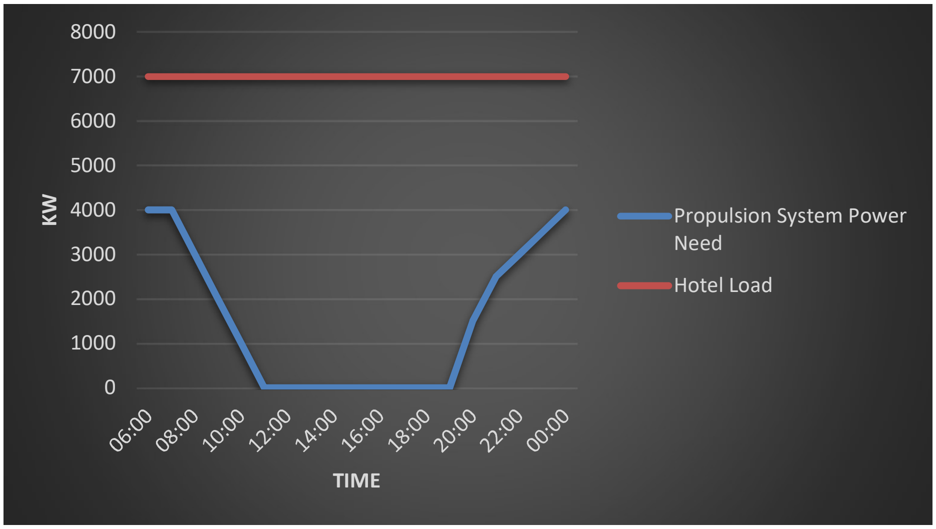


Figure 4. Propulsion system power need when arriving and departing port.

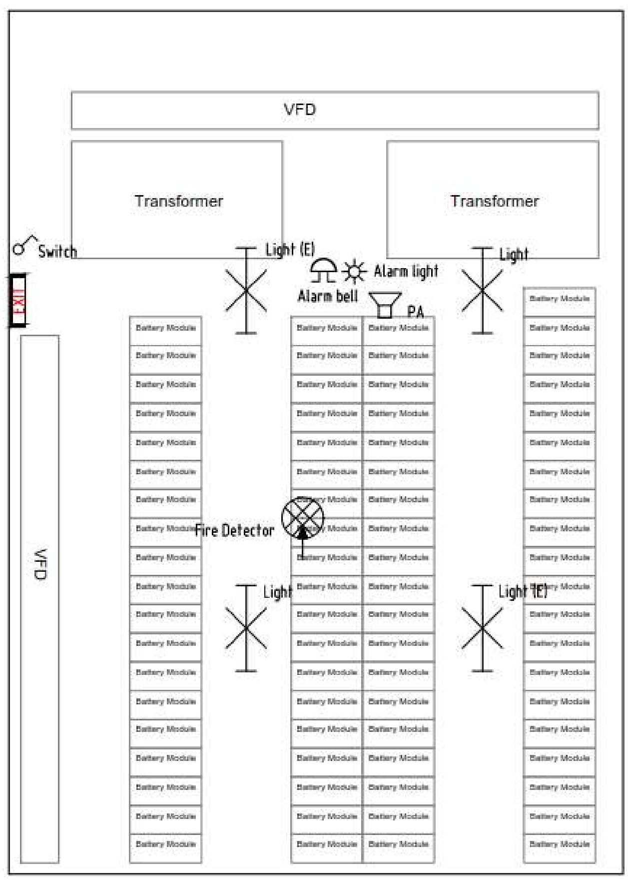
Based on classifications, battery manufactures and other calculations we made, total battery capacity can be from 10 MWh to 14MWh, when choosing scenario one. Chosen location for battery system enables enough space to install calculated battery capacity. Charging demand for this system will be quite high, around 1,4 MW for nine hours. Depending on how long the stay in the port is, it can be done partly there and the rest in sea voyage. Estimated lifetime for batteries in scenario one is 10 years if it is used once a week and if used daily, lifetime will be around five years.

For scenario two, battery capacity need is too big to be installed in the selected room. It would be to high investment to have a reasonable payback time. Scenario three, when battery size is limited to 10 MWh. All three engines can be shut down at Beginning Of Life (BOL) for B hour(s) before entering the port and at End Of Life (EOL), the time period is limited to 15% less than in BOL. When departing, at BOL battery system can be used for one hour and at EOL, the time period is limited to 20% less than in BOL. Charging power in port is around 1,1 MW for nine hours and can be also done during sea voyage. Estimated lifetime is same as in scenario one.

In scenario four, one diesel engine is used with battery system for B hour(s) before arrival and when departing the port. Charging is done when the ship is moored. Estimated lifetime of the batteries is longest, 10 years even when used them each port call every week. It also lowers size of the battery system to a 2,7 MWh. But this scenario doesn’t fully cut out emissions from the combustion engines.

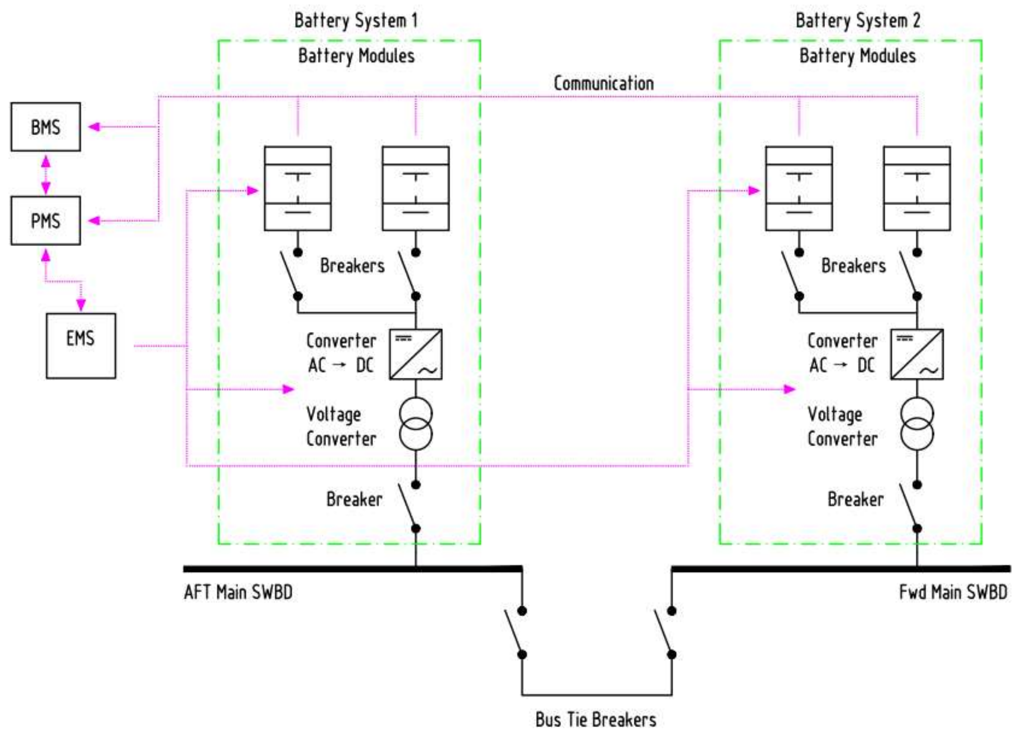
5 BATTERY ROOM DESIGN

This chapter will consist of what is needed to take in consideration in design (concentrating on electrical side) for scenario one, but the electrical design would be same for any alternative scenario. After removing selected potable water tanks, existing lighting and other safety system, the battery room needs to fulfill SOLAS 12 requirements before any electrical equipment can be installed in the room. When all the necessary demolition work has been done, new local board, frequency converter, transformers and batteries will be installed in the room. When installing new electrical equipment, cable trays and routes need to be taken in consideration. The new Air Controlling system (AC-system) arrangements should also be taken in consideration. The following chapters will take a closer look in these systems individually. These electrical equipment's is shown picture below (Picture 8).



Picture 8. Electrical equipment's in the battery room.

5.1 Electrical equipment



Picture 9. Diagram from main switchboard to battery system and communication for BMS and EMS.

Battery modules are supplied from main switchboard through breakers, transformers and converter. BMS gets data from battery modules and transmits it forward to PMS and EMS, they make decision on what the battery system should do. Main switchboard aft and forward is supplied from combustion engines or via shore connection. This can be seen from the top picture, where are the connections and communications for the battery system (Picture 9). When discharging batteries transformers and converters transforms electricity back to main switchboard for propulsion system or hotel load. Lighting, emergency lighting, fire detection and fire door supply can be taken from its' fire zone loops and circuits. Fuses and contactors are chosen to match electrical current and voltage.

5.2 Transformers and frequency converters

There are variable-frequency drives (VFD) for DC to AC change voltage between the batteries and the main switchboard to desired level. In this case, power supply from main switchboard is 11kV AC and the battery voltage is 1 100 VDC.

5.3 Public address system

Public Address system (PA-system) is for fire and emergency announcements, usually mounted in the roof. Speakers are linked to other speakers in the same area and the chosen area can be controlled from the Bridge or from local audio rack. In public spaces speakers can play music, fire and emergency announcements. In crew areas, only emergency announcements are required. If necessary, speakers can be explosive proof. PA-system cabling is done with fireproof cables. Example speaker for the battery room (Picture 10).

Picture 10. DNH, VES-561-54(T) speaker (DNH www-pages 2018)

5.4 Safety systems

All the safety systems are monitored at least from Bridge or room where engineer crew member is working. Cabling is done with proper fireproof cables. Safety systems need to be tested when installed and necessary documentation shall be done.

5.4.1 Gas and fire detection

If the room is classified to non-hazardous area, gas and fire detection do not need to have explosive classification. When the battery room is noted as hazardous, detectors are noted as explosive classification. According to supplier, one optical smoke detector will be installed in the battery room. Detector detect combustion gases consisting of visible particles. Mounted in place where it can detect the gasses that have evaluated from gas composition analysis. Indication of gas or fire will go to BMS and to Bridge. AC-system gets information from the Bridge. Fixed fire extinguish system will be installed in the battery room as well, depending on chemistry of batteries, fire extinguish system will use water mixed extinguish substance. Example smoke detector (Picture 11).

Picture 11. Autronica BHH-31A smoke detector, conduit box BWP-40B and base BWA-40A/1. (Autronica www-pages 2018)

5.4.2 Alarm system

Alarm bell and visual alarm is installed in a way that they are observed by the responsible worker. Battery room alarm system is added to same alarm systems in the cruise ship and they are monitored from the Bridge. Alarms are typed to non-explosive proof or explosive proof, depending on rooms classification. Example alarm light (Picture 12) and alarm bell (Picture 13).

Picture 12. E2S, L101X Xenon Beacon, alarm light. (E2s www-pages 2018)

Picture 13. Friedland, 56-230R, alarm bell. (Friendland www-pages 2018)

5.4.3 Emergency lighting

Exit sign will be installed next to door to guide responsible worker from the battery room to nearest escape route. Two decorative lamps will be used in emergency circuit to provide light in emergency operation. Low location lighting is not needed to be installed due to not having corridors in battery room. Example exit light for the battery room (Picture 14).

Picture 14. Selcast, LED-4700 3,1W IP67, exit light. (Selcast www-pages 2018)

5.5 Normal lighting

Led lighting fixtures are installed to provide light in normal operation. They are installed between battery modules and they are controlled from switch in the room. If necessary, lighting fixtures can be explosive proof. In picture 9, there are four lighting fixtures and two of them are in emergency circuit. Example led light for the battery room (Picture 15).

Picture 15. Glamox, MAX LED, Ex rated. (Glamox www-pages 2019)

5.6 Calculations

After installing all the required equipment and all the cabling is done, necessary calculations and analysis need to be done to make sure that battery system is safe, and all connections are done correctly. These calculations and analysis are: electrical load analysis, short circuit calculation, selectivity analysis, emergency stop schematic and I/O automation lists.

5.7 HVAC

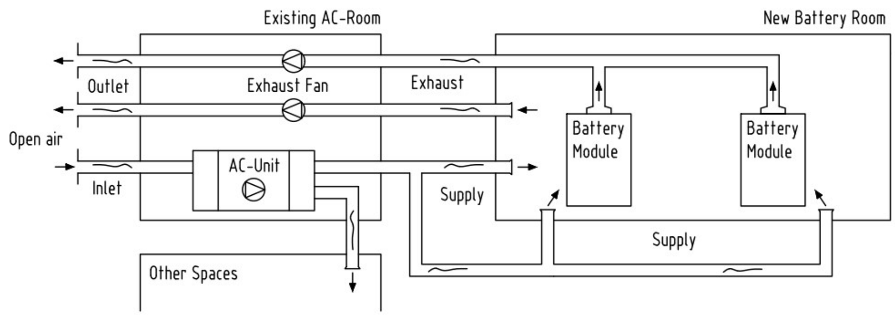
Usually battery suppliers install gas extraction ventilation pipes directly to battery modules to extract toxic/flammable gases directly to open air. Gas extraction fan needs to be explosive rated. By doing this way, the battery room is classified as non-hazardous space, air supply can be taken from air handling unit that serves other spaces, or with a dedicated fan coil unit installed in the room. Air exhaust require direct exhaust to open air by independent exhaust fan. (Picture 16). (DNV GL Part 6 chapter 2 2018, 19-20)

If battery supplier does not have the possibility of installing gas extraction pipes directly to battery modules, battery room is classified as hazardous space (Picture 17). Meaning that the room can be exposed to explosive and/or toxic gases and every equipment in the room needs to be explosive rated. This is problem for transformers and frequency converters, because there are no explosive rated transformers and frequency converters this big on the market. (DNV GL Part 6 chapter 2 2018, 19-20)

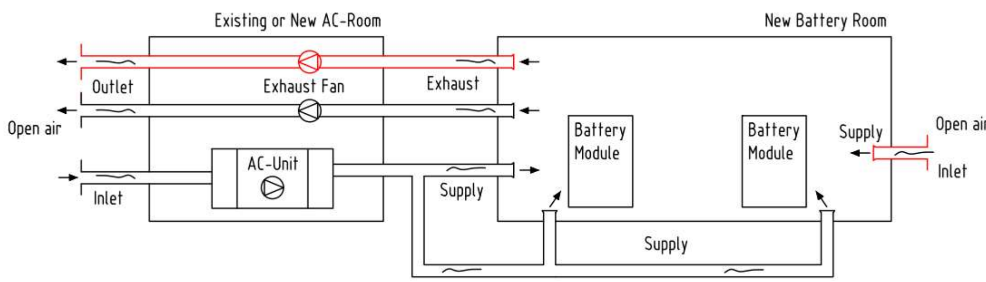
For hazardous space, independent air handling unit is installed in new or existing AC-room to supply air to the battery room. In addition, emergency air supply and exhaust are also installed in the battery room. Emergency air supply provides air directly from open air. Emergency air exhaust fan exhaust flammable and/or toxic gasses to outside of the ship, exhaust fan is explosive rated. When flammable and/or toxic gases are detected in the room, normal operation air ventilation system is shut down and emergency air supply and exhaust is turned on. Safety pressure valve or explosion protection need to be taken in notice in battery design if batteries are sealed. (DNV GL Part 6 chapter 2 2018, 19-20)

Depending on the gas composition analysis, supply air diffusers will be placed on floor level and exhaust diffusers on close to roof level if the gases are expected to be lighter than air. If not, supply air diffusers will be placed on roof level and exhaust diffusers on floor level. Ventilation system gets the indication from gas detectors, fire detectors and from cell temperature. It can be controlled outside the room, for example from the Bridge.

The heat load from batteries, electrical equipment, surrounding rooms and outside the ship, for example the sun, has to be considered when calculating AC-system size. In hazardous space emergency exhaust fan is non-sparking type and is calculated to provide capacity to six air changes per hour (DNV GL Part 6 chapter 2 2018, 20). New air handling unit will need supply of 440V or 230V and control circuit of 24V. Exhaust fan need supply of 440V or 230V and indication from fire/gas detectors.



Picture 16. Non-hazardous space air ventilation.



Picture 17. Hazardous space air ventilation. Emergency supply and exhaust is marked in red. (DNV GL Part 6 chapter 2 2018, 19-20)

6 CONCLUSIONS

Purpose of this thesis was to do a detailed analysis of required electrical installation when installing batteries to an existing ship. Furthermore, an assessment of current battery technology and the different requirement these may have on the electrical installation was to be done. Spaces, scenarios and other data used in the thesis were from existing project(s) at Foreship Ltd, with my task to go deeper into them and learn from them. I believe that I and the company can use this as template for coming projects.

From current battery technology perspective, it's looks more suitable to design battery systems for smaller ferries, yacht and exploration cruise ships. Mainly due to power demand in above-mentioned ships are lower, enabling lower investments and shorter payback time. However, battery technology is developing every year, enabling increased energy density for batteries and thus the required footprint is getting smaller. New chemistries in batteries and new technologies (Fuel Cell) also helps to cut down emissions, not only relying on Li-NMC technology. I think that the energy density of batteries will be multiple times higher in next five to ten years

As we can see from the thesis, most important system is air ventilation system. Every thing is depending on temperature: lifetime, efficiency and safety. If exhaust is not done directly from battery modules, all equipment needs to be classified as explosive rated and that will cost more and make designing more complicated.

I have learned a lot from this thesis work, and I hope it will carry my career for long time. I didn't have any marine studies in my electrical and automation engineering program, so basically everything concerning marine engineering is new to me. I am so thankful to Foreship Ltd who trusted in me and gave me this thesis work to learn from battery system and give expertise to Foreship Ltd in future. Special thanks to Jan-Erik Räsänen who guided me through this thesis work and also believed in me.

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