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A case study about complete battery implementation onboard tugs

Bachelor thesis in the Marine engineering Programme

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Cover:
Actual footage of R/T Adriaan in transit (Kotug, u.d.)

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Abstract

New regulations are presented as a reaction to the shipping industry`s contribution to the global warming and emission of other pollutants. New sustainable solutions to energy production onboard ships are therefore needed.

Battery power have been presented as one of the solution to lower dangerous emissions from burning fossil fuels in combustion engines. Fully electric cars powered by stored energy in batteries already exists and can be seen as an emission free solution. However, the concept is not common within the shipping industry, even if there is a rising interest in the subject. This paper is presenting that vessels with a fixed route such as ferries have showed the biggest interest in adapting this concept with battery. However, hybrid systems are more common in the shipping industry but could act as an important first step when going from diesel to battery.

The purpose of this thesis is to investigate the environmental and economic benefits and disadvantages of converting a hybrid tugboat to a fully electric vessel, how much the local society, close to where the vessel operates have to gain on this retrofitting to a fully electric propulsion line and what the difference in cost between the hybrid propulsion line and the fully electric.

The results are achieved with help of scientific literature and calculations with information from the company that owns the vessel we are investigating for this case study. The results of converting a hybrid vessel to a fully electric vessel with a battery energy storage system onboard shows that the benefits for the local area where the ship is operating, regarding costs for health issues related to harmful emissions of NOx (Nitrogen Oxides), SOx (Sulphur Oxides), PM (Particular Matter) and VOC (Volatile Organic Compound), are high. Considering the results when calculating the global effects on CO_2 (Carbon dioxide) emissions, the same benefits with the energy system change is not as great since the result show a very little difference, depending in which country the electricity is produced in. Regarding the production of the li-ion (Lithium-Ion) batteries, the calculations are showing that only a fraction of the total CO_2 emissions from the battery are coming from the production.

Keywords: Hybrid, diesel-electric, battery, lithium, life cycle analysis, sustainability, emissions, local effects, global effects, tugboat, propulsion

Sammanfattning

Nya förordningar presenteras till följd av skeppsindustrins bidrag till den globala uppvärmningen och andra miljöföroreningar. Därför behövs nya hållbara lösningar för energiproduktion ombord på fartyg. Batterisystem har presenterats som en av lösningarna för att minska farliga utsläpp från förbränning av fossila bränslen i förbränningsmotorer. Fullt eldrivna bilar som drivs av batterier finns redan och har på ett sätt deklarerats som en utsläppsfri lösning. Hybridsystem där det ena kan vara batteri är vanligare inom sjöfartsindustrin där man ofta kräver mer flexibilitet i dess arbete. Konceptet med fullt batteridrivna fartyg är inte helt vanligt inom sjöfartsindustrin, även om det finns ett ökat intresse för ämnet. Den typ av fartyg som har anammat detta koncept med en batteridriven framdrift är fartyg som har en fast rutt, till exempel färjor på grund av dess monotona arbete. Att köra samma rutt fram och tillbaka flera gånger om dagen och ankomma samma hamnar gör implementeringen lättare. Hybridsystem är vanligare inom sjöfartsindustrin där man kräver mer flexibilitet i dess arbete.

Syftet med denna avhandling är att göra en fallstudie för att utreda vilka miljömässiga och ekonomiska fördelar som finns och vad nackdelarna med att konvertera en hybrid bogserbåt till ett helt elektriskt fartyg är. Avhandlingen ska även fokusera på hur mycket lokalsamhället, inom närområdet där fartyget är verksamt, har att tjäna på denna eftermontering till ett helt elektriskt framdrivningssystem och hur stor skillnaden är i kostnad mellan hybrida framdrivningssystem och helt elektriska.

Resultaten uppnås med hjälp av vetenskaplig litteratur och beräkningar med information från det företag som äger det fartyg fallstudien baserar sig på. Fallstudien påvisade att fördelarna med att bogserbåten övergår till helelektrisk är stora med hänsyn till de lokala utsläppen av NOx (Kvävedioxider), SOx (Svaveldioxid), PM (Partiklar) and VOC (Lättflyktiga organiska föreningar). Samma resultat gällde dock inte för de globala effekterna på koldioxidutsläpp eftersom skillnaden var väldigt liten beroende på det valda landet där elen produceras. Beräkningarna i rapporten visar att tillverkningen av litiumbatterierna endast står för en bråkdel av de totala koldioxidutsläppen under dess beräknade livslängd.

Nyckelord: Hybrid, diesel-elektriskt, batteri, litium, livscykel, analys, hållbarhet, utsläpp, globala effekter, bogserbåt, framdrift

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Kent Salo at Chalmers, that helped us with environmental part of the thesis by providing us with articles concerning the subject of emissions.

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Nomenclature

Letter	Name
η_{Trans}	Transformer efficiency
B_c	Battery cost (€)
B_e	Emission from producing this battery (kg)
B_{fc}	Battery fuel cost/hour (€)
B_p	Battery power with correcting factors (kWh)
B_w	Battery weight (Kg)
$B^{0.5}$	City population
$C-Rate$	Characteristics for charging/ discharging (6)
$Charge_C$	Charging correction (36%)
$CO2_g$	Grams CO2 in 1-liter fuel (gram)
$Cycle_C$	Cycle correction (25-85%)
D	Dimensions battery (m^3)
DP_i	Diesel power installed (kW)
D_p	Diesel power installed (kW)
D_r	Discharge rate/ Charge rate (amph)
E_{A24}	emission R/T Adriaan (CO2/24h)
E_{Area}	Exposure area
$E_{CO2KOTUG}$	emission (CO2/ kWh)
E_D	Energy density (kg/kW)
F_{ch}	Fuel consumption/ hour (m3)
F_v	Ventilation factor
H_c	Hybrid cost (€)
H_{fc}	Hybrid fuel cost (€)
H_{MEMC}	Hybrid main engine maintenance cost (€)
I	Inflation (2012-2018 4%)
M_e	Emission from production (CO2/kWh)
M_{ch}	Maintenance cost/h (€)
M_t	Maintenance time interval (hours)
P_1	Power needed at 6 knots (kW)
P_2	Power needed at 8 knots (kW)
P_{24}	Total power needed for 24h (kWh)
P_3	Power needed at 12 knots (kW)
P_{Tot}	Total power needed for one running cycle (kWh)
P_{ULSMGO}	Price ULSMGO (€)
P_{ch}	Power consumption/hour (kWh)
P_e	Price electricity (€)
P_{kWh}	Price/kWh (€)
P_{peak}	Maximum power outtake at once (kW)
V	Voltage (volt)

1 Introduction

The international shipping industry is responsible for carrying over 90% of the world trade. As the world population continues to increase, the demand for imported goods transported by sea will also be greater and lead to more handling in port. The transported goods are expected to increase from 10 billion to 17 billion in 2030 (International chamber of shipping, 2014). Ship emissions will continue to increase at the same rate as shipping demand unless practices change. Without emission control regulations, CO_2 emissions could potentially increase by over 250% in 2050 (International Maritime Organization, 2014).

MARPOL Annex VI was in 2011 revised to prevent ship pollution. This change restricted emission levels of NOx (Nitrogen Oxides), SOx (Sulphur Oxides) and PM (Particular Matter). Some sensitive areas, ECA (Emission Control Areas) will face further reduction in the limits. Also, SECA (Sulphur Emission Control Areas) was introduced in 2015 in order to avoid acidifying the air, forcing companies to use LFO (Light Fuel Oil) with a sulphur content of not more than 0.1% (International Maritme Organization, 2011). Further regulations are entering the market in 2020 and will push the global limit down to 0.05%. This could lead to a cleaner environment and counteract premature deaths. However, the operation costs are expected to increase considerably as these fuels with lower sulphur are more expensive (Ship & Bunker, u.d.).

With these increases in environmental regulations and possible increase in operational cost, rising interest in finding new fuel-efficient solutions or other alternative power sources are likely to increase. Furthermore, harbours are often located in urban areas and vessels operating in those areas are more likely to face stricter regulations in the future (Kennedy, Soong, & Lindtjorn, 2013).

Electrification of the society has been going on for a while. Shore based electrical vehicles are expected to increase and thereby reduce the emissions from transportation on road. There is a whole new generation of renewable power sources. The technological issues of implementation are gradually being overcome but the economic possibility is still in some way constrained, mainly from higher prices than older proven technologies.

(Kihm & Trommer, 2014)

1.1 Purpose

The vessel examined throughout this paper is a tugboat running on both a diesel engine as well as a battery system connected to an electric propulsion line. The research paper will analyse the differences between running only on a battery system and operating on a diesel-electric hybrid system. *Thus, the purpose of this paper is to compare the economic and environmental benefits and limitations associated with the two different systems*. It is important to highlight that a fully converted tugboat does not currently exist in the market. The first section will look into the investment and running costs related to the two systems, mainly comparing the previous fuel cost with the new cost on charging the battery. The second section of this research paper will mainly focus on the environmental aspects and compare them with the environmental impact for each system.

1.2 Research question

- To what extent is it economically reasonable for a tugboat to switch from a diesel-electric hybrid propulsion system to a fully electric battery system?

- To what extent will the local society and the local stakeholders benefit if tugboats were to change from a diesel-electric hybrid system to a fully electric battery system?

1.3 Delimitations

The investigation was limited by the following aspects:

- Limited to information that we received from KOTUG, the owners of the vessel R/T Adriaan. Even if most diesel-electric tugboats have similar engine layout tugs with battery pack installed is not that common.

- The local effects are limited to northern Europe due to the similarity in climate and CO_2 will not be measured locally due to its mostly global effects.

- The emissions from the production of lithium battery will be limited to a cradle-to-gate perspective and limited to only CO_2 emissions due to the literature that was found. When contacting recycle companies, the combined point is that almost no lithium is recycled. Only a few companies around the world are handling the recycle process and one major recycler said that they dismantle the li-ion batteries and send the lithium to another company in Europe the rest is however recycled, due to the difficulty to receive information about the recycled lithium, only the emissions from production is accounted for.

2 Background and theory

The history and theory behind batteries will be presented in this chapter both for marine applications and in general. The working principles of Lithium-Ion batteries and different propulsion systems will be described to give a basic knowledge about the subject.

2.1 Historical overview over batteries onboard

One of the first batteries used onboard boats hade 128 zinc plates that was dissolved in a solution consisting of hydrochloric and nitric acid. Not long after they have launched the boat carrying this battery it started to give away nitrous fumes and almost suffocated the crew and drove away the spectators from the riverside. The crew managed to disconnect the battery and remove the zinc plates which ended the process and shut down the system. After this the inventor Nicholas abandoned his interest in electric boats for now (Swanson W. , 2015).

Many different solutions in battery design ware tried out after this launch failed. An inventor George Lechlancè tried to use dry cell battery with zinc, manganese and ammonium chloride, this was the first efficient rechargeable battery. However, the improvement of the internal combustion engine took over when it came to introduction in the 1920s and the popularity of commercial electric boats drastically declined (Swanson W. , 2015).

For special purposes such as environmentally sensitive areas electric boats were still an alternative. (Electric Boats, 2014) The specific power to energy density has been too low as well as the expected life time on older battery types such as Lead-acid have been too short. This meant that the battery has not been able to meet the requirements for bigger marine propulsion applications in the past (Mjøs, o.a., 2016).

Due to the emergence of new technologies such as li-ion batteries with a much higher energy density than traditional lead-acid batteries the possibility to use batteries onboard ships have changed. The invention of the li-ion battery in the 80s has been driven by consumer electronics, cam recorders etc. It was not until the automotive industry saw the interest in batteries that the development of high power and bigger energy applications took off (Mjøs, o.a., 2016).

2.2 Lithium - Ion battery

Lithium is the lightest material in the periodic table and has therefore been a good starting point when trying to achieve a high power to weight ratio. The main components of a lithium battery are the anode, the electrolyte solution and the cathode. When a battery is charged the positively charged lithium ions pass from the cathode through the separator and into the layered structure of graphene in the anode, where they are stored until the battery starts to discharge and the reverse process starts (Burrows, Holman, Parsons, Pilling, & Price, 2009).

2.2.1 Main Components

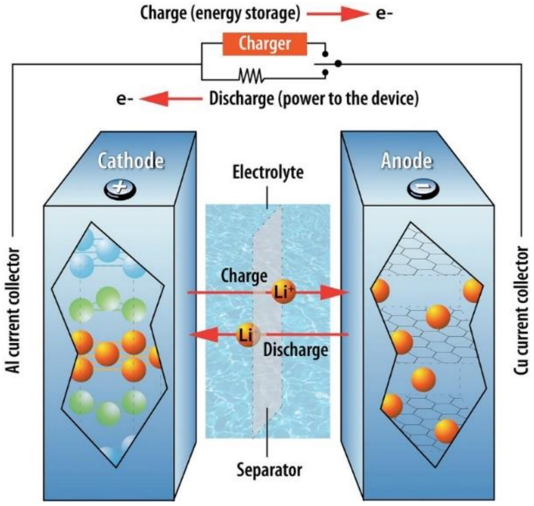

Figure 1 Main components of lithium batteries

Cathode: This side is commonly called the positive side as seen in Fig. 1. and consists of many different material mixes depending on the desired characteristics. Note that the batteries used in smartphones are not the same as the ones on bigger installations such as Tesla cars or even bigger applications with other characteristics. As table 1 is showing aluminium among other materials is used here instead to transfer current when charging and discharging.

Table 1 Cathode materials

Cathode Material	**Energy density (Wh/kg)**	**Cost**	**Lifetime**
$LiCoO_2(LCO)$	546	Medium	Medium
$LiMn_2O_4(LMO)$	410-492	Low	Low
$LiNiMnCoO_2(NMC)$	610-650	High	High
$LiFePO_4(LFP)$	518-587	Medium	High
$LiNiCoAIO_2(NCA)$	680-760	High	Medium

Lithium is not the only metal that is used in lithium-ion cells. There are many cathode types, and they all have different formulations. Some of the major ones are shown in Fig. 2.

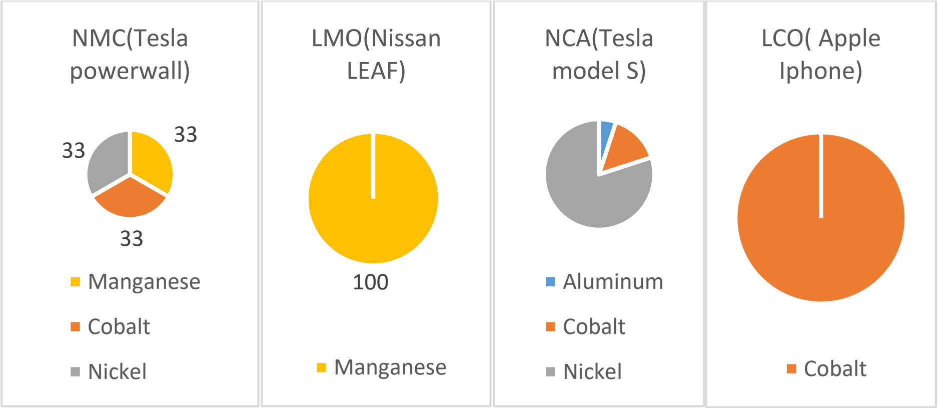

Figure 2 Chemistry of the cathodes

Electrolyte: As seen in the Fig. 1 the battery is filled with a substance to make it possible for the lithium-ions to travel between cathode and anode. It is important that this electrolyte is extremely pure, to be able to achieve efficient charging and discharging (BASF, 2011).

Separator: A layer of polymeric membranes is placed between the two electrodes to prevent a short-circuit. Only lithium ions are able to pass through this filter. If this filter bursts the electrodes will come into contact with each other and the battery will become hot very quickly and might result in fire or explosion (BASF, 2011). This was the case with the exploding Samsung Galaxy note 7 (MOYNIHAN, 2007).

Anode: The anode is located on the negative side of the battery as seen in Fig. 1. It is made of graphite which is a form of carbon in a layered structure. To transfer and collect the electrical current a copperplate is needed during charging and discharging (Burrows, Holman, Parsons, Pilling, & Price, 2009).

2.3 Material limitations

The performance of li-ion batteries is in most cases limited to the storage capacity of the cathodes because the anode materials offers a higher storage capacity. Although there are other important materials that will determine the performance of a li-ion battery such as anode, cathode and electrolyte (Chaofeng, Zachary G. , & Guozhong , 2016).

2.4 Expected life

The expected life of a li-ion battery depends strongly on the range it is charged and the way that its used. If only the theory behind how a li-ion battery works is considered, it should work for ever. However, in reality cycling times and temperature differences have to be taken in to account when a battery is designed. Table 2 illustrates how much impact the surrounding temperature has on the life span of the batteries.

To measure the performance of a li-ion battery and thereby its lifespan three things are measured: Capacity, internal resistance and self-discharge, where the capacity is the most accurate indicator (Batteryuniversity, 2018).

Heat and high voltage are two of the major causes that could make the li-ion battery suffer from severe stress. A battery that is being exposed for 30˚C or more is considered to have a raised temperature and if the voltage is kept above 4.10V/Cell it is also considered as high voltage. Exposure to both high temperatures and high voltage could be more stressful than normal charging or discharging. As showed in the Table.2 there is a huge difference between if the battery is fully charged and exposed to high temperature compared to the lower charged battery without the added temperature (Asakura, Shimomura, & Shodai, 2003).

Table 2 Charging temperature from total discharge

Temperature	**40% Charge**	**100% charge**
0˚C	98%(after 1 year)	94%(after 1 year)
25˚C	96%(after 1 year)	80%(after 1 year)
40˚C	85%(after 1 year)	65%(after 1 year)
60˚C	75%(after 1 year)	60%(after 3 months)

Most consumer electronics are charged at 4.2V/Cell to reach optimal runtime on the devices. But other users, such as the industry are more concerned about the longevity and may therefore choose lower charging current. By changing the loading current from 4.2V in steps of 0.1V the life cycle will double for each 0.1 step. Unfortunately, this could lead to a reduction of the total amount of energy stored (Asakura, Shimomura, & Shodai, 2003).

If longevity is desired the optimal charging voltage is said to be 3.92V/Cell. According to Choi & Lim, 2002 this is supposed to be a threshold, going lower will not lead to any further benefits (Choi & Lim, 2002). In addition to keeping the charging current on a desired level the battery charger needs to turn of the electrical current once it has reached its maximum power and instead switch over to a more normal level for the battery, this is like relaxing the muscles after training (Batteryuniversity, 2018).

There have been numerous of DST (Dynamic Stress Test) to reflect over the best ways of using li-ion batteries. The test seen in Fig. 3 shows the correlation between battery life and cycle span. To prolong the battery lifetime the best way is to cycle between 75-65%, but then only 10% of the available battery power installed could be used. The longest runtime and best exploitation of the battery is to cycle between 100-25% as seen in Fig. 3. However, the life time and number of cycle are shortened drastically. Electric vehicles are ranging from 85-25% and trying to take the best use of both worlds (Bolun Xu, Oudalov, Ulbig, & Andersson, 2018).

Figure. 3 shows how the capacity will change depending on how the battery is used.
The values are taken from the interpolated version on (Batteryuniversity, 2018).

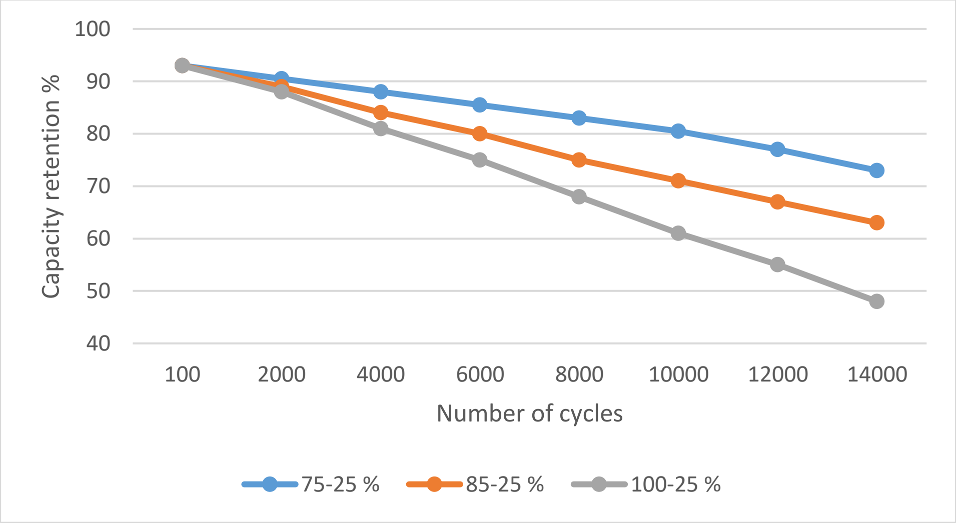

Figure 3 Correlation between Number of cycles and Capacity retention

2.5 Battery price forecast

The future in technology could be hard to predict, new materials are discovered all the time and could be a game changer for older already proven technologies. As the EV (Electric Vehicle) market is expected to grow from 1% to 32 % of the market by 2030 (Berckmans, o.a., 2017) the need for batteries will drastically increase and massive investments in battery manufacturing will be needed. This mass production could act as the main dragging force in decreasing battery costs. Additionally, this could mean further improvements in terms of energy density and safety.

Material cost are by far the biggest cost in a battery pack with 66% of the total production cost. And the biggest cost of the material is the active component responsible for the intercalation of the li-ions. By replacing this with a cheaper material such as silicone could even further reduce the cost by 30% per kWh (Berckmans, o.a., 2017).

li-Ion batteries will become competitive with fossil fuel such as diesel or gasoline as shown by the numbers in Table. 3 shows. This is to show a comparison of costs to the industry between batteries and fossil fuels (Desjardins, 2017).

Table 3 Price comparison of li-Ion batteries and diesel fuel (Desjardins, 2017)

Price Lithium	Fossil fuel price (ULSMGO)
240-dollar/kWh	3 dollar/gallon
150-dollar/kWh	2 dollar/ gallon
100-dollar/kWh	Goal

The cost of the new emerging silicone-based li-ion battery is estimated to come down to as low as 100 dollar/kWh by the year 2020-2025. For the NMC (Nickel Magnesium Cobalt) batteries, this number will be reached in 2025-2030. (Berckmans, o.a., 2017)

Figure. 4 shows the total price prediction from (Berckmans, o.a., 2017) and how it could change over time as the NMC batteries are getting more popular.

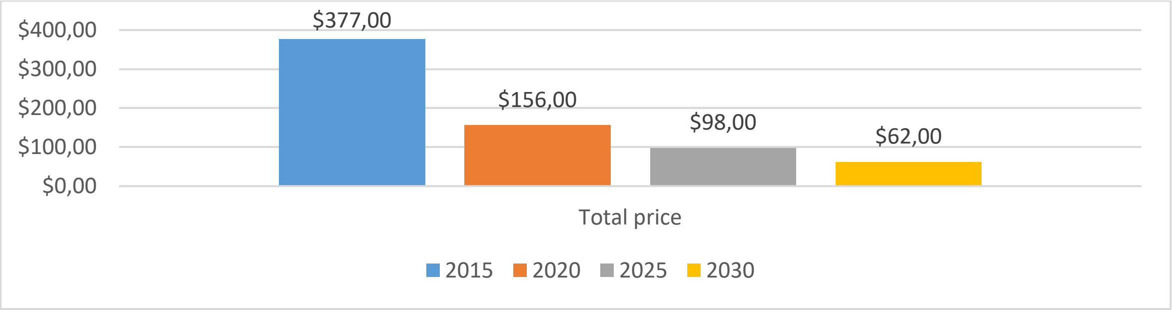

Figure 4 Sales price prediction in kWh from (Berckmans, o.a., 2017) own calculations

Figure. 5 shows the prediction in price in 2020 from different companies and research groups.

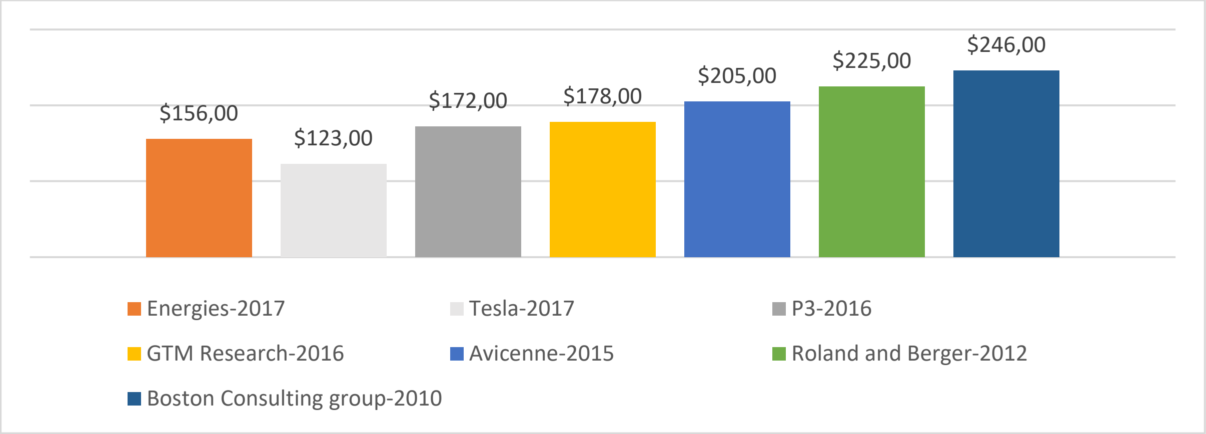

Figure 5 Sales price prediction (kWh) in 2020 prediction from different companies *(Berckmans, o.a., 2017)*

2.6 Propulsion system

Figure.6 shows a typical propulsion system from diesel electric vessel with batteries. All engines are connected to the main power grid and could provide with charging power to the batteries or with power to propel the vessel. Note that the batteries are too small to provide power at the higher power outtake, but for transit they are used frequently.

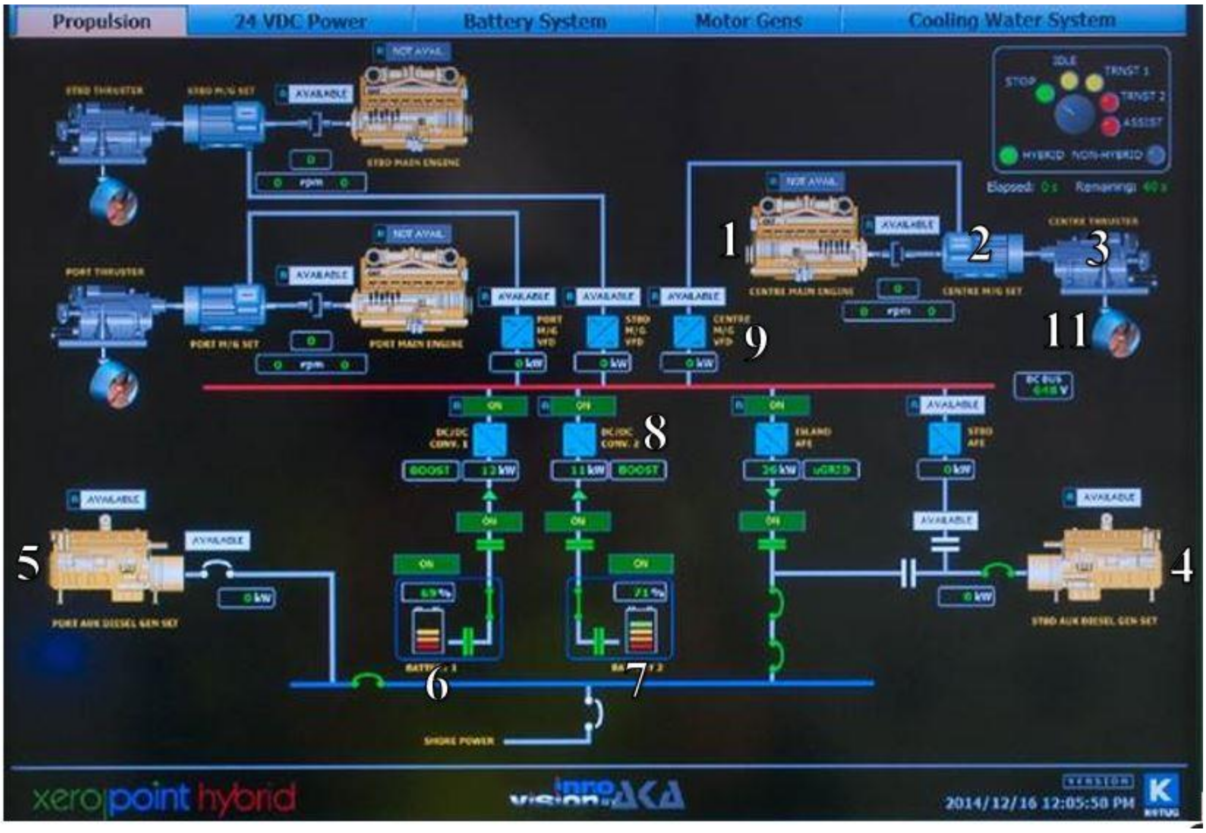

Figure 6 Propulsion system onboard R/T Adriaan after conversion to hybrid

Table 4 Explanations to Figure 6

Numbers	Machinery
1	Main engine
2	Generator/electric motor
3	Gearing
4	Aux engine (small)
5	Aux engine(Big)
6	Battery 1
7	Battery 2
8	Rectifier
9	Transformer
11	Pod

2.6.1 Diesel electric

The electrical production onboard is in most cases produced by several mid to high speed diesel engines that powers a generator to produce electricity. The engine will have different rpm depending on the frequency (50 or 60 Hz) and the number of poles (Kuiken, 2008).
The electrical current is transformed down to the consumers that requires lower operating current.

The electric motor drives the propeller when running diesel electric. To maintain control over the ship speed, the rpm (revolution per minute) needs to be changed depending on speed desired. The AC (Alternate Current) motor rotates at the same speed as the diesel engine but could be controlled by changing rpm on the engine (Harvey, 1925). Both the diesel engines and the generators are following each other's speed. For a diesel engine, keeping constant speed is the best way to operate for an efficient operation. Generator sets are therefore starting and stopping depending on the load (Ådnanes, 2003).

If there is more than one consumer this method of starting and stopping is not optimal and the possibility of connecting more generators is going to be difficult. Another difficult way is to change the magnetization to the AC motor instead and keeping the generator at constant speed. Although the most common way nowadays is by using inverters, meaning that the frequency to the electric motor is changed and thereby its speed. The current is at first converted to DC (Direct Current) and then electronically converted back to AC to make a fake Sinus wave (Alfredsson, Jacobsson, & Rejminger, 2003).

2.7 Vessels running on battery

In the following section a few examples of vessels that are highlighted to give a short overview of different types of vessels that are running on batteries.

2.7.1 E/S Movits

E/S Movits was converted in 2014 to pure battery propulsion with a battery pack of 180 kWh. The batteries are made of NiMH (Nickel Metal Hydride). 180 kWh is enough to manage normal operation for 1.5 hours. The maximum power that are possible to charge at one time is 600 kilowatts at supercharging. However, batteries could also be normally charged during night time. Since the electricity is taken from windmills the emissions have almost gone down to 0 from 300 tons CO_2, 3 tons NO_x and 160 kg of PM every year. (Johansson, 2014)

2.7.2 Ampere

Ampere or as it was called before Zero Cat is supposed to generate zero emission and minimum sound when it travels between Lavik and Oppedal in Norway, approximately 34 times every day. It is propelled by two 460kW electric motors and powered by li-Ion batteries with an output of 1000kWh weighing 10 tons. (Ship-Technology, 2016) The power grid in the area was relatively weak and not able to provide the necessary electricity to charge the batteries in only 10 minutes. This problem was solved by using battery banks at each docking station and let them charge until the ferry returns. The cost of expanding the grid would be way to high compared to this solution. (Siemens, 2016)

2.7.3 Scandlines Tycho Brahe

The world's biggest battery powered car ferry will start operating this year. The launch was previously planned to be last year (2017), but technical problems with the loading stations delayed the project. The power needed to make the trip is only 1500kWh and are done with li-Ion batteries with a total capacity of 4160 kWh. The charging time will only be 14.5 minutes in total for each transit between Sweden and Denmark (Helsingborg-Helsingör) (Fredelius, 2017) The power needed in the harbours is 10000 kW to charge in the necessary time. The fuel savings is calculated to around 8000 tonnes of diesel every year. (Larsson, 2018)

2.7.4 ReVolt

Revolt is a new shipping concept to transport containers in the short sea segment, meaning short traveling distances with the intention to move cargo from road to sea. It will only be powered by batteries and have very low maintenance costs due to clever design. They will also have a very low charging rate on the batteries meaning that the battery life could be expected to around 15 years. One of the goals are also to make the whole ship run completely without crew to save even more money. It will have a battery capacity of 5422 kWh (DNV, 2015)

These examples suggest that the use of batteries onboard tugboats should not be seen as entirely impossible.

2.8 Emissions

Today the most used fuel in the shipping industry are from fossil sources. The fuel used onboard Adriaan is called ULSMGO and has a heating value of 42.612 MJ/kg (Biomass Energy Data Book , 2011). When the fuel is combusted in the engine following molecules are produced: CO, CO_2, H_2O, NOx and SOx (Kuiken.K, 2012).

2.8.1 PM (Particulate Matter)

PM is a mix of solid material and liquids that are found in the air.PM are divided into different types PM_{10} and $PM_{2.5}$, depending of the size of the particle. PM_{10} means that the particle is not more than 10µm(micrometer) and $PM_{2.5}$ means that the particle is not more than 2.5 µm(micrometer) (EPA, u.d.).

Different types of particles have different sources of origin, the larger type of particles (PM_{10}) often occurs from wear of asphalt from roads. Smaller particles ($PM_{2.5}$) is the type that occurs from combustion and industrial processes (Naturvårdverket, u.d.). PM_{10} or smaller are said to be the most dangerous since it can get deep in to our lungs and cause heart and lung diseases (Naturvårdverket, u.d.), Short term exposure of high doses can aggravate asthma (EPA, u.d.).

2.8.2 NO_x (Nitrogen Oxides)

NOx is a reactive and poisonous gas that is a result of combustion of different fuels under high temperature and pressure in combustion engines (Naturvårdsverket, u.d.), (EPA, u.d.).
Breathing in high concentrations of NOx is poisonous and can cause irritation on lungs and airways (Naturvårdsverket, u.d.).

2.8.3 SO_x (Sulphur oxides)

SO_x are the common name for different Sulphur emission from combustion, the most common type of Sulphur emission is SO_2 (Sulphur Dioxide) (SMHI, u.d.). The main source of SO_2 comes from when burning fossil fuels (EPA, u.d.).

When fossil fuel that contains sulphur is burned the it releases Sulphur dioxide into the air. The SO_2 mixes with the water in the air and could cause acid rain (Naturvårdverket, u.d.).

2.9 Charging

It is important to understand that in order to keep the battery as a better solution than the normal combustion engine the electricity that the battery is charge with needs to be taking into consideration. If the battery is charged with electricity produced only from coal it could emit more CO_2 than its alternative that uses a combustion engine instead. The European electricity mix are divided in several areas and they all have a different contribution to CO_2 emissions. Fossil fuels and waste combustion (53%), nuclear (25%) and renewable energies (hydro and wind, 21%) (Tarascon & Larcher, 2015).

2.10 Regulations

What does the class society require from a vessel running on batteries as a main source for propulsion? The additional class notation Battery (Power) applies to battery installations in battery powered vessels (Veritas, 2015). This means that vessel that runs with batteries as the main power supply still needs to have the same redundancy requirements as ¨ordinary¨ ships (GL D. N.).

Vessels that uses batteries for the main source of power to the propulsion line are included in an additional class notification Battery (Power) (GL D. , 2015).Vessels that have battery sources as an additional source with an exceeding capacity of 50 kWh is classified as a hybrid vessel and are not included the classification Battery power but in the additional class notification: Battery Safety (GL D. , 2015).

According to DNV (De Norske Veritas) the arrangement of vessels that are included in the Battery(Power) notification, the battery pack onboard the vessel needs to be divided in to two independent sources that are separated in different battery spaces (ABS, 2018). The different spaces must not include piping or cable arrangement that are supporting vital systems onboard the vessel that are essential for the vessels, to prevent loss of steering or propulsion (GL D. , 2015).

When the vessel’s main source of power is battery power, the minimum capacity requirements of power must be sufficient for the intended operation of the vessel. This designed capacity shall be stated in the appendix to the class society (GL D. , 2015).

3. Method

In this chapter the different methods for how this report was done and how the results were brought forward are presented. The method consists of two main parts, literature and in calculations

3.1 Literature studies

For this thesis a literature study was carried out to gain understanding of the vessel that was going to be the subject of matter for this case study and technology behind batteries. Most of the information regarding vessel specifics and emission data are given by the company KOTUG who owns the tugboat RT Adriaan.

Databases that have been used for this report:

- Web of Science
- Google Scholar
- Science Direct
- Reg4Ships

Key words that have been used when searching for literature for this report:
Hybrid, diesel-electric, battery, lithium, life cycle analysis, sustainability, emissions, local effects, global effects, tugboat, propulsion

3.2 Case description R/T Adriaan

The chosen vessel for the case study is tugboat the R/T Adriaan who was retrofitted to hybrid in 2014. R/T Adriaan was the first vessel in the world to be retrofitted into hybrid with batteries and acted as benchmark to show the possibilities for implementing batteries. The overall goal from this retrofit was to lower the emissions and secondary lowering the fuel and maintenance cost. Table 5 are showing the specific ship particulars. (Maritime Journal , 2013)

Table 5 Ship particulars

Year Built	2010
Year Retrofitted	2014
IMO	9489936
Call sign	9HTI9
Flag	Malta
Homeport	Valetta
Vessel type	Tug3
Gross Tonnage	463
Deadweight	275 t
Length Overall	31.63m
Breadth Extreme	12m
Main engines	3* Caterpillar 3512 1765kW
Aux engine	1* Caterpillar C9 140kW
Aux engine	1*Caterpillar C18 450kW

Hybrid (Battery)	Corvus Energy 98 kWh

3.3 Method of Calculation

This part of the method consists of the different type of calculation that was made in this report. Some equations have been written in MATLAB and also calculated to save some time due to that some variables could change during the writing of this report, and some equations have been done by hand. The equations in this chapter are the ones considered to be of most importance for the result. A complete list of all equation is found in the appendix.

3.3.1 Calculation method running profile over 24h

To know the battery size and the power needed onboard to make one mission, the running profile for 24 hours had to be calculated. This was done with numbers from KOTUG based on the running profile used to compare conventional diesel and hybrid before and after the retrofit. When the running time in each running condition was known (6 Knots, 8 Knots and Assist) an assumption of a normal towing operation for 24 hours could be made. With Eq. 1-5 the time spent on every running mode was calculated and summarized in the picture below. (See table 6)

Table 6 Original running profile

Task	Hours	Power Kw
Stop	14	0
Transit 6 knots	6	400
Transit 8 knots	2	880
Assist 12 knots	2	5000

Figure.7 shows the time spent in minutes on every running mode during a running cycle of one 24-hours period. Based on the running profile in Table 6, it can be seen in Fig.7 that the charging time is 140 minutes. The time spent on transit in and out from and to missions are 40 minutes and divided in two parts, 8 knots and 6 knots and time spend on theses speeds are 10 respectively 30 minutes. The actual towing time is only 20 minutes before the vessel needs to turn back.

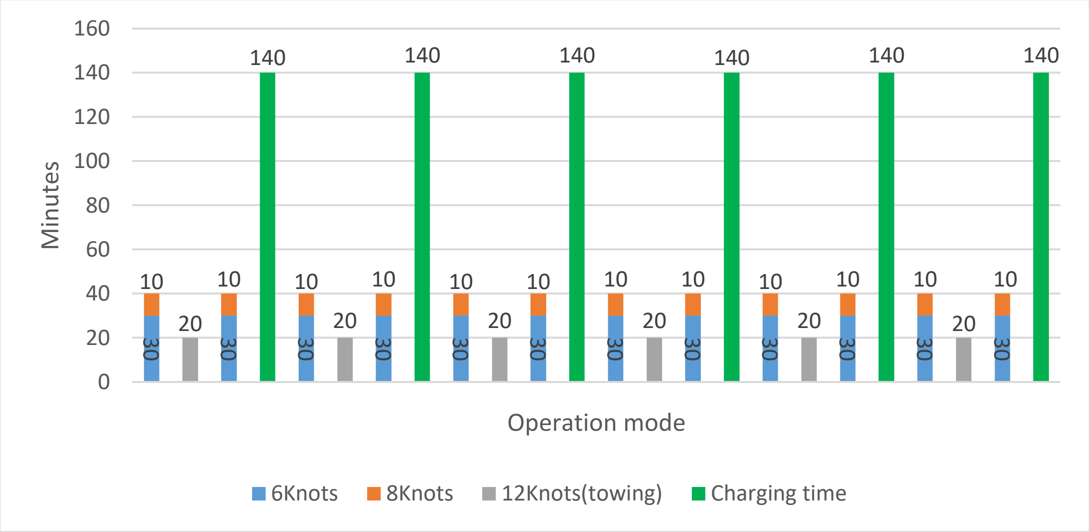

Figure 7 Running cycle over 24h. Time in minutes spent on every running condition

3.3.2 Calculation method battery need

With the new running profile and power outtake from engines at different running conditions the total power needed for each condition and thereby one towing mission could be calculated. Power at different running conditions are showed in Table 7 and Fig. 8. When the power needed for one mission is known its multiplied by the chosen battery degradation constant.

Note that the running profile is set to have as many opportunities to charge during the day and not the longest charging times. To make the battery as small as possible and not carrying around excess battery power on shorter trips the decided profile was as seen in Table 7. It is for instance possible to increase the range if the battery size is extended as well.

The battery needs to last minimum 14000 cycles according to the running profile and is therefore multiplied by the corresponding cycle degradation (36%). The chosen degradation cycles between 85-25% of the batteries capacity meaning that there is only 60% of the battery available at all time if the 14000 cycles need to be achieved. (See Eq. 6 and Fig.3 in background chapter). The total Energy consumption was divided by the losses when transforming the electricity (14%).

To validate if the battery could deliver the required power similar to running with diesel engines at load peaks the maximum power output was calculated. This is also the same as maximum charging power. See Eq. 7

For a further description of the terminology the reader is referred to (MIT Electric Vehicle Team, 2008).

Table 7 Numbers to calculate battery power

Operating mode	**Time spent**	**Energy consumption(kWh)**	**Power needed(kW)**
6 knots	1/2h*2	200*2	400
8 Knots	1/6h*2	147*2	880
12 Knots(Assist)	1/3h	1667	5000

Figure. 8 shows the power needed in the different modes of operation. The total of these three stacks will be the battery power needed to make a whole cycle. (transit out, assist, transit in and standby/charging).

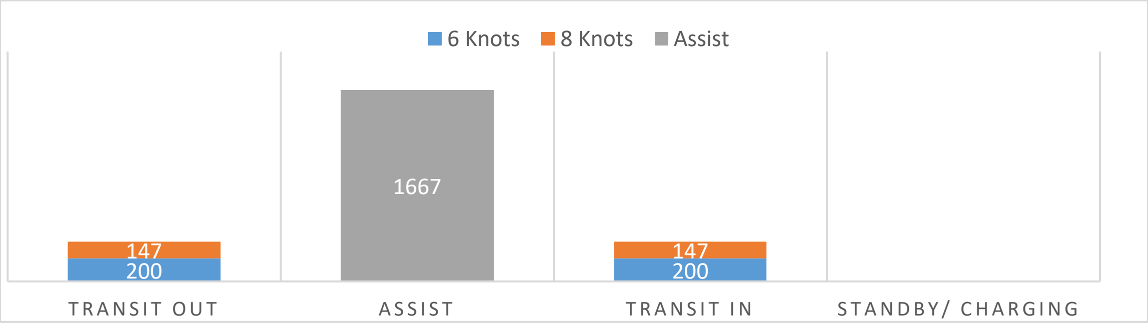

Figure 8 Power usage in kWh during different running conditions

3.3.3 Fuel price comparison Diesel, hybrid and full battery

To see different fuel cost between the hybrid propulsion line and the full battery propulsion line a price comparison was made. The current fuel price was compared to the average cost for shore power that recharges the batteries when the vessel is at jetty.

Average fuel consumption for 24 hours of operation was supplied from KOTUG. The average fuel consumption was then multiplied with the fuel price of ultra-low sulphur marine gasoil (ULSMGO) (Ship & Bunker, u.d.) and gave the fuel cost for 24 hours (Eq. 15).

To compare the hybrid with the fully electric, the needed amount of power to recharge the vessel after each assist needed to be calculated. The needed power is then multiplied with the cost for electricity (shore power) for different countries (Eq. 16). The average price in the Netherlands for big consumers are for instance 0.0757 €/kWh (Gov.UK, u.d.), while the current price for shore power at the harbour in the Netherlands is 0.2 €/kWh according to KOTUG.

Table 8 Comparison between energy prices, comparison between charging battery and running on diesel

Machinery	Average Consumption per 24h	Price
Hybrid	1.6 mt (2014)	498€/mt (Netherlands)
Battery	16470kWh	0.071 €/kWh (Netherlands)
Battery	16470kWh	0.054 €/kWh (Sweden)
Battery	16470kWh	0.2 €/kWh (KOTUG)

3.3.4 Emission comparison Hybrid and full battery

To get a clearer perspective of the differences between a hybrid propulsion line and a fully electric, a comparison of the CO_2 emissions from the two propulsion lines is presented. According to a presentation from KOTUG, the hybrid vessel emits 8665kg of CO_2 when running with a combination of battery and diesels engines during a 24-hour period.

To be able to compare the CO_2 emissions, numbers from (Ang & Bin, 2016) Eq. 14 was used. With an average density of 850 Kg/m^3 (Shell, u.d.) of ultra-low sulphur fuel oil (ULSFO) that is used onboard the R/T Adriaan and the amount of carbon in the fuel is 85.3% by mass (Global Combustion, u.d.).

To give the report more validation, calculations was performed using data from KOTUG that shows how much fuel the R/T Adriaan consumes every running hour.

From the amount of carbon in fuel, the amount of air needed for combustion was calculated by assuming an air-fuel-ratio (AFR) of 2.65 between the air and fuel. By adding the mass of carbon and air, the amount CO_2 in kg per litre of fuel was found and the total was calculated with Eq. 19.

3.3.5 Machinery pricing

The cost for investing in an electric propulsion line was done with the help of numbers from KOTUG. According to KOTUG, the average cost for batteries when the vessel was retrofitted was approximately 1000 € /kWh. Other electrical equipment was 750 000€. The approximate battery investment is calculated by multiplying the needed battery power times the price for what one kWh of battery powered costs according to Eq. 11

The original investment could be hard to determine but numbers from (Kwasieckyj, Hybrid propulsion systems, 2013) are suggesting a price for this type of machinery to be around 400 Euro per kWh in 2012 plus the inflation in 2018. By multiplying the installed power onboard by 416 the numbers for the original investment are given according to Eq. 13.

3.3.6 Maintenance cost

The maintenance cost for different machinery and battery was provided by KOTUG and multiplied to match the chosen running profile over 14000 battery cycles which corresponds to 6.6 years.

The engines are according to information from KOTUG completely overhauled after 20 000 running hours for a cost of 180 000 Euros per engine. To get an approximate maintenance cost per running hour Eq. 18 was used. The total cost for the 3 engines are added together and added to the total cost for maintenance of the auxiliary equipment onboard such as purifiers, filters and more. This cost is accordingly to KOTUG around 25000 Euros per year. These costs were added together and then divided by how many running hours the vessel operates for 6.6 year, that is the maximum year the batteries will be used. Adding these number gives an approximate running cost per hour for 6.6 years. (see Table 13 in the Results section)

Only the cost for doing the heath check are accounted for in the maintenance cost of the batteries, according to KOTUG this is done every fifth year for a cost of 5000 euro. This cost is divided in to a yearly cost then multiplied with the estimated lifespan of the batteries for 6.6 year then divided with the vessels running hours for 6.6 year. The maintenance cost was assumed to be the same for every battery size.

Table 9 Maintenance cost

Cost	**Task**	**Interval**
180000€ per engine	Overhaul engines	Every 20.000 hour
25000€	Regular maintenance	Every year
5000€	Battery check	Every fifth year

3.3.7 Battery production

In this thesis there is also a focus on how much CO_2 the production of the li-ion battery release. The method used for calculating the emissions from the batteries was done with help of fixed number for how much CO_2 every produced kWh of power emits, look at Table. 10 for a more detailed picture.

These numbers are summarized in a report that were done with purpose to present the findings of a literature review of currently available life cycle assessments of vehicle batteries, with specific focus on production (Mia Romare, 2017)

The reason why these numbers was deemed appropriate for the study was because of its presentation of numbers for NMC type battery. That is the same type used in the vessel used in this study. These number are expressed in Kg of CO_2 for every produced kWh. (Hanjiro Ambrose, 2016) (Jens F.Peters, 2015).

In the literature that was found regarding the subject of LCA (Life Cycle Analysis) for lithium batteries, the amount of emissions in kilograms of CO2 per produced kWh is in a linear lifespan, from the collecting of the resources to the production of the battery and then ends with packaging the product and make it ready for a possible costumer, this is called a cradle-to-gate assessment (see Fig.9 below). It generally means the total emission of CO2 during the fabricating and manufacturing of the product. It does not include amount of emission for when the product is used. (Lyngaas, u.d.). Other of analysis is cradle -to-grave, were the recycle process is taking in to consideration when looking on the product total emission of its life time (see Fig. 10 below).

The emission is calculated by multiplying the installed battery power onboard the vessel in kWh with 254 (kg/kWh).

Table 10 The average CO2 emission and energy need per kWh (Mia Romare, 2017)

Study	**MJ/ kWh**	**CO2 Kg/kWh**
Ambrose and Kendall	316–2318, likeliest 960	248–258, likeliest 254

Figure 9:Illustrates the LCA of Cradle-To -Gate

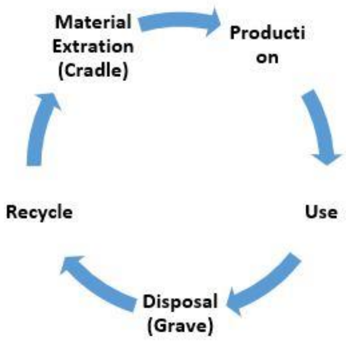

Figure 10: Illustrates the LCA, Cradle- To-Grave

3.3.8 Environmental cost on society

The emissions from the energy usage have been compared to a report that have numbers on the price society have to pay for pollutions. NOx, SOx, PM and VOC are the pollutants that the report have looked at. The gains in converting a hybrid vessel to fully electric should not only be an opportunity to do something good for the climate change but also a way to reduce the effect on society.

When looking on the social costs for the release of GHG (Greenhouse gases) it is divide into 3 different areas: local, regional and global (Trafikverket, 2018),due to the fact that the vessel in this report is operating close to the larger cities in Europe, the report is focused on the local effect of the emissions.

Local effects are those that occur near the release of chemical compounds.
The most extensive emissions consist of combustion particles, NOx, SO_2, CO_2 and VOC.
CO_2 is considered a greenhouse gas is affecting the climate the other emission is considered to have more local effect (Trafikverket, 2018).
To be able to see approximately how much the economic cost on the local society have, is done with help of an exposure) unit, how much each person is exposed for the emissions, that is expressed in SEK/ exposure unit) (Trafikverket, 2018).

The first step:

first the exposure unit needs to be calculated to see how the area or city is exposed. This is done with help of Eq. 20

The ventilation factor varies between 1.0 and 1.6 depending on where the area is located. This factor is done with the zones in Sweden. (Trafikverket, 2018)

The second step:

The cost in SEK / Kg is done just by multiplying the exposure from the first step with values from table. 11 (see below).

Table 11 emission in local areas expressed in SEK/exposure unit (Trafikverket, 2018)

Type	Price
SOx	2.0
VOC	3.4
PM	17.2
NOx	585.9

4 Result

This chapter will explain the findings from previous calculations. The most fundamental aspect in the report, was the size of the battery. Therefore, the results are presented starting with this aspect, followed by chapters about economic aspects and environmental aspects.

4.1 Stored Battery power onboard

With the collected data from references above the battery size was calculated and determined.

Figure. 11 illustrates how the needed power for the battery will change due to cycle correction and charging correction. Note that the correction factors are only used for the battery to be able to deliver the needed power even after 14000 cycles. It is noteworthy that the total power installed is almost twice the power needed.

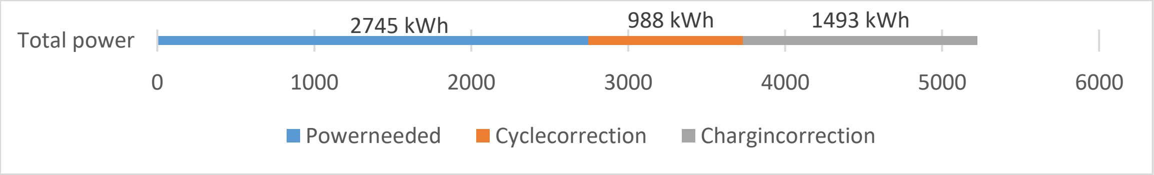

Figure 11 Total power(kWh) needed in battery

Table 12 are illustrating the total energy consumption during one whole day. The amount of energy that needs to be delivered in order to complete one day of missions.

Table 12 Energy consumption kWh

Total Energy consumption during one mission	**With losses**	**Total 24h (6 Cycles)**
2361	2745	16472

4.2 Economical Results

4.2.1 Machinery price

Figure. 12 Shows the different initial investment cost when installing the battery. Note that the hybrid only includes the initial cost for the diesel engines and the full battery only includes the cost for the batteries. Inverters and other electrical equipment that could be needed is not included.

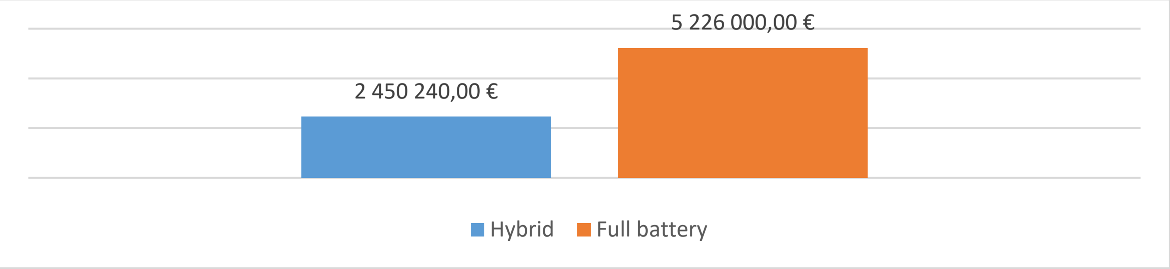

Figure 12 cost for propulsion line: hybrid and fully electric in Euro

4.2.2 Energy source comparison Price

Figure. 13 illustrates the different cost in Euros per produced kWh of electricity both when it is produced onshore and onboard. The onshore produced stacks are divided in cost for the electricity and tax, these two combined are equivalent for comparison with hybrid (not seen in the figure). According to KOTUG, the process for connecting to shore power is approximately 0.2 Euro for the electricity to charge their much smaller battery. The numbers are for consumers ranging 2000-19999 MWh per annum except for the current price paid by KOTUG.

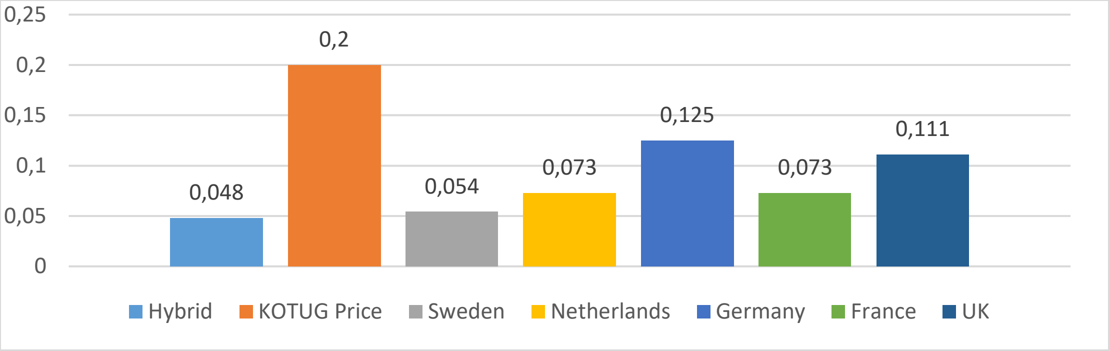

Figure 13 Price Euro/ kWh for produced electricity *(Gov.UK, u.d.)*

Figure. 14 illustrates the cost for running the vessel in different countries for 24 hours. The diesel stack shows the cost for running the vessel with ULSHFO. The other stacks show the running cost per 24 hours when the vessel is fully electric and charged at jetty in different countries. The KOTUG staple is higher due to the average shore power cost was higher according to KOTUG.

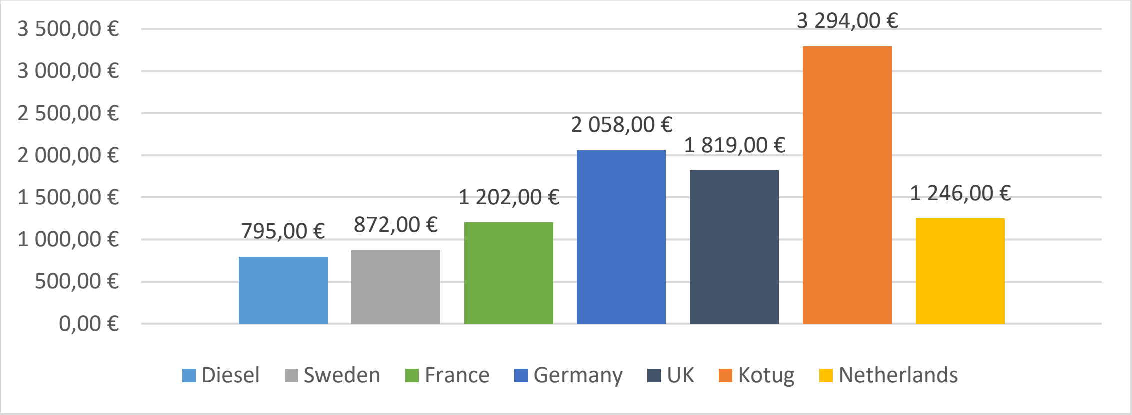

Figure 14 Fuel and electric cost per 24/hour

4.2.3 Maintenance

Table 13 shows the maintenance cost. Both for the cost per hour and how much they cost per year in Euros, for the different propulsion lines.

Table 13 Maintenance cost for different systems

Propulsion Line	Hybrid	Battery
Cost per hour	34.5 €	0.28€
Cost per year	120585 €	1000 €
Total Cost for 6.6 year	803 097 €	6660 €

4.2.4 Total Cost

Figure. 15 illustrates the approximative total cost for invest and run the two different propulsion lines for 6.6 years, the hybrid which is current propulsion and the battery powered propulsion line. The fuel cost is calculated in bunker prices in Rotterdam for the hybrid and the fuel cost for the battery powered propulsion line is showed is the cost for shore power in the Netherlands.

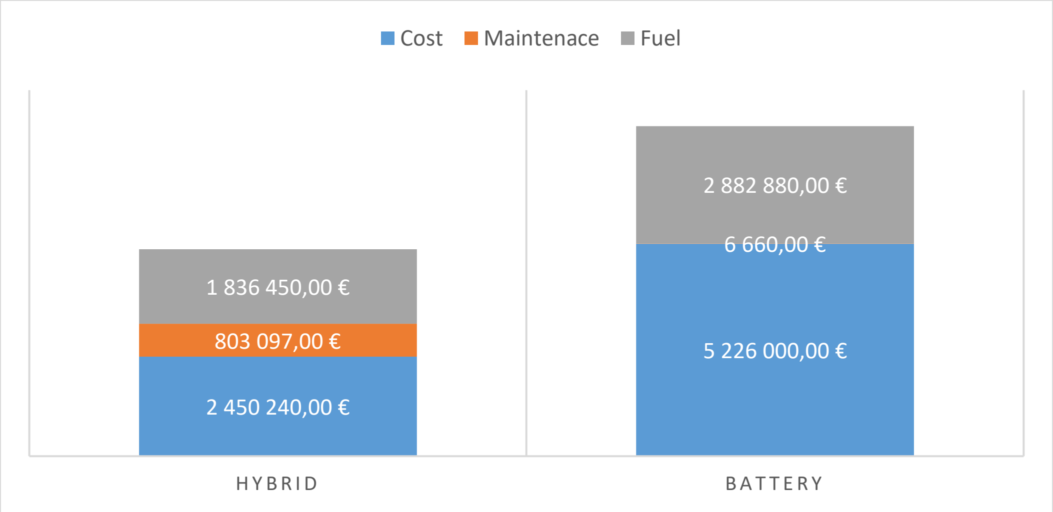

Figure 15 Approximative cost for the different Propulsion Lines for 6.6 years

4.3 Environmental Results

In this chapter, the environmental results will be presented; how the batteries contribute to the environment; how charging the batteries with power from ashore are also emitting CO_2 and what the social costs are of people getting effected in a negative way from other harmful emissions.

4.3.1 Social cost

Table 14 shows the cost of different types of emissions for the local society every year in Euros when the vessel RT Adriaan runs with a hybrid Propulsion Line. If the vessel would be designed with fully electric propulsion the local cost would be zero.

Table 14 Approximate cost for exposure to emission in Gothenburg in KEuros/Year

Type	**Hybrid Propulsion**	**Battery Propulsion**
NOx	54	0
SOx	1	0
PM	425	0
VOC(C_XH_Y)	2	0
Total Cost	482	0

4.3.2 Energy Production

Figure. 16 shows the emissions from producing one kWh of electricity in different countries around the world and thereby the difference in where the battery is charged at different parts of the world. The highest stack is India and lowest is Sweden. The differences are highly depended on Sweden's high usage of the "zero" CO_2 emission types of production facilities such as water power and nuclear. The stack called "Hybrid(Own)" are based on our own calculations according to the assumed air-fuel ratios.

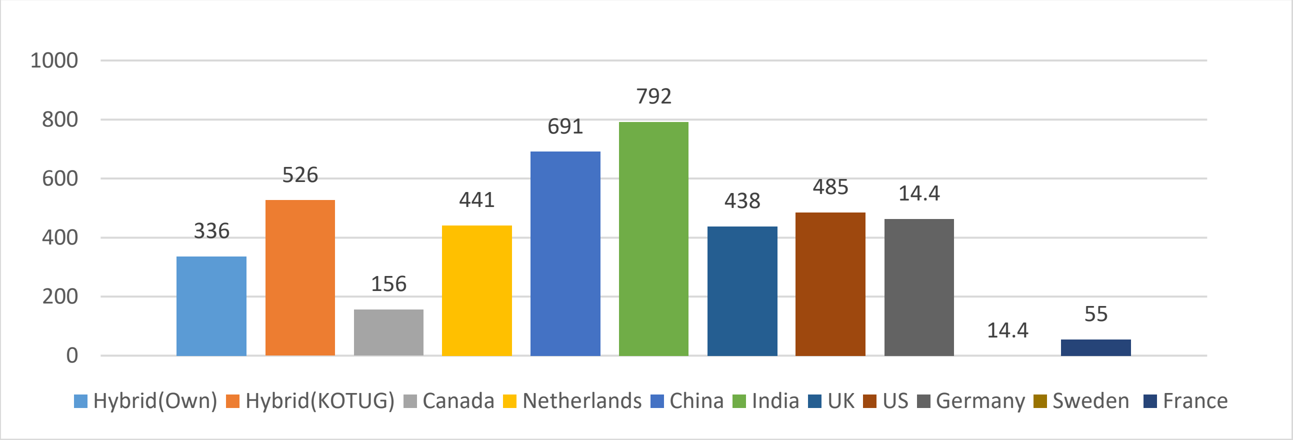

Figure 16 Gram CO2/ kWh produced electricity Data retrieved from (Ang & Bin, 2016)

Table 15 illustrates the amount of CO2 emission in tons from when the vessels runs with diesel combines with batteries compared with the fully electric. The middle table shows our own calculations for how much the vessel will emit during 24 hr. The hybrid values are originally taken from KOTUG.

Table 15 CO2 Emission in 24hrs from different source tons and grams

	Hybrid	**Hybrid (Own Calculation)**	**Fully Electric (Netherlands)**
Fuel	8.7t	5.5t	
Shore Power	0.043t		7.3t
Total	8.7t	5.5t	7.3t
CO2 emissions/ kWh produced	529g	336g	441g

Figure. 17 and 18 illustrates how much the of CO_2 that is emitted during the production of the battery (Here the battery production is considered a fixed amount of CO_2), compared to the emission that is emitted from producing the shore power needed for recharging the batteries when the vessel is at jetty.

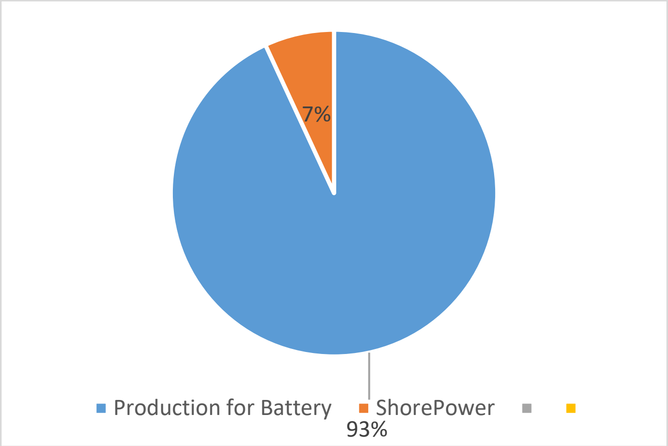

Figure 17 Emission Sources during the batteries Lifetime (Germany)

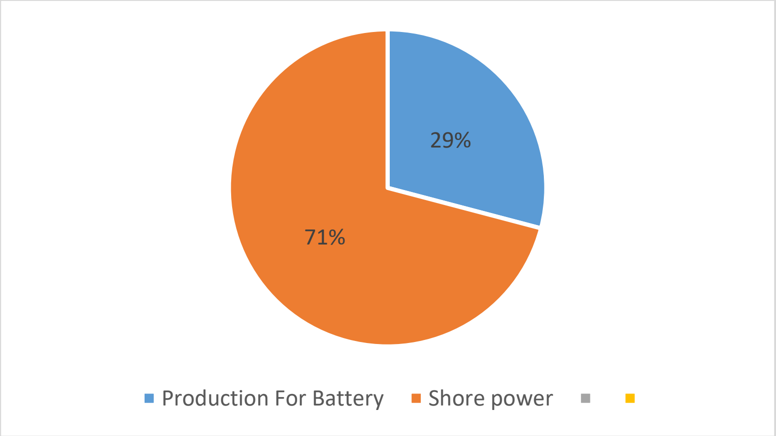

Figure 18 Shows Emission Sources during the batteries Lifetime (Sweden)

5.Discussion

5.1 Result discussion

5.1.1 Result battery size

The battery size for the fully electric is designed after the current vessel specifics for the R/T Adriaan, they are sized to match the main engines for the hybrid propulsion. The batteries are also compensated to be able to last longer.

More installed battery power onboard the vessel means that the battery will not be fully discharged after each assist or task. Leading to more weight and less space onboard. Our running profile is therefor designed to discharge and recharge the battery for 14 000 times (see Fig. 3). This would give a life span of roughly 6.6 years. This number can of course variate depending on how the vessel is being used, pushing the batteries capacity by fully discharge and recharge lowers the batteries life span. But less usage would mean a longer life span.

The running cycle for how the vessel is being operated does not leave much room for mistakes, tasks like longer assist time is not possible. Operation possibilities at other places than around where the loading dock is located is therefore sacrificed.

5.1.2 Investment cost

The battery price was taken from the original investment cost of the retrofit. That number is from when the retrofit which was done in 2014 and for a much smaller battery. No other comparison from battery prices from 2014 was done, therefor a more detailed overview of the prices from that time should increase the reliability. However, the battery investment cost from 2015 as seen in Fig. 4 are indicating on a much lower initial investment price. Since the battery from 2015 are not mentioned to be classified for marine use the price could be much higher as equipment approved for marine usage often are more expensive compared to systems ashore. The numbers for installing the battery are also taken from the original investment and not scaled to fit the new much bigger battery pack. This should also be investigated further to increase the reliability of the work.

The exact investment cost for this type of diesel machinery layout is very hard to determine, but rough numbers of 416 Euro/ installed kW from Kwasieckyj, Hybrid propulsion systems, 2013 are indicating on a price for the R/T Adriaans specific propulsion layout. The lack of information concerning the auxiliary equipment for the engines such as purifiers and air compressors are not considered and could increase the total machinery investment cost. To make the reliability higher the price for pumps and surrounding equipment also needs to be considered.

One factor to be considered could be that the diesel engine has been produced over a long time and the most cost-effective way to produce it should soon reach its limit. While the battery production is showing tendency to rise faster than ever before, the room for cost improvements could be bigger and in the end lead to lower production cost. This trend could be seen in the Fig. 4 and .5 at battery price forecast section.

The diesel engines will still be in good condition and work proper after 6.6 years if they are maintained according to the cost suggested from the manufacturer, while the battery pack will have to be replaced every 6.6 years with a new one to keep up with the degradation of usage. The current cost for purchase of a new battery are also needed to be considered and could change rapidly as batteries are forecast to become cheaper. The uncertainty of all these things are making this part of the report hard to validate.

5.1.3 Energy source price comparison

The importance origin of the fuel either diesel or electrical charging power to the batteries are proven to have a big impact on the total running cost for every 24 hours. When comparing the alternatives in Fig. 14 with each other it can be seen that the current hybrid system is the most profitable. The only country coming close to match the numbers is Sweden with just a few percent higher cost in charging the batteries instead of running on the hybrid system. These numbers are very much dependent on the current bunker price and could be changed in the future both higher and lower.

The values in Fig. 14 are very much dependent on the initial cost per kWh. The biggest stack called KOTUG is based on the price for shore power provided from KOTUG to charge the currently existing hybrid vessels with a much smaller battery and electrical consumption. The other electrical charging numbers are taken from Gov.UK, u.d.

The overall power needed from ashore every year when running on the fully electric system will change as the battery are storing more energy. As that number are increasing a discount per used kWh will be given in form of cheaper energy, high consumers are paying less per used kWh. This could in some way explain the extremely high number from KOTUG compared to the others, nonetheless this could also indicate that the actual price is higher. All the electrical prices are taken from current values
and could therefor change over time. This means that the results are only applicable whit each other at this current date and not valid over time. The whole society are going towards electrification and that might lead to more research in cheap and sustainable electric as well as companies competing to get costumers could change the prices over time.

5.1.4 Maintenance

The yearly and hourly maintenance cost are compared in Table 13 and are showing a huge difference with only a fraction of the cost for the battery. Same as the investment cost, the price for auxiliary equipment such as rectifiers, is taken from the much smaller battery installed in the hybrid, the cost could therefore be higher when the batterie size increases. However, still not high enough to overcome the cost to maintain the original hybrid system. The number given from KOTUG could be said to be fairly accurate since the numbers correspond well to what could be expected on a system like this. The result should therefore be seen as close to reliable.

The lack of moving parts in the battery pack could be one of the factors to much lower maintenance costs. The maintenance only consists of checking the condition of the battery and no further expenses on parts are needed. Of course, electric motors and other electrical equipment have the possibility to breakdown and might need to be overhauled over time or even replaced but no exact number for this could be determined. The battery is replaced when it has reached its maximum running cycles of 14000 in this case.

5.1.5 Environmental results

The local and society costs from a diesel-electric hybrid tug boat is illustrated in Table .14. The biggest cost for the society are coming from PM and are estimated to be around 425 kEuro every year for city a similar to Gothenburg(Sweden). The other most costly pollutant is the NO_x and comes in on 54 kEuro every year. The numbers are very much depended on how well the area is ventilated, winds and the terrain around could have a huge impact. The results are considered as reliable since the formulas are taken from (Trafikverket, 2018).

When the vessel is fully powered by battery all the emission cost is lowered to zero due to the fact that the combustion is removed from the vessel, however the electricity needs to be produced somewhere else and could have a more global effect.

The environmental effects of producing electricity are more concentrated to the CO_2 emissions, these are compared between different countries. Numbers related to emissions from every produced kWh from KOTUG was a bit unclear and not fully explainable in terms of how KOTUG got these. Numbers calculated by us during another air fuel ratio was therefor also compared.

5.1.6 Energy source CO_2 comparison

As the Fig.14 describes the difference in terms of emissions per produced kWh around the world is huge and, in some ways, divided in developed and developing countries. A country seen as developed is Sweden and it could possibly be one of the best countries for implementing shore power and installing batteries onboard since most of the electricity comes from sources that does not emit CO_2 in the air.

The numbers in Fig.14 and Fig.15 could however be misleading and should not be seen as other than just average in country. The CO_2 emissions from every produced kWh could in some cases be low but the possibility still remains that other harmful environmental factors could be more present, for example if most of the power would come from the nuclear power that emits less CO_2 than diesel or coal but that leaves dangerous radiation from its depleted uranium fuel rods that needs to be stored for many years.

When looking at the different production of the energy sources such as electricity it is important to keep in mind that fossil fuel such marine gas oil also needs to be produced and this process also emits CO2 and other harmful emission.

From a local environmental perspective, the study found no downsides worth mentioning of running on a battery powered tugboat. No emissions that effect the local area or pollutants that are having a negative impact on the local societies health. The fact still remains that batteries still needs to be produced somewhere, even if this takes away the local effects in the harbour, the problem with emission could instead change place and pollute somewhere else.

Thee emissions are seen from a global perspective, the amount CO_2 emitted from when the batteries are produced are compared in Fig.15 & 16. which illustrates the distribution of CO_2 over the batteries life span. The production of the batteries only stands for a small part of the total emissions that are emitted. Something that the authors didn’t expect in the beginning of the work.

What is not taking in consideration in this report is the amount of CO2 that is emitted to produce the diesel-engines and all its auxiliary system. Due to lack of information on this subject is main reason it is not included in the report but is however a vital part when comparing the diesel engines and the battery pack installed onboard the vessel.

5.2 Method discussion

The method of choice was at first to do a literature overview over the recent progress in hybrid systems onboard different ships and compare the benefits from this progress. The method was later abandoned due to the complexity of comparing different ship types and what they and their machinery system have contributed to the progresses in electrifying the world fleet. Therefore, the contact with a company called KOTUG was instead established and the project took off into another direction. The new method was instead to be a case study about the possibilities to fully make the vessel A/T Adriaan into battery power. Literature gathered from the previous idea was then collected and sorted to fit our new study.

The choice to not conduct any interviews was based on the lack of time in the end of the study. A contact with one of the tugboats in Halmstad was established but not furthermore used. Since the paper consist of a lot hypothetic numbers gathered from different sources a look from the industry and their thoughts could have been useful and possibly contribute to more validation of the work.

5.2.1 Data collection

Most of the calculations was based on information from KOTUG which had performed a study of their own from 2014 when the vessel was retrofitted from only diesel to hybrid vessel.

The choice to use MATLAB was done with the purpose to save time in calculating certain parts that was depended on the amount of power that needed to be stored onboard the vessel. Due to that the power needed was changed during the writing, just changing one number and get all others has been proven to be useful. Certain equations needed be done by hand due to that the saved time in using a program was not enough.

5.2.2 Running profile

The study lacked many of the important data concerning new battery size and running profile, therefor a running profile for 24 hours was created to handle de difficulties of comparing different energy sources.

Thus, the foundation for making assumptions such as energy consumption and average time spent on every running condition was collected. The authors had in mind that one of the biggest problems could be size and weight before the report was started. The running cycle was after this created to make the smallest battery possible and still fulfil the requirements for one cycle. Making the battery pack bigger would have a more negative impact on the environment in the form of more CO_2 will be emitted in to the atmosphere, more material would needed be to produce more batteries and more shore power would be needed.

5.2.3 Background literature

To gain better understanding of how batteries work, what they are made of and how the impact on the environment will change as this type of propulsion solution could become more common among ships operating in near coastal areas, subject related literature was reviewed and further analysed. Since this is more emerging among electrical cars, an overview of what technologies that are upcoming in that field was looked on further to see if there was anything applicable to the marine industry.

5.3 Reliability and validity

Due to the fact that the results from this case study could be hard to generalize when tugboats are operating in different harbours and with different characteristics on machinery system the report was limited to a specific ship, R/T Adriaan. Most of the comparing numbers are taken from KOTUG and their own measurements they did when promoting the hybrid conversion. Since many of the measurements are done by one single company the reliability of the original values in the report could be questioned.

The results should therefore only to be seen as providing an example from one case over the problems and sustainability of total battery conversion in this particular case of investigation. But since the results are strongly dependent form the numbers given by the company the validity could be questioned. However, the paper should still be considered to be accurate whit the given values at hand.

6. Conclusion

The purpose of this paper was to analyse the differences between running on a hybrid vessel propelled by a diesel-electric system and supported by a battery pack compared to a propulsion line with only batteries. Furthermore, compare the environmental and economic benefits and limitations associated with the two systems.

The first section focused on the economic aspects and determined that battery at this current date is the most expensive option, but future forecasts concerning battery price are showing that batteries will have the possibility to become the best economic solution.

The second part concentrated on the environmental aspects and determined the propulsion system with batteries to be the best in lowering the local social costs while the CO_2 emissions from energy production are better in most countries.

Therefore, the answer to the first research question is the following:

Answer 1: *The economical enticement for using battery power is not currently beneficial in the present but have the possibility to be in the near future.*

Therefore, the answer to the second research question is the following:

Answer 2: *The local society where the vessel is operated will benefit but the emissions from* CO_2 *will not have a huge global impact.*

Appendix

Battery power, size and weight.

Equation 1. Power needed at 6 Knots

$$P_{6Knots} = t * P_1$$

Equation 2 Power needed at 8 knots

$$P_{8Knots} = T * P_2$$

Equation 3 Power needed at 12 knots(assist)

$$P_{12Knots(assist)} = T * P_3$$

Equation 4 Total power needed for one running cycle

$$P_{Tot} = \frac{P_{6Knots} + P_{8Knots} + P_{12Knots(assist)}}{\eta_{Trans}}$$

Equation 5 Total power needed for 24h

$$P_{24} = P_{Tot} * 6$$

Equation 6 Battery power needed with correction factors

$$B_p = P_{Tot} * Cycle_C * Charge_C$$

Equation 7 Discharge rate and charge rate

$$D_r = \frac{B_P}{V} * C - Rate$$

Equation 8 Maximum power outtake at once

$$P_{peak} = \frac{D_r * \mathrm{V}}{1000}$$

Equation 9 Battery weight

$$B_w = E_D * B_P$$

Equation 10 Battery volume

$$B_V = D * B_P$$

Economical

These equations will describe and compare the fuel cost, Hybrid and Charging the battery with shore power.

Equation 11 Battery Cost

$$B_c = Price * B_P$$

Equation 13 Diesel Engine cost

$$H_c = D_p * DP_i * I$$

Equation 15 Hybrid fuel cost

$$H_{fc} = F_{ch} * P_{ULSMGO}$$

***Equation** 16 Battery fuel cost*

$$B_{fc} = P_{ch} * P_e$$

Equation 17 Price/kWh

$$\frac{Price}{kWh} = \frac{H_{fc}}{P_{24}}$$

Equation 18 Maintenance price/ hour for one main engine

$$M_{ch} = \frac{H_{MEMC}}{M_t}$$

Emissions

This part will present the calculations on how the CO_2 emissions was determined to be able to compare the two alternatives with each other.

Equation 14 Emission from running 24 hours (KOTUG)

$$E_{CO2KOTUG} = \frac{E_{A24}}{P_{24}}$$

Equation 19 Emission from running 24 hours (Own calculations)

$$E_{CO2OWN} = \frac{((CO2_g * 2.65) + CO2_g) * F_{ch}}{1000}$$

Equation 12 Battery Emission

$$\mathrm{B}_e = M_e * B_p$$

Equation 20 Exposure

$$E_{Area} = 0.029 * \mathrm{Fv} * B^{0.5}$$

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