On cable sizing for solar panels on ships

Bachelor thesis for Marine Engineering Program

ANDREAS EDVARDSSON
RUBEN HAGBERG

DEPARTMENT OF MECHANICS AND MARITIME SCIENCES
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden, 2022

On cable sizing for solar panels on ships

Bachelor thesis for Marine Engineering Program

ANDREAS EDVARDSSON
RUBEN HAGBERG

Department of Mechanics and Maritime Sciences
Division for Maritime Studies
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden, 2022

On cable sizing for solar panels on ships

ANDREAS EDVARDSSON
RUBEN HAGBERG

Department of Mechanics and Maritime Sciences
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

Department of Mechanics and Maritime Sciences
Chalmers University of Technology
Göteborg, Sweden 2022

PREFACE

This is a bachelor thesis written by two marine engineer students from the Chalmers university of technology. The marine engineer program which includes sciences from many different fields that are related to ships. The marine engineer program includes 180 higher education credits, and the bachelor thesis are 15 higher education credits. The authors of this bachelor thesis would like to thank Jimmy Ehnberg for the good ideas and measurement data from solar panels for the bachelor thesis.

On cable sizing for solar panels on ships

ANDREAS EDVARDSSON
RUBEN HAGBERG

Department of Mechanics and Maritime Sciences
Chalmers University of Technology

SAMMANDRAG (in Swedish)

Den marina sektorn har börjat leta efter olika sätt att sluta använda fossila bränslen. Ett alternativ som har rederier har börjat undersöka i är solpaneler ombord. För att solpanelerna ombord ska fungera på ett bra sätt behövs en bra optimerad kabel. Syftet med denna studie är att ta reda på hur olika storlek på kablar påverkar miljön och ekonomin när dem används ombord på fartyg. Fokus i denna studie kommer vara kablar från en solpanelsinstallation med en livslängd på 20 år. Beräkningar för att estimera miljöpåverkan och ekonomi påverkan har gjorts för olika kabelstorlekar för både koppar och aluminium. För att få en bra bild av hur belastningen från solpaneler kan se ut har data från en installation i Göteborg använts, denna data sträcker sig över ett år. I studien har 10 olika storlekar på kabel har analyserats på både koppar och aluminium. För koppar är storlekarna från 35 mm^2 – 400 mm^2 och för aluminum 50 mm^2 – 500 mm^2. Studien visar att man kan minska utsläppen på att öka kabel storlek, man kan även se att kostnaden minskar kraftigt när man ökar kabel storleken.

Nyckelord: Kabeldimensionering, Solpanel, Koppar, Aluminium

On cable sizing for solar panels on ships

ANDREAS EDVARDSSON
RUBEN HAGBERG

Department of Mechanics and Maritime Sciences
Chalmers University of Technology

ABSTRACT

With the marine sector starting to look for ways to stop using fossil fuels solar panels have started to become popular and a properly sized cable is needed for an efficient operation. The aim of this study is to see how different cable sizes affect the environmental and economic aspect on board ships. The focus will be on cables from a solar panel installation over a 20-year lifespan. Calculations to estimate energy losses, the cost and environmental impact for the different cable sizes for both aluminum and copper are presented, using data from solar panels installed in Gothenburg to get a good representation of the power produced over a year. The calculations look at 10 different cross section areas for both aluminum and copper. For aluminum the range is from 50-500 mm^2, and for copper range is from 35-400 mm^2. The study shows that using the minimum allowed cross section area on the cable is far from the best option, the result shows that there is significant gain from using a larger cross section area for both the environmental and economic aspect.

Keywords: cable sizing, solar panel, copper, aluminum

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

One of the big topics in the shipping industry today is the need for greener shipping solutions, in anticipation for the fossil fuel reserves running out in the future and the climate change being at an all-time high. The International Maritime Organization (IMO) has implemented a strategy to reduce the greenhouse gas emissions from ships using different systems to track energy efficiency onboard ships. The goal is to have a reduction of emissions from the shipping sector by 70% CO_2 reduction by 2050 compared to 2008 (IMO, 2018). This task will be extremely difficult within the marine sector since most ships are running HFO fuels and the sector is moving towards different fuels but not very fast. According to IMOs GHG study 2020 the GHG emissions from ships was 977 million tons in 2012 and 1076 million tons in 2018 which is an increase by 9,6%. Only looking at CO_2 from the shipping sector, in 2012 there was 962 million tons and 1056 million tons by 2018 which is an increase by 9,3% (IMO, 2020). This has made the big shipping companies start thinking about more renewable energy sources and greener shipping operations in general. One of the solutions that looks very promising for the shipping industry is the use of solar panels. Solar panels are a very popular solution on land, but solar panels will have some limitations at sea because of the accessibility onboard ships. Another limitation onboard ships are that there is not that much space to place the solar panels. For solar panels to be a solution to work optimally onboard ships a properly sized cable that reduces the energy losses is needed.

1.1 Background

The subject of power loss is a well-researched subject at least on the shore side but not so much on ships. A study by Waseem et al. made in 2018 which looks at optimizing cable size for overhead and underground cables. There is also a study made by Jones & McManus, 2010 that looks at optimizing cable size for 11kV cables for both underground and overhead cables. There are not many studies in the marine sector about the subject that looks at the differences between the marine sector and the shore side. The differences are not that significant but there are still some unexplored differences that are intended to be discovered in this study.

1.2 Aim of the study

The aim of the report is to investigate how different cable sizes affect energy losses, environmental impact and life cycle cost of the cables. The focus will be a cable from a solar power installation system onboard a ship. The various aspects that will be discussed are technical, environmental, and economic aspects to find what is the most efficient for each aspect.

1.3 Research question

Which benefits are there to increasing cable size from power produced by solar energy?

1.4 Delimitations

The study will focus on energy loss in cables in different diameters and materials. The materials that will be used in this study will be aluminum and copper. That's because these two materials are the ones that are used the most in electrical cables. The diameters that is going to be used in this study are going to be cable diameters that are listed in the table for maximum current for a specific cable for electrical installations onboard ships according to DNV-GL.

The temperature is an important factor when talking about cables. Temperature is also very difficult to get a value for because there are many factors to consider. Cables also behaves in different ways when there are different temperatures. When the temperature increases the resistance in the cable also increases making the energy losses larger in the cable. There will be a discussion about this later but for the calculations a temperature of 20℃ will be used in this study.

The cables used will have a lifespan of 20 years and are expected to have the same performance as in the calculations during this time. The lifespan is chosen because a ship's lifespan nowadays is around 20 years and cables are not reused on newer ships. The cable will be recycled for new cables that's why the lifespan on the cables in this study will be 20 years.

The voltage used in the system will be 440 V. That voltage is the voltage that is usually used onboard vessels. That's why this study only will use 440 V voltage in the systems.

This study will not use the solar panels for more than power production. The economic and environmental aspects for the solar panels will not be studied or presented.

There are many different greenhouse gases that are being emitted when relying on diesel generators for electricity, some of which are NO_x and SO_x. These will be converted to CO_2e and will discuss these emissions as CO_2 emissions instead and not take in to account the individual effects on these emissions.

2. THEORY

2.1 Solar panels

Solar panels use energy from the sun and converts it to electricity. Solar panels are made out of smaller solar cells that is the part that makes the electricity. These solar cells are composed of different layers of Silicone, Boron and Phosphorus, among other materials. Sunlight absorbs the photons to initiate an electric current between the different layers. This process is called Photovoltaic Effect and is the most efficient way to convert solar energy to electricity today. The efficiency of these solar panels varies depending on the technologies but most used are around 15-20%. (McEvoy et al., 2013)

2.2 Cable construction

The basis of cable construction is the conductor. Conductors can be in different materials. The cables are constructed for what the cables are going to be used for. Cable sizes are different for which current the cable is going to manage. When selecting cable size, a factor is the load current (Kirar, M. K & Aginhotri, G. 2012). Cable construction is so different because different cables must manage various currents. Some cables also must resist external influences such as weather. In this study the focus will be on power cables. Power cables are also constructed in different ways. There are two different types of power cables: “non-shielded cables” and “shielded power cables” according to (Shoemaker & Mack, 2017). The main difference between these two types is that the non-shielded cables are used for the lower primary voltage. The voltage in the non-shielded cables normally does not exceed a voltage of 7,200 V. The different parts in the non-shielded cables are conductor, insulation, and the cable jacket.

2.2.1 Conductor

The conductors are the center part of any cable. Conductors can be made in various materials. The different materials used for the conductor have various electric resistivity. Electric resistivity is how much flow that the material can resist. If the material has a high resistivity the material has a low flow through the material and if the resistivity is low, there is a higher flow of electricity. The most common conductors are copper and aluminum (Waseem et al., 2018). The reason why these are the most common material for the conductor is because both these materials have very low resistivity for the cost of the material (Heaney 2003). The low resistivity makes the flow of electric power though the cables easier. Resistivity of materials are affected by the temperature of the material. Materials can have a different resistivity if the temperature is different in the material. The resistivity of metals increases if the temperature increases (Heaney 2003). Resistivity is given for different materials with the same temperature, that temperature is 20℃. Resistivity has the unit of ohm meters [Ω m]. Resistivity for copper is 1.68 x 10-8 [Ω m] at 20℃ and the resistivity for aluminum is 2.82 x 10-8 [Ω m] at 20℃ (Helmenstine, 2019).

2.2.2 Insulation

The insulation mainly functions to prevent the electric flow. Insulations are designed to withstand mechanical, environmental, and electrical stress. (Shoemaker & Mack, 2017) The insulation is made with different materials. Insulator materials have low conductivity. Conductivity is the reverse of resistivity. So, if the material has a low resistivity the materials conductivity is high. Materials with a low conductivity are good to use as insulation. Materials used for insulation are porcelain, glass, fiberglass, and polymers (Shoemaker & Mack, 2017).

2.3 Energy losses in a cable

When power loss in cables is mentioned the main thing that is discussed is the heat loss in the cable, the cause for this is a phenomenon called Joule heating/Joule Lenz Law. Joule heating is the process where some of the energy going through a cable is converted into heat. This happens in resistive materials when sending an electric current through it, the heat is generated when the electrons from the current being sent through the cable collide with the conductor's electrons. This is the power loss that is most significant in cables when transferring energy and is what will be calculated. The formula that is used to calculate power losses in cable is:

$$P_L = 3 * I^2 * R \tag{1}$$

which gives an answer in energy loss over the cable. I is the current going through the cable and R is the resistance over the cable. The calculation of power losses in cable, see equation (2) were made according to (Waseem et al., 2018), but altered to suit this study.

3. METHOD

Analysis was made to see which benefits there are to changing cable size with the production from solar panels. The aspects that were analysed were technical, economic, and environmental aspects. The technical aspects were analysed to see how much energy can be saved with the change to a larger size cable. To be able to analyse technical aspects calculations were made to see how much energy losses there are in the cable. Equation (2) were made for this analysis. When the calculations were done the same calculations were made but with a larger size cable. The difference when a larger size cable was put in the calculations, was the resistance (R) in the equation (2). Resistance (R) are affected by the cross-section area of the cable (A) as can be seen in equation (3). The cross-section (A) is change for the different cable sizes. To analyse different materials in the cable the cable resistivity (ρ) was changed in equation (3). Cable resistivity (ρ) were different for the different materials. This will also change the resistance (R) in equation (2). When all the calculations were done the results were compared. The compensation was made to see which material and cable size has the least energy losses.

To see which benefits there are to changing cable size the environmental aspects were also analysed. Calculation of emission (4) was made to analyse the environmental aspects. The calculations were made to see the emissions over the lifespan of the cable. Calculations were made for the different cross section areas. In the calculations the difference was P_L from equation (2) and $E_{Production}$ from equation (4) for the different materials and cross section area. $E_{Production}$ for aluminum and copper cables are presented in Table 1. $E_{Generator}$ were the same for the different cable types. P_L were multiplied with $E_{Generator}$ to get the emissions from the generator that produced the power lost in the cable. $E_{Generator}$ are presented in Table 1. Analyses of the result from calculation (4) were made to see which cross section area released the least amount of emissions. Comparisons were also made to compare the different cable types to see which cable type has the least amount of emissions released.

Next aspect that was analysed was the economic aspect. The economic aspects were analysed to see which cable type was the most advantageous in an economic aspect over the lifespan of the cable. To analyse the economic aspect, calculations of cost (5) were made. The components of the calculation (5) were produced with inspiration from a study in the field (Jones & McManus, 2010). Calculations were made for the different cross section areas and different materials. The difference is that P_L from equation (2) and $C_{Purchase}$ from equation (5) will be different for the different cross section areas and materials. $C_{Purchase}$ are presented for the aluminum and coper cables in Table 1. $C_{Produce}$ will be the same for the different cable types. P_L were multiplied with $C_{Produce}$ to get what it costs to produce the power that are lost in the cable. $C_{Produce}$ are presented in Table 1. Analyses of the results were made to see which cross section areas were the most profitable. Comparisons between the cable types were made to see which material was most profitable.

3.1 Calculations of energy losses in cable.

The calculations of energy losses in cable are used to see how much energy losses there are in the cable. P_L are the energy losses in the cable over the lifespan of the cable [Wh]. I is the current in cable [A]. t is the time which in this case are the lifespan of the cable [Year]. R are the resistance of the cable [Ω]. ρ are the cable resistivity [Ω m]. L are the length of the cable [km]. A is the effective cross-sectional area of the conductor [mm^2].

$$P_L = 3 * I^2 * R * t \tag{2}$$

$$R = \frac{\rho}{A} * L \tag{3}$$

3.2 Calculation of emission

$E_{Emission}$ are the total emissions from the cable under the lifespan. $E_{Production}$ are the emissions that are released from the production of the cable. $E_{Generator}$ is the emissions from the generator to produce the energy lost in the cable.

$$E_{Emission} = E_{Production} + P_L * E_{Generator} \tag{4}$$

3.3 Calculation of cost

C_{Cable} are the cost of the cable over the lifespan. $C_{Purchase}$ are the cost of the purchase of the cable. $C_{Produce}$ are the cost of the energy produced by a generator to get the same energy that is lost in the cable.

$$C_{Cable} = C_{Purchase} + P_L * C_{Produce} \tag{5}$$

3.4 Ethical aspects

Ethical aspects that are considered with this method are that some of the values in the calculations are values from companies. Values from companies do not have to reflect reality. One value that is from a company is fuel consumption. That is a value that the company doesn’t want to share the real value because that can make the company look bad. Then when we use it, the emissions will be lower than the reality. Then we spread incorrect information and that's morally wrong. But to get values for the calculation the values must be studied or taken from companies. This study does not have the time or money to get the real values. This study will have this in mind when the results and discussion are presented.

The result from this study may look better than reality. This means that the result may look more promising than they actual are, then the author to this study would spread misleading information. Then if the results are tested or that the change to larger cables are made, the benefits may not be the same as the result form this study.

Changing to larger cables need more metals for the conductor. This means that there would be more mining of metals. The working conditions for the workers mining metals may not be that great. This will depend on were in the world the metals come from, some mines in the world may not have that great working conditions for the workers but other mines will have it. The author of this study has this in their mind when writing this study.

With the change to larger cables the cables will weigh more. This will mean that the workload on the workers working with the cables will be larger. The workload would affect the workers negatively such as injuries and tear on their bodies. The authors of this study will have this in mind and disuse this later in the study.

This study will only investigate the emission of CO_2, the study will not investigate other environmental impact. This means that there are other environmental impacts that doesn’t get mentioned or recognized as a problem. The authors of this study will have this in mind and discuss this later in the study.

4. RESULTS

In this part the inputs and the results from the equations are presented. First the inputs for the equations are presented then the results from the equations.

4.1 Inputs

The solar panel installations that are used in this study are 400 m^2 in area. The power produced from solar panels data is provided by Jimmy Ehnberg (Personnel Communication, 2022). The data provides measurement data from a solar panel installation in Gothenburg. Periods for the measurements are from 2016, the data are measured each hour. The power from the measurement data is presented in Table 1.

The current (I) are calculated with the power and the voltage. Current (I) that are used for the calculations are presented in Table 1.

In this study the diameters used are regulated by regulations from DNV. The regulations regulate the lowest allowed diameters for a current from an electric installation. Lowest diameter used in this study is the lowest allowed diameter from the regulations. The diameters for aluminum and copper cables are presented in Table 1.

Resistivity (ρ) used in equation (2) for aluminum and copper are presented in Table 1.

The cable length (L) used in equation (3) is 1 meter so that the results are presented per meter cable.

$C_{Purchase}$ in equation (5) are the purchase cost of the cables. $C_{Purchase}$ for aluminum and copper cable are presented in Table 1.

The price of fuel for Marine Diesel Oil (MDO) are presented in Table 1. Price of fuel is taken from Rotterdam. That's because Rotterdam is the nearest port where the fuel price is presented. The fuel price is presented in dollars from (Rotterdam bunker prices, 2022) to get the price in SEK the exchange rate are set to 1 dollar = 10 SEK. The fuel price used are presented in Table 1.

The generator used in this study is a Wärtsilä 20 using MDO as fuel, the fuel consumption of this specific engine is presented in Table 1.

$C_{Produce}$ in equation (5) are the cost of fuel price multiplied with the fuel consumption which is like the electricity price but onboard on a ship. $C_{Produce}$ are presented in Table 1.

$E_{Production}$ is from a study in the field Bao et al. (2017) which provides a life cycle assessment on copper and aluminum cables. To get only the emission from the production of the cables, 98% from the total result was extracted. 98% was used because Bao et al. (2017) explains that 98% of the total results are from the cable's production. The values used for $E_{Production}$ are presented in Table 1 which are per meter cable.

$E_{Generator}$ are the emissions from the generator producing the energy lost in the cable. $E_{Generator}$ are presented in Table 1 for the fuel MDO (Marine diesel oil).

Table 1. Input data for the calculations

Inputs	Values	Reference
Power (P)	79 [kW]	
Current (I)	103 [A]	
Diameters Copper cables	35 - 400 [mm^2]	(DNV, 2021)
Diameters Aluminum cables	50 - 500 [mm^2]	(DNV, 2021)
Resistivity Aluminum (ρ)	2.82×10^{-8} [Ω m]	(Helmenstine, 2019).
Resistivity Copper (ρ)	1.68×10^{-8} [Ω m]	(Helmenstine, 2019).
$C_{Purchase}$ Aluminum	0.126 per mm^2 [SEK]	(EBR,2020)
$C_{Purchase}$ Copper	0.88 per mm^2 [SEK]	(EBR,2020)
Price of fuel	11510 SEK/ton	(Rotterdam bunker prices, 2022)
Fuel Consumption	190,0 g/kWh	(Wärtsilä, 2020)
$C_{Produce}$	0,002187 SEK/Wh	
$E_{Production}$ Aluminum	0,00166 kg/CO_2e per mm^2	(Bao et al, 2017)
$E_{Production}$ Copper	0,00198 kg/CO_2e per mm^2	(Bao et al,2017)
$E_{Generator}$	0,65 CO_2 kg/kWh	(Winnes & Fridell.,2009)
Density copper	8,96 g/cm^3	(Density of Metals and Alloys, 2005)
Density aluminum	2,69 g/cm^3	(Density of Metals and Alloys, 2005)

4.2 Energy losses over the lifespan

Figure 1 shows the energy losses over the lifespan per meter cable of the different sized aluminum and copper cables. The cross-section area is shown in the x-axis and the energy losses are shown in the y-axis. Aluminum cables is the blue colored line and copper cables are the red colored line. As seen in Figure 1 the energy losses for aluminum and copper cables are at its highest point at the smallest allowed cross section area. Then the energy losses steadily decreasing as the cross-section area is increased according to Figure 1. The energy losses for aluminum cable at a cross section area of 50 mm^2 is 9457,8 [Wh] and at cross section area of 500 mm^2 the energy losses are 945,8 [Wh]. Energy losses for copper cable at cross section area of 35 mm^2 is 8769,5 [Wh] and at cross section area of 400 mm^2 the energy losses show 767,3 [Wh].

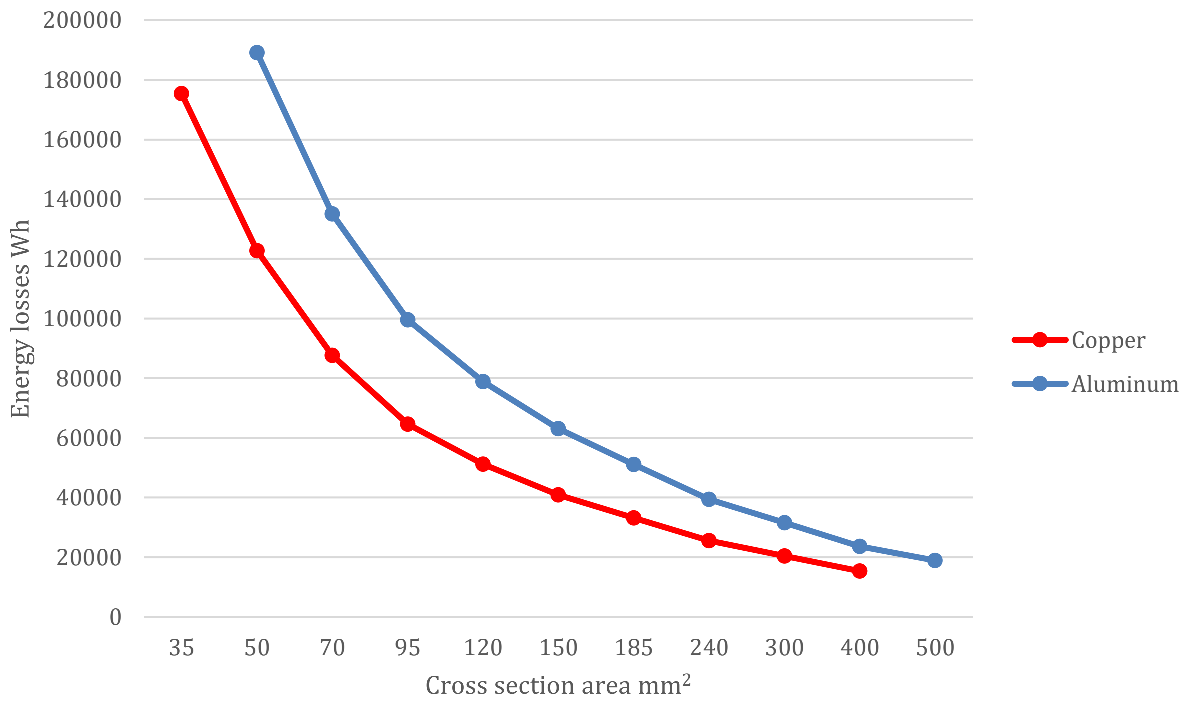

Figure 1: Energy losses from aluminum cables and copper cables at different cross section areas over 20 years.

4.3 Emissions over the lifespan

Figure 2 shows the emissions from aluminum and coper cables over the lifespan per meter cable. Cross section area of the cable can be seen on the x-axis and kgCO_2e on the y-axis. Aluminum cables is the blue colored line and copper cables are the red colored line. Emissions over the lifespan get lower from the smallest allowed cross section for aluminum and copper cables. Emissions over the lifespan for aluminum cables gets lower until cross section 300 mm^2 as can be seen in Figure 2. After cross section 240 mm^2 the emission over the lifespan starts to increase again for aluminum cables. As can be seen in Figure 2 the emission over the lifespan decreases for copper cables until cross section area 185 mm^2, then the emissions over the lifespan start to increase again. For aluminum and copper cables the most emissions over the lifespan comes from the smallest allowed cross section as can be seen in Figure 2.

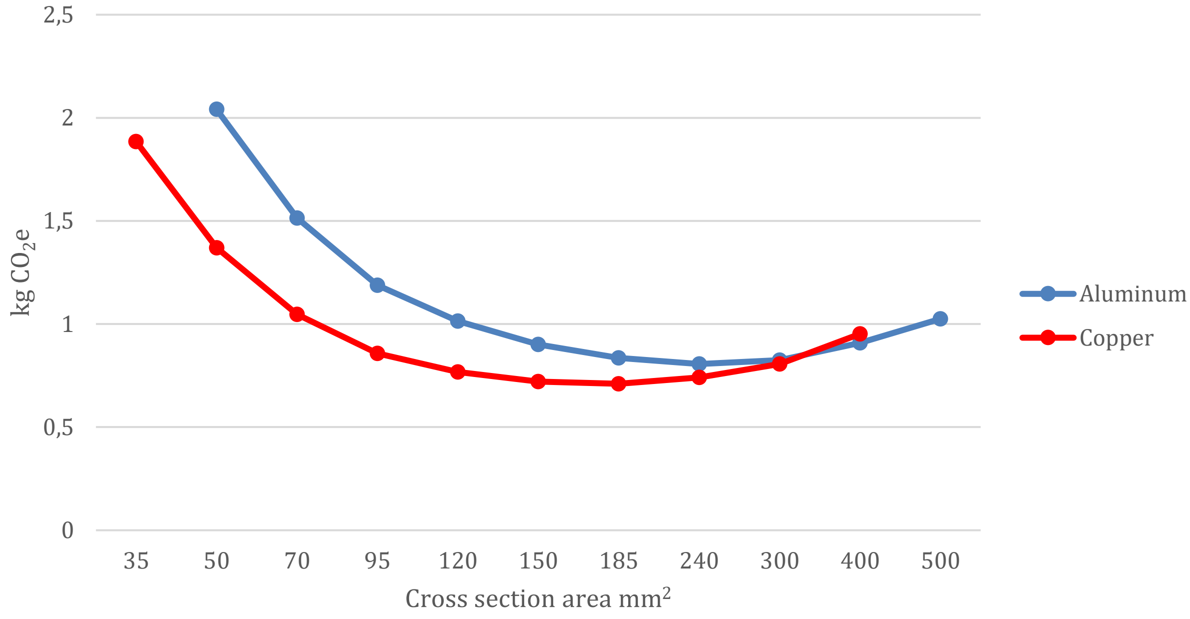

Figure 2: Emissions at different cross section areas over the lifespan from aluminum cable and copper cable.

4.4 Life cycle cost

Figure 3 shows the cost for aluminum and copper cable over the lifespan per meter cable. The cable cross section area can be seen on the y-axis and the cost on the x-axis. Aluminum cables is the blue colored line and copper cables are the red colored line. In Figure 3 there can be seen that the life cycle cost for aluminum cables is becoming lower from the lowest allowed cross section area until the cross-section area of 400 mm^2. After cross section area of 400 mm^2 the costs increase for aluminum cables. The lowest life cycle cost for aluminum cables is for cross section 400 mm^2 as can been seen in Figure 3. For copper cables the lowest life cycle cost is for cross section 120 mm^2 as can be seen in Figure 3. Aluminum and copper have the highest life cycle cost at the smallest allowed cross section. It’s interesting to notice that the largest cross section for aluminum and copper cables are not the cross section with the highest life cycle cost as can be seen in Figure 3.

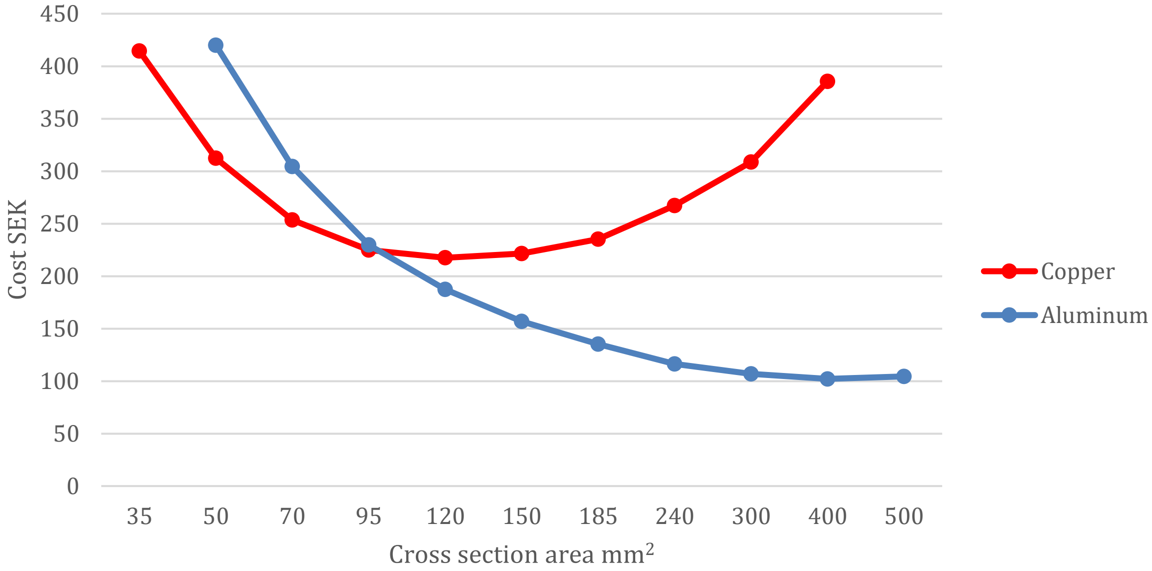

Figure 3: Life cycle cost over 20 years from aluminum and copper cable at different cross section areas.

5. DISCUSSION

This part of the study is discussion. The discussion will start with the method in which the inputs and the calculations are discussed. Then the results from the calculations are discussed. The result discussion starts with energy losses over the lifespan, then the emission over the lifespan. Then there will be discussion on the life cycle cost. The discussion part will end with discussion on other advantages and disadvantages on larger cable sizes.

5.1 Method

Method used to study the research question was to calculate different aspects of different cable cross section areas and different materials. This method worked well to answer the research question. The downside to this method is that the use of values from companies and research may not reflect the actual values. This can mean that the result from this method may not be reliable to the actual values. The method also just shows results from specific cases because the calculations need specific values.

5.1.1 Inputs

The solar panels area in this study are 400m^2. The area may not reflect the area that can be used on board to fit solar panels. Area of the solar panels has a big effect on the power produced by the solar panels. This means that if the area is lower than 400m^2 the power produced by solar panels will be lower than seen in this report. The power produced can also be larger than the power produced in this report. Results in the report will be affected if the area of the solar panels are larger or smaller. Power produced by the solar panels also is affected by where the solar panels are located, if the solar panels are on a sunny location there will be more power produced by the solar panels. The location of the solar panels is in Gothenburg. Gothenburg is not famous for being the sunniest location in the world. This means that the power produced from the solar panels can be higher, which would have affected the results. The location is a big factor when looking at the power produced by the solar panels. Solar panels can be tilted for a higher power produced, which means that the result would be different if the solar panels are tilted or not this would also affect the result. The result would be affected just because then there would be more power produce by the solar panels. This would mean that there would be more energy losses, which means that there can saved more energy with changing to a larger cable size. Environmental and cost results would also be affected by larger power production by the solar panels. In an environmental aspect there would be more emissions released from the generator, which means more emissions released overall. This will mean that the change to a larger cable would have a greater impact on the overall emission released. In a cost aspect the overall cost would also be affected by larger power produced by the solar panels. The overall cost would be greater with larger power produced. The impact from changing to a larger cable size would be greater as they would be for the environmental aspect.

Voltage will affect the current that is used. The voltage that is used is 440V. This voltage is commonly used onboard ships all over the world. But the voltage will affect the current used. The current used will affect which cross section area used for the cables. Energy losses in the cables would also be affected by the current. There would have been less energy losses if the current would have been lower. If the current would have been higher the energy losses would be higher. This means that the result would have been affected and not the same as the result shows.

Emissions from the transportation of the cables are not a part of the calculation of emission. Emissions from transportation will be the same for the different cable types and the different cross sections. Then the emission would not affect the result more than that the total emission would be higher. The figures would have looked the same for the result. One other component that isn't in the calculations that would affect the result is that the recycling of the cable. Recycling the cables would lower the emission from the cable. This is because then the materials and part of the cable could be used again, which means the emission from the cable would be lower. This means that the emission could be decreased if the recycling process would be in the calculation of emission. The result for emissions would be affected if the recycling process would be in the calculations. Recycling process would affect the result with which cross section area that has the lowest amount of emission released. The cross section for the lowest amount of emission released would have been a smaller cross section area if the recycling process would be in the calculation of emissions. This means that the optimum cable size in an environmental aspect would have been smaller if the recycling process would have been in the calculation of emissions. Then there would be less emissions released with smaller cross section areas.

The fuel that is used is MDO, the emission from the fuel will affect the result. If there would be another fuel used for the generator the emission from the fuel would be different. Emission from the cable production $E_{Production}$ in calculation 2 would have been affected if there was another fuel used for the generator. $E_{Production}$ will have an impact on the result if the value would be higher or lower. These values are from a study in the field which can’t guarantee that the value reflects reality. This means that the result from the calculation of emission could be higher or lower in reality. Which can mean that the result looks better than reality or worse than reality.

There are many types of emissions. In this study there are only CO_2 emission analyzed. This means that the overall emission from aluminum and copper cables would be higher if there would be more emissions analyzed. Which means that the result from the emission calculations would be higher if the other emissions was in the calculations.

The fuel price has a big impact when calculating the cost over the lifespan for the different cable types. Fuel price will vary day to day. The fuel price can also differ from different locations. Some locations have a lower price on fuel than others. This means that the result will differ for different fuel prices. If the fuel prices are higher than the fuel price used, then cost would have been higher and if the fuel price would have been lower the cost would have been lower. The fuel prices are also higher than just because ships can get a lower price than the price used. This is because shipowners can get better prices on fuel than what is available to the public. Another reason is that fuel companies don't want to release their fuel price to the public. This means that the fuel price used can differ from what was used in the calculations. This will affect the result and show that the cost will be higher than reality.

Purchase costs as can be seen in Table 1 are also not a reflection of reality. This is because when buying large amounts of cables from the same manufacturer the price usually gets cheaper than the prices available to the public. The diesel generator that is used for generating the power losses is in new condition. This means that the fuel consumption can be higher than the fuel consumption presented this can be because of wear. If the fuel consumption is higher than the cost for the generated power will be higher.

Lifespan of the cables are set to 20 years. This is a long period, some of the parameters that are used for the equations can be change over this period. For example, fuel price can be very different from the fuel price used in the equations. This means that result from the life cycle cost can be different, if the fuel price is higher than the overall cost would look higher for the cables life cycle cost. Same thing for if the fuel price were lower than the overall cost would be lower for the cable's life cycle cost. Another parameter that can be affected can be the fuel consumptions of the generator. This can be changed with the wear of the generator or if the generator is exchanged to a newer model. The generator could be affected be wear this would affect the life cycle cost, the wear would make the fuel consumption higher. This would make the life cycle cost for the cables higher. If the generator is exchanged to a newer model the affect would probably be that the fuel consumption would be lower. Which would lower the life cycle cost of the cables.

Over the period of 20 years, there can also be other changes such as regulation changes. If there are regulation changes this could affect which cross section area that are used for cables. This would mean that the results would be different. Probably there would only be added cross section area that can be used for the cable. This can mean that there would be more diameter to use for the cables. This would not affect the current result as much, just because the current diameter would probably still be in the regulations. Another regulation that can be changed over the lifespan could be regulations over which fuels that are in use. This would mean that there would be another fuel in use. This would affect the result in the emission and the life cycle cost. The emission would be affected because the new fuel would probably be better in an environmental aspect. This would mean that the emissions from the cables would be lower overall. If the fuel is change there would also the cost be affected, if the new fuel has a lower cost than would the life cycle cost for the cables be lower. If the cost for the fuel would be higher than the life cycle cost for the cable would be higher. There are lots that can happen over the lifespan of the cables which would affect the results.

5.1.2 Calculations

The calculations used would have more parameters. Some of the parameters from reality are not included in the calculations. The parameters not used in the calculations are values that would have been the same for the different cable sizes and cable types. Some examples are emission for transportation of cable or the installation cost. Emissions for the transportation of cable would have been the same for the different cables. This is because the cables would not be transported by themselves and the emission from transportation would not be affected by the different cable types. This means that Figure 3 would have looked the same, only difference would have been the exact values for the different cross section areas. Installation cost would have the same effect on Figure 4. Just because the installation cost would have been the same for the different cables. Another parameter that would affect the result are the temperature factor. The temperature factor is not a parameter in the equations, but this parameter would affect the result. The reason why the temperature would affect the results are that with a temperature change in the cable, the resistivity would be affected with a temperature change. If the temperature would be higher the resistivity would as be higher. This means that there would be more resistance in the cable. Which means that there would be more energy losses in the cable. If there would be more energy losses this would also affect the emissions and the life cycle cost. The parameters used in the calculation are the components that will affect the result the most because these components vary from the different cable sizes and cable types.

5.2 Energy losses over the lifespan

Energy losses get lower when the cable has a larger cross section area as can been seen in Figure 1. This means that there are less energy losses with larger cable sizes. Which means that there is more energy gained with larger cable sizes. When comparing aluminum and copper the only difference is that aluminum has more energy losses then copper. This means that there is less energy lost with copper as the conductor in the cable. There are less energy losses for all different cross section areas. Both aluminum and copper get less energy losses with a larger cross section area as seen in Figure 1.

5.3 Emission over the lifespan

Emissions from the cable gets lower when the cable cross section is changed to a larger cross section for both aluminum and copper cables as can be seen in Figure 2. The emission for aluminum cables decreases from the lowest allowed cross section until cross section 240 mm^2. This means that 240 mm^2 are the best cross section in an environmental aspect for aluminum cable over the lifespan. From this cross section the emissions start to increase again. For copper cable the cross section with the lowest emission is 185 mm^2 as can be seen in Figure 2. This means that 185 mm^2 are the best cross section in an environmental aspect for copper cables over the lifespan. The cross section with the lowest emission is different for aluminum and copper cables. Copper cable has a smaller cross section for the lowest emission then aluminum. This means that copper has a smaller cross section optimum in an environmental aspect. When comparing aluminum and copper cables, copper cables have less emission released until cross section 400 mm^2 where copper cables have more emission released then aluminum cables. This means that copper cables have less overall emission released over the lifespan until cross section 400 mm^2. Emissions get lower when changing to a larger cable size for both aluminum and copper cables as can be seen in Figure 2. It's interesting that the lowest allowed cross section for both aluminum and copper cables has the higher emission release over the lifespan. This means that the emission can get lower just by changing to a larger cable from the lowest allowed cross section. If the cables are changed to a larger cross section, then the emission will get lower. This means that the overall emission could get lower with changing to a larger cross section. As can be seen in Figure 2 the larger cross section used have a lower emission released then the lowest allowed cross section for both aluminum and copper cables. This means that changing cable from the lowest allowed cross section to 400 mm^2 cross section would lower the emission released for both aluminum and copper cables over the lifespan. The overall emission could then be lowered if the cables are changed to a larger cable size. This means that in an environmental aspect it's better to change the cable to a larger cross section cable then the lowest allowed cross section. This means that the overall emissions from solar panels can get lower with the change to a larger cable size.

The result from the emissions would be higher if there were other emissions analyzed. This means that the overall emissions would be higher. The figure would look the same but the emission from each cables size would be different.

5.4 Life cycle cost

Life cycle cost are becoming lower when changing to a larger cross section for both aluminum and copper cables as can be seen in Figure 3. For aluminum cables the life cycle cost is the lowest when the cross section is 400 mm^2 as can be seen in Figure 3. Then the life cycle cost starts to increase. Life cycle cost for copper cables is the lowest when the cross section is 120 mm^2 then the life cycle cost starts to increase again. This means that in an economic aspect the best cross section for aluminum cables is 400 mm^2 and for copper cables the best cross section is 120 mm^2. This means that aluminums optimum cross section is larger than coppers optimum cross section. Both aluminum and copper cables have a lower life cycle cost when changing to a larger cross section then the lowest allowed cross section as can been seen in Figure 3. Aluminum and copper cables has the highest life cycle cost when the cross section is the lowest allowed cross section. This means there are economic benefits over the lifespan when changing the cable to larger cables size from the lowest allowed cross section. As can been seen in Figure 3 the largest cross section used are 500 mm^2 for aluminum cables and 400 mm^2 for copper cables doesn't have the highest life cycle cost. This means that the change from the lowest allowed cross section to any of this cross section there will still be benefits in an economic aspect for both cable types. Then there can be money save over the lifespan of the cables if there are a change to a larger cross section form the lowest allowed cross section. The profit can be invested in sustainability solutions such as solar panels. This also shows that there can be more profits with solar panels, because then the overall cost of the solar panel installation will be lower.

When comparing aluminum and copper cables, the difference is that copper has a lower life cycle cost when looking on cross section 50mm^2, 70mm^2 and 95mm^2 but aluminum has a lower on the other cross section. This means that if the cable has any of this cross section, copper cables have a lower life cycle cost then aluminum cable. If the cables have any of the other cross section, the life cycle cost are lower with an aluminum cable as can been seen in Figure 3. Aluminum cables has the lowest overall life cycle cost when analyzing all the cross sections. This means that aluminum cables are the most profitable in an economic aspect. Aluminum cable are the best when comparing with copper cables in an economic aspect. Just because an aluminum cable has a lower life cycle cost when the cable size is 95 mm^2 or higher. This means that an aluminum cable with a cross section of 400 mm^2 have a lower life cycle cost then all the cross section for a copper cable. This means that there are more cost benefits with changing to larger aluminum cable then changing to a larger copper cable. Even though there are cost benefits with changing to a larger cable size for both aluminum and copper cables from the lowest allowed cross section.

5.5 Advantages of a larger cable

This part will explain some other advantages with a larger cable size onboard ship. These are other aspects than the ones already shown in the result. These advantages will be shortly explained to shown that the are other advantages onboard ship with a larger cable size, starting with voltage drop. When a current is being sent through a cable there will be a slight voltage drop over the cable. When increasing the size of the cable the voltage drop will drop, making the system more efficient. Voltage drop can also lead to malfunctions in some components and poor performance. All of this will be avoided when cable size is increased.

When using a larger cable size there are better possibility to use the same cable for future electric installations. The reason why the possibilities are becoming better are because then the cable will be able to manage the workload from the installations. This makes the cable more flexible for future installations. A larger cable also ensures that the cable will have a smaller chance to fail if the cable gets damaged by something during the installation for example. This means that a larger cable size is more reliable than a smaller cable size.

A larger cable will manage power spikes better then smaller size cables. With installing a larger cable comes an increased capacity of the cable, which will help dealing with short term power spikes in the cables. This also means that a larger cable can handle more load for a longer period. This might not be needed all the time but can be useful in some situations for example if some electrical equipment fails and short circuits, the cable won't be damaged as bad as if it was a smaller cable.

When operating a ship all spare parts need to be available onboard in case something would happen. The benefit of increasing cable size is that you can have more of the larger cable onboard and still use it for smaller installations without any downside. This means that the smaller cables can be exchanged by the larger cable to make it easier onboard to choose cable for the installation. This can make it so the ships don't have to keep many different cable sizes for different installations and instead have one or two bigger cable sizes that will work for all installations.

5.6 Disadvantages of a larger cable

This part will explain some other disadvantages with a larger cable size onboard ship. These disadvantages will be explained shortly just to show that there are some disadvantages with a larger cables size.

When only having larger cables onboard and they are needed for something it will be harder to install and move them because of the weight. This also means that running a larger cable through a small cable gland or having to pull the cable up several stories the workload will be higher which might lead to injuries on the crew because of the weight of the cable. It is obvious that a larger cross section cable will weigh more than a small cross section area cable but when comparing copper and aluminum cables things start to get interesting. The density of copper 8,96 g/cm^3 and the density of aluminum is 2,69 g/cm^3. This means that any cross-section area of a copper cable will be ~3 times heavier than an aluminum cable of the same cross section area, this makes working with aluminum cables a lot easier and better for the crew than working with copper cables (Density of Metals and Alloys, 2005).

6. CONCLUSION

The aim of this study was to determine if increasing cable size in a solar panel installation onboard had any benefits regarding environmental and economic aspects. A total of 10 different cross section areas were analyzed for aluminum and copper each, which was compared to find the best environmental option and the most cost-effective option. The results show that there are significant benefits to increasing cable size both for the environmental aspect as well as the cost aspect. The result also shows that the cheapest point is not the best for the environmental aspect and vice-versa. The results and discussion also show that aluminum cables are easier to work with and the aluminum cables are by far the better choice when looking at the cost.

6.1 Recommendations for further research

There are some recommendations for further research that the authors want to mention. One recommendation is to do on site measurement of the energy losses on the cables. If the measurements are done on site, then the result would reflect the reality better. The energy losses would also have more exact values. Measurement would mean better values for the rest of the equations. Another recommendation would be to have more parameters in the equations to get a better reflection on reality. One parameter that can be change for better results would be to take the fuel price over a period. This study only looks on the fuel price for a specific day but if the fuel price would be over a period, then the fuel price would vary from day to day. This means that the fuel price would reflect reality better if the fuel price is over a period. Another recommendation would be to do research on different fuel for the generator. Then if there are some changes in the regulation of the fuel for generators. There would also have a result that can reflect other fuel. Then if the generator has another fuel the result would reflect this fuel also.

Other recommendations for further research would be to research the recycling process. In this way the result from the emission would reflect reality better. The recycling process would also affect the result greatly, then there would affect the emissions results. Then the emissions results would reflect reality better and the cables would have more benefits in an environmental aspect. For further research there would be good with more research on other emissions from the cable. It would mean that the emission would reflects all the emissions from the cables not only the CO_2 emission. There are more emissions from the cables that also affect the environmental aspect. Another recommendation would be to research the temperature as a parameter in the equations. Then the results would reflect reality better because the cable are not always 20°C which are the temperature that the resistivity are taken for aluminum and copper. Then if the cable has another temperature the resistivity would be different from the resistivity that are used. This would affect the results and if the temperature would be a parameter, then there would be a result that reflect reality better.

REFERENCES

Boden T; Marland G; Andres R J (1999): Global, Regional, and National Fossil-Fuel CO2 Emissions (1751 - 2014) (V. 2017). Carbon Dioxide Information Analysis Center (CDIAC), Oak Ridge National Laboratory (ORNL), Oak Ridge, TN (United States), ESS-DIVE repository. https://doi.org/10.3334/CDIAC/00001_V2017

Shoemaker, T. M. & Mack, J. E. (2017), The Lineman's and Cableman's Handbook (13th Edition), McGraw-Hill Education.

Waseem, M., Khan, R., Zakria, M., Jamal, S. Perveen, S. (2018). Optimized cable sizing – an economical approach to energy saving with reduced power loss. 2018 International Conference on Power Generation Systems and Renewable Energy Technologies (PGSRET). https://doi.org/10.1109/pgsret.2018.8685987

Jones, C. I., McManus, M. C. (2010). Life-cycle assessment of 11kV electrical overhead lines and underground cables. Journal of Cleaner Production, 18(14), 1464–1477. https://doi.org/10.1016/j.jclepro.2010.05.008

Bao, W., Lin, L., Song, D., Guo, H., Chen, L., Sun, L., Liu, M., Chen, J. (2017). Comparative study on life cycle environmental impact assessment of copper and aluminum cables. IOP Conference Series: Earth and Environmental Science, 94, 012166. https://doi.org/10.1088/1755-1315/94/1/012166

Heaney, M. B. (2003), Electrical Conductivity and Resistivity, J.G Webster (Red), Electrical Measurement, Signal Processing, and Displays. (ss. 142 - 149), CRC Press. https://doi.org/10.1201/9780203009406

Helmenstine, A. M. (2019, June 16). Table of Electrical Resistivity and Conductivity. Thoughtco. Retrieved Mars 28, 2022, from https://www.thoughtco.com/table-of-electrical-resistivity-conductivity-608499

Rozegnał, B., Albrechtowicz, P., Mamcarz, D., Rerak, M., Skaza, M. (2021). The power losses in cable lines supplying nonlinear loads. Energies, 14(5), 1374. https://doi.org/10.3390/en14051374

McEvoy, A., Markvart, T., Castañer Luis. (2013). Solar cells materials, manufacture and operation. Elsevier.

EBR. (2020). EBR Kostnadskatalog 2020 Lokalnät 0,4-24 kV samt optonät.
In-text: (EBR, 2020) sid 38-39

DNV.(2021). Part 4 Systems and components Chapter 8 Electrical installations, Retrieved April 3, 2022, from https://rules.dnv.com/docs/pdf/DNV/RU-SHIP/2021-07/DNV-RU-SHIP-Pt4Ch8.pdf

Wärtsilä.(2020). Wärtsilä 20 [Fact sheet]. Retrieved Mars 2, 2022, from https://www.wartsila.com/marine/products/engines-and-generating-sets/diesel-engines/wartsila-20

Initial IMO GHG strategy. International Maritime Organization. (2018). Retrieved Mars 4, 2022, from https://www.imo.org/en/MediaCentre/HotTopics/Pages/Reducing-greenhouse-gas-emissions-from-ships.aspx

Fourth IMO GHG Study 2020. IMO. (2020). Retrieved April 22, 2022, from https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Fourth%20IMO%20GHG%20Study%202020%20-%20Full%20report%20and%20annexes.pdf

Rotterdam bunker prices. (2022). Ship & Bunker. Retrieved April 7, 2022, from https://shipandbunker.com/prices/emea/nwe/nl-rtm-rotterdam#MGO

Hulda Winnes & Erik Fridell (2009) Particle Emissions from Ships: Dependence on Fuel Type, Journal of the Air & Waste Management Association, 59:12, 1391-1398, DOI: 10.3155/1047-3289.59.12.13

Kirar, M. K., Aginhotri, G. (2012). Cable sizing and effects of cable length on dynamic performance of induction motor. 2012 IEEE 5th Power India Conference, PICONF 2012. https://doi.org/10.1109/POWERI.2012.6479482

Density of Metals and Alloys. (2005). ASM Handbooks Online. Retrieved May 13, 2022, from https://dl.asminternational.org/handbooks/edited-volume/25/chapter/347147/Density-of-Metals-and-Alloys

DEPARTMENT OF MECHANICS AND MARITIME SCIENCES
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden, 2022
www.chalmers.se

CHALMERS