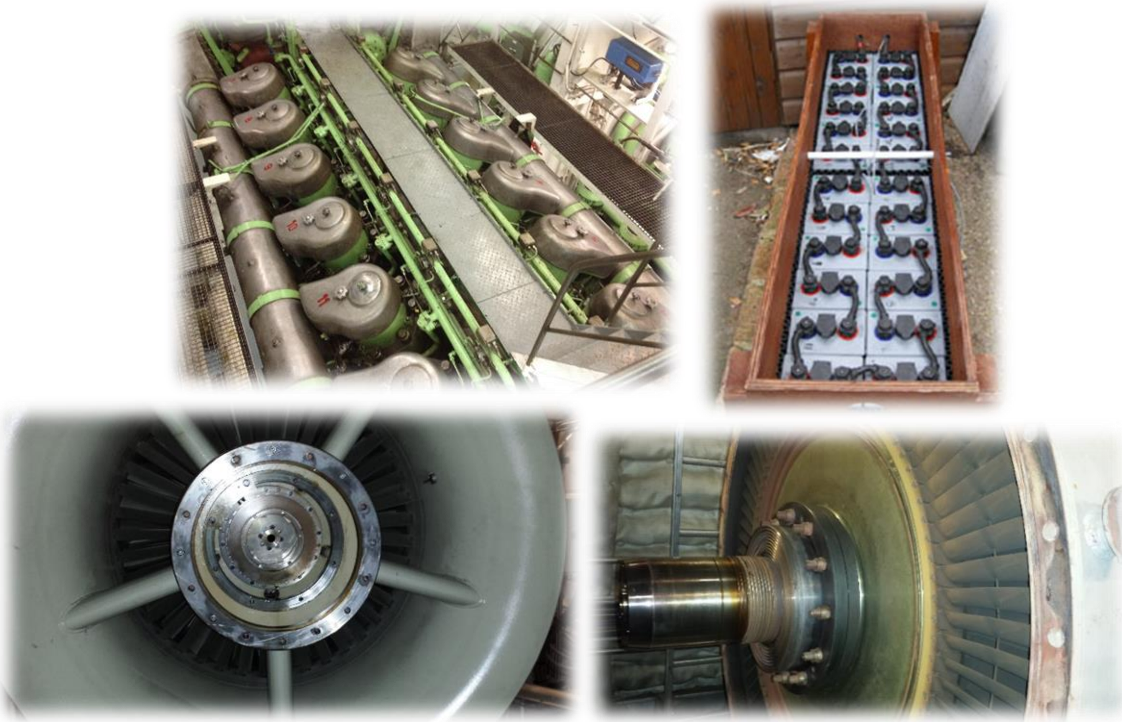

ALTERNATIVE HYBRID PROPULSION ON SHIPS

A SWOT analysis of gas turbines and diesel engines combined with batteries

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Diploma thesis in the Marine Engineering Programme

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Gotheburg, Sweden, 2018

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Cover: (Clockwise from top left): Diesel engine (Authors' own picture), Battery pack to a marine hybrid system (Hybrid-Marine LTD, 2008), Gas turbine power inlet (Authors's own picture) Gas turbine power outlet (Authors' own picture).

Alternative hybrid propulsion on ships

Abstract

Diesel-battery hybrids can be found all around the world in different set-ups depending on the purpose of the specific unit. They can be used in vehicles as power supply, in power plants to produce power on land or as propulsion on ships. Gas turbine-battery hybrids in a marine perspective are not as common. Gas turbines are, however, common as propulsion or as an auxiliary drive on ships. Due to the high emission standards that are upcoming in the near future this hybrid set-up is a good way for lowering emissions and for bringing batteries to even more use than it is today.

In this literature review the results are achieved by various tools and facts about which batteries are best for marine propulsion, what different hybrid methods are used and lastly a SWOT analysis. The SWOT analysis shows the strengths, weaknesses, opportunities and threats from an overview perspective of the different configurations.

The subjected area is new and not a lot of information is given from credible sources, because of this, the report answered the result through a SWOT analysis. The SWOT analysis gave us several important findings however the most important one is rethinking from an environmental perspective.

Keywords: Gas turbine, batteries, comparison, ship, combination, propulsion, diesel, hybrid.

Alternativ hybrid framdrivning på fartyg

Sammanfattning

Diesel-batteri hybrider förekommer runt om i världen under olika arrangemang beroende på syftet med installationen. De förekommer som kraftförsörjning i fordon, i kraftverk för att skapa ström eller som framdrivningsmetod på fartyg. Gasturbin-batteri hybrider är ur ett marint perspektiv inte lika vanligt. Gasturbiner är dock vanliga som framdrivningsmetod eller som hjälpframdrivningsmetod på fartyg. På grund av kommande höga utsläppsförordningar är detta hybridarrangemang ett bra sätt att reducera utsläppen och för att introducera fler batterier till marknaden.

I denna litterära analys är resultaten uppnådda genom varierande sökverktyg och fakta om vilka batterier som är bäst anpassade för framdrivning av fartyg, vilka olika hybrid arrangemang som används och till sist en SWOT analys. SWOT analysen visar styrkor, svagheter, möjligheter och hot ur ett överblickande perspektiv för de båda arrangemangen.

Forskningsområdet är relativt nytt och det fanns inte mycket information att tillgå från legitima källor, på grund av detta visas resultat med hjälp av en SWOT analys. Genom SWOT analysen fann vi flera resultat men det viktigaste var att få in ett nytänkande ur ett miljöperspektiv.

Nyckelord: Gasturbin, batterier, jämförelse, fartyg, kombination, framdrivning, diesel, hybrid.

Acknowledgements

On the authors behalf we would like to give a special thanks to all that has been involved and helped us with this literature review. Hybrid Marine has provided us with information on hybrid propulsion in a marine environment and given us pictures to use. Corvus and AllCell have been helpful and have provided us with a lot of information, pictures and diagrams on batteries and helped us understand which ones are the most suited for hybrid combination.

A special thanks to our handler Ulrik Larsen that have been with us from the start of the writing process to help us with layout, planning and tips on where more information could be found.

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Abbrevations

LIB, Lithium-ion battery
LAB, Lead-acid battery
VRLA, Valve regulated lead-acid battery
GT, Gas turbine
ICE, Internal Combustion Engines
HSS, High-speed Sea Service
LOA, Length over all
WHRG; Waste Heat Recovery Generator
LCA, Life Cycle Analysis

1 Introduction

This report was originally meant to focus on *Stena Carisma* and if it would be possible to retrofit the vessel to a hybrid with batteries to use as propulsion in and out of port, instead of using its gas turbines. The literature research on the subject: *Gas turbine-battery hybrids in a marine application* gave little to no results.

Since the shipping industry is under constant environmental pressure (Geertsma, Negenborn, Visser & Hopman, 2017), the need for new ways to power the ships are necessary and the use of auxiliary drives such can reduce the emissions and fuel consumption (Sciberras, Zahawi, Atkinson & Juando, 2013). As of today, the most used and most reliable propulsion method for ships with hybrid propulsion in the merchant fleet is the diesel engine (Woud & Stapersma, 2008). This is because the diesel engine has proved to be reliable, has been around for decades and the knowledge about the diesel engine technique is vast. Due to the environmental pressure in the marine industry, the most convenient auxiliary drive to concern would be batteries as they do not contribute to any emissions when used as a power supply (Geertsma et al., 2017).

Gas turbines on the other hand are known for high thermal efficiency (Smil, 2010) but aren't as widespread as the diesel engines when used as prime mover on ships nor when used in a hybrid system. According to PEi (2018) a remarkable trend in the power industry over the last few years has been the decreasing cost of battery technology. The costs have fallen so rapidly that installations with tens of megawatts of power contributed by batteries are becoming economical in a growing range of uses, including optimizing the performance of gas turbines. In the future one can see more Gas turbine-battery hybrids.

This report will, by using a SWOT analysis and as a literature review, answer why gas turbine-battery hybrids are less frequently used compared to diesel engine-battery hybrids and which type of batteries to use in the hybrid system.

1.1 Purpose

This literature aims to investigate why gas turbine-battery hybrids are less frequently used compared to diesel engine-battery hybrids.
To further analyze the possibility of battery hybrids as a marine propulsion method the study also examines what type of battery is the most efficient for this application.

1.2 Research questions

The research questions will be discussed and answered separately.

- Why gas turbines-battery hybrids are less frequently used compared to diesel engines-battery hybrids.
- Which batteries are most suitable for hybrid propulsion?

1.3 Delimitations

For this study the following delimitations exist:

- The study will not target any specific vessel type.
- Only Gas Turbine-battery and Diesel-battery hybrids are treated.
- No specific gas turbine is considered.

2 Background and Theory

Maritime transport is essential to the world's economy as over 90 % of the world's trade is carried by sea and it is, by far, the most cost-effective way to move goods over the world (UN-Business Action Hub, 2008). However, to be able to keep doing this at this current time with all the climate changes and oil prices going up, more cost efficient and more environmentally friendly solutions for propulsion is needed.

2.1 Energy and power density

Energy density is the amount of energy stored in a unit volume of a material or a device (Jelley, 2017) and is a common term used when comparing different fuels and energy storage devices. According to Hanania et al., (2018), a material can release energy in four different types of heat reactions, nuclear, chemical, electrochemical and electrical. Energy density is typically expressed in watt-hours per litre (Wh/L) or Megajoules per litre (MJ/L). Fuels and energy storage devices such as batteries are often categorized by energy density.

Power density is the amount of energy harnessed, transformed or used per unit volume per unit time (Jelley, 2017). Hanania et al., (2018) explains that a system with high power density can store or discharge a lot of energy while still having a small amount of volume, therefore it is expressed in W/cm^3. Power density is used to get an overview over what engine is preferred no matter the size, an easy comparison can be made to see which one suits one specific application.

2.2 Hybrid propulsion

In hybrid propulsion, a direct mechanical drive provides propulsion when high speed and high mechanical efficiency is needed. In addition to this, an electric motor which is coupled to the same shaft through a gearbox or directly to the shaft driving the propeller provides propulsion when the ship operates at low speed. Running a main engine inefficiently at low speeds is therefore avoided. A typical layout for such a hybrid propulsion is a combustion power supply, from diesel engines or gas turbines and a store power supply from energy storage systems such as batteries (Geertsma et al., 2017).

2.2.1 Benefits of hybrid propulsion

The industry of shipping is under a lot of environmental pressure to reduce emissions, if no measures are taken the CO2 emission is anticipated to increase by 50-250 % by 2050 (Geertsma et al., 2017). Geertsma et al., (2017) further discusses that the shipping industry already contributes to 15 % of the global NOx emissions which is anticipated to increase if nothing is done. More advanced methods of propulsion such as hybrids are used to maintain energy better and to get less emissions that can contribute to a reduced CO2 and NOx emissions. Auxiliary drives can provide alternative propulsion systems for marine vessels making it potential to achieve improved environmental performance and reduced fuel consumption during low-speed sailing (Sciberras et al., 2013).

All-electric and hybrid ship propulsion has become a leading area of research, prompting investigation in system design (Jaster, Rowe and Dong, 2014). According to Geertsma et al., (2017) the recent trend to design more efficient and versatile ships has increased the variety of hybrid propulsion options. Hybrid architectures with advanced control strategies can reduce fuel consumption and emissions up to 10-35 %. This also improves noise reduction, maintainability, maneuverability and comfort. Geertsma et al., (2017) further discusses that while the pressure to reduce emissions and fuel consumption has increased, the operating profile of ships has increased diversely: offshore vessels perform numerous tasks, such as dynamic positioning and transit while tugs require full bollard pull when towing and require limited power during transit or standby (Volker, 2013). The diverse operational profile makes it harder to optimize the power and propulsion plant for a specific operation. Thus, electric propulsion for various ships such as cruise ships has been adapted. Although electrical propulsion is efficient at low speed, it introduces conversion losses of 5-15 % of the propulsion power because of its electrical components such as transformers, electric motors and generators (Geertsma et al., 2017).

2.3 Gas turbines

Gas turbines have many different uses. They can for example be a power source in the middle of a metropolitan city or the Himalayan mountain range (Boyce, 2012). This report will handle the subject of having gas turbines as prime movers on a ship. Modern ship propulsion started with steam engines but were later replaced by the diesel engines also known as ICE (internal combustion engines). Diesel engines are the most common engine today, but other alternatives are starting to show up such as gas turbines. The main aim for engineers during 1900 was efficiency, engineers had already found out that steam turbines was a good energy source (Smil 2010).

Royal air force (RAF) officer Frank Whittle patented the gas turbine design in 1935, the invention was expensive to build because of the unusual amount of high quality parts that was needed. But the company that did undertake it made a profitable amount on it. The gas turbines started on planes and was beginning to flourish during the Second World War and was introduced commercially in 1952 which made gas turbines the only new fossil-fueled prime mover in the twentieth century. (Smil 2010)

2.3.1 Environmental Impact

Europeans conventionally is more proactive in the beneficial environmental solutions than people in the United States, except California. The tide has, however, turned in the United States as they realized that the global warming is not a “myth”. This have led to many countries starting to work together regarding the environment. If something can produce power by burning less carbon per unit of power one is more efficient by conserving the fossil fuel on earth and if gas turbines are fitted with waste-heat-recovery systems a gas turbine will use less fuel per unit of energy compared to without a waste-heat recovery system (Soares, 2015). Kayadelen & Üst (2013) reports that if the usage of clean fueled gas turbines in marine vessels is increased, it is possible to reduce SOx emissions by nearly 100 %, NOx emissions by 85-90 % and CO2 emissions by 15-20 % if compared to a two-stroke slow speed diesel engine fueled by HFO. Unfortunately, gas turbines and steam plant propulsion are not very common on ships.

2.4 Working principle of gas turbines

In ICEs the combustion takes place inside a cylinder covered by cylinder walls where fuel is injected and mixed with air, there is a spark plug (Otto) which ignites the fuel and air mixture or here is an ignition by pressure (Diesel). From that we gain work from the fuel and therefore something can start to rotate, in ICEs that is called a crankshaft (Kuiken, 2008).

Gas turbines work a bit different, far more complex in the terms of parts, design and theory. But it is simpler in the overview perspective of how it works. In a gas turbine the air is compressed before the fuel is added. All gas turbines must have four parts that is necessary for the design to work: compressor, combustor, turbine and an exit nozzle (Smil, 2010).

As shown in Figure 1, air enters the compressor intake with atmospheric pressure and temperature. The air is then compressed and passes through to the combustion system. In the combustion chamber the fuel and air is combined and ignited to the maximum cycle temperature as shown in Figure 2. The heated air is then expanded through the gas producer, shown in Figure 3 (between point 3 and 5), there the air that has been heated up and pressurized can utilize the energy to start the mechanical energy the turbine needs to rotate the compressor and the air expands through the power turbine (Figure 3 point 7) to drive the load that the gas turbine is connected to. The then goes through the exhaust and the cycle can start over. To get the turbine working in the first place a start system is used so that the turbine can get the sufficient speed, pressure and temperatures to make the cycle work. (Petrowiki, 2012)(Nada, 2014)

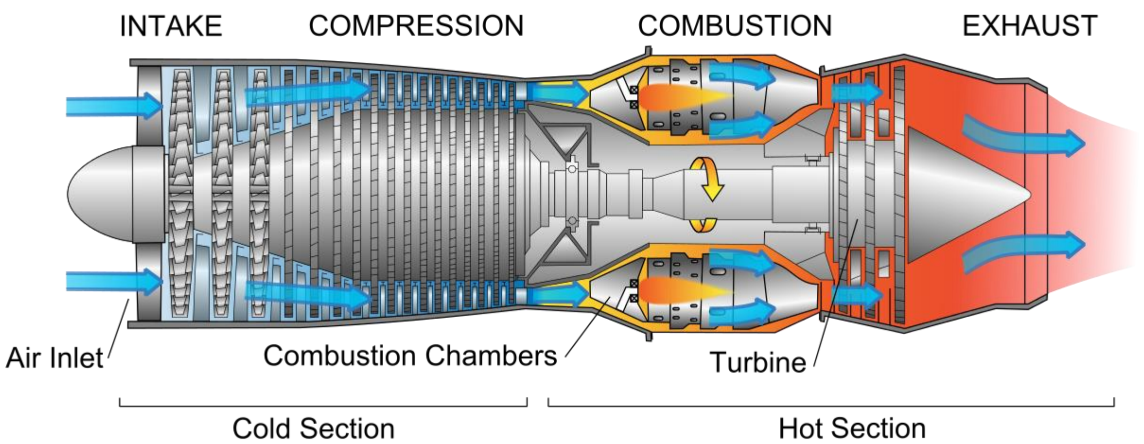

Figure 1 a cross section of a gas turbine to show how it works from the compression to the exhaust. (Wikipedia, reprinted with permission).

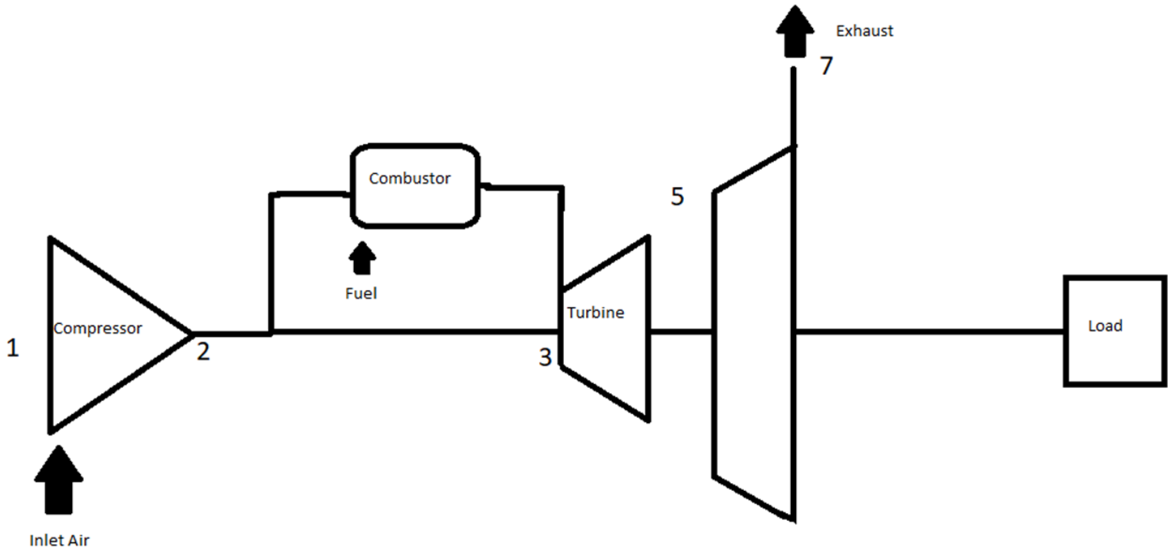

Figure 2 a simplified simple-cycle gas turbine principle. (Petrowiki, 2012. Authors own figure)

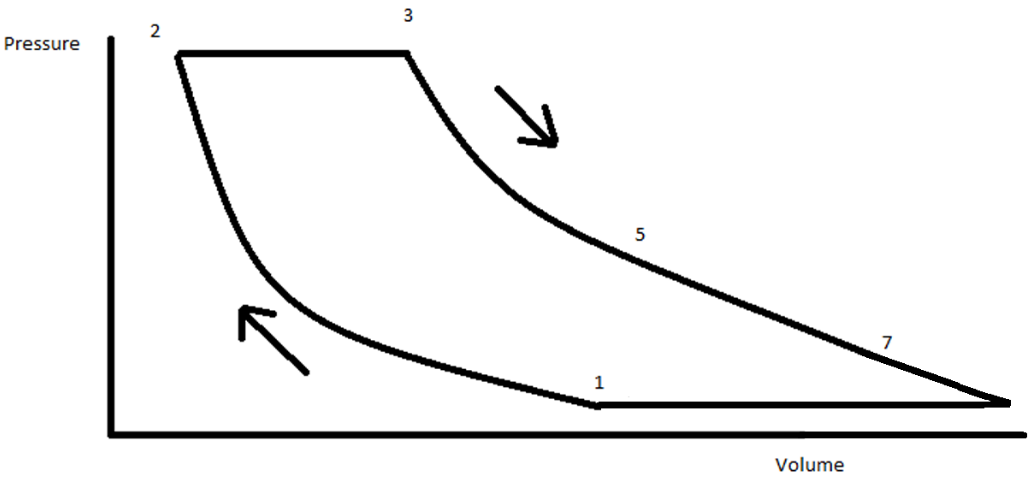

Figure 3 Brayton cycle for gas turbines, (Petrowiki, 2012. Authors own figure)

2.4.1 Gas turbine thermal efficiency

To increase the gas turbines thermal efficiency, one needs to rebuild or add parts to the gas turbine. The biggest efficiency loss is heat. There is a lot of heat loss from the exhaust that can be taken care of by making the cycle a “recuperative cycle” also called a “regenerative cycle” where the air from the compressor is pre-heated from the energy going from the exhaust. This is done by placing a heat exchanger from the exhaust (Petrowiki, 2012).

2.5 Batteries

According to Palermo, 2015 (*How Do Batteries Work?)* a battery is a device consisting of one or more electrochemical cells. Batteries consists of three main components: an anode, a cathode and an electrolyte ion substance which chemically reacts with the anode and cathode. During the discharge of electricity phase the first chemical reaction takes place between the anode and the electrolyte. This reaction makes the electrons to flow through the circuit back to the cathode where another chemical reaction takes place. The process is reversed when charging the batteries. When the material in the anode and cathode can no longer be used in the reaction, the battery is unable to produce electricity (Palermo, 2015).

The batteries that will be in focus in this research are the secondary batteries, also called accumulator which compared to the primary batteries can be recharged (Palermo, 2015). The electrolyte substances used in the secondary batteries differs. The batteries in focus in this report will be the lithium-ion battery (LIB) and the lead-acid battery (LAB) since these are the two main battery types that are being used for generating electric propulsion and energy on ships.

The LIB concept with the mechanism that charged lithium ion is used as the electrolyte was initially conceived in the 1970’s (Albright, Edit and Al-Hallaj 2012). It was first commercialized by Sony in 1991 and is the battery which most research activities revolve around these days. (Scrosati 2011). Scrosati (2011) further explains that the LIB can be found primarily in cell phones, cameras, computers, satellites and electric vehicles. Albright et al,. (2017) writes that the LIB can be separated into two groups with the main thing that differs are the chemical variations; lithium iron phosphate (LFP, LiFePO4) and metal oxides (NCM, NCA, Cobalt and Manganese).

Another commonly used battery is the lead-acid battery. The LAB has been around sense 1859 when French psychician Gaston Planté invented the first rechargeable battery using lead acid as electrolyte substance (Kurzweil 2010). This type of battery is usually used when high currents in a short time are needed. Therefore, they are primarily used for starting engines or as auxiliary power supplies. Other applications are electric powered vehicles like cars and forklifts (Kurzweil 2010). According to Albright et al., (2012) the LAB can be divided into two categories: flooded and valve regulated (VRLA). These two types have an identical internal chemistry, there are however three thing the flooded LAB requires compared to the sealed/valve regulated; upright orientation to prevent electrolyte leakage, ventilated environment to diffuse gases created during the cycle and routine maintenance of the electrolyte.

3 Method

A combination of literature review and SWOT analysis have been used to get both a theoretical and a real-world perspective in this study. These two methods have provided us with enough information and data to answer the research questions.

3.1 Literature review

To partly answer the questions a literature review was conducted. A literature review is a comprehensive survey with focus on a specific field of interest by using bibliographic finding tools both online and in libraries. In the case of this study it was gas turbines and secondary batteries that were the main fields of interest.
The literature review provided us with a sufficient amount of data and information, mainly from databases in Chalmers Library's search engine but also from course literature from previous courses. The relevant and useful literature for our fields of interest was found using English search words.

The result from the literature review is presented in running text with complemental charts, tables and figures to give an uncomplicated overview.
The selection of the documents for the literature review was made by the authors based on the documents reliability and relevance to the research questions. The relevance of a document is determined by how well the content of the document is analogous to the research questions and if the document is up-to-date and not older than 15 years.
The reliability of the documents was determined by if the documents were reviewed and published in a scientific journal or if the documents was analogous to the course literature. Some documents were not published in a scientific journal but were established as a trustworthy source of information.

3.1.1 Search words

Hybrid, Propulsion, Hybrid propulsion, Hybrid marine, Lead-acid, Lithium-ion, Lead-acid vs Lithium-ion, Batteries, Battery Propulsion, Battery Marine, Diesel Engines, Marine Propulsion, Gas turbine marine, Gas turbine hybrid.

3.1.2 Search engines

Chalmers Library.
Web of Science.
Google Scholar.

3.1.3 SWOT analysis

To answer question number one a SWOT analysis was conducted. A SWOT analysis is a strategic planning technique to help identify the *Strengths*, *Weaknesses, Opportunities* and *Threats* related to the subject. The user of a SWOT analysis often asks and answer questions to generate essential information for each category which makes the analysis useful and to identify advantages and disadvantages.
We have chosen to use a SWOT analysis to make an understandable comparison between the two hybrid systems and since there is no clear answer to the question the SWOT analysis is a good way to show the advantages and disadvantages of the different systems.

4 Hybrids in marine propulsion

There are three main different configurations when talking about hybrids with many variations, Diesel/Electric propulsion, Serial hybrid and Parallel hybrid (Hybrid-Marine LTD, 2008).

4.1 Diesel/Electric propulsion

Figure 4 gives an overview of a diesel/electric propulsion system. The internal combustion engine (ICE) is connected directly to a generator with a diesel/electric system. The chemical power from the fuel is converted into electrical energy from the generator. Furthermore, the electrical power runs through a motor controller and an electric motor which then rotates the propeller shaft, giving propulsion. There can be more than one generator connected and additional electrical motors connected, but by a strict definition this is not a hybrid system even though its often referred to one and this is because to be a hybrid system it needs to involve electrical storage (Hybrid-Marine LTD, 2008).

Oil tanker *MT Excello* shown in Figure 4, uses this kind of hybrid propulsion. Four Diesel engines are powering four generators which in turn produces electricity to power the two electric motors for the propellers called Azi Pods.

Figure 4 Excello in open water (Authors own figure).

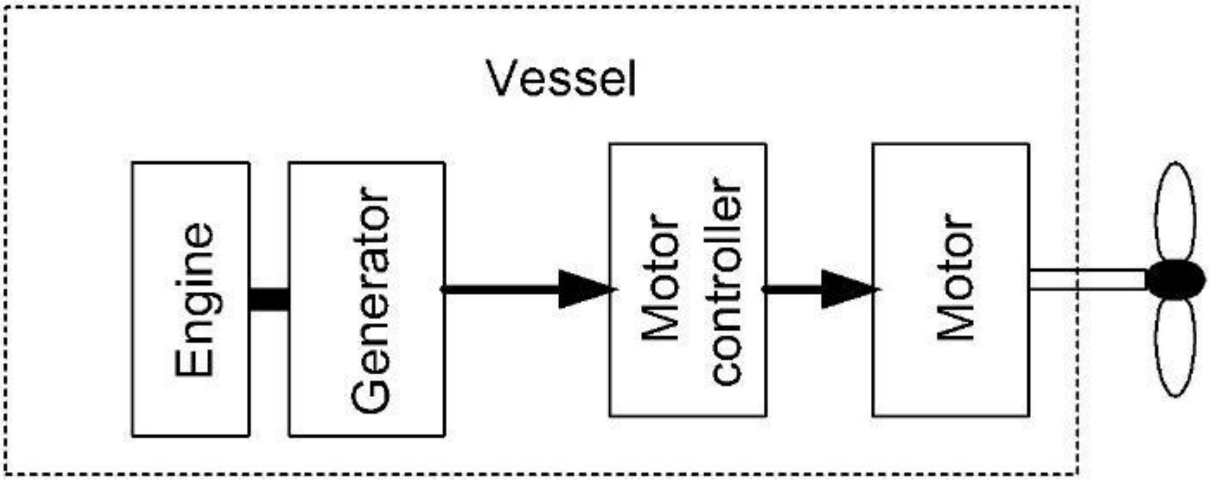

Figure 5 basic overview of a diesel/electric system and how it fits together. (Hybrid-Marine LTD, 2008) Reprinted with permission.

4.2 Serial hybrid

Figure 5 shows the serial hybrid from an overview perspective. This hybrid system is quite like the diesel/electric hybrid. It generates electricity from chemical energy from the main engine, but a battery bank is also connected in this system which is charged from the main engine which means that one could stop the main engine and run only on battery power from the battery bank. The electricity inside the ship that is in everyday use can also be reserved from the battery bank, also called domestic electricity (Hybrid-Marine LTD, 2008).

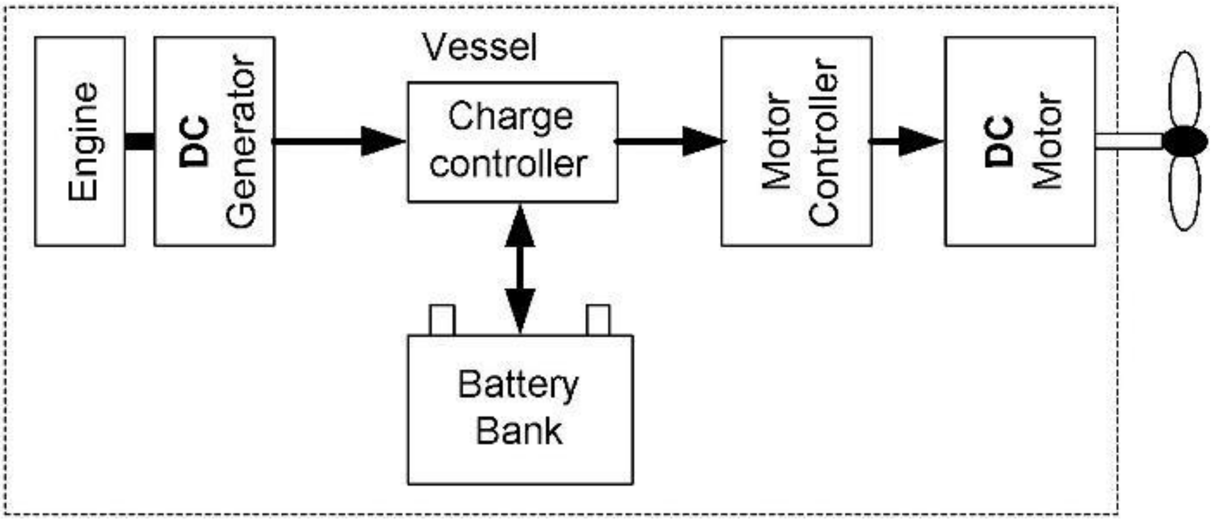

Figure 6 basic overview of a serial hybrid. (Hybrid-Marine LTD, 2008) Reprinted with permission.

4.3 Parallel hybrid

Figure 6 shows the parallel hybrid from an overview persepctive. This setup consists of maintaining the mechanical connection between the engine and propeller shaft and the electric motor is acting on the propeller shaft. The power split is a mechanical gearbox and it can be chosen to either run on electrical power from the battery bank or to run on the main engine or with both electricity and the main engine. The propeller can be disconnected to charge the battery bank from the engine with a clutch (Hybrid-Marine LTD, 2008).

HNLMS Rotterdam is a navy vessel that uses this kind of propulsion where the energy is devided so the vessel can either be propelled by mechanical or electrical energy this is commonly used in smaller vessels that is participating intense operations such as navy vessels, destroyers, off shore work and towing vessels. Why this is used for example on towing vessels and navy vessels is because the engine is usually only runs on 20 % power during towing and patrols, so it is inefficient to burn fuel on that low engine speed. This is though only efficient enough for running on low engine power for a significant time. (Geertsma et al., 2017)

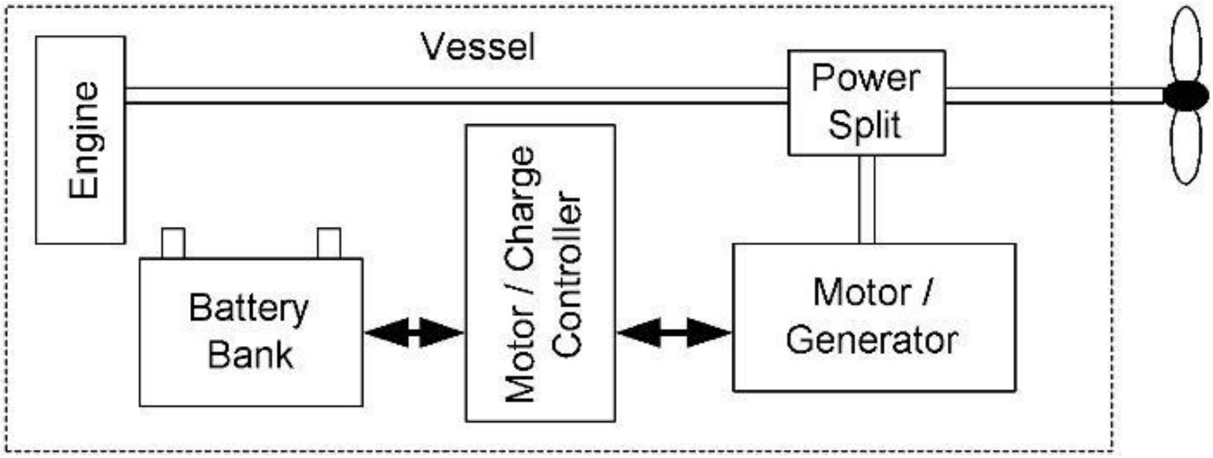

Figure 7 basic overview of a parallel hybrid. (Hybrid-Marine LTD, 2008) Reprinted with permission.

5 Gas turbines in marine propulsion

According to Kayadelen & Üst (2013), gas turbines are the preferred choice for naval vessels because of the turbines compactness, high power density compared to diesel engines, acceleration, stealth and low start-up time. They are ready to run on full power in just 30 seconds since there is no warm-up time compared to diesel engines.

5.1 Gas turbines versatility and application

The gas turbine is the most versatile item of turbomachinery today (Soares, 2015). It can be used in several different modes in critical industries, power plants, oil plants and so on (Soares, 2015). Where electricity needs to be produced a gas turbine would be a wise choice. They come in all kinds of different sizes (Boyce, 2012).

The gas turbine generally works in the same way whether it is on land, in the air or at sea. However, the different areas all have different environmental issues (Soares, 2015). On land the gas turbines are stationary which makes the design to be less expensive and not built to sustain longer periods of vibrations that can be caused on an airplane or a ship for example.

The gas turbine is the best suited prime mover when fuel costs, capital costs, maintenance costs and time planning to completion is considered. The gas turbine has the lowest maintenance and capital costs among other prime movers and it's the fastest completion time to full operation (Boyce 2012).

In marine applications the gas turbine is usually used for propulsion by driving the propeller via a gearbox. It can also be used as a stationary part and just generate electricity which means that it can be used in many different scenarios. Because the gas turbine can be so versatile that means that the ship can use electricity for propulsion or produce electricity from things that would be wasteful otherwise, like steam and that is called a WHRG or Waste heat Recovery Generator (Soares, 2015). The Siemens SGT-500 former GT35 can be used for both propulsion and electricity generation. It is a lightweight, high-efficiency, heavy-duty industrial gas turbine. Its special design features are high reliability and fuel flexibility. It is also designed for single lift which makes the gas turbine very suitable for sea applications because you can change out the unit quick and replace with a new one (Soares, 2015). Leduc (2001) explains that another common setup of gas turbine powered ship is the use of water jets, this type of propulsion is effectively a large adjustable water pump driven by the gas turbine. This setup is common on fast ferries such as *Stena Carisma.*

A major disadvantage of the gas turbine is the low part load efficiency, this leads to the requirement of running the gas turbine at a high rpm compared to a piston engine to achieve a satisfactory compression ratio. The compression ratio is directly proportional to the thermal efficiency, which in turn means low rpm equals low thermal efficiency. This makes cruising speed a problem for ships with gas turbine propulsion (Soares, 2015).

6 Batteries in marine propulsion

Alnes et al., (2017) wrote that the use of electrochemical batteries for the operation of ships is by no means a new concept. The first known boat powered by batteries was a 24-ft vessel build in St. Petersburg, Russia, in 1839 that could carry 14 passengers at a speed of 3 knots. It was however not until the late 19th century that electric boats powered by batteries were produced and utilized in large numbers. These boats were small and mainly used in inland rivers and lakes due to range limitations and the dependence on charging stations for the batteries. The emergence of the internal combustion engine (ICE) led to a drastic decrease in the popularity of electric power ships (Alnes et al., 2017).

Det Norske Veritas and Germanischer Lloyd (DNV GL) which is the world's largest maritime class society, supports the safe introduction of large maritime battery systems with battery rules such as type approval services, industry guideline and advisory services (Alnes et al., 2017). Alnes et al., (2017) further explains that a 2011 study by DNV GL demonstrated that energy storage technologies represent a substantial potential for improving both fuel economy and reducing emissions in the maritime industry.

According to Shahan (2015) the first all-electric battery-powered car and passenger ferry in the world was delivered in 2015. The ferry is the Norwegian ferry: *MF Ampere* which operates the Lavik-Oppedal route all year long and has a capacity of 360 passengers and 120 vehicles (Ampere Electric-Powered Ferry, 2014). According to Corvus energy (2014), the ferry is powered by 160 Corvus AT6500 modules with a total energy output of 1040 kWh and a weight of 20 metric tons. The vessel's batteries are recharged by shore charging stations on each side of the route. The shore charging stations each supports 410 kWh with 63 Corvus AT6500 modules (Corvus energy, 2014).

6.1 Benefits and challenges of batteries as a power source and propulsion plant

- The batteries can provide the required electrical power and enable switching off numerous engines when they would be running inefficiently at the same load. The batteries can then be recharged when the engine is operating with lower SFC, CO2 and NOx emissions. This setup can save fuel, reduce emissions, increase comfort because of reduced noise and temporarily enable sailing without emissions, noise and vibrations from the engines (Zahedi, Norum & Ludwigsen, 2014).
- Batteries can provide back-up power during a failure of the combustion power supplies (diesel generators and gas turbines), this in turn can potentially reduce the installed power on vessels with a requirement for high availability of propulsion as the need for running extra diesel engines is reduced (Zahedi et al., 2014).
- Batteries can enable peak shaving; the battery delivers power when high power is required and recharges when less power is required. This in turn allows the engines to run more efficiently and the installed power can be reduced (Dedes, Hudson & Turnock, 2012).
- Batteries can allow for maintenance of the prime mover at sea since it can be used as propulsion.

Some challenges with batteries as power source and propulsion plant are:

- The purchase and installation costs of batteries needs to be minimized by reduced installed power from the main power sources such as diesel generators (Geertsma et al, 2017).
- The control strategy needs to ideally share dynamic load between the batteries and the combustion power suppliers in such a way that the fuel consumption, emissions and maintenance of all power suppliers are minimized (Geertsma et al, 2017).

6.2 Comparing lithium-ion to lead acid

It is common knowledge that today there are a variety of batteries available on the power market. As mentioned earlier in the thesis under the *Batteries* chapter, the two main types of battery chemistries which will be in focus are the lead acid and the lithium ion. When comparing batteries there are a couple of factions to take into account.

6.3 Environmental impact

The environmental impact of the batteries does play a large role in a branch of industry with high environmental standards issued by Marpol. The batteries themselves doesn't produce any emissions (Geertsma et al., 2017), it is however, the production, manufacturing and disposal of the batteries that contribute to the environmental impact.
The LAB requires more raw material than LIB to achieve the same energy storage which leads to a larger impact on the environment during the mining process. (Albright et al., 2012). In contrast to the large amounts of environmental impact from the production of LAB, a study from the Battery Council International (2014) showed that the recycle rate of the lead from LAB in the U.S between the years 2009-2013 was 99 %.

The lithium is not free from environmental impact, (Albright et al., 2012) writes that the major components of a lithium-ion cell require the mining of different materials such as copper, aluminium, iron and lithium carbonate. According to a LCA-report made by Romare & Dahllöf (2017) the greenhouse gas emissions of current LIB production are 150-200 kg CO_2-eq/kWh.
Albright et al., (2012) further discusses that lithium-ion recycling industry is not as developed as the lead acid recycling. The lithium-ion materials have however shown high ability for recovery and recyclability, so it is expected that the lithium-ion will rival the lead acid in terms of recycling.

6.4 Safety

Both LIB and LAB are capable of going into thermal runaway, which means that the cell rapidly heats up and emits electrolyte, flames and dangerous fumes. The risk for thermal runaway is higher with the LIB due to the higher energy amount in a smaller volume (Albright et al., 2012). Feng et al. (2018) separates the causes for thermal runaway in to three different conditions: *Mechanical abuse, electrical abuse and thermal abuse*.
Destructive *deformation* and *displacement* that is caused by an applied force to the battery are the two most common features of the mechanical abuse. Deformation of the battery may occur during a collision which can cause the battery separator getting torn and causing an internal short circuit and flammable electrolyte leaks out from the battery (Feng et al.,

2018).
The electric abuse can be caused by mainly three different conditions according to Feng et al (2018). An *external short circuit* can be caused by deformation during a collision, water immersion, contaminated conductors or electric shock during maintenance. The hazard of the external short circuit can be reduced by using protective electronic devices.
Overcharging the battery can be harsher than other abuse due to the excessive energy is filled into the battery during the process.

The outcome of overcharge varies depending on how high the current is. During a test the battery cell exploded under high current but only swelled under low current according to Takashi, Komatsu and Maeda (2012). According to Feng et al., (2018) the overcharge can occur when the voltage of any cell is not well monitored and to prevent this, voltage regulation and material modification should be considered.
The *over discharge* is according to Feng et al., (2018) another possible electrical abuse condition. The over discharged is caused by the poles reversing and the voltage becoming negative, this leads to abnormal heat generation.
Feng et al (2018) further discusses that the thermal abuse condition is the direct cause of the battery thermal runaway. Internal short circuit is the most common feature of thermal runaway, almost all the conditions are accompanied with internal short circuit. It occurs when the cathode and anode get contact with each other due to the failure of the battery separator. Once it is triggered, the electrochemical energy stored in the materials releases with heat generation.

6.5 Rate performance

A critical consideration when determining what capacity of battery to use is how long the system will take to discharge. The shorter the discharge period, the less capacity is available from the batteries (Albright et al., 2012).

Figure 3 shows how long it takes for LIB and LAB to deliver their full capacity.
A 100 Ah VRLA (LAB) delivers 80 Ah if it is discharged over a four-hour period compared to a 100 Ah LIB which delivers around its full capacity after four hours. (Albright et al., 2012).

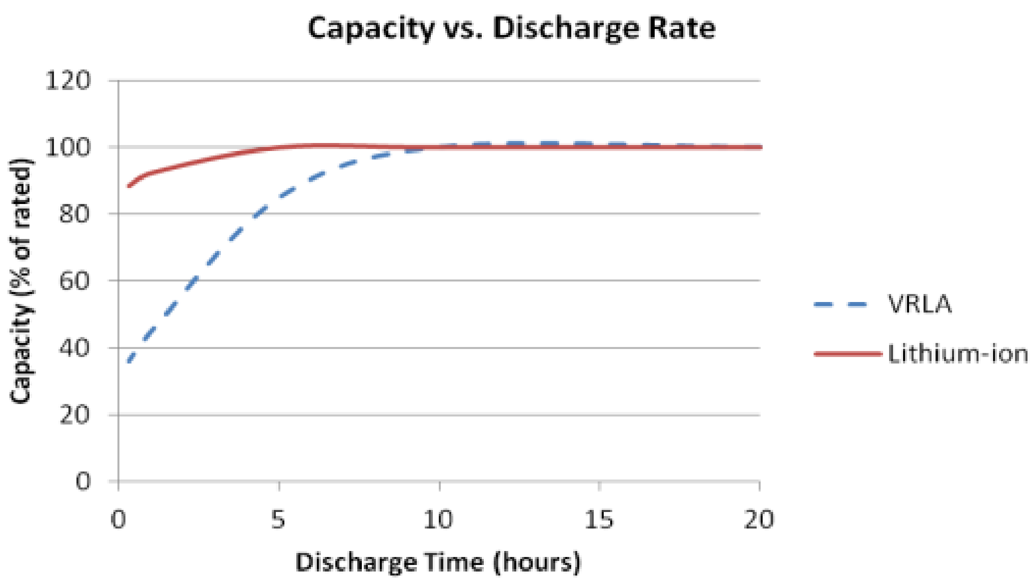

Figure 8 the capacity increases over time (Albright et al., 2012). Reprinted with permission.

Figure 8 shows how both batteries lose capacity in cold weather environments. It is, however, shown that the LIB loses significantly less capacity than the LAB when the temperature drops.

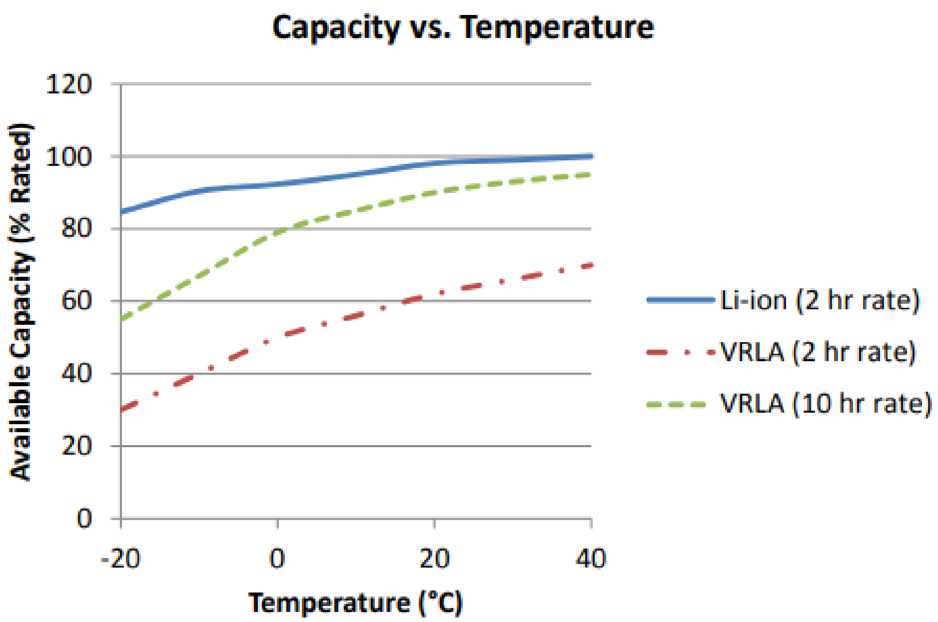

Figure 9 in cold climates the capacity loses capacity (Albright et al., 2012). Reprinted with permission

6.6 Cycle life and capacity

By fully charging and discharging a battery makes one battery cycle and the battery life is based on the number of cycles the battery can perform until it loses its capacity to both store and deliver energy (ADB, 2009). Suratsawadee, Sukruedee, Chatchai and Nipon (2014) wrote that the LIB has a higher amount of cycles than the LAB and according to Albright et al., (2012) the LIB can support around 1900 cycles in its lifetime compared to the LAB's 1000 cycles. The cycle life can be furthered increased with a higher ambient temperature and limiting the discharge rate. Suratsawadee et al., (2009) further discusses the LIBs' higher energy density, with lithium ion containing around 250-360 Wh/L compared to the lead acid's 54-95 Wh/L.

Figure 9 below shows the cycle life data for a LIB and an AGM style LAB. Since the cycle life is influenced by the discharge, the figure shows multiple discharge percentages for the LAB. The LAB must be limited to 30 % discharge to be comparable to a LIB at 75 %, this in turn means that the LAB must be 2.5 times larger in capacity to the LIB to get a comparable life.

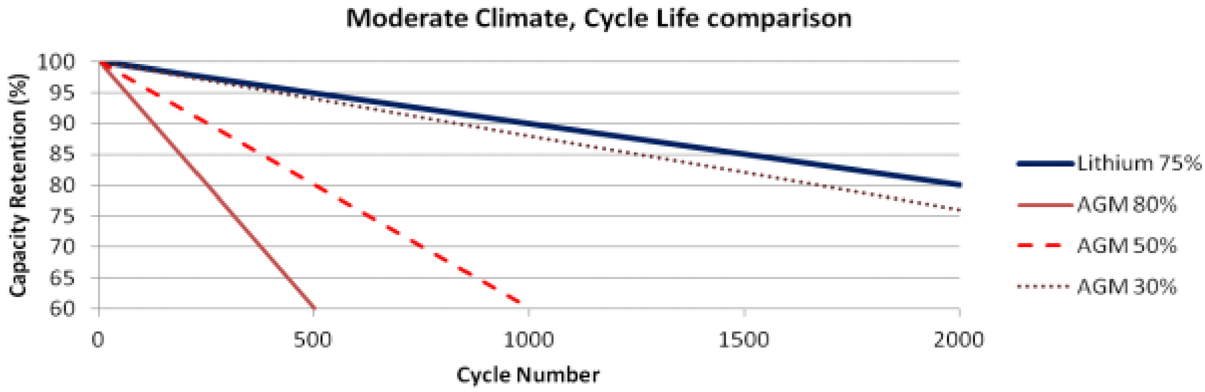

Figure 10 Cycles in moderate climate around 25 Celsius (Albright et al., 2012). Reprinted with permission.

Figure 10 shows the cycle life data in slightly hotter climate, the disparity between the LIB and LAB is further exacerbated. The LIB remains stable while the LAB decreases significantly.

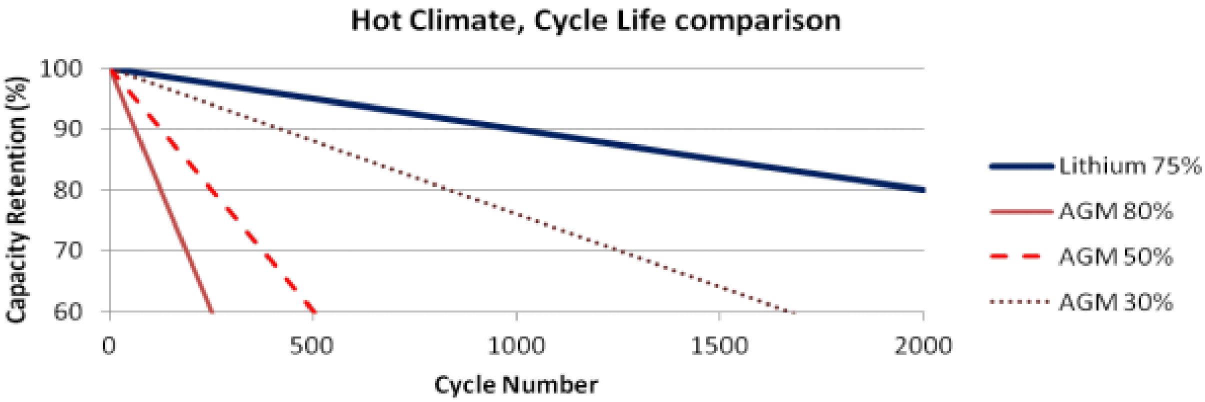

Figure 11 Cycles in hot climate around 33 Celsius (Albright et al., 2012) Reprinted with permission.

6.7 Voltage comparison

The most important factor when evaluating if the batteries can be interchangeable within a given electrical system is the voltage range of each chemistry (Albright et al., 2012). According to an article where a comparison of lead-acid and lithium-based battery behaviour and capacity fades off in charging applications by Krieger, Cannarella & Arnold, 2013 the LIB does not only show the least degradation under variable charging, but also the best voltage performance as well. Their constantly low resistance means that as the batteries age, their capability of power generation is relatively constant and can still endure a pulse charge without a significant change in voltage or efficiency. Krieger et al., 2013 further discusses that the voltage performance of the LIB suggests that it can continue to accept variable charge and meet variable demand over time.

6.8 Conclusion

Both LIB and LAB offer different pros and cons, for a marine propulsion application high energy density and high lifetime is to prefer. Weight is also of uttermost importance on the ship, as stated in section 2.2.6 the LAB would need to be 2.5 times larger in capacity to be able to get the same lifetime as a LIB. According to Periodictable (2018) the density of lead is 11.34 g/cm3 and lithium is 0.535 g/cm3. Because of this fact, a LIB will be significantly lighter than a LAB with the same volume and still having a higher capacity and energy density.

Even if the LIB is more suitable as a marine propulsion system in terms of energy output and weight the cost is to be taken into account. A cost analysis comparing the price of LIB and LAB by PowerTech (2015) shows that the initial cost of the LAB is lower than the LIB cost in terms of purchase price. It is, however, needed to take the cycle life of the batteries into account in this cost. As stated in section 2.2.6 the lifetime of the LIB is higher than the LAB and that the LAB is more temperature sensitive than the LIB.

As stated in section 2.5, LIB is the battery that most research is focused on these days. The LIB's increase in popularity has led to a discussion if the World's reserve will be able to support the raising demand. According to Vikström, Davidsson & Höök (2013), the International Energy Agency states that if by 2050 100 million alternative vehicles are produced annually using lithium battery technology, the lithium reserves would be exhausted in a few years. Vikström et al., (2013) also points out that it is important to acknowledge that much can happen in battery technology until 2050 and that IEA projects that a new generation of batteries will outperform LIB before 2040.

Table 1 below shows how important the cycle life is when comparing the costs.

	VRLA (moderate climate: 25°C)	VRLA (hot climate: 33°C)	Lithium-ion
System size	100 kWh	100 kWh	62.5 kWh
Battery Cost	$12,000 ($120/kWh)	$12,000 ($120/kWh)	$37,500 ($600/kWh)
Cycle Life	1,000 @ 50% DoD	500 @ 50% DoD	1,900 @ 80% DoD
Installation	$20/kWh	$20/kWh	$3.6/kWh
Transportation	$28/kWh	$28/kWh	$5/kWh
Lifetime cost	$0.34/kWh throughput	$0.67/kWh throughput	$0.40/kWh throughput

Table 1 cost comparison of LIB and LAB (Albright et al., 2012) Reprinted with permission.

It is shown that it is not a big difference between the total lifetime cost of the LIB and LAB since the lifetime of the LIB is far superior to that of the LAB. Since the temperature on board varies depending on weather and other systems the LIB is more reliable as a propulsion system.
The conclusion of this comparison will be to use Lithium-ion batteries because of:

- Lower weight
- Higher cycle life
- Balanced lifetime cost
- Higher energy density
- Constant voltage
- Lower environmental damage

7 SWOT analysis

7.1 Gas turbine-battery hybrid

Table 2 shows the SWOT analysis of the gas turbine battery hybrid. It is important to note that this shows the complete hybrid set up, so the part-load problem with the gas turbine is therefore not mentioned as a weakness as it is instead mentioned as an opportunity. Both tables compare to each other, for example the start-up time of the gas turbine-battery hybrid is lower than the start-up time of the diesel engine-battery hybrid. It is also important to note that since both hybrids use batteries some things are not mentioned as they are the same for both hybrids, for example the ability to perform maintenance while out on the sea.

This is not the same for the threats since it is always important to acknowledge the possible threats, in this case the LCA of the LIB and future of the raw material is only mentioned in the gas turbine-battery hybrid but is still current for the diesel engine-battery hybrid. A more in-depth comparison of the two hybrid set-ups will be further discussed in chapter 7.3.

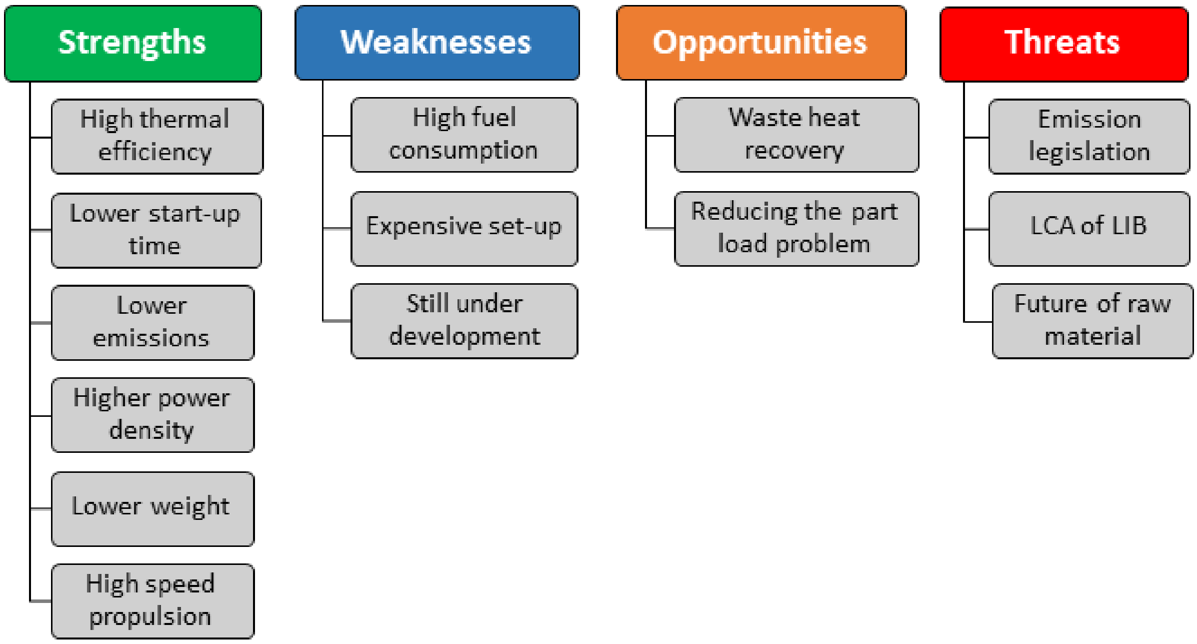

Table 2 SWOT analysis of a gas turbine-battery hybrid (Authors own table)

7.2 Diesel battery hybrid

Table 3 shows the diesel engine-battery hybrid. Since both hybrids uses batteries, the same threats from the batteries apply here as in the gas turbine-battery hybrid.

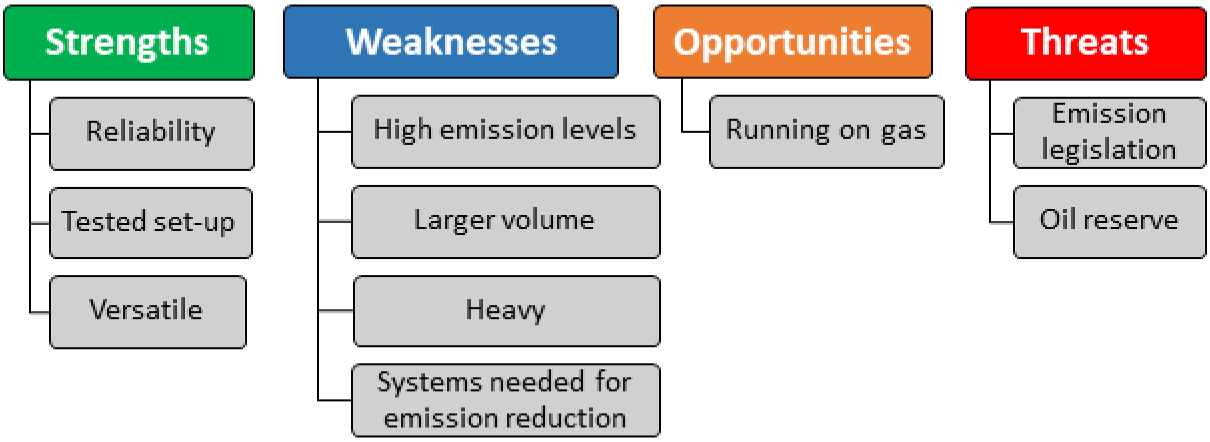

Table 3 SWOT analysis of diesel battery hybrid (Authors own table)

7.3 Discussion

One big difference is the weight of each set-up. The gas turbine-battery hybrid will be much lighter than the diesel engine-battery hybrid since it generally has higher power density, this also allows for higher speeds while sailing. It is also worth to point out that the diesel hybrid will take up much more volume with surrounding systems such as the emission reduction systems. The diesel engine has on the other hand a major advantage over the gas turbine with its high reliability and tested set-up.

From an environmental view, the gas turbine hybrid is more environmental friendly than its counterpart with lower emission levels. Both set-ups have future emission legislations in common since they can run on the same fuel. Even if the batteries themselves don't produce any emissions, the production and manufacturing of them does. Therefore, the LCA of the battery is a threat since future emission legislations can prevent the same production as before. Furthermore, since both set-ups concludes the use of lithium-ion batteries both have the threat of the raw material of the batteries depleting.

Both hybrids can of course run on diesel oil, so it is a threat for both hybrids. It is though important to know that the gas turbines are running on more versatile fuel.

The opportunities differ between the hybrid set-ups, the part-load problem with the gas turbine is reduced due to the use of batteries at lower speeds. The possibility to use the waste heat recovery system further increases the fuel and thermal efficiency of the gas turbine.

8 Conclusion

When taking the SWOT-analyses in regard one can see that both hybrid setups have their advantages and disadvantages.

The study was about why gas turbine-battery hybrids are less frequently used as marine propulsion compared to diesel engine-battery hybrids and the answer is still not clear after this literature review. SyndiGate Media Inc (2017) wrote that GE and Southern California Edison showed the world a new gas turbine-battery hybrid system that should balance out renewable energy in 2017. This shows that the reason for so few results from the literature review is that the subject is relatively new and still under development.

One of the larger benefits to a gas turbine battery hybrid is if a power surge were to happen the batteries could provide that power instead of having the turbine to waste fuel and the poor efficiency on a gas turbine on low loads would be nullified due to the batteries being able to produce most of the propulsion at low speeds.

Ships that would be suitable for this type of hybrid would most likely be smaller sized ships that are running on low speed but are in demand of power, ferries with a fixed route, navy vessels that are on patrol, towing vessels that are in operation and supply vessels. With today’s batteries and gas turbines due to the weight we do not believe that it would be suitable for a high-speed ship or ships that are dependent on weight. Parallel hybrid system would probably fit for the best with this kind of set-up and demand.

Due to lack of information and companies that have tried the idea, future research is needed. As the gas turbine battery hybrid propulsion in a marine perspective is still new and quite a wide subject, the future work suggestions would be:

- An efficiency comparison between the two systems (diesel battery hybrid and gas turbine battery hybrid).
- A life cycle analysis between the two systems.
- How the batteries can fix the part load problem with gas turbine as propulsion on a vessel.

9 References

SyndiGate Media Inc. (2017) *GE and Souther California Edison Debut World's First Battery-Gas Turbine Hybrid*. https://search.proquest.com/docview/1889043557/citation/3504268086D542B9PQ/1?accountid=10041

PEi. (2018). Gas Turbines and Batteries: *A Perfect Pairing*. http://www.powerengineeringint.com/na/general-electric/gas-turbines-and-batteries-a-perfect-pairing.html

Woud, H. K., & Stapersma, D. (2008). *Design of Propulsion and Electric Power Generation Systems*. Institute of Marine Engineering, Science & Technology (2008). www.imarest.org

Alnes, O, Eriksen, S, Vartdal, B.J. (2017). Battery-Powered Ships: A Class Society Perspective. IEEE Electrification Magazine, 5 (3), 10-21, 10.1109/MELE.2017.2718823

Geertsma, R.D, Negenborn, R.R, Visser, K, Hopman, JJ. (2017) Design and control of hybrid power and proplusion systems for smart ships: A review of developments. *Applied Energy (194),* 30-54. https://doi.org/10.1016/j.apenergy.2017.02.060

Sciberras, E.A,Zahawi, B, Atkinson D.J, Juando, A. (2013) Electric auxiliary propulsion for improved fuel efficiency and reduced emissions. *Journal of Engineering for the Maritime Environment (229),* 36-44. https://doi.org/10.1177/1475090213495824

Jaster, T, Rowe, A, Dong, Z. (2014) *Modeling and simulation of a hybrid electrc propulsion system of a green ship*. *IEEE Xplore*. http://ieeexplore.ieee.org/document/6935601/

Volker, T. (2013) *Hybrid propulsion concepts on ships*. *Zeszyty Naukowe Akademii Morskiej w Gdyni, vol (79),* 66-76.

Palermo, E. (2015) *How Do Batteries Work?* https://www.livescience.com/50657-how-batteries-work.html

Hanania, J, Heffernan, B, Jenden, J, Leeson, R, Mah, T, Martin, J, Stenhouse, K, Donev, J. (2018). *Energy Density*. http://energyeducation.ca/encyclopedia/Energy_density

Kurzweil, P. (2010) Gaston Planté and his invention of the lead–acid battery—The genesis of the first practical rechargeable battery**.** *Journal of Power Sources, (14),* 4424-4434. https://doi.org/10.1016/j.jpowsour.2009.12.126

Scrosati, B. (2011) History of lithium batteries. *Journal of Solid State Electrochemistry, 15 (7-8),* 1620-1630. https://doi-org.proxy.lib.chalmers.se/10.1007/s10008-011-1386-8

Shahan, C. (2015). World's First All-Electric Battery-Powered Ferry. Z. Shahan. *Clean Technica.* https://cleantechnica.com/2015/06/13/worlds-first-electric-battery-powered-ferry/

Zahedi, B, Norum, L.E, Ludwigsen, K.B. (2014) Optimised efficiency of all-electric ship by DC hybrid power systems. *J Power Sources, Vol (255),* 341-354.

Dedes, E.K, Hudson, D.A, Turnock, S.R. (2012) Assessing the potential hybrid energy technlogy to reduce exhaust emissions from global shipping. *Energy Policy, Vol (40)*, 204-218. https://doi.org/10.1016/j.enpol.2011.09.046

Ship-Technology. (2014). Ampere Electric Powered Ferry https://www.ship-technology.com/projects/norled-zerocat-electric-powered-ferry/

Battery Council International (2014) *Recycling rate of lead from lead-acid batteries climbs to 99%* http://c.ymcdn.com/sites/batterycouncil.org/resource/resmgr/Press_Releases/Recycling_Study_Press_Releas.pdf

Vikström, H, Davidsson, S, Höök, M. (2013) Lithium availability and future production outlooks. *Applied Energy, volume* (110), 252-266. https://doi-org.proxy.lib.chalmers.se/10.1016/j.apenergy.2013.04.005

Nasdaq (2018) *Commodity Prices* https://www.nasdaq.com/markets/commodities.aspx

Kayadelen, H.K, Ust, Y. (2013) Marine Gas Turbines. In *7th International Advanced Technologie Symposium IATS*, 1st November, 2013, Istanbul, Turkey.

Leduc, M. (2001) *The Gas Turbine: The emerging prime mover*. http://www.dieselduck.info/machine/01%20prime%20movers/gas_turbine/gas_turbine.htm

Corvus energy (2014) *World's first all-electric car ferry* http://corvusenergy.com/marine-project/mf-ampere-ferry/

Feng, X, Ouyang, M, Lu, L, Xia, Y, He, X (2018) Thermal runaway mechanism of lithium ion battery for electric vehicles: A review *Energy Storage Materials (10)*, 246-267, https://doi.org/10.1016/j.ensm.2017.05.013

Takahashi, M, Komatsu, K, Maeda, K. (2012). *The safety evaluation test of lithium-ion batteries in vehicles: investigation of overcharge test method*. ECS Trans, 41 (39).

Albright, G. Edie, J. Al-Hallaj, S. (2012) A Comparison of Lead Acid to Lithium-ion in Stationary Storage Applications. *AllCell Technologies LLC.* http://www.batterypoweronline.com/wp-content/uploads/2012/07/Lead-acid-white-paper.pdf

Romare, M, Dahllöf, L. (2017) *The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries: A Study with Focus on Current Technology and Batteries for light-duty vehicles* C 243. IVL Swedish Environmental Research Institute http://www.ivl.se/download/18.5922281715bdaebede9559/1496046218976/C243+The+life+cycle+energy+consumption+and+CO2+emissions+from+lithium+ion+batteries+.pdf

Suratsawadee, A, Sukruedee, S, Chatchai, S, Nipon, K (2014) *Comparison theEconomic Analysis of the Battery between Lithium-ion and Lead-acid in PV Standalone Application,* Energy Procedia, 56, 352-358, https://doi.org/10.1016/j.egypro.2014.07.167

Asian Development Bank (2009) *Lead acid: A growing environmental problem* https://www.adb.org/sites/default/files/linked-documents/43207-013-phi-oth-08.pdf

Krieger, EM, Cannarella, J, Arnold, CB. (2013). *A comparison of lead-acid and lithium-based battery behaviour and capacity fade in off-grid renewable charging applications*. *Energy (60)*, 492-500.

Periodictable (2018) *Density of elements* http://periodictable.com/Properties/A/Density.al.html

PowerTech (2015) *Lithium-ion vs Lead-Acid cost analysis*. https://www.powertechsystems.eu/home/tech-corner/lithium-ion-vs-lead-acid-cost-analysis/

Smil, V (2010) *Prime Movers Of Globalization: The History and Impact of Diesel Engines and Gas Turbines.* Cambridge: MIT Press

Kees, K. (2008). *Disesel engines for ship propulsion and power plants from 0 to 100 000 kW. Part 1*. Groningen: Target Global Energy Training.

Soares, 2015, *Gas Turbines – A handbook of air, land and sea applications (2nd edition): A handbook of Air, Land and Sea Application*, 3,11, 1-662. http://dx.doi.org/10.1016/B978-0-12-410461-7.00001-8

Nada, T. (2014). *Performance characterization of different configurations of gas turbine engines*, 3, 121-132. https://doi.org/10.1016/j.jppr.2014.07.005

Boyce, M P. (2012). *Gas Turbine Engineering Handbook (Fourth Edition).* Butterworth: Elsevier.

PetroWiki. (2012). *Gas Turbine Engines*. http://petrowiki.org/Gas_turbine_engines

Jelley, N. (2017). *A Deictonary of Energy Sience.* Oxford: Oxford University Press. 1, 3. https://10.1093/acref/9780191826276.001.0001

Hybrid-Marine LTD (2008) *What is a Hybrid?* http://www.hybrid-marine.co.uk/10.html

UN-Business Action Hub (2018) *IMO https://business.un.org/en/entities/13*